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TSSG

Bio-Inspired Routing and Resource Management for Future Networks

Thesis submitted in partial fulfilment of the requirements for the award of *Doctor of Philosophy*

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Declaration

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Doctor of Philosophy, is entirely my own work and has not been taken from the work of others save to the extent that such work has been cited and acknowledged within the text of my work.

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Abstract

Communication systems have continually played a major role in our lives. In particular in recent years, the Internet has transformed the way people interact and communicate, which has led to increased number of services and functionalities. However, with the increase in changes in network environments, more adaptive, flexible, efficient and scalable techniques are needed to enhance the operation of the network, and at the same time minimise human intervention. The communication network management community have addressed this problem, through the notion of "autonomic network management". One particular approach of addressing autonomic mechanisms is by borrowing mechanisms and processes that are exhibited by biological systems (e.g. reaction to changes in their environments).

This thesis has investigated new bio-inspired solutions that are able to address the challenges of the Future Internet. The thesis will present new bio-inspired mechanisms to provide (i) efficient routing, (ii) energy-aware networking, (iii) adaptive bandwidth allocation and (iv) support of multiple service providers. In the case of (i), the bio-inspired routing protocol is scalable and supports complex and highly dynamic services environments efficiently and robustly (e.g. dynamic traffic, large scale networks). The bio-inspired energy awareness in (ii) is maximising the benefits of the solution in (i) to reduce dramatically the energy consumption of infrastructure networks without disrupting the delivery of services. In the case of (iii), a bio-inspired bandwidth allocation mechanism adapts to new traffic conditions in order to maintain the quality of delivery for prioritised traffic in the event of bandwidth starvation. Lastly in (iv), the new architecture of the Internet, requiring efficient and fair resource allocation between multiple service providers sharing common physical resources, will be provided by an adaptable and flexible bio-inspired model.

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I would like to express my deepest gratitude and appreciation to my supervisors, Dr. Sasitharan Balasubramaniam, Dr. Dmitri Botvich and Dr. William Donnelly, for their guidance and encouragements throughout my PhD. In particular, Dr. Sasitharan Balasubramaniam for giving me the opportunity to study within the TSSG, and abroad. Without him, this research would have not existed.

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List of the Author's Publications

This thesis consists of this introductory part and the following eight original peer-reviewed publications, as well as two additional articles currently in a peer-review process for journal publication (Articles IV and V), presented in chronological order, grouped by research themes and reprinted at the end of the thesis. However, the first publication of this list has not be included in the Appendix since the extended version is in Article VII.

PGBR Support for Service-Oriented Architecture

Article: Sasitharan Balasubramaniam, Dmitri Botvich, Julien Mineraud and William Donnelly, "Parameterised Gradient Based Routing (PGBR) for Future Internet," In the proceedings of the *2009 International Conference on Advanced Information Networking and Applications (AINA '09).* IEEE, 2009, pp. 58–65 (*this paper is not added to the Appendix, since the extended version is in Article VII*)

> *Contribution:* My contribution to this research article is the design, the development and the implementation of the bio-inspired routing protocol "Parameterised Gradient Based Routing (PGBR)", as well as conducting all the experiments. I took also part in the review process, and was the presenter of the article at the AINA '09 conference in Bradford, UK.

Article I: Sasitharan Balasubramaniam, Dmitri Botvich, Ray Carroll, Julien Mineraud, William Donnelly, Tadashi Nakano and Tatsuya Suda, "Adaptive dynamic routing supporting service management for Future Internet," In the proceedings of the *2009 IEEE Global Telecommunications Conference (GLOBECOM '09)*. IEEE, November 2009, pp. 4926–4932

Contribution: My contribution to this research article is related to the routing protocol PGBR, which is part of a dual-layer solution for efficient service management for the Future Internet. For this research article, I personally designed the set of experiments to evaluate the performances of PGBR as well as the combined solution. In addition, I investigated a new model to dynamically adapt the parameters of the routing protocol depending on the load of the network. I also took part in writing some parts of the paper as well as proof reading.

Article II: Sasitharan Balasubramaniam, Dmitri Botvich, Ray Carroll, Julien Mineraud, Tadashi Nakano, Tatsuya Suda and William Donnelly, "Biologically inspired future service environment," In *Computer Networks*, vol. 55, no. 15, pp. 3423–3440, October 2011

Contribution: This article is an extension of Article I. Consequently, my contribution also relies in the evaluation of the PGBR routing protocol to support dynamic service management via a fully bio-inspired solution. In order to evaluate the routing protocol more in depth, I implemented a version of the back-pressure routing protocol for wired networks and compared it to PGBR and OSPF using the ns-3 network simulator. Parts of my contribution also include the writing of the routing section in the paper as well as conducting all of the experiments for the routing and the combined solution.

Article III: Julien Mineraud, Sasitharan Balasubramaniam, Jussi Kangasharju and William Donnelly, "Fs-PGBR: a scalable and delay sensitive cloud routing protocol," In the proceedings of the *ACM SIGCOMM 2012 conference on Applications, technologies, architectures, and protocols for computer communication.* Pages 301–302, ACM New York, NY, USA, 2012

> *Contribution:* My contribution to this research article is the development of a new normalised hop count metric to enhance the performances of route discovery of PGBR. The contribution includes the writing of the article, as well as performing all the experiments for the evaluation of the new metric.

Energy Management using PGBR

Article IV: Julien Mineraud, Sasitharan Balasubramaniam, Jussi Kangasharju and William Donnelly, "Parameterized Green Gradient Based Routing (PG^{2}BR) for an Energy Efficient Internet," Submitted

> *Contribution:* My contribution to this research article is the development of the PG^{2}BR protocol to efficiently save energy in wired core infrastructure networks. The contribution also includes the writing of the article, as well as performing all the experiments to evaluate the new protocol. These experiments also include a sensitivity analysis of PG^{2}BR.

Article V: Julien Mineraud, Liang Wang, Sasitharan Balasubramaniam and Jussi Kangasharju, "Reducing Data Center Energy Use Via Renewable Energy Aware Routing and In-Network Caching," Submitted

Contribution: My contribution to this research article is the development of the rePGBR protocol that favours routes with highest green renewable energy usage. The contribution also includes the writing of the article but the sections related to content caching, while the experiments were collected cooperatively with PhD student Liang Wang.

Bandwidth Management via BiRSM

Article VI: Sasitharan Balasubramaniam, Dmitri Botvich, Julien Mineraud, William Donnelly and Nazim Agoulmine, "BiRSM: bio-inspired resource self-management for all IP-networks," In *IEEE Network*, vol. 24, no. 3, pp. 20–25, May 2010

Contribution: My contribution to this research article was the development and the implementation of the bandwidth management protocol, as well as conducting all the experiments and collecting the results. I also took part in writing some parts of the paper, as well as proof reading.

Management of Multiple Providers

Article VII: Sasitharan Balasubramaniam, Julien Mineraud, Patrick Mcdonagh, Philip Perry, Liam Murphy, William Donnelly and Dmitri Botvich, "An Evaluation of Parameterized Gradient Based Routing With QoE Monitoring for Multiple IPTV Providers," In *IEEE Transactions on Broadcasting*, vol. 57, no. 2, pp. 183–194, June 2011

Contribution: My contribution to this research article is the development of the PGBR routing protocol. In order to evaluate the routing protocol, I also implemented a well-known bio-inspired routing protocol known as Ants. I was responsible of the full evaluation of the routing protocol, as well as the integration to the complete solution. Quality-of-Experience results where obtained in cooperation with PhD student Patrick McDonagh. Finally, parts of the contribution also include the writing of some parts of the paper, as well as proof reading.

Article VIII: Sasitharan Balasubramaniam, Julien Mineraud, Philip Perry, Brendan Jennings, Liam Murphy, William Donnelly and Dmitri Botvich, "Coordinating allocation of resources for multiple virtual IPTV providers to maximize revenue," In *IEEE Transactions on Broadcasting*, vol. 57, no. 4, pp. 826–839, December 2011

Contribution: My contribution to this research paper is the adaptation of the Lotka-Volterra inter-species competition model to the allocation of resources for multiple service overlays sharing common resources. I was also responsible of conducting the experiments for the evaluation of the model. I also took part in the writing of that article.

Simulation Environment

Article IX: Julien Mineraud, "An implementation of Parameterised Gradient Based Routing (PGBR) in ns-3," In the proceedings of the *Network Operations and Management Symposium Workshops (NOMS Wksps)*, 2010 IEEE/IFIP, pp. 63–66, April 2010

Contribution: I was the only contributor of this research paper.

Chapter 1

Introduction

In this chapter, the background research, motivation and objectives of the research undertaken in this thesis will be addressed. First, I will present the background and motivation in section 1.1, which will be followed by the description of the scope of this thesis in section 1.2. Finally, Section 1.3 describes the organisation of the thesis.

1.1 Background and Motivation

In this section, I present the background research that motivated the research presented in this thesis. I will first describe the current communication networks' infrastructure in the section 1.1.1, and in section 1.1.2, I will describe its possible evolution to the Internet of Tomorrow. Finally, section 1.1.3 will enumerate the challenges of the Future Internet.

1.1.1 Communication Networks Today

In its early years, the Internet was designed to provide communication of raw data between universities for research purposes [1]. The amount of data transported over the network was limited, as was the network's size of the Internet. As the Internet's growth increases, its usage is changing as well.

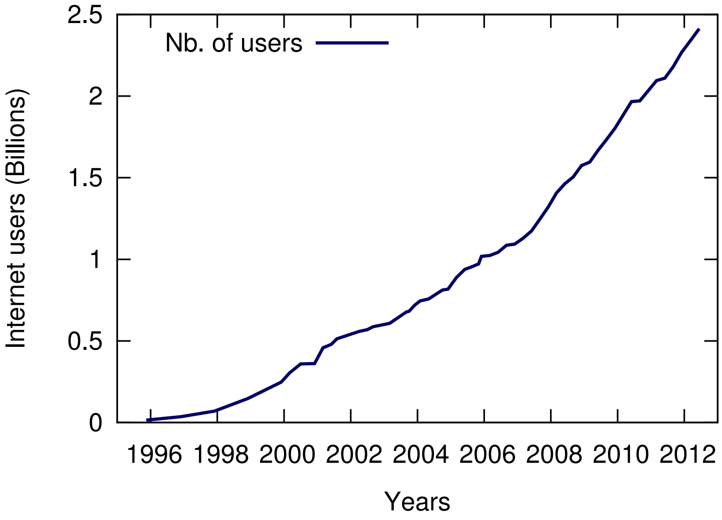


Figure 1.1: Number of Internet users [2]

Today, the Internet is playing a major role in everybody's life. As shown in Figure 1.1, the number of Internet users grew from a few million in 1995 to an impressive 2.4 billion in June 2012, which correspond to a third of the world's population [2]. The popularity of the Internet is resulting from the new services that emerged in the recent years, consequently leading to the incredible expansion of the Internet infrastructure. Through a virtuous cycle, the expansion of the infrastructure led to new service availability, which in turn increased the popularity of the Internet even more.

The most popular services of the early Internet were file transfers, e-mails and static web pages browsing. The services evolved in complexity resulting in users to have video conferences (e.g Skype), watch full HD Internet Protocol TeleVision (referred to as IPTV) [3–5], use Internet telephony (VoIP) or peer-to-peer (P2P) applications for file sharing as well as live video streaming. The emergence of dynamic web pages supporting Video-On-Demand (VoD) (e.g. Youtube, Vimeo, Dailymotion, etc.) and large social applications (e.g. Facebook, Twitter) further increased peoples reliance on the Internet [6, 7].

However, in addition to the growing number of services and Internet users, these applications are now generating tens of gigabytes of data to be transported across the network [8, 9], putting today's Internet under enormous stress. In the last few decades, the traffic generated by these older applications was predictable. Unfortunately, the huge volume of traffic these newer and larger applications are now generating is unpredictable. As a result, the complexity of managing the Internet's resources increased tremendously. The increase in complexity is not only limited to the important volume of traffic or the number of services and users, but also to the number of providers and communication systems supporting the providers. We are now witnessing service providers, such as IPTV providers, and carrier network providers, which are composed of interconnected heterogeneous network. These heterogeneous networks are spanning both physical as well as virtual networks (the virtual networks would represent the providers that are sitting on the network providers).

1.1.2 Communication Networks of Tomorrow

The current Internet infrastructure is already challenged in numerous aspects. The research community is now actively investigating two approaches to fulfil the requirements of the Future Internet:

- The first approach consists of fixing existing protocols to add additional functionalities in order to address the challenges of communication networks of tomorrow. This approach is the less expensive in term of implementation and testing.

- The second approach, referred as "clean-slate", opts for a radical option as it completely transforms the architecture of the Future Internet without the constraints of the current architecture, which was designed 40 years ago [10]. Unlike the first approach, the main drawback of the "clean-slate" architectures is the difficulty to evaluate their performances in large testbeds. This, unfortunately, refrains the actors of the Internet (such as the network providers) to implement these new architectures to their networks.

Either way, future communication network's protocols must easily integrate to the architecture of the adopted solution. The increasing demand of security, reliability, robustness, pervasive communication or mobility requires these protocols to be integrated into the Future Internet architecture holistically. Consequently, the Future Internet must integrate mechanisms that would co-exist and cooperate to maximise the benefits of the whole architecture, providers, as well as the end users.

Key features of the Future Internet include (i) the integration of service-oriented paradigms to support high quality of services' delivery, (ii) propose an ubiquitous access to heterogeneous networks that may have different technical characteristics and business models. These networks include wired networks, wireless infrastructure networks, wireless ad-hoc networks, sensor networks, body sensor networks and even nano-scale networks (e.g. e-health). Finally, (iii) autonomic behaviours would allow the Future Internet to smoothly integrate new technologies, to contain the expansion of the Internet by minimising its carbon footprint, as well as to ease the management by minimising human interventions. In the next sub-sections, I will go deeper in the motivation to include the key features (i), (ii) and (iii), and show why they would support the new needs of the Future Internet architecture.

Service-oriented Architecture

In order to maintain the high quality of service delivery that made the Internet so popular, the Future Internet must integrate service-centric or service-oriented protocols to its architecture. These protocols must be highly flexible and adaptable to the network conditions while supporting the management of services. For example, services such as live IPTV could adapt the service data rate, to maintain sufficient quality for the end-user, and to perform this in simple manner while being aware of the conditions of the network. The management of services could be enhanced by specialised overlay networks, which in the case of our example would be an IPTV provider overlay network. The IPTV provider could additionally use bandwidth management mechanisms, which would ameliorate greatly the quality of delivery of the services to maximise the end-user's satisfaction and/or increase the provider's revenue.

In particular, cloud computing is recognised as the next generation infrastructure that would revolutionise the way users access services [11]. Essentially clouds are next generation data centres using virtual networks, which will execute various software services [12], that are dynamically provisioned on-demand [13]. As the number of these services increases, management will become an issue. The key challenge of cloud computing is maintaining high availability of the services while minimising service' disruptions [14]. Discovery of services is therefore becoming a crucial issue to ensure that the service's requirements are met, even in the case of failure. In addition to an effective discovery mechanism, service-oriented networks could integrate content sharing capabilities to the network routers, that would bring the service's content closer to the end-users [15–18]. Consequently, the latency of services would be improved as well as reducing the workload of data centres.

Another challenge in cloud computing is the ability to maintain energy efficient data centres for future green ICT [19]. The ever growing popularity of cloud computing will result in millions of services available to the users, running a very large number of servers in data centres, thus increasing the energy consumption of the data centers.

Ubiquitous Connection to Heterogeneous Networks

The Internet of Things [20] is a novel paradigm that refers to the pervasive present of connected devices such as Radio-Frequency IDentification (RFID) tags, mobile phones or sensors including body sensors and nano-sensors. These devices are believed in the future to be all interconnected in a pervasive environment composed of multiple and numerous heterogeneous networks. These devices should be able to communicate and cooperate to achieve greater goals. Users will be submersed into a connected world through a variety of networks, such as appliances network, sensor networks and even body sensor networks in addition to the traditional terminals we use today (home routers, laptop, tablets, ect.).

For instance, the U.S. National Intelligence Council [21] declared that by 2025 Internet nodes may reside in everyday things and that currently individuals, businesses, and governments are unprepared to such eventuality (i.e. impacts on the economy, security threats, etc.).

The profusion of new applications taking advantages of the opportunities enabled by these technologies, could produce gigantic volume of data to be transported, stored or shared over the Internet. As a result, the challenges of the service-oriented architecture will be emphasised, where efficient discovery of services, cloud computing, content caching and energy management would play a greater role.

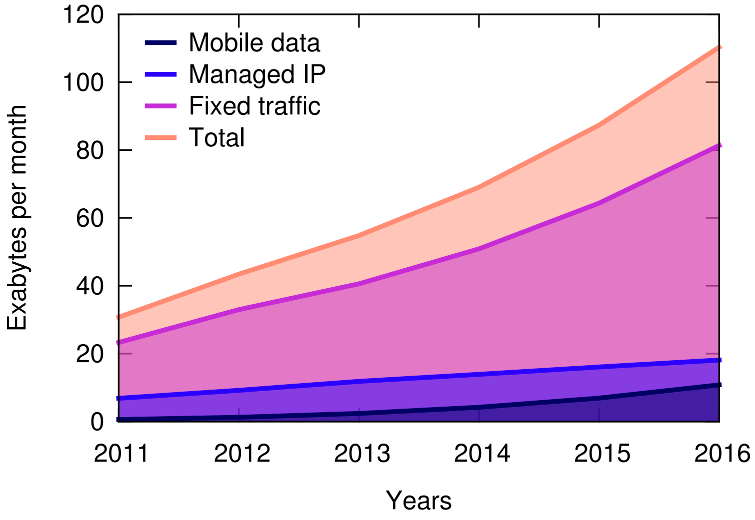


Figure 1.2: IP traffic growth forecast: 2011–2016

As shown in Figure 1.2, Cisco [22] foresees in the next five years a considerable increase of IP traffic. In this figure, “Mobile” includes all the mobile data and well as Internet traffic generated from mobile devices such as notebooks or mobile phones. “Internet” denotes all the traffic transported over the Internet backbone and "Managed IP" includes all corporate IP Wide-Area-Network (WAN) as well as all IP traffic from IPTV or VoD. The total traffic to be transported over the Internet is expected to grow more than three and a half times larger in the space of a few years. In particular, the growth rate of mobile traffic is incredibly high (e.g. the expected mobile traffic in 2016 is 20 times higher than in 2011). By 2025, with the introduction of the Internet of Things, it is possible that these networks may produce tremendous amount of data. This shows the necessity of the Future Internet architecture to evolve in a efficient, scalable and autonomous manner.

Autonomic Networking

Resulting from the multiplication of complexities in the Future Internet networking, the key requirement of the Future Internet is to make the Internet as autonomous as possible, where this autonomy relies in self-* properties (e.g. self-organisation, self-healing, self-evolving, self-management, etc.).

Autonomous behaviour was first proposed in [23–25] to support efficient management of complex computer systems. Self-governance and self-management were the key properties introduced to the systems. Communication networks of the Internet could benefit from these self-* properties to efficiently adapt to the increasing number of heterogeneous devices, that may be frequently connected or disconnected to/from the network, the wide variety of services available, as well as the highly dynamic traffic behaviour generated from these services.

By introducing self-organisation to the Future Internet through embedded autonomic properties into service-oriented architecture as well as the underlying infrastructure, one could minimise human intervention and maximise fulfilment of end-user needs [26].

In particular, routing and resource management have been designated as the key issues for the Future Internet [27]. The new standards of the Future Internet imply that routing and resource management protocols must be scalable, adaptable, efficient, flexible and energy-aware. Enabling the protocols with such properties introduces several challenges that will be presented in the following section.

1.1.3 Challenges of the Future Internet

While the previous section has presented an overview of the expected development from the current Internet infrastructure to the Future Internet architecture, the current state-of-the-art solutions are still far from supplying the requirements of the Future Internet in a holistic fashion. I envision that the routing and resource management protocols of the Future Internet include autonomous and self-* properties which will support fast deployment of these protocols over the current Internet in order to address the challenges brought by the emerging services and the fast growing popularity of the Internet. This section addresses the challenges that are considered by this research.

Challenge 1: Efficient delivery of services (C1)

Today's Internet users usually expect 99.999% reliability for their service delivery. Consequently, the routing and resource management protocols of the Future Internet will require great efficiency in providing high Quality-of-Service (QoS) or Quality-of-Experience (QoE). Usually, in communication networks, QoS is characterised by four primary parameters: bandwidth, delay, jitter and loss [28]. Each service is having its own requirements for the QoS performances. For example, file sharing does not require short delays and jitter but a high bandwidth, while VoIP requires short delays and jitter but has low bandwidth requirements. In the case of IPTV, QoE is often used instead of QoS, as it is a measure that combines user's expectation and perception and is often used to appreciate the quality of delivery of multimedia services [29–32].

Challenge 2: Adaptability (C2)

Adapting algorithms change their decisions to accommodate with the changes within the topology, and sometimes to the traffic (e.g. traffic-aware protocols) [33].

In the current Internet infrastructure, the topology of networks are constantly changing due to the frequent connection and disconnection of devices, as well as possible failures (failures may also be transient failures due to updates of software on the devices). The foresight of the Internet evolution will emphasise this phenomenon. In an Internet of Things, where any object is a Internet node, the topologies of the Future Internet may be constantly evolving. Therefore the protocols for routing and resource management of the Future Internet must adapt to these volatile topologies and the numerous services they provide, while minimising disruption to the end-users, as well as minimising human intervention.

Challenge 3: Flexibility (C3)

In the future communication networks, the network operator should be able to easily tune the routing and resource management protocols to fit new arising objectives. In today's communication network research has been undertaken to provide a flexible router architecture to switch between routing scheme to fit to the new network objectives [34]. Furthermore, it is difficult today to foresee what would be the future applications requirements as well as the new technologies composing the network of the future. As a result, the protocols of the Future Internet should be highly flexible and easily configurable to adopt numerous and diverse behaviours.

Challenge 4: Scalability (C4)

Over the last decades, the size of the Internet increased tremendously and is now composed of billions of interconnected devices [27]. With the emergence of new technologies where everyday objects could be potentially connected to the Internet and uniquely addressable, there will be more infrastructures, more links and more access points, resulting in the exponential growth of the Internet infrastructure in the next decades. Therefore, a considerable challenge for the routing and resource management of the future would be the scalability. Nowadays the current state-of-the-art solutions are far from being highly scalable as the size of the current Internet is already too large, resulting in many efforts from the research community to fix the lack of scalability of the current protocols. Consequently, new approaches are required for the Future Internet to address scalability as a key issue.

Challenge 5: Energy efficiency (C5)

Currently, the whole Internet is consuming a large quantity of energy to provide new applications to the end-users. The Internet infrastructure may be responsible by 2020 for up to 10% of the world's electric consumption [35]. The research community is actively trying to find energy efficient techniques to reduce the electricity bill of the Internet, focusing largely on energy-efficient data centres (most of today's services are located in the data centres) as well as developing new technologies less demanding in terms of energy usage. As the popularity and the size of the Internet increase, the energy requirements of the Internet will dramatically increase proportionally. In order to make the Future Internet sustainable, the new protocols should provide efficient energy management by minimising the need of fossil fuel energies as well as favouring the use of green renewable energies to support the Future Internet energy needs.

1.2 Research Scope of The Thesis

This section discusses the scope of the research presented in this thesis. The scope of the thesis covers the research of efficient mechanisms for wired core infrastructure networks.

The architecture that has been investigated during the completion of this thesis is a dual layered architecture. On the bottom layer resides a a physical core infrastructure network that interconnects several networks, such as data centre networks, enterprises networks or metropolitan networks. The networks are connected to each other through gateways, where the wired core infrastructure will provide the connectivity to the Internet. The core network is composed of a large number of routers, interconnected with high speed links (around 100Gbps), which may span over countries or continents. These core networks are usually owned by Internet Service Providers (ISP). On the upper layer sits a multitude of service providers, using physical or virtual networks.

In Section 1.2.1, I first discuss why biologically inspired mechanisms could address the challenges enumerated in the previous section, and why biological inspiration represents a viable research direction for the routing and resource management of wired core infrastructure networks. In this thesis, the research work is divided into two parts. The first part of the research work is the development of a bio-inspired routing protocol that is easily adaptable, highly scalable, service-oriented and able to adopt various behaviours. This part will be presented in Section 1.2.2. In particular, I focused on the ability of the routing protocol to co-exist with other mechanisms that may have opposite objectives. The second part of the research work, presented in Section 1.2.3, is the development of bio-inspired mechanisms for resource management in core infrastructure networks. In particular, I focused on (i) the management of the available bandwidth by prioritising certain traffic types over others and (ii) the management of multiple service overlays (e.g service providers) sharing common resources from physical networks (e.g. carrier network providers). Lastly, Section 1.2.4 presents the main objectives of this research, which are presented in the form of research questions.

1.2.1 Biological Inspiration for Autonomic Networking

The biological world has been extensively studied by the research community, where various complex behaviours have been discovered from single cellular systems to complex interactions of organisms. As a result, biological inspiration has been successfully applied to various research fields, such as robotics, artificial intelligence as well as computing (the state-of-the-art of bio-inspired solutions is presented in Section 2.2). Consequently, the research presented in this thesis is utilising multiple biologically inspired mechanisms that are applicable to the Future Internet, where each of these bio-inspired processes should posses self-* properties (e.g. self-organisation, self-healing, self-evolving, self-management). The heterogeneity of the Future Internet will further increase the need for co-existence of multiple concurrent mechanisms in the system, therefore, highlighting the crucial role of symbiosis for a greater good.

1.2.2 Bio-inspired Routing

In order to address the scalability challenge (**C4**), it is essential for routing protocols to be distributed. As previously mentioned, the future size of networks will discard all centralised solutions to provide satisfying results. Using biological inspiration, where billions of organisms successfully interact with each other through various communication mechanisms, the routing protocol could inherit self-* properties from these biological models to address many challenges (e.g. Challenges **C1** – **C4**).

Adaptable Parameters

Challenge **C3** implies that the Future Internet routing protocols must ensure that they can easily be adaptable to various requirements. Consequently, these protocols should enable various routing behaviours using the minimum number of parameters (as simplicity is the key of good management). Bio-inspired solutions make complex computations with simplistic models and easy configurations, thus these model are potentially good candidates for efficient routing (Challenge **C1**). Finally, the different sets of parameters should provide adapted QoS for every services' requirements.

Energy Management

As mentioned in Challenge **C5**, the energy management of the Internet will be crucial in the next decades. To improve the energy awareness of communication networks, it is important that all the components of the Internet architecture are optimising their network resources. Introducing energy awareness in core infrastructure networks implies that devices may be powered-off when they are unused. Unfortunately, energy management may negatively impact on the QoS to the end-users (Challenge **C1**), by diminishing the number of available resources. As a consequence, it is important to ensure maximum service delivery while maximising energy savings that is transparent to the end-users.

1.2.3 Bio-inspired Resource Management

The bio-inspired resource management has been addressed in this thesis from two angles. The first angle is referring to the bandwidth management that distributes the available bandwidth of the network's paths to various service types (paths may also be virtual and refer to end-to-end connections). The second angle is the management of multiple overlays sharing the same resources from a physical network holistically.

Bandwidth Management

In order to address the challenges **C1** and **C2**, bandwidth management protocols may be introduced to further improve the management of services, which must be first supported by routing. An objective of the bandwidth management is to provide the service providers with a dynamic bandwidth management mechanism, which could decide on resource usage by prioritising certain traffic types or users. For instance, a provider may consider user's subscription profiles (for example Bronze, Silver or Gold) and prioritise "Gold" users in case of bandwidth starvation.

In fact, I believe that efficient routing is not sufficient to maximise the satisfaction of network users, as well as the provider's. Once the resources are running out, it is essential to use such mechanisms to limit the perturbations on existing services or users.

Adaptation is a controlled process and can occur at different time scales. There could be short bursts of service demand (high popularity of a particular service for a very short lapse of time), or the traffic demand may vary during day time, where popular services in the morning may be different from the popular services in the evening (medium time scale). Finally, there could be deeper changes in the service's demand, where the popularity of services may vary in a longer time scale.

Consequently, bandwidth management protocols for the core infrastructure networks of the future must be highly adaptable (Challenge **C2**), effective (Challenge **C1**) and finally flexible (Challenge **C3**) at different time scales.

Multiple Providers Management

Virtual overlay networks are efficient in provide an abstraction of the the underlying topology, while satisfying the Quality of Service (QoS) of the services. These virtual overlay networks, enables service providers to manage new services without modifying the underlying network protocols. Consequently, overlay networks can enable the services of the Future Internet to be smoothly integrated to the existing architecture, while minimising the cost of deployment. However, as the diversity of providers increases, the challenge resides in the co-existence of multiple virtual overlay providers. For instance, in today's networks, overlay networking consists of a single overlay network using some physical resources that are leased by a carrier network provider. In the future, it is expected that multiple virtual providers will co-exist in the same network, thus introducing new challenges to network management. The main challenge will reside in resource management, where each individual virtual service provider's decision will impact the performance of the underlying infrastructure, which can potentially degrade the performances of the other virtual providers.

Overlay networks allows us to make the Future Internet more flexible (Challenge **C3**) by diversifying a single communication networks into multiple types of networks (e.g. physical network and overlay networks), where the overlay networks can individually manage their own resources using bandwidth management solutions. Furthermore, these multiple overlays are numerous and allowing the overlays to co-exist together makes this approach scalable to high number of entities (Challenge **C4**).

However, from the perspective of the underlying networking infrastructure provider (the "carrier") virtualisation presents new management challenges, in particular how to efficiently and fairly allocate available resources to multiple virtual networks. Consequently, it is essential to incorporate resource management mechanisms to the Future Internet architecture that support this scenario efficiently (Challenge **C1**).

1.2.4 Research Questions

The research presented in this introduction explores the new objectives of protocols for routing and resources management of wired core infrastructure network to successfully cope with the new usages of the Internet. The objectives of this study are represented by the following research questions:

Q1. Routing: *What biologically inspired routing protocols can support an evolving services environment in large scale networks, while ensuring scalability, adaptability, and flexibility?* (Challenges **C1**, **C3** and **C4**)

Q2. Bandwidth management: *What biologically inspired bandwidth management protocols can support efficiently services at different time scales?* (Challenges **C1**, **C2** and **C3**)

Q3. Energy management: *Can a bio-inspired routing protocol be adapted to minimise the consumption of fossil fuels energies for the future networks?* (Challenges **C1** and **C5**)

Q4. Multiple providers: *What biologically inspired model can fairly allocate resources to multiple virtual overlay services providers sharing common underlying resources in a revenue driven fashion?* (Challenges **C1**, **C3** and

C4)

1.3 Document Organisation

In this chapter, the motivation and objectives of the research have been addressed resulting in a number of research questions, leading to a survey of relevant literature in Chapter 2. A summary of the research contribution will be presented in Chapter 3. Finally, the reprinted research papers containing the contribution of my research will be accessible in the Appendices A to E.

Chapter 2

State of the Art

In this chapter, I am presenting the state of the art that inspired the research conducted in this thesis.

State-of-the-art solutions are divided into two sub-sections. Section 2.1 presents the state-of-the-art solutions for routing and resource management of infrastructure networks, while the state-of-the-art solutions for biologically inspired solutions for communication networks will be presented in Section 2.2.

2.1 Routing and Resource Management of Infrastructure Networks

In this section, I present the state-of-the-art solutions for routing and resource management of infrastructure networks, which includes routing (Section 2.1.1), bandwidth management (Section 2.1.2), overlay networking (Section 2.1.3) as well as energy management (Section 2.1.4). As the scope of my thesis focuses on the management of resource for core infrastructure networks, I only consider in this review the state-of-the-art solutions that improve the resource management of wired infrastructures.

2.1.1 Routing Protocols

Routing protocols are the cornerstone of resource management of infrastructure networks [36]. They allow the end-users of the network to access a large variety of services [11]. A routing protocol aims to maximise resource usage while providing connectivity between the nodes of the network. When routing was in its infancy, it was static; the routing tables, including all necessary information to forward packets, were manually set by the network's operators. However, the growth of the network size made route management infeasible, leading to the development of more automated and sophisticated solutions [33, 37–40].

Inter-domain vs. Intra-domain Routing

Internet has a two level routing algorithm. The first level is the inter-domain routing [41]. The inter-domain routing protocol of the Internet is called BGP (Border Gateway Protocol). The networks that this protocol interconnects are called Autonomous Systems (AS), which are operated by different organisations such as an Internet Service Provider (ISP) or a university. Each AS may use its own intra-domain routing protocol such as a link-state routing protocol or a distance-vector routing protocol. The routing decision made on the inter-domain routing are mainly based on economical decisions or privacy concerns between the different autonomous systems (i.e. ASes sending their users' requests to other AS in order to deliver the services). In this thesis, I considered the routing management that is performed within the AS and as a consequence, only intra-domain routing protocols will be covered by this literature survey. In the rest of the thesis a routing protocol refers to an intra-domain routing protocol.

OSPF

The most famous and popular intra-domain routing protocol is the Open Shortest Path First (OSPF) [37, 38]. The protocol supports a variety of distance metrics, such as path delay or reliability. It is a dynamic routing protocol that adapts to topological changes [42]. Each router of the AS using OSPF computes the shortest distance between itself and all the other routers using the Dijkstra's shortest path algorithm on a graph representation of the network topology [43]. As the size of ASes may be very large, the OSPF routing protocol includes a hierarchical system that splits the topology into areas, thus minimising the need of topological information to compute the routing tables (e.g. outside an area, the destination are known but not the topology). Furthermore, OSPF uses also ECMP (Equal Cost MultiPath) to balance the load on paths that are equally short, and consequently improve the performances of the protocol. More details about the internal processes of OSPF can be found in [37, 42].

Unfortunately, this protocol has several drawbacks. Firstly, even if the router does not require the knowledge of the full topology to compute its routing table, gathering all the information necessary and computing the routing table could be time consuming for very large networks, and provokes scalability issues [27]. Secondly, during the updating process, protocols are subject to packet looping [44] which degrades considerably the performance of the algorithm [45]. Thirdly, link-state protocols (such as OSPF) were designed to find routes between the nodes of the network without any regards to the traffic consumed by the network. Furthermore, the traffic patterns that are emerging from new and more advanced services are now impossible to predict [46], which makes these routing protocols not suitable for the Future Internet. However, it is possible to design robust routing protocols with limited knowledge of the traffic demand [47].

As a consequence, different approaches have been undertaken to support the requirements of the Future Internet including improving existing protocols as well as investigating new routing paradigms.

Improving Existing Protocols

Extensive research has been conducted to solve OSPF's limitations, including but not restricted to improving the load balancing of the network, reducing the convergence period during OSPF's route updates, integrating support of services' requirements and improving the robustness of the protocol. Almost all the papers presented in this section enhanced the OSPF protocol because of its wide implementation in the current Internet infrastructure, resulting in a cost effective implementation of their solutions. As a result, weight changes have been intensively investigated as they provide the cheapest modification to the original protocol. In fact, weight changes are ideal to avoid congestion as well as resolving problems such as failures, or hot-spots, at a cheap cost. As previously stated, weights of the links will change the output calculation of the Dijkstra shortest path algorithm [43], resulting in the modification of the routing information supporting the objectives defined by the new set of weights.

For example, Fortz et al. [48, 49] investigated the possibility of making weight changes to the OSPF routing protocol to avoid overloaded link. The authors pointed out that optimising the weights considering a set of constraints is a NP-hard problem. Consequently, to find the best set of link weights, the authors used local search in a combinatorial optimisation problem, solved by linear programming. In conclusion, weight changes, even in small proportion, can improve OSPF's performances, but are not optimal. A major disadvantage is also the need to have knowledge of the traffic matrix between all source and destination points.

Similar research has been conducted by Antic et al. [50] to improve the load balancing of the network by modifying OSPF's weights. Load balancing is usually responsible for maximising the network resource usage and simultaneously improving its efficiency (i.e. networks should minimising disruptions to existing and future traffic flows). The authors introduced LB-SPR (Load Balancing Shortest Path Routing), which unfortunately also performs its weights optimisation from Integer Linear Programming (ILP) calculation. ILP is very expensive in term of computation time and thus, does not scale well. However, the authors claimed that their protocol facilitates a fast bandwidth reservation without prior knowledge of the traffic demand (the authors made assumption on the probability of Point-of-Presence (PoP) to generate traffic instead of the usual traffic matrices). More details can be found in section 2.1.2 on the importance of bandwidth reservation to improve the services' delivery. Others approaches have been undertaken to extend OSPF in order to support QoS requirements [51–53].

Because weight changes or network failures provoke topological changes, loops can occur when forwarding table updates are responding to these changes. To address this challenge, Francois et al. [44] introduced ordering in the update of forwarding table databases (FIB) that can be both applied to predicted and unpredicted changes within the network topology. For such processes, fast convergence is a major requirement, since end-users usually expect 99.999% reliability for their service delivery. The algorithm determines the rank to perform the update, where ranks are modified according to the situation (i.e. link up or down). The only information required to calculate the rank is the Shortest Path Tree (SPT) and the reverse SPT which correspond to the shortest route from all routers to the root. Once the rank is calculated, routers update their FIB after a delay period. The authors investigated the possibility of speeding up the process by introducing completion messages which are sent once the update is completed. The authors showed that the increase of FIB update time is relatively small and reasonable for the network operators of large Tier-1 ISP that prefer to avoid packet loss when performing maintenance operations.

Efficient and fast recovery from failures is likewise a key issue for the Future Internet. Ensuring that fast recovery can be performed for longer term failures (e.g. node failures) or short term transient failures is important to ensure minimum performance degradation for end-users. Several research works have been proposed to introduce multiple backup paths using combinatorial algorithms [54, 55]. Unfortunately, all these optimisations require the knowledge of the traffic conditions, making them impracticable for the Future Internet. From a different perspective, pro-active solutions have also been investigated in [56, 57].

Recently, in [58], Xu et al. stated that a combination of a link-state routing and multiple backup paths could provide optimal throughput. Regrettably, their solution requires prior-knowledge of current traffic demand, which consequently discard it for its integration to the Future Internet architecture.

New Routing Approaches

New routing approaches have been investigated in the recent years to solve the issues introduced by the new Internet's usages.

For instance, in [59], Gopalan et al. focused on a new routing protocol that does not rely on Dijkstra shortest path algorithm. In fact, their algorithm focuses on reducing the number of over-utilised links to maximise the load-balancing of the network, while providing bandwidth and delay guarantees. Additional disjoint backup paths are also provided to further improve the robustness of their solution.

From a different angle, Basu et al. [60] proposed a new routing mechanism based on potentials that attract the packets to their destination using hop-by-hop routing decision. The solution aims to maximise throughput by reducing congestion. However, the protocol aims to avoid congested links but cannot prevent congested hot-spots.

One the one hand, an advantage of hop-by-hop routing is its scalability; unlike OSPF and other link-state protocols, the routers do not need an extensive knowledge of the network topology to perform intelligent routing decisions. On the other hand, hop-by-hop routing could suffer from packet looping even when no topological change occurred, leading to extensive delays while routing packets towards their destination. Many research works also trusted hop-by-hop routing as a viable solution to support efficient and scalable routing [46, 57, 61].

In particular, a family of hop-by-hop protocols, called back-pressure protocols [62–64], are theoretically throughput optimal. They rely on the algorithm originally proposed by Tassiulas and Ephremides [65] to maximise throughput in multi-hop wireless networks. The algorithm chooses the next hop that presents the largest differential between the queue size of the neighbouring node and the current node for a particular destination. These recent approaches have tried to address the poor delay performances of the original protocol, its high packet loss in large networks as well as the complex implementation as an operational protocol (e.g. it requires instant knowledge of queue sizes of neighbouring nodes).

One approach that could minimise the drawbacks of hop-by-hop routing is called flow-aware networking [66]. Flow-aware networking was introduced to enable singularity of the network management to a single service. In this case, all the data packets belonging to the same service are assumed to have similar requirements, and would be aggregated to the same flow. Consequently, only the first data packet of a flow will suffer from packet looping and extensive delays, while the following data packets will be routed according to the routing decision made from the first packet (excluding the loops). To conclude, flow-aware routing enables strong support of the services' requirements that maximise end-to-end quality of delivery, as well as facilitating the bandwidth management presented in the following section.

2.1.2 Bandwidth Management

Bandwidth management techniques are highly recommended to maintain acceptable quality of service delivery to the end-users when the network is experiencing congestion. In fact, once the traffic overloads the network (i.e. offered load is close to the capacity of the network), the performances of delivery collapse. There are two approaches to maintain the quality of delivery. The first approach relies in providing additional capacity to the network. This can be done either by a traffic-aware routing protocol which is responsible of finding the resources or by supplying additional resources to the network. The second approach is the use of admission control algorithms [28] that help provide QoS guarantees. Other techniques such as traffic throttling, which requires the sender of traffic to adjust the input rate, have not been considered in this literature survey.

Adaptive Bandwidth Control algorithms (ABC) [67] can be separated in two categories. The first category allows end-to-end per flow reservation of bandwidth to maintain the performance of service delivery (Integrated Services). Regrettably, OPSF was not designed either to provide scalable and fast bandwidth reservation. Therefore, the development of reservation protocol was necessary. An example of this reservation protocol is the Resource reSerVation Protocol (RSVP). A problem of end-to-end flow reservation protocol relies in the difficulty to measure the available bandwidth, which also represents a considerable challenge and could significantly impact on the performances of the bandwidth control techniques [68–70].

The other category is based on a local decision at the router to preserve scalability that favours some services over others. This technique is called Differentiated Services (DiffServ). When DiffServ is used conjointly with Multi-Protocols Label Switching (MPLS), it provides a scalable framework for QoS provisioning in IP networks [67]. MPLS is a technique used to enable traffic engineering over IP networks (Traffic engineered networks are also referred as DiffServ-based networks [71]). MPLS Traffic Engineering relies upon the use of traffic engineering extensions of link-state protocols, such as OSPF. Additionally, an interesting advantage of MPLS is its ability to recover fast from link or node failures by bypassing them from upstream routers using alternative paths. This led to to research solutions such as [55] to provide guaranteed bandwidth reservation on MPLS-enabled networks in the event of failure.

Furthermore, automated bandwidth resource management has been investigated to address the challenges of the Future Internet [72, 73]. Although a number of different solutions have been proposed in recent years to manage resource adaptively [67], these solutions do not address the challenges in a holistic manner. A number of self-optimisation techniques have been proposed to adaptively and effectively reinforce the performances of DiffServ-based networks [74, 75].

Davy et al. [70] described two admission control algorithms based around the estimation of the effective bandwidth required to satisfy QoS targets for admitted IPTV flows. The approach employs a revenue-maximising algorithm that utilises information relating to the price, duration and request frequency for different content items to make profit-optimal admission control decisions.

Unfortunately, none of the above admission control techniques provides a flexible and adaptable bandwidth management system at different time scales.

2.1.3 Overlay Networks

Overlay networks are virtual networks [76], existing on top of physical network, which provide additional functionalities to the network management without changing the underlying infrastructure, resulting in a very cost effective strategy for the Future Internet. Overlay nodes (virtual routers) have been enhanced with complex functionalities, which are not included in the native physical router [77], and can sense the underlay network (e.g. load, drop of performances, congestion, extensive delays) in order to change the routing decision without modifying the physical router.

One of the earliest works on overlay networks was proposed in [78] to create a fault tolerant network that can route around failures with minimal disconnection time. The approach targets inter-domain network solutions, but could be applied to intra-domain routing. The routing is performed on the underlay physical network by BGP, while the overlay provides the QoS support for the overlay paths.

Application layer overlays are becoming very popular in today's networks because they provide an efficient service management, without modifying the underlying network technology [79–81]. In the case of [79], the authors did a survey on the use of virtualised networks as a service for cloud computing, as virtualised networks providing high QoS are an important feature of efficient cloud computing. In fact, overlay networks enable heterogeneous systems to co-exist and cooperate to support new kind of applications and services for future communication networks.

Such diverse services are generating a highly variable traffic over the network and the use of overlay networks using appropriate routing could help reduce the stress on the underlying infrastructure. For instance, Kodialam et al. [82] introduced a two-phase routing solution that is used to maximise throughput for service overlay networks.

In the future networks, it is expected that resources abstraction and network virtualisation will be widely used. Unfortunately, when multiple overlay networks share common resources, they may interfere with each other. As a result, Keralapura et al. [83] studied the impact of co-existence of overlay networks. The authors found that race conditions occurs when at least two overlays synchronise, and thus, provoke traffic oscillations and cascade reactions. Some critical observations showed that, in today's overlay networks, (i) cascading reactions could become common as the number of co-existing overlays increases, (ii) there is no single administrative control, and (iii) that path performance degradation is one of the reason to trigger events in overlays that might lead to race conditions. This is due to the fact that multiple overlays may share common primary and backup paths on the underlying topology. Consequently, the multiple overlays also increase the probability of producing bottleneck links that would require a synchronisation between the overlays. The authors showed that reactions are lowest when overlays cooperate non-aggressively.

From a different angle, the method proposed by Seetharaman et al. [77] minimises the disadvantages of selfish behaviours by predicting the other layers' reactions. This implies that the Future Internet should include new mechanisms that minimise the negative interactions [84–88] between multiple overlays in order to maximise the overall network performances as well as the individual overlays.

2.1.4 Energy Management

Information and communication technology (ICT) is an important contributor to the world global power consumption [89]. Today, ICT is responsible for 10% of the world consumption and its share may increase as the growth of the Internet continues [35]. This new landscape has shifted ICT researchers towards developing solutions that can improve energy consumption of communication networks, and at the same time minimise CO_2 emissions [90, 91].

Gupta and Singh [92] published the pioneering work on the importance of reducing the energy consumption of communication networks. They noted that networking devices consume a large quantity of energy even in the idle mode, mainly because they are powered-on 24/7. The main drawbacks of reducing the energy consumption within the network are (i) its vulnerability to link or node failures (ii) and the deprecation of quality of service delivery, both resulting from the reduction of available resources. Chaberek et al. [93] extended the approach of Gupta and Singh to investigate the benefits of energy-awareness while designing networks to save energy. Their study showed that the combination of an energy-aware design and energy-aware routing protocols will lead to tremendous savings of energy.

Resulting from these discoveries, two principal approaches have been undertaken to maximise energy savings in ICT networks:

- **Energy-aware optimisation:** Several energy optimisation techniques such as in [35, 94, 95], use either Integer Linear Programming (ILP) or heuristics to solve the multi-commodity flow problems under certain constraints. These constraints may include maintaining a certain level of traffic throughput and minimisation of energy consumption of the network. However, as the Internet continues to increase in popularity, this may lead to varying traffic demand. Therefore, requiring pre-knowledge of traffic demand may not be ideal for managing communication networks of the future.

- **Energy-aware routing protocols**: For instance, research works such as [96–98], have enhanced the functionalities of OSPF to integrate energy-awareness to the protocol. In particular, Arai and Yoshihara [96], developed a mechanism that changes OSPF's weights to save energy, while Cianfrani et al. [98] introduced sharing of shortest path calculation to maximise the reuse of common links, thus giving the opportunity to power unused links off.

Recently, researchers also investigated the use of overlays to reduce the energy consumption of backbone networks [99, 100].

2.2 Bio-inspired Communication Networks

In this section, I present the state-of-the-art of biologically inspired solutions to manage communication networks. Section 2.2.1 describes the benefits of biological inspiration to answer complex problematics, while Section 2.2.2 present biologically inspired approaches dedicated to the resource management of infrastructure networks.

2.2.1 Biological Inspiration

Applying bio-inspired techniques to different disciplines of science has received wide spread popularity in recent years, and to computer science in particular where the study of biological processes and its applicability to systems has resulted in robust and improved performances [101–105].

For example, based on the hormonal communication model, Shen et al. [106] highlighted strong autonomic qualities for their modules, which includes collaborative behaviours, asynchronous coordination and scalability. Authors also successfully achieved autonomous locomotion of various robot shapes such as snakes, legged insects and rolling track with rare non-recovery stops. Moreover, Prodan et al. [107] explored the application to electronics of biology processes that characterises the development of a simple organism (e.g. a cell) to a complex one (e.g. an adult human). In addition, a self-healing technique has been applied to help the overall system recovering from faulty processors. A similar approach has also been undertaken in [108].

For a perspective of communication networks, Carreras et al. [109] investigated bio-inspired approaches to support services in pervasive communication environments, in particular focusing on the heterogeneity, scalability, and complexity requirements of services. Bio-inspired solution have also been developed for different network devices, such as sensor networks [110–113].

Several other research bio-inspired solutions have been successfully applied to communication networks, including but not restricted to: (i) the self-organisation of groups for the Future Internet using *Quorum sensing* modelling [114], (ii) improving the performance of TCP using the *Lotka-Volterra* inter-species competition model [115] to dynamically adjust the TCP window size [116], (iii) ameliorating the service discovery in peer-to-peer networks using ants' pheromone trails [117], and (iv) implementing autonomic service evolutionary process based on genetic evolution [118–120].

The large success of biologically inspired solutions to address computing research problems has shown the great potential of bio-inspired model for the challenges arising from the Future Internet.

2.2.2 Bio-inspired Resource Management of Infrastructure Networks

In this section, I present the state-of-the-art bio-inspired solutions dedicated to the routing and resource management of infrastructure network, starting with a short introduction to highlight the powerful computation available from biology to design networks.

Bio-inspired Network Design

Tero et al. [121] demonstrated that *Physarum polycephalum*, a slime mould, could help design transportation networks. This type of mould searches for food sources, and tends to approximate the Steiner Tree connecting them (e.g. calculating a Steiner Tree is a NP-hard problem). The growth of the mould could be influenced by the environment, such as the substrate, physical barriers or light regime. These conditions enabled the authors to recreate real-world environment, such as lakes or mountains. The authors applied the mould to connect 36 food sources representing 36 Japanese cities; the starting point of the mould is from Tokyo. The mould was able to recreate the Japanese railway system in a cost efficient manner. They compared the network performances to the real greater Tokyo railway network and the minimum spanning trees optimised for different characteristics (cost, efficiency, robustness).

Inspired by this discovery, the authors developed a mathematical model to design transport networks that performs better than the *Physarum* networks in term of cost savings, while maintaining similar robustness and efficiency. The mathematical model is also scalable as it uses only local rules. The authors foresees opportunities for this model to improve routing protocols or topology control of self-organised networks.

Bio-inspired Routing

A biological model that has been favoured to enhance routing is the *Ant Colony Optimisation* (ACO) that is inspired from ants' pheromone trails [122]. For instance, in [123], Caro and Dorigo developed "AntNet", a fully distributed routing protocol. Each router participating in the routing is periodically sending ant agents to random destination. The agents stochastically choose the best next hop according to the pheromone trails laid by other agents, that they will update themselves once they return from the destination to the source. The quantity of pheromone would be decided by the quality of the path found (e.g. based on delay performances). The pheromone table is also used for the routing of data packets, but using reinforced values to favour the best routes. The protocol is achieving near optimal performances in small-scale networks. However, in large-scale network, the agents have difficulties finding the destination which as a results slows down the reaction of the protocol to changing network conditions.

Kvalbein et al. [46] used a hop-by-hop routing paradigm that is inspired from biological *Homeostasis*. The protocol was designed to provide load latencies and minimal packet drops using multiple paths. The selection of the path is done by the *homeostasis* process that reacts to the load variations to locally select the best next hop. Unfortunately, the protocol is based upon distance-vector or link-state protocol such as OSPF. Thus, it inherits the same scalability problems from the underlying routing protocol. The protocol does not support multiple services to prioritise certain traffic types according to their requirements.

Bio-inspired Overlays

Biologically inspired solutions were also introduced to adaptively manage overlay networks. Liebnitz et al. [124] proposed a self-adaptive overlay network solution based on bio-inspired techniques. The mechanism is based on attractor-selection algorithm that considers the path quality. The algorithm considers the symbiosis of the decisions to maximise positive impacts on the network condition. In the event of quality degradation, the path will automatically change to improve the QoS requirements of the application. Unfortunately, the protocol assumes each router has the complete knowledge of the network topology and require adequate input parameters to function correctly. Therefore, the protocol may suffer from bad performances in a large topology with highly dynamic environment.

Bio-inspired Energy Management

From an adaptive routing protocol perspective, Kim et al. [125] proposed “AESR”, which is adapted from the “AntNet” protocol. The algorithm favours routing along highly loaded links, which could possibly lead to powering-off lightly loaded links. The authors coupled the pheromone information collected by ants to a traffic centrality factor that redirect ants to highly loaded links. This technique is able to reduce the energy consumption of real networks by up to 60%, using a single parameter β (factor to weight the traffic centrality). Unfortunately, the choice of β might impact negatively on the network QoS performances. The authors suggested to enable the optimisation only during the periods where the network is underloaded. Even in this conditions, the optimisation for energy savings is not applicable in dynamic traffic condition as the protocol does not integrate a mechanism to power-on devices when the resources are over-utilised. Consequently, the protocol may suffer from severe disturbances in the service delivery. This degradation will be amplified on large topology due to the restriction inherited from the "AntNet" protocol which was described in the previous subsection.

2.3 Literature Review Summary

The first part of this chapter reviewed papers representing the current state of the art of routing and resource management. Each reviewed paper highlights the problems induced by the new usage of the Internet. The past research also showed how researchers tried to modify existing protocols, such as OSPF, at cheapest possible cost to ensure the best performances/cost trade-off. Unfortunately, the solutions optimised unique objectives and do not support multiple service type requirements. Overlays management has also been highlighted as a promising solution to support the needs of the Future Internet, but multiple overlays introduce great complexity in the management of resources due to race conditions. The literature review was concluded with the review of state-of-the-art solutions to maximise energy savings of core infrastructures, where the optimisations either assumed the full knowledge of the traffic conditions or experienced severe degradations in the quality of service delivery.

The second part of this chapter reviewed papers from biological inspirations, and the reviews demonstrated that biological processes can help model complex behaviours and achieve great performance results due to the inherited qualities of biological processes (self-* properties). A subsection of this chapter reviewed papers that used bio-inspired mechanisms for routing and resources management of core infrastructure networks.

In order to supply the functionalities required by current and future Internet architectures described in the introduction, I believe, from this literature survey, that new bio-inspired paradigms that would co-exist and cooperate could represent a competitive approach (in term of trade-off between cost and performance) against current state-of-the-art techniques, as they benefit to the whole system in a holistic manner.

Chapter 3

Research Summary

I believe the research work described in this thesis makes a significant contribution towards routing and resource management of core infrastructure networks. The different parts of the contribution will be described in this chapter. First, Section 3.1 presents a novel bio-inspired routing protocol, while Section 3.2 presents new mechanisms for resource management. This will be followed by Section 3.3 which describes the tools that were used to validate this research. Finally, Section 3.4 presents my answers to the research questions that were introduced in Section 1.2.4.

3.1 Bio-inspired Routing

In this section, I present a novel bio-inspired routing protocol for core infrastructure networks. First, Section 3.1.1 describes the mechanisms composing the protocol as well as the biological models that the protocol inherited. This will be followed by Section 3.1.2 which describes how the routing protocol supports complex service-oriented architectures. Lastly, Section 3.1.3 presents additional features of the protocol to reduce the carbon footprint of the network, while minimising the negative impacts on the network's users.

3.1.1 Parameterised Gradient Based Routing (PGBR)

In this thesis, I present a bio-inspired routing protocol, that I believe is very ideal for wired core infrastructure networks. However, the adaption of the protocol to other network types, such as ad-hoc wireless networks, has also shown positive results [126].

The bio-inspired routing protocol is called “Parameterised Gradient Based Routing” (PGBR) and is integrating three concepts, from which two are biologically inspired, while the third one is service-oriented:

1. ***Chemotaxis*:** *Chemotaxis* is a biological process that allows bacteria to mobilise itself towards a destination point, by sniffing the chemical gradient emitted from the destination node [127, 128]. Bacteria have the ability to mobilise itself erratically depending the quantity of chemoattractants that is within the environment. As the bacteria gets closer towards the destination point, the bacteria will have less erratic behaviour and more deterministic mobility pattern as it gets closer to the destination. Similarly to the process of using an attractant/repellent gradient field that attracts the bacteria, PGBR generates a chemical gradient field that attracts the discovery packet hop-by-hop towards its destination by choosing the next hop with the highest gradient. The gradient field is generated using a gradient equation that defines the type of chemoattractants, where each chemoattractant will correspond to a certain service type.

2. **Reaction-diffusion:** The PGBR routing algorithm is based on hop-by-hop decision routing, where each router monitors its environment and diffuses the collected information to one-hop neighbours. Such process is inspired from a reaction-diffusion mechanism that creates self-organisation mechanism of cells through cell-cell interactions [108, 129]. The reaction-diffusion mechanism generates the quantity of chemoattractants and chemorepellents, referred as gradient field, to lead the discovery packets towards their destination by the

most appropriated path.

3. **Flow-based routing:** The last concept embedded in the PGBR routing protocol is flow-based routing [66]. Flow-based routing allows the routing protocol to abstract and regroup network packets into flows that have similar requirements. The benefits of such mechanism is the possibility of supporting differently all kind of services. The discovery process is performed for each flow abstraction that may use a different gradient field, thus leading the discovery packet to a route that is adapted to the service's requirements. More details can be found in Section 3.1.2 on how the behaviour of the PGBR discovery mechanism can be modified to fit new objectives.

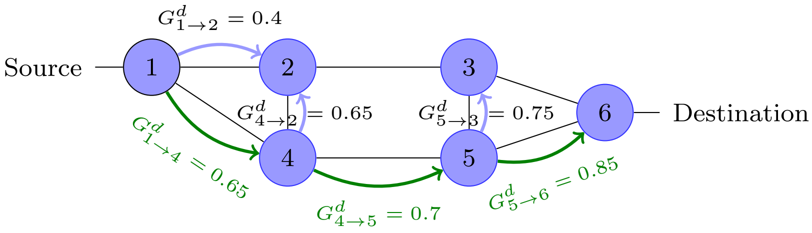
Consequently, using these three concepts, PGBR is able to provide multiple and diverse behaviours if one changes the chemoattractants and chemorepellents of the environment.

Definition of the Attractants and Repellents

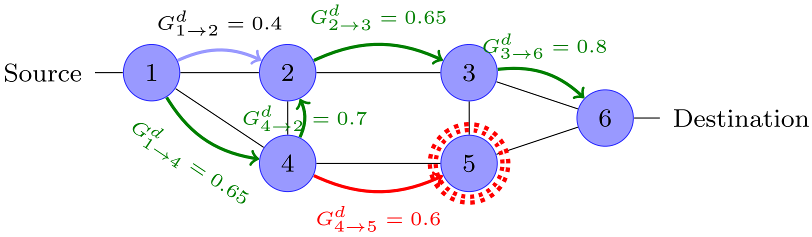
The gradient field that is used by PGBR's discovery mechanism (i.e. *Chemotaxis*) is generated with a gradient equation, that defines two types of repellents and one attractant, and can be represented as follows:

$$G^d_{i \to j} = \alpha l^n_j + \beta l^l_{i \to j} + \gamma h^d_j \tag{3.1}$$

where $G^d_{i \to j}$ is the gradient of the link $i \to j$ for the destination d, l^n_j is the load of neighbour node j, $l^l_{i \to j}$ is the load of link $i \to j$ and h^d_j is a normalised hop count value of node j to the destination d, which defines the relative distance to the node from the destination. The normalised hop count value h^d_j is calculated during the topology formation, and will remain static. The values l^n_j and $l^l_{i \to j}$ represent the chemorepellents, where the discovery packet is attracted by the normalised hop count value h^d_j while avoiding congested links and hot-spots respectively modelled by l^n_j and $l^l_{i \to j}$. Formally, $l^l_{i \to j}$ is calculated from the ratio between available bandwidth and the maximal bandwidth of the link $i \to j$ (n.b. $l^l_{i\to j} = 1$ when available bandwidth is maximal and 0 otherwise), while l^n_j is the average value of $l^l_{j\to k}, \forall k \neq i$. The three-tuple ($\alpha$, β, γ) modifies the gradient field to maximise or minimise the importance of the chemorepellents and chemoattractant to change the behaviour of the discovery.



(a) Discovery of paths along gradient field using *chemotaxis*



(b) Gradient field modification by the reaction-diffusion mechanism

Figure 3.1: Route discovery process for PGBR

An example of the gradient field generated by the gradient equation is shown in Figure 3.1.1, where the discovery packet is attracted by the nodes with the highest gradients between the source and the destination. This behaviour can be observed in Figure 3.1a, where the discovery message goes hop-by-hop on the path "1 → 4 → 5 → 6". The reaction-diffusion mechanism of PGBR ensures that the gradient field is representative of the new traffic conditions. For instance, in Figure 3.1b, the node 5 senses a performance degradation and informs its neighbours using that mechanism. As a result, the PGBR discovery avoids the problematic node by diverting from the original path (i.e. the path is now "1 → 4 → 2 → 3 → 6").

Unfortunately, the reaction-diffusion mechanism depends on the frequency of updates between neighbours. On the one hand, if the frequency of messages is too high, the number of messages produced by PGBR may flood the network and the route discovery may suffer from unstable gradient field. On the other hand, if the frequency is too low, the gradient field will not be fully representative of the new traffic conditions. Consequently, the choice of frequency of the reaction-diffusion mechanism has a great impact on the performances of the PGBR routing protocol and must be chosen wisely (e.g. Table 3.2).

In the event of discovery packet looping, a back-tracking mechanism has been integrated to the PGBR discovery mechanism, using only local information, to select the next best hop in a fully and efficient distributed manner. More details about the back-tracking mechanism can be found in Article V.

Evolution of the Normalised Hop Count Definition

The definition of the chemoattractant has evolved during the research process to increase its efficiency. First, the normalised hop count was represented by the division of the current number of hops from the neighbour to the destination and the worst number of hops to the destination.

The equation for $h_i^d(j)$ was:

$$h_i^d(j) = 1 - \frac{w^d(j)}{W^d}, \text{ where } W^d = max(w^d(k)), \forall k \tag{3.2}$$

where $w^d(j)$ is the minimum distance of node j to destination d. For instance, if a node is the furthest from the destination, its normalised hop count value would be zero, while a closer node would have a strictly positive h_j^d, that is bounded by $h_d^d = 1$. Unfortunately, when the topology is extremely large, the normalised hop count values, for the nodes remote from the destination, may be very small (the concentration of attractant is negligible).

In Article III, the definition of $h_i^d(j)$ has been modified to counter the scalability problem. The normalised hop count is now calculated using differentials of concentrations rather than the concentration itself [130], and is represented as:

$$h_i^d(j) = \frac{max(w_i^d(k)) - w_i^d(j)}{max(w_i^d(k)) - min(w_i^d(k))}, \forall k \text{ neighbour of } i \tag{3.3}$$

As the result, the discovery was enhanced due to the better definition of the attractant that provides a better balance with the repellents for every nodes in the topology, independently of their location.

3.1.2 PGBR Support for Service-Oriented Architecture

In the Appendix A, a collection of published articles relates the added benefits of using PGBR for complex service-oriented architectures, with numerous and diverse services.

PGBR is different from other gradient based routing protocols, such as the traffic-aware potential based routing [60] (PBR), because PGBR is (i) fully decentralised to improve its scalability, (ii) avoids congested hot-spots (i.e. repellent l_j^n), where PBR only avoid congested links (i.e. repellent $l_{i \to j}^l$). In fact, the strength of the algorithm relies in its ability to adapt to varying traffic demand, by manipulating the three-tuple (α, β, γ), and at the same time maximising the use of underlying network resources. Currently, the same three-tuples are used by all the routers within the topology and the local modification of α, β and γ by a router has not been investigated.

The utilisation of multiple parameters sets can achieve different objectives. For instance $(0.2, 0.2, 0.6)$, in comparison to $(0.2, 0.4, 0.4)$, attracts traffic to take on the shortest routes (more weight is attributed to the attractor) while the second parameter set would tend to balance the network. This was confirmed by the evaluations of PGBR conducted in Articles I, II and VII.

During this study, PGBR gradient equation was discovered to mimic several state-of-the-art routing protocols. To further explain this relation to existing protocols, the PGBR's parameters set of $(0.0, 0.0, 1.0)$ would act like a shortest path routing (SPR) protocol. On the other hand, the parameter set of $(0.0, 0.0, 0.0)$ would behave more like random walk and $(x, y, 0.0), \forall (x, y)$ would behave similarly to the back-pressure routing protocols. As a result, the gradient field equation of PGBR is flexible, and can exhibit multiple behaviours, including the emulation of most current state-of-the-art routing protocols, by manipulating a few parameters. The manipulation of these parameters could be dynamically performed through simple policies that can easily be configured by the administrators of the network. An example of these policies is documented in Article I, where the values of α and β were dynamically adapted to fit the network conditions.

3.1.3 Energy Management using PGBR

In this study, I showed in two articles that PGBR is able to support energy management while providing high quality of service delivery to the end-users. State-of-the-art solutions recognise that routing protocol must aggregate traffic to a smaller topology, which subsequently allow unused devices (i.e. routers or link-cards) to be powered-off. Unfortunately, reducing the topology size impacts negatively on the delivery of services, as they are less resources available. Unlike, OSPF or other link-state protocols, PGBR allows maximum usage of the underlying resources. Consequently, in Article IV, a two-phase mechanism was introduced to either power-on paths in the network when resources are under-provisioned or power-off paths when resources are over-provisioned. The two-phase mechanism sitting on top of PGBR is called “Parameterised Green Gradient Based Routing” (PG^{2}BR). It has several advantages compared to state-of-the-art solutions:

- PG^{2}BR is using the standard PGBR gradient field equation to discover new routes. Thus, the objectives of the network administrators will be maintained transparently.
- PG^{2}BR only uses information provided by the original protocol (e.g. link load, node load or hop count).
- PG^{2}BR does not require knowledge of the traffic pattern and applies its energy saving mechanism throughout the day without disrupting the users of the network.

However, in Article V, the energy management is performed differently. The approach taken was the definition of a new gradient field equation that includes awareness of green renewable energies, which can be represented as follows:

$$G^d_{i \to j} = \alpha g(j) + (1 - \alpha) h^d_j, \quad 0 \leq \alpha \leq 1 \tag{3.4}$$

where $g(j)$ represents the greenness of neighbour node j, where the greenness is related to the ratio of brown energy required to power the router. In the case of a "brown" router (i.e. router fully powered by fossil fuel energy), $g(j)$ would be nil, while a "green" router (i.e. router fully powered by renewable energies) would have a greenness equal to 1. Within this equation, "brown" energy acts as the repellent, thus leading PGBR, referred to as "Renewable energy-aware Parameterized Gradient Based Routing" (rePGBR), to discover routes consuming less quantity of fossil fuel energy. Unlike equation 3.1, equation 3.4 does not support load balancing of the network. This is due to the decision of the network operator to combine rePGBR with an efficient caching strategy that would reduce the traffic within the network as well as providing fast and effective service delivery to the end-users. More details on the caching and its cooperation with rePGBR can be found in Article V.

Meanwhile, these studies showed that PG^{2}BR or rePGBR are adaptable and efficient to provide significant energy savings without disrupting the delivery of services to the end-users.

3.1.4 Implementation of PGBR

This section regroups the different algorithm that compose the PGBR routing protocol. As previously mentioned, the PGBR routing protocol is composed of three different concepts. One of these concepts is the reaction-diffusion mechanism. Currently, the reaction-diffusion mechanism of PGBR is performed using one-hop messaging. Each router periodically sends a message on each of its interface with the current load information of that link as well as the router's node load. The packet structure has been described in Table 3.1. The messages are sent periodically according to the monitoring window for the link sensing (see Table 3.2).

0 1 2 3

0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1

Packet Sequence Number	Reserved
Link load	
Node load	

Table 3.1: Reaction-diffusion packet header

Mechanisms	Parameters	values
Reaction-diffusion	Link sensing window	1 min
	Updates interval	1 min
Discovery	TTL	255
Flow-based routing	Table checkup interval	10 s
	Maximum flow delay	2 s

Table 3.2: PGBR parameters

PGBR includes also a second concept, a flow-based mechanism, that abstracts and regroups network packets into flows that have similar requirements. Each flow will be addressed with a unique id that would be accessible in the packet header. When a router receives a network packet, it looks up into the flow routing table to find the routing information about the flow. If the information is present in the flow routing table, the packet will be routed accordingly (e.g. forwarded to next hop, local delivery to the above layer, dropped or buffered in the case of discovery). Otherwise, the router will initiate a new flow discovery (third concept) and buffer the network packet. The discovery mechanism will be described in details in the following subsection. PGBR also includes a mechanism that cleans up the flow routing table. For instance, a flow routing entry is considered outdated if no network packets have been using the entry for a period of time (see Maximum flow delay in Table 3.2). To be noted that dropped packets are also considered as using the flow routing entry. At the end of every table checkup interval (see Table 3.2), the mechanism removes outdated entries from the table information.

Discovery mechanism

<table>
<tr><td colspan="4">0 1 2 3</td></tr>
<tr><td colspan="4">0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1</td></tr>
<tr><td colspan="2">Packet length</td><td colspan="2">Packet Sequence Number</td></tr>
<tr><td>Packet Type</td><td>Reserved</td><td>Time To Live</td><td>Hop Count</td></tr>
<tr><td colspan="4">Source Address</td></tr>
<tr><td colspan="4">Destination Address</td></tr>
</table>

Table 3.3: Discovery packet header

The PGBR discovery mechanism only uses local information in order to find an appropriated path between a source and a destination for a particular traffic type (i.e. determined by α, β and γ). The algorithm 1 describes the behaviour of PGBR to select the next best hop once a discovery message arrives at a node u for destination d, with $u \neq d$. Unlike the discovery packet header in Article IX, the new version of PGBR does not store the addresses of visited nodes in the discovery packets, but uses only the local information available at the router. The new discovery packet header is described in Table 3.3.

The local information stored at the router is visible on lines 2 and 3 of the algorithm 1, where PGBR stores the list of incoming neighbours (neighbours that have sent the discovery message to node u) and the list of outgoing neighbours (neighbours to whom node u has sent the discovery message). These lists are necessary to avoid packet looping and are also used by the back-tracking mechanism of the PGBR discovery. The first action of the discovery mechanism is to update

Algorithm 1 Selection of next hop during discovery

```
Require: Destination $d$, incoming neighbour $iN$
 1: $u \leftarrow$ current node
 2: $qIn \leftarrow$ list of incoming neighbours
 3: $qOut \leftarrow$ list of outgoing neighbours
 4: if $iN$ is not nil then
 5:     $qIn \leftarrow qIn + iN$
 6: end if
 7: $nextHop \leftarrow nil$
 8: $bestG \leftarrow -1$
 9: for neighbour $v$ of $u$ do
10:     if $v \notin qIn \cup qOut$ and $G_u^d(v) > bestG$ then
11:         $bestG \leftarrow G_u^d(v)$
12:         $nextHop \leftarrow v$
13:     end if
14: end for
15: if $nextHop$ is nil then
16:     repeat
17:         $nextHop \leftarrow last(qIn)$
18:     until $nextHop \notin qOut$
19: end if
20: if $nextHop$ is not nil then
21:     $qOut \leftarrow qOut + nextHop$
22: end if
23: return $nextHop$
```

the list of incoming neighbours with iN if it is not nil (see line 4-5, iN is nil only when u is the source node).

From line 7 to 14, the protocol checks which of its neighbours, that are neither in the outgoing and incoming lists, has the highest gradient value (e.g. gradient equation 3.1). Only checking unused neighbours reduces the probability of discovery packet looping.

From line 15 to 19, if the next hop has not been found previously, the back-tracking mechanism of PGBR sends back the discovery message to the last neighbour that have sent it, as long as this neighbour is not part of the outgoing list. A neighbour that is included in both lists is equivalent to a dead-end for the discovery. The next action is then to update the list of outgoing neighbours and, finally to return the selected neighbour. To be noted that in the event of the algorithm returns nil as next hop, the discovery will be dismissed. Another parameter that can dismiss the discovery is the Time-To-Live (TTL, see Table 3.2) value.

The end of the discovery process occurs once the discovery message reaches the destination node. Then, the destination node backtracks the discovery message to the source with the difference that this discovery packet will update the flow routing information on each nodes it visits, as well as deleting the local information stored during the discovery. Once the back-tracking discovery message reaches the source, it updates the flow routing table entry and releases all buffered packets (packets buffered during the discovery process) into the network. More details about the implementation of PGBR can be found in Article IX.

3.2 Bio-inspired Resource Management

In this section, I present two novel bio-inspired mechanisms that efficiently manage the resources of core infrastructure network and which may be used in combination with the bio-inspired routing protocol presented in the previous section. Section 3.2.1 presents a protocol that adaptively controls the available bandwidth of the resources discovered by the routing protocol, while Section 3.2.2 presents a bio-inspired mechanism that has been developed to manage multiple providers sharing common resources.

3.2.1 Bandwidth Management via BiRSM

In Article VI, a novel bandwidth management mechanism was introduced to address the need of service providers to (i) handle the distribution of resources to their customers and (ii) calculates the quantity of resources that needs to be purchased from the carrier.

The main challenge for the bandwidth management mechanism is the allocation of the resources at different time scales, including short, medium and long-term resources allocation strategies. *Blood Glucose Homeostasis* [131] is the regulation process of blood glucose in the human body to maintain a stable environment. The bandwidth management mechanism "Bio-Inspired Resource Self-Management" (BiRSM), documented in this thesis, is inspired from this biological model. The system responds to negative feedback (deviation of the blood glucose levels) from environmental changes to restore stability. BiRSM uses similar approach to help the providers managing fairly their resources in order to improve their revenue.

In the scenario of Article VI, the providers subscribe resources from the carrier through BiRSM for each virtual path of their overlay network. For each allocated capacity, the BiRSM performs call admission by managing resources for multimedia (high priority) and data traffic (low priority). The self-management process observes patterns in the traffic behaviour and self-tunes in order to manage the resources at different time scales to optimally maximise call admission. As in the *homeostasis* process, BiRSM uses three mechanisms that enables the providers to increase their revenue for short, medium and long-term, which will be described with greater details in the following sub-sections.

Short-Term Resources Allocation Strategy

BiRSM sets a boundary between the different traffic types to maintain a fair sharing of the resources. On the one hand, in the event of under-utilised resources, BiRSM aims to maximise resource usage by allowing certain traffic types to cross the boundary. This behaviour is inspired from a classical resource management strategy [67]. On the other hand, in the event of bandwidth starvation, each service type may use only the part of the bandwidth that was allocated to it. However, I proposed a resistance-based mechanism for resource reclaim, that enables multimedia traffic not be be interrupted when data traffic claims its resource back. However, if this situation repeats itself, the resistance decreases (similarly to the resistance effort of the human body [132]) to ensure a certain degree of fairness. The resistance factor is monotonically decreasing as the time passes. Like in the body adaptation to effort, the medium-term resource allocation strategy will help reduce the need of the short-term resistance.

Medium-Term Resources Allocation Strategy

Using the medium-term resource allocation strategy, BiRSM self-adapts the resources by considering the degree of changes in traffic pattern as well as the state of the network. In BiRSM, the boundary is divided into time zones where within each zone the boundary may have a different position. The approach used to tune the boundaries is based on a process, which predicts the multimedia capacity required for a specific time zone on the next day. Therefore, the movement of the boundary is reconfigured at the end of each day. In this study, it has been shown that the boundary smoothly adapts, day after day, to the traffic pattern to prioritise multimedia traffic over data traffic, such as the body predicting the amount of glycogen required to create energy for the daily workload [132]. This process is comparable to the training process that self-tunes the body to suit the intensity of daily activities.

Long-Term Resources Allocation Strategy

While the movement of the boundaries will satisfy the resources required for multimedia traffic and in turn increase the overall revenue, this has come at a cost of lower throughput for data traffic. As described earlier, the purchase of spare capacity to increase total path capacity is based on a trade-off strategy. When the short and medium-term allocation strategies are not improving the provider's revenue, the BiRSM solution will allow the provider to autonomously determine and purchase a suitable quantity of spare capacity from the underlying carrier. More details about BiRSM can be found in Appendix C.

3.2.2 Management of Multiple Providers

Appendix D presents the articles that have been published on the management of multiple providers, where each provider uses an overlay network sharing common resources with the other providers from the underlying infrastructure. In both Articles VII and VIII, the investigated scenario included multiple IPTV providers using virtual overlay topologies over a single physical carrier infrastructure. The work published in Articles VII and VIII will be presented in more details in the following sub-sections.

PGBR Support for Multiple Providers

In Article VII, the support of multiple IPTV providers was provided by PGBR. The proposed scenario in this article assumes a number of IPTV providers that have virtual overlays on the underlying network infrastructure. The proposed resource management scheme incorporates the PGBR routing algorithm to deliver the streams from each IPTV provider through the underlying network. In real deployment of IPTV contents, each content will have different QoS requirements (e.g. Standard Definition content may be different from High Definition content). Therefore, for the various different types of contents, a different set of α, β and γ should be applied to equation 3.1, based on the quality requirements. As discussed in Section 3.1.1, PGBR allows easy configuration of resources discovery via the manipulation of the three-tuple (α, β, γ).

The simulations of Article VII showed that PGBR was able to deliver more IPTV contents over an IP network than the traditional solutions, while ensuring that quality is maximised for end-users, resulting in an increase of revenue for all the IPTV providers.

Multiple Providers Resource Allocation via Lotka-Volterra Inter-species Competition Model

Unlike the management of multiple providers described in the previous sub-section, the research presented in Article VIII focuses on providing fair resource allocation between multiple service providers.

The aim of this study is to determine how multiple virtual IPTV providers could co-exist and share their resource over the underlying network, without compromising the quality and revenue of each provider. Therefore, the best solution would be to use some form of resource fair sharing technique managed by the carrier to distribute the resources amongst the providers. The biological model used for fair sharing of resources is the Lotka-Volterra inter-species competition model, used in ecology to model the dynamics of resource competition [115]. This model allows multiple species to co-exist together, where each species will have different aggressive behaviour towards the resources (some species may be more aggressive than others, but they are still able to co-exist together). Based on this concept, the model enables the carrier to fairly allocate resources to competing providers in a manner that maximises its own revenue, and fairly shares the resources so that each provider can still exist. IPTV providers must continually evolve to improve sustainability and meet continually changing environments (e.g. user demand). The Lotka-Volterra competition model is represented as:

$$\frac{dn_i}{dt} = \epsilon_i \left(1 - \frac{N_i + \gamma_{ij} N_j}{K_i}\right) N_i \tag{3.5}$$

where N_i represents the type of species i, ϵ_i represents the growth rate, γ_{ij} represents the ratio of competition between species i and j, whilst K_i represents the carrying capacity of the environment.

The advantage of the competition model is that each provider can specify a competition value against all others species and the model will predict a fair sharing of the physical resources. Furthermore, the model is compatible with large number of service providers.

Simulations in Article VIII showed that, through the environment of competitiveness, the model shows improved revenue for the carrier and for the IPTV providers that are competitive (i.e. having many subscribers or a large quantity of traffic demand). At the same time, the coordinated resource distribution, allows each provider to efficiently manage its resource without affecting the performance of other providers. More details and results (with up to 10 providers competing for resources) can be found in Article VIII.

3.3 Validation

In order to validate the findings of my research in this thesis, simulation work has been conducted first on my own flow-based network simulator. It was implemented as a discrete time event simulation written in Java for collecting the results found in Articles I, VI and VIII. The network simulator included only the discovery process where the traffic demand was already abstracted into flows. Consequently, details about packet-level routing and metrics where not available.

Even though the simulator presents a simplified approximation of network flows, it provided a realistic insight of the potential of PGBR routing, as well as the BiRSM bandwidth management mechanism. Finally, this was confirmed, when the PGBR routing protocol was implemented for the ns-3 network simulator [133]. Unlike my own Java-based simulator, the ns-3 network simulator provided several advantages. Ns-3 is a novel open-source network simulator, under GNU GPLv2 license [134]. The simulator is taking advantages from the development of several other open-source network simulators, such as the popular ns-2 [135], while avoiding their disadvantages. Weingärtner et al. [136] did a comparison study of these open-source network simulators that further strengthened my decision to choose ns-3 as the development platform for PGBR. The decision has been made to facilitate the dissemination of future work (ns-3 is a popular network simulator amongst the research community) as well as minimise development time when PGBR would be tested on real hardware for experimentation (ns-3 permits using the same code for simulation and experimentation). Another point is to challenge PGBR for more realistic scenarios (e.g. realistic topologies [137,138] and traffic patterns [139]). With the Java-based simulator, there was no notion of packets, thus models were simpler. With ns-3, PGBR protocol evolved to handle packet-based events and, therefore, making possible its future integration into real architectures. The detailed implementation of PGBR to ns-3 is documented in Article IX, and the implementation was used to perform simulations in Articles II, III and IV.

However, a few exceptions have been made in Articles VII and V. On the one hand, the simulation work in Article VII was done with the QualNet network simulator [140]. This simulator was necessary to retrieve information necessary to calculate the Quality-of-Experience of the multimedia flows. Unfortunately, the simulator is not open source, and consequently the development of PGBR shifted to ns-3. On the other hand, the experimental work in Article V were performed on a cluster of 240 Dell PowerEdge M610 nodes, where each node has a double quad-core CPUs, 32GB of memory, runs a linux 2.6.32 kernel, and is connected to a 10-Gbit network. The experimental cluster was capable of simulating large network size, with voluminous traffic that was required to collect the output data produced for that article.

3.4 Answers to the Research Questions

In this section, I present the answers to the research questions that also are the objectives of this research. This will be followed by Table 3.4 that compiles all the published articles and the research questions they cover.

Q1. Routing: *What biologically inspired routing protocols can support an evol-*

ving services environment in large scale networks, while ensuring scalability, adaptability, and flexibility?

Answer: Routing protocols are the cornerstone of efficient resource management. They define how much resources are available. In biology, the *chemotaxis* process facilitates the mobility of bacteria in large environment, in a fully distributed fashion. The PGBR routing protocol has inspired its route discovery from *chemotaxis*, and changes the discovery environment throughout a second biologically inspired process, known as reaction-diffusion. Using this fully decentralised mechanism, the PGBR routing protocol is highly scalable. The protocol integrates a flow-based discovery process that makes the protocol highly adaptable to new network conditions, because the new services requested by the network's end-users will be routed using the most adequate route within the new network configuration. Finally, through the selection of a few parameters (e.g. Equation 3.1), PGBR was able to support various traffic types, as well as mimicking state-of-the-art routing behaviours.

Q2. Bandwidth management: *What biologically inspired bandwidth management protocols can support efficiently services at different time scales?*

Answer: Service providers must have the ability to allocate their resources efficiently at different time scales. The *blood glucose homeostasis* responds to negative feedback from environmental changes to stabilise the environment. Similarly to the response of effort within the human body, the biological mechanism is used to stabilise the environment at short, medium and long-time scales. BiRSM is a bandwidth management protocol that have been inspired by this biological model. It provides efficient and adaptable control of the bandwidth allocation to the network administrators with short, medium or long-term strategies in order to improve the service providers' revenue, while minimising disruptions of existing and prioritised services in the case of bandwidth starvation. The process improves gradually at the end of every day to mimic the ability of the human body to predict the required quantity of energy for a daily workload (i.e. maximise fitness).

Q3. Energy management: *Can a bio-inspired routing protocol be adapted to minimise the consumption of fossil fuels energies for the future networks?*

Answer: The exponential growth of the Internet led to a tremendous increase of its energy consumption. I believe significant reduction of energy consumption can be obtained through core infrastructure network management. Using the power of PGBR to maximise usage of underlying resources, a dual-phase mechanism was introduced to dramatically reduce the energy consumption of the network by powering-on or off paths in the network. The PGBR was able to minimise the impacts on the service quality of delivery to the end-users, while adaptively modifying the underlying topology to save energy. Another approach discovered was the benefits of an energy-aware (e.g. renewable energy) gradient equation (see Equation 3.4) that minimise the need of fossil fuels energy in a dynamic environment with changing weather conditions. The alliance of renewable energy-aware routing and an efficient caching strategy showed that disruptions of services can be avoided, while greatly reducing the carbon footprint of the network.

Q4. Multiple providers: *What biologically inspired model can fairly allocate resources to multiple virtual overlay services providers sharing common underlying resources in a revenue driven fashion ?*

Answer: In this research, the support of multiple providers has been supplied by (i) the PGBR routing protocol and (ii) by the Lotka-Volterra inter-species competition model. In the case of (i), PGBR is maximising the usage of underlying resources, allowing the services providers to increase their number of subscribers. In addition to (i), the Lotka-Volterra inter-species competition model allows each service provider to compete with the other providers to further increase their revenue. The biological model is fairly allocating the available resources between providers sharing common physical resources, such as multiple species competing for natural habitat. Consequently, in both cases, the revenue of the service providers was increased significantly, while (ii) increased as well the revenue of the network carrier (i.e. the competition between service providers is based on the pricing of using the carrier's resources).

Article	Appendix	Research questions	Challenges
Article I	Appendix A	Q1	C1, C3 and C4
Article II			
Article III			
Article IX	Appendix B	Q3	C1 and C5
Article V		Q3	
Article VI	Appendix C	Q2	C1, C2 and C3
Article VII	Appendix D	Q1 and Q4	C1, C3 and C4
Article VIII		Q4	
Article IX	Appendix E	Q1	

Table 3.4: Publications, Research questions & Challenges

Table 3.4 compiles the articles documenting the results of the research that have been published. They have been separated in five appendices. Appendix A presents three papers focusing on the evaluation of PGBR (as part of the answer for **Q1**) to maximise resource usage, as well as supporting highly evolving service environment. Two of the papers (Articles I and III) have been presented during conferences, while the third paper, Article II, is a journal publication. Appendix B regroups the two journal articles, currently under peer-review process, that cover the solutions for the research question **Q3**. Appendix C is composed of a single magazine article that documents the bio-inspired solution answering the research question **Q2**. Appendix D is composed of two journal articles that address the challenges of managing multiple service providers sharing common resources (**Q4**). Additionally, Article VII also documents part of the answer of the research question **Q1**. Lastly, Appendix E is composed of a single workshop paper to validate the integration of the PGBR routing protocol within the current Internet protocol stack.

Chapter 4

Conclusions & Future Work

In this chapter, I present, in Section 4.1, the conclusions of the research that has been presented in this thesis, and I conclude this thesis, in Section 4.2, by presenting the possible directions to continue this research.

4.1 Conclusions

This thesis has outlined the advantages of the application of multiple bio-inspired mechanisms to support routing and resource management of core infrastructure networks for today's and tomorrow's Internet architectures. Several motivation factors such as the need of future communication systems to be adaptive, scalable, robust and energy efficient, while providing high quality of service delivery to the network users have been presented and bio-inspired solutions to these motivating factors have been investigated.

The increasing popularity of the Internet is resulting from the availability of new complex services such as full High Definition IPTV, large social applications or dynamic web sites supporting Video-On-Demand. The emergence of new technology and paradigms, such as the Internet of Things where each object could be potentially connected to the Internet, will revolutionise the way communication networks are used, as well as the diversity of services, amplifying the need of protocols meeting the requirements of the Future Internet. The inability of current state of the art to achieve simultaneously all the above features motivated this research work to evaluate bio-inspired mechanisms.

A literature survey has outlined the challenges of core infrastructure networks and current state-of-the-art solutions addressing these challenges, with critical evaluation. The literature survey also shows the possible benefits of applying biological principles to solve networking issues. These biologically inspired techniques enhance networking mechanisms with autonomic properties, such as self-management, self-configuration, self-healing or self-organisation, and have shown tremendous potential to support the Future Internet requirements, while minimising the need of human intervention.

In this thesis, I have described three bio-inspired protocols that can be used simultaneously to maximise routing and resource management of core infrastructure networks. All the protocols are service-centric in order to maximise their quality of delivery to the end-users.

The selection and evaluation of appropriate bio-inspired mechanisms have been undertaken, and their integration to the protocols has shown significant economical benefits compared to state-of-the-art solutions. One of the protocol is the "Parameterised Gradient Based routing" (PGBR) that is inspired from *chemotaxis*. The routing protocol is scalable, adaptable and provides efficient delivery of services. Furthermore, the protocol's robustness allows network's operator to easily change its behaviour to match the requirements of new challenges. The protocol has been extensively evaluated through simulations and experiments, and has proven to overcome challenging issues arising as the complexity of the scenarios increased (for instance, when the protocol has been modified to include energy awareness, while sustaining the objectives of the network operators). Two other bio-inspired mechanisms have been proposed to further enhance the management of services provided by PGBR. The first one, BiRSM is a novel bandwidth management protocol inspired by *homeostasis* and the second one supports the management of multiple service providers using the Lotka-Volterra inter-species competition model.

The evaluation of these protocols, specially the routing protocol, has been undertaken to show the integration to current Internet architectures to help support new features such as reducing the carbon footprint of the infrastructure, and state-of-the-art services management in complex environments. Performance evaluations have further demonstrated that the proposed techniques outperformed state-of-the-art solutions and integrated well to Future Internet architecture.

Finally, the dissemination of the research work has been done through the publication of eight original peer-reviewed publications, including three journal articles, one magazine article and four conference papers (two conferences, one workshop and a poster). Currently, two additional articles are in a peer-review process for journal publications (ACM SIGCOMM CCR and IEEE JSAC). The reproduction of each article can be found in the appendices of this thesis, except the publication for the "IEEE AINA '09" conference since Article VII is its extended version.

4.2 Future Work

The following topics may serve as possible directions of continuation for the research presented in this thesis.

New Attractants and Repellents for Improved PGBR Discovery

PGBR is a routing protocol that has been developed considering its modularity as a key feature. PGBR provides a module for the definition of the gradient equation that defines the route discoveries. Throughout the research conducted for this thesis, the application of new attractants and repellents has improved the performances of PGBR. Consequently, a possible direction for continuation of the proposed protocol could rely in a better definition of attractants and repellents. For instance, the routing protocol may benefit from improving its reaction-diffusion mechanism by using information from two-hop or three-hop neighbours.

Enhanced Discovery Mechanism for PGBR

Currently, PGBR discovery are done once for each service delivery. The introduction of of new data flows in the network may impact on the quality of the previously discovered flows. The evaluation of PGBR that has been conducted during my research has shown the capacity of PGBR to address this issue better than state-of-the-art solutions. However, PGBR may benefit from an interaction of end-to-end flow monitoring process to rediscover alternative routes once the quality of prioritised flows drops significantly. Similar degradation of quality may occur during node or link failures. Further improvements to the discovery mechanism may include piggybacking more information about the network's status on the discovery packet that could be used by routers to maximise the routing performances.

Evaluation in Scenarios of Increased Complexity

The routing protocol has been evaluated in complex service environments. For instance, the energy-aware versions of PGBR were able to maximise energy savings without disrupting service deliveries. Unfortunately, the energy-aware protocols may be vulnerable in the event of failures (as the size of the network is dramatically reduced to a minimum), and existing services may be greatly disrupted while the protocol adapts to the new topology. As outlined by the literature survey, resilience to failure is a key feature of the Future Internet systems. PGBR may benefit from positive trade-offs between energy savings, quality of delivery and resilience to failures.

Resource Management of Wireless Infrastructures

In this thesis, I have presented protocols to efficiently manage the resources of wired infrastructures. The protocols that have been presented in this thesis could be modified to efficiently support wireless networking, as wireless networks are widely used in the Internet's infrastructure. For instance, the PGBR protocol would need to adapt its attractants and repellents to cope with the challenges of wireless devices (e.g. mobility, frequent failures, etc.).

Bio-inspired Communication Eco-system

The literature review has highlighted the need of the protocols of the Future Internet to co-exist and cooperate in symbiosis for the benefit of the whole architecture. In this thesis, I have shown the benefits of combining multiple bio-inspired techniques to improve the performances of managing the resource of core infrastructure networks. Currently, the protocols of the Internet are addressing a few challenges but their actions may negatively impact the other protocols. As a result, the development of new bio-inspired protocols that are aware of their environment, such as entities of an eco-system, would holistically contribute to the infrastructure. A possible direction for future research relies in the creation of a richer bio-inspired communication eco-system, which already includes the protocols documented in this thesis.

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Appendix A: PGBR Support for Service-Oriented Architecture

Article I

Sasitharan Balasubramaniam, Dmitri Botvich, Ray Carroll, Julien Mineraud, William Donnelly, Tadashi Nakano and Tatsuya Suda

Adaptive dynamic routing supporting service management for Future Internet

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Contribution: My contribution to this research article is related to the routing protocol PGBR, which is part of a dual-layer solution for efficient service management for the Future Internet. For this research article, I personally designed the set of experiments to evaluate the performances of PGBR as well as the combined solution. In addition, I investigated a new model to dynamically adapt the parameters of the routing protocol depending on the load of the network. I also took part in writing some parts of the paper as well as proof reading.

Adaptive Dynamic Routing Supporting Service Management for Future Internet

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Abstract— **There is currently much debate in defining what form the Future Internet will take [22, 23, 24]. The current Internet is struggling to meet the needs of an ever-evolving society. This is largely due to the Internet now become a thriving marketplace with services at the core. The range, number and complexity of services are set to increase with an even more dynamic service environment envisioned in the future. However, as these services grow, service composition will become an important feature of the service environment, leading to new challenges in service discovery and composition mechanisms. At the same time, dynamic service environments will also require that the underlying infrastructure networks are flexible enough to handle the changing service landscape. One area this is particularly important is in dynamic routing to deal with highly dynamic and frequent service changes. In this paper, we adopt mechanisms from biology and apply these to the problems identified, resulting in an integrated Bio-inspired service management and dynamic routing solution for Future Internet. We demonstrate how the bio-inspired mechanisms not only improve each problem individually, but through their integration also improve overall network performance. Simulation results are presented to validate the proposed solution.**

Keywords- Bio-inspired networking, service management, dynamic routing

I. INTRODUCTION

Services that can be tailored to meet the user's needs are predicted to be a principle driver of the Future Internet. However, following the Internet's huge increase in popularity in the last 10 years, it is already under significant pressure to meet the current requirements of users. This is largely due to the fact that the original Internet infrastructure was developed for a limited set of services with static traffic behaviour. The Future Internet will be a much more dynamic environment and as such will face numerous challenges. Particularly important is the ability to support efficient and flexible service management in order to meet changing user demands. At the same time we must ensure that infrastructure networks are able to cope with these changes by means of efficient delivery of services through the core networks.

The future will witness large numbers of disparate services, each with different capabilities. While it is important that services are available in large quantities to maximize user choice, service composition will be required in ensuring that appropriate services are available and tailored to the user's needs. However, large quantities of services lead to problems in efficiently discovering the most suitable services for the users, and composing these services efficiently inline with the changing service environment (e.g. ensure the composed service uses the most up-to-date and relevant service versions). While the improvements made in service management will lead to greater user satisfaction, they will also place more pressure on the underlying communication networks. In particular, one aspect of the Internet that will need to be enhanced is routing to support dynamic traffic (resulting from changes at the service layer), and to perform routing in a distributed and dynamic manner [13].

Taking inspiration from biological systems to enhance adaptive and autonomic communications systems has gained tremendous popularity in recent years [5, 6, 7, 9, 14, 15, 16, 17, 18, 19, 20, 21]. At the same time service management and composition [1, 2, 3, 4], along with dynamic routing [10, 11, 12, 13] have become established areas of research. While much attention has been paid to individual systems, an integrated solution for Future Internet is still under investigation. In this paper, we propose a *Bio-inspired Future Internet* solution that addresses each individual problem and integrates these into a single solution. The proposed architecture will include a service management layer that allows services to autonomously compose and evolve to changing user demand, and an infrastructure layer that dynamically routes traffic through the core network infrastructure to efficiently deliver these services. Besides the adaptive nature of the proposed architecture, the aim of our solution is also to ensure a high degree of system autonomy that will minimise human intervention.

The paper is organized as follows: Section 2 presents a high level description of our Bio-inspired Future Internet solution, followed by the service management layer in section 3, and the dynamic routing mechanism in section 4. Section 5 presents a description of the integration of the two layers. Section 6 will demonstrate the validity of the proposed solution through simulation, and lastly section 7 will present the conclusion.

II. BIO-INSPIRED FUTURE INTERNET

Our proposed Bio-inspired Future Internet solution is illustrated in Figure 1. In this paper, we focus only on content-based services, where the Service Management Layer manages these services for the user's applications (e.g. from composed web services to Video on Demand (VoD) for set top boxes in homes). Example functionalities of the Service Management Layer includes composing services to meet user's requirements, or adaptation of service components to suit the access network resources or device capabilities (e.g. filtering of multimedia streams [3]). Our vision of the future is that services will evolve very fast, as developers create new services or upgrade their functionalities. Also, developers should not have to deal with the mechanisms of how these services are composed, evolve or populated to other servers. These processes should be performed autonomously. The diversity of services (and compositions) will also lead to very dynamic traffic behaviour, which is not well suited to current routing approaches. Hence dynamic and adaptive routing will be required at the underlying infrastructure networks.

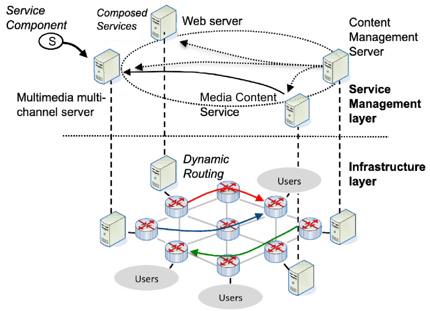


Figure 1. Proposed architecture

Our objective is to create a bio-inspired solution that meets the objectives of the individual layers illustrated in Figure 1. and ensure that the co-existence of the two layers will lead to improved scalability, efficiency, adaptability, and robustness [8]. Different Bio-inspired solutions have been applied to each layer of the proposed architecture, where a combination of mechanisms from *Biological lifecycle* and *Chemotaxis* are applied to the Service Management Layer, and *Chemotaxis* mechanism is applied to dynamic routing at the Infrastructure Layer. The following sections will describe how each of these techniques will contribute to each layer.

III. SERVICE MANAGEMENT LAYER

This section describes the mappings of bio-inspired techniques to service management, as well as mechanisms of creating composed *Service Groups* (*SGs*). The application of Biological lifecycle mechanisms will enable a more efficient service management process. The approach builds on the previous work of Autonomous Agents supporting self-organising services (referred to as *Service Agents (SA)*) [2], where added functionalities include mechanisms for SAs to coordinate and form SGs. The composed groups will evolve and change as services evolve and user demand changes. This provides service developers/providers with a degree of autonomy, as services can be deployed onto an server where the biological service lifecycle then takes over, ensuring 'fitter' (more useful) services thrive and weaker ones do not.

A. Service Agents Biological Lifecycle

The SAs reside on a node known as the *Application Server* (*AS*) and contain service content that support specific user applications. The SAs are analogous to biological entities (e.g. bees, bacteria), where these biological entities share a common behaviour throughout their lifecycle. The migration, replication and death behaviour of the agent is represented as x. Each SA carries a set of factors (v_i), a weight (w_i) associated with the factor, and a threshold (θ_x) that governs the behaviour of the agent. In the event of any changes in the environment, the behaviour x is invoked when $\sum v_i w_i > \theta_x$.

Migration: The SAs are able to perform migration by moving between different ASs. The movement is driven by the load on the current AS platform (AS_i). In the event that load on AS_i increases over a certain threshold, the SA will start to investigate the load of neighbouring AS_j for migration.

Energy Management: Each agent contains energy and is able to manage this energy throughout its life. When the SA resides on an AS, it expends energy for using the ASs resources (e.g. CPU, memory). At the same time, as the SA serves requests as part of a service group, it is able to gain energy for its contribution. Therefore, if a SA is part of many groups, it is able to gain large quantities of energy as its popularity increases.

Replication: SAs are also able to replicate themselves when the number of requests for that particular agent is high. This is due to the fact that each SA is only able to support a certain number of users. The SA will consider the number of requests it receives over a period of time, and if greater than the set threshold and the agent contains sufficient energy to replicate, the agent will begin replication.

Death: In the event that the SA gains less energy (e.g. SA becomes less popular) compared to the energy expended on the AS, the agent will die off. Through this process, SAs are able to live and die depending on the popularity of the service, which creates an evolving environment for services.

Service gradient search: Due to the large number of ASs, an efficient distributed search technique is required. When a query is transmitted it should be attracted towards the AS holding the particular SA. We use simple *Diffusion* of service advertisements to the ASs in close proximity, which creates a gradient field that will attract the queries towards the AS holding the SA. We assume that each AS platform contains a directory of SAs within its vicinity, where a hop count value is maintained for each SA.

Initially, when placed on an AS, the SA has a certain amount of energy it can use to propagate the hop count. As the agent diffuses this value to the neighbouring ASs, the agent details and hop count will be entered into the directory (Figure 2). As each AS receives the diffused hop count value, it will reduce the hop count value and continue to diffuse this to its neighbouring ASs. The process will continue until the hop count reaches zero. To find a SA, a query is diffused into the environment. When this query reaches an AS, the AS searches neighbouring ASs to find the service entry with the highest hop count. This process continues until the query reaches the AS containing the actual service agent. Therefore, by migrating from AS to AS through a higher hop count value, the query will get attracted to the SA. An example of this is presented in Figure 2, where a query for SA_3 approached AS_5 which passes this to AS_6 since AS_6 contains a higher hop count value for SA_3. If an AS has no entry for an SA, the query is passed to the next AS randomly, resulting in a random walk. The process is based on micro-organism motility, where a chemical gradient formed in an environment is sensed by the micro-organism to migrate towards the source (also known as chemotaxis [6]).

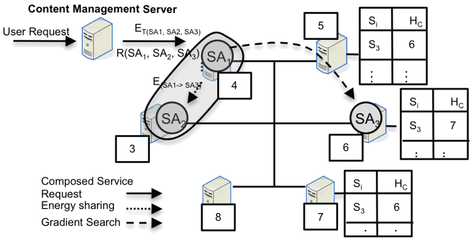


Figure 2. Gradient based query and energy sharing

Each SA entry in the AS directory has a set Time to Live (TTL). After a fixed period of time, the hop count of each SA will get reduced by one. Therefore, the SA will be required to update these entries, using a portion of its energy, to continually emit and update the hop count values. However, this is also dependent on the amount of energy the SA is gaining. In the event that the SA does not gain enough energy, it will only be able to use a small portion of energy for maintaining entries in peer ASs. Therefore, when the service reduces in popularity, the gradient emission will reduce, leading to increased resistance for the search process. This mechanism creates an automated, distributed, evolving process for discovering services, where new services with latest functionality will flood the AS networks, and as services loose popularity, the agents will slowly disappear.

B. *Dynamic Service Composition*

As described earlier, the primary goal of maximizing value to users is through composition of various services. The key towards composing the services is for services to discover other services that can enhance their collective value. Initially a request R_i from a user will be translated to a set of SAs ([SA_1, SA_2…]). The translation process will be performed through a *Content Management Server* (CMS), where the CMS may contain a specific service description solution that relates different services. Once the set of SAs is determined, a query is sent to the closest AS (AS_F) to determine if it holds an SA (SA_{ASF}) from the query. If it does, the SA_{ASF} will be the leader of the group and dispatch parallel queries for other SA in the set (in the event that the first AS does not contain a SA in the set, the AS will send this query to the neighbour and the whole process will repeat). Once all the SAs of the set have been found and are available to join the service group, a reply is sent to the SA_{ASF}, and the composition is formed.

C. *Service Management Evaluation*

In this sub-section, we present evaluation of the service management mechanism. The simulation compares service management incorporating the bio-inspired (SM-B) and the non-bio (SM-NB) case. In SM-NB, services do not have bio-inspired functionalities such as migration, death, replication, or gradient search (search is based on query flooding). The performance evaluation is presented Figure 3. The tests were performed on a 100 node topology to validate the scalability of the solution. Two sets of experiments were performed: the first set evaluated the effects of varying the gradient size and the second set for varying the composition size. The varying gradient size included a minimum gradient size (1 hop), maximum gradient size (maximum hop count between network edges), and half gradient size (half of the maximum size). In our simulation, for both the flooding (SM-NB) and gradient-based search (SM-B), we employed a broadcast search.

With message broadcasting there is a cost incurred in the number of messages used per search. Figure 3(a) shows the average number of messages per search used for both flooding and gradient-based searches across varying gradient sizes. The SM-NB solution consistently requires approximately 1270 messages to discover the best route. For SM-B, the gradient search differs greatly depending on the gradient size. At the minimum gradient, the number of messages is large (1200). This is logical given that, at minimum gradient, the search is limited to one hop of the actual node. As the gradient increases to half, the average number of messages reduces dramatically to 225. At full gradient the number of messages required is 0, since at full gradient the target node is visible to every other node in the network. Figure 3 (a) also shows the blocking rates experienced at varying gradient sizes. For the SM-NB we see that the blocking rates are relatively consistent (0.65 - 0.66). For the SM-B case we can see that the rejection rate is quite high (0.52) for minimum gradient size. However, as the gradient radius increases the blocking probability also decreases. This also resulted in greater replication for the full and half size gradient, and fewer deaths, ultimately leading to a higher number of agents. Figure 3(b) shows the blocking rates for varying composed service sizes. For SM-NB, as the size increases from 2 to 5 services, the blocking rate increases from 0.5 to 0.8. This is due to the fact that as the composition size increases, this in effect increases the number of agent requests. Hence the SAs reach their limit of the number of requests they can serve leading to a large number of requests being rejected. SM-B shows a very small blocking increase (0.06 - 0.14) from 2 to 5 composition size, directly attributed to increased migration (14 – 32733) and replication (1470 – 1777) resulting from the increased agent requests.

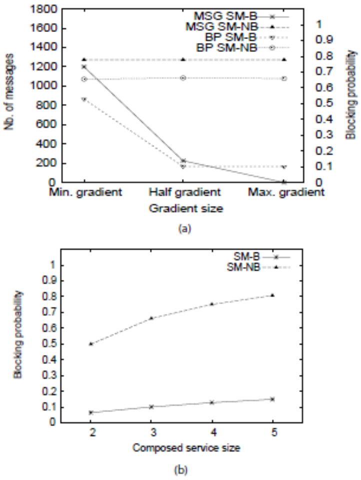
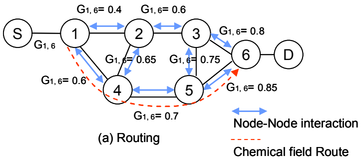


Figure 3. (a) No. of messages & Blocking rate vs. varying gradient size, (b) Blocking probability vs varying composition size

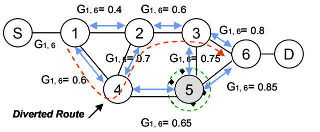
IV. PARAMETERISED GRADIENT BASED ROUTING

The objective of the dynamic routing mechanism is to support the changing traffic demand resulting from user's service requirement changes. The dynamic routing process is known as *Parameterised Gradient Based Routing* (*PGBR*) (full detail of the routing process can be found in [25]), and is inspired from the chemotaxis mechanism. Although the PGBR routing mechanism is similar to the service query search, the minor difference is how the gradient field is formed. In the case of PGBR it is formed based on the local interactions between nodes (Figure 4), unlike the service query search where the gradient is based on diffusion from the source. The route discovery is performed for each source-destination pairs, through a gradient attraction process. An example of route discovery is presented in Figure 4, where a route for S, D = (1→6) is found along path 1 – 4 – 5 – 6. An example of gradient attraction is at node 1, where node 1 selects the link to node 4 since it's gradient is higher than to node 2 (G1, 6,1→2 = 0.4 < G1, 6,1→4 = 0.6).

The advantage of using a gradient field that is set up by the environment is that the field is able to adapt and change with respect to the changes in network load. This is ideal for distributed routing, as it allows the route to divert around loaded nodes of the network (see Figure 4. (b)).



(a) Routing



(b) Diverted route from increase node load

Figure 4. Illustrative example of PGBR routing

Our work on PGBR has been previously evaluated, where PGBR was compared with the Shortest Path (SP) algorithm as well as the ANTS distributed routing algorithm. More information can be found in [25]. In this paper, minor extensions were made to [25] (which had static α and β parameters), where these parameters adaptively change with respect to network load. Example of the changes for α and β for different traffic types are shown in Figure 5. (γ is always statically set to 1).

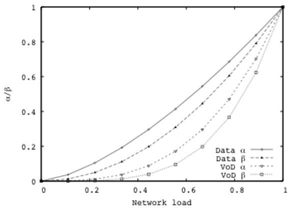


Figure 5. Selection of β and α with respect to network load

V. INTEGRATED SOLUTION

The previous sections presented the bio-inspired solutions for the Service Management Layer and the PGBR routing mechanism at the Infrastructure layer. Since our objective is to create a holistic solution to support the Future Internet, this section will present how the two layers will interact and integrate (Figure 6). The interaction of the two layers is similar to the co-evolution process in Biology. The process of co-evolution is where a change in a given system causes change in a related system. In this case, as the Service Management Layer copes with the changing demand from users, the underlying network supports this by manipulating the routing based on the node and link load observed in the infrastructure layer.

Initially, a user request arrives and is processed by the CMS. The CMS determines the appropriate composed service for the request, maps it to actual SAs and then passes it to the closest AS. In the example in Figure 6. SA_1 sends parallel requests for SA_2 and SA_3. If SA_2 and SA_3 are available, they respond to SA_1 who then returns an invocation to begin streaming to the user. Each AS will independently discover the routes at the underlying layer and begin streaming.

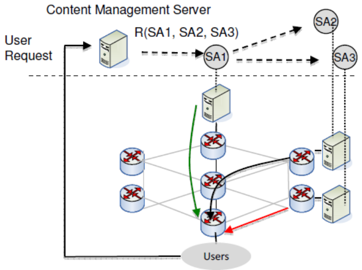


Figure 6. Integration of Service management layer and PGBR routing

VI. SIMULATION

This section presents the results for simulation of the integrated Service Management and Infrastructure Layers. The topology configurations used for the simulation is illustrated in Figure 7. The objective of the integrated solution is to investigate the improvements of applying bio-inspired techniques to both the Service Management Layer and the Infrastructure layer, and to compare this to standard approaches. Therefore, comparisons were made for full bio-inspired solution at service management layer and underlying network (SM-B: PGBR); bio-inspired service management and shortest path (SM-B: SP); and standard service management with shortest path (SM-NB:SP). The results are presented in Figure 8. – 13.

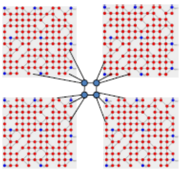


Figure 7. Topology configuration. 4 Domains - Blue nodes are AS and red nodes are Infrastructure router nodes

We have subdivided the simulation duration into 3 zones, where for each zone we bias the incoming request rate for a particular service type. Our objective is to see how the prioritization of services impacts on the lifecycle of the agents (e.g. death, replication, migration) and how this in turns affects the underlying routing. Zone 1 is biased towards HTTP services, while zone 2 is biased towards VoD (low) and zone 3 towards VoD (high). No particular service is biased before zone 1 and after zone 3. The average composition size is set to 3 services per group.

TABLE I. PARAMETERS FOR TOPOLOGY

Domain	No. of Nodes	No. of Links	No. of AS
1	107	360	16
2	103	342	16
3	109	386	16
4	106	366	16

TABLE II. TRAFFIC TYPE PARAMETERS

Traf fic Type	Distribution for Service time (average - seconds)	Average Flow Quantity (Kbps)	Proporti on of total requests (%)
HTTP	Uniform (5-25)	2	40
VoD (L)	Uniform (5-25)	300	30
VoD (H)	Uniform (5-25)	700	30

TABLE III. PARAMETERS FOR SERVICE MANAGEMENT

Parameter	SM-B	SM-NB
Arrival Rate	16 per/s	16 per/s
Average Composition size	3	3
Max. gradient size	14 hops	Flooding search
Replication Threshold	11 requests	-
Migration Threshold	17 agents per Platform	-
Energy To Replicate	200 units	-
Energy to Migrate	300 units	-
Gradient Search TTL	4s	4s
Agents Per Node	3	3
Starting Energy	1500 units	1500 units
Energy Per Request	5	5
Platform Energy Cost	3	3
Execution Time	25 s	25 s
Transmission Delay (sec)	0.0001s	0.0001s

Figure 8 presents the average throughput measured at the network level for the three different combinations of solutions. As expected, the SM-B:PGBR gave the best performance and was able to provide higher throughput for all zones. This is reflected in the ability of SM-B to efficiently discover SAs (including replicated SAs) while the PGBR was able to efficiently discover the routes at the Infrastructure Layer as the service demand changed between zones. Since zone 1 was biased towards HTTP services, the overall throughput is lower than in zone 2 and 3 which was biased towards VoD (L) and VoD (H), respectively.

The average throughput results also reflect on the average blocking probability (Figure 9) (includes blocking at both layers). The blocking probability in zone 1 was lowest for SM-B: PGBR (0.02) compared to SM-B:SP (0.06) and SM-NB:SP (0.32). For zone 2 and 3, we can see that average blocking probability for SM-B:PGBR was 0.3 compared to SM-B:SP (0.46) and SM-NB:SP (0.56). The results also show the improvement of PGBR routing in comparison to SP for SM-B. Figure 10 illustrates the number of agents throughout the simulation and complies with the biasing of each type of agent for each zone (where zone 1 had the largest amount of replication for HTTP agents, while zone 2 and 3 replicated a large number of VoD (L) and VoD (H) agents, respectively).

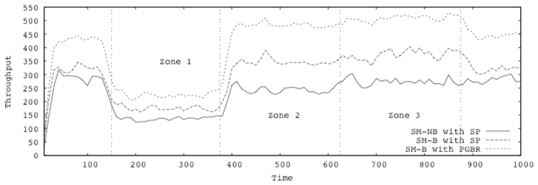


Figure 8. Average throughput

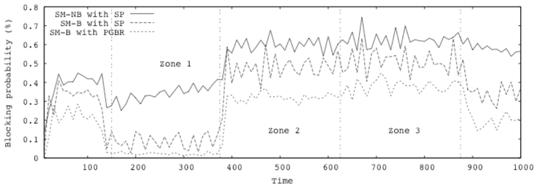


Figure 9. Average Blocking Probability

Figure 11 compares the average energy attained by the SAs and compares this to SM-NB. As shown in the figure, the SM-NB has constant energy consumption for all its SAs (due to the constant execution of the SAs on the AS), while for the SM-B the average energy was affected by service demand. Although there is an increase in the number of SAs in Figure 10 for zone 1, there is a slow decline of energy in Figure 11. A similar trend can also be observed when VoD (L) and VoD (H) demand started to increase. This is due to the replication process, where the parent agents offload energy to the child. As zone 1 transitioned to zone 2, we can see the number of HTTP SAs reduce (caused by death) in Figure 10 and this reflects the lower demand for those agents. At the same time, we can also see an increase in energy, since the death of a SA means that the remaining SAs will need to serve more requests. Figure 12 presents the migration number of each type of SA and shows that in zone 2 there was a high number of migration for HTTP SAs even though their demand has dropped. The is because there was a large number of HTTP SAs replicated in zone 1 still present in zone 2, and as VoD (L) increased its replication, this started loading the AS. As the AS gets loaded, the migration process of the HTTP SAs is triggered (HTTP SAs require less energy to migrate and so would migrate before the others). However, the migration starts to stabilize when the HTTP SAs die off towards the middle and end of zone 2. Zone 3 demonstrated a high migration rate for VoD (H) since the demand was the highest.

While the SA's are changing from zone to zone, this also causes the PGBR to discover new routes as the demand evolves and changes. This has been reflected in the average blocking probability as well as the throughput in Figure 8. and Figure 9. Figure 13 presents the average network load balancing, and shows that the PGBR support for SM-B improves the load balancing over SP. This is also supported by the average link utilization, where SM-B:PGBR utilizes a larger amount of link capacity (0.307) than other solutions (SM-NB:PGBR = 0.239, SM-NB:SP=0.134, SM-B:SP=0.169).

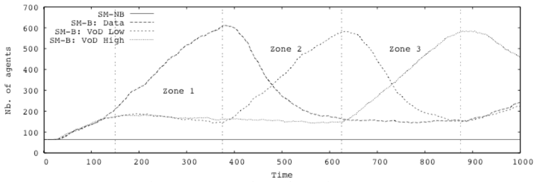


Figure 10. Number of Service agents

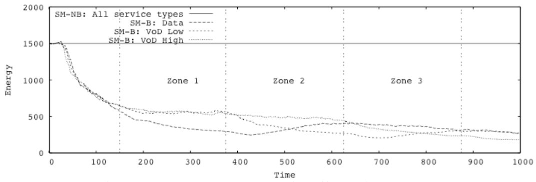


Figure 11. Average Energy for all Service Agents

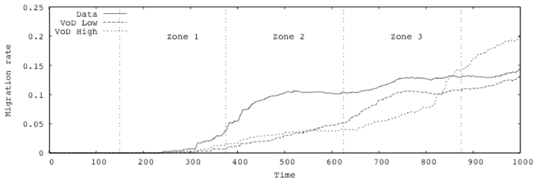


Figure 12. Average number of Migration by Service Agents

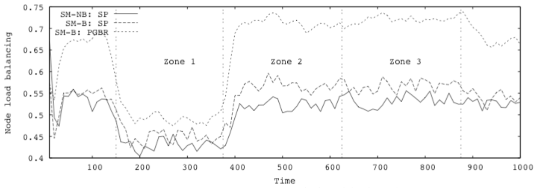


Figure 13. Average network load balancing

Therefore, the combined SM-B:PGBR demonstrated the benefits of applying bio-inspired techniques to both layers. The results demonstrate how the PGBR was able to adapt to any load resulting from service demand changes (low load in zone 1 to higher load in zone 2 and 3). Even though the two layers function independently, this reflects on the process of co-evolution where the changes in the Service Management Layer will change the behaviour of the PGBR and cater for varying types of load in the underlying networks.

VII. CONCLUSION

In defining a Future Internet there are clearly many fundamental issues that need to be resolved. We propose that more dynamic service management will be required as the volume, complexity and flexibility of services grow to meet the increasing sophistication of user requirements. These mechanisms should ensure more efficient management, allowing the service environment to find a 'natural equilibrium', removing the need for intervention by the service developer/provider. Given this dynamic service-oriented environment we also suggest that a more flexible and robust routing mechanism is needed to handle the huge fluctuations in traffic type and demand.

In this paper we presented a Bio-inspired Future Internet solution to address these challenges. The Service Management and Infrastructure Layers both adopt biological mechanisms to achieve their individual goals of improved capabilities and performance. We have also shown how both layers work in harmony, with the service management layer improving the user experience while providing more efficient management, which in turn is supported by the underlying Infrastructure layer. Finally, we have also provided validation of our architecture through simulations, which show that our proposed solution out performs the current standard techniques, outlining its pertinence to the foundation for the Future Internet.

ACKNOWLEDGMENT

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Appendix A: PGBR Support for Service-Oriented Architecture

Article II

Sasitharan Balasubramaniam, Dmitri Botvich, Ray Carroll, Julien Mineraud, Tadashi Nakano, Tatsuya Suda and William Donnelly

Biologically inspired future service environment

In *Computer Networks*, vol. 55, no. 15, pp. 3423–3440, October 2011

Contribution: This article is an extension of Article I. Consequently, my contribution also relies in the evaluation of the PGBR routing protocol to support dynamic service management via a fully bio-inspired solution. In order to evaluate the routing protocol more in depth, I implemented a version of the back-pressure routing protocol for wired networks and compared it to PGBR and OSPF using the ns-3 network simulator. Parts of my contribution also include the writing of the routing section in the paper as well as conducting all of the experiments for the routing and the combined solution.

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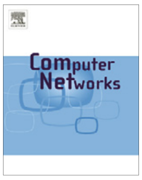

Biologically inspired future service environment

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ABSTRACT

In recent years, a major factor that has attracted numerous users to the Internet is services, and it is anticipated that this trend will continue into the future. As the Internet of the future becomes increasingly service centric, this brings with it a number of well established challenges. With large volumes of services, service discovery becomes one of the most decisive issues, and even fundamental tasks such the management and maintenance of services become challenging. Also, as services evolve and change to meet users demands, an efficient delivery mechanism (routing and resource management) is required in the underlying network. In order to address these challenges, this paper proposes an integrated bio-inspired service management and distributed routing solution for future service environments. The proposed solution will demonstrate how biological processes can improve both the individual layers of service management and underlying infrastructure, as well as improve overall performance when these two layers are integrated. Simulation results are presented to help validate the proposed solution.

1. Introduction

Since its early introduction, the Internet has transformed the way people interact, communicate, and gather information, and as time progresses, the Internet will continue to attract new users. This is supported by a number of factors, such as developments in network access technologies as well as end user devices. However, one major factor in peoples increased reliance on the Internet is in the significant growth in the number and types of services [2]. Services on the Internet have advanced tremendously in recent years, starting from simple web services, to more advanced multimedia services (e.g. IPTV at standard or high definition [1]). With low barriers to entry, the Future Internet will witness large numbers of disparate services, with a wide variety of goals and capabilities. While this provides significant choice and value for end users, this will also result in new challenges for service providers as well as the network infrastructure. Firstly, from a service management perspective, the increase in number of services will lead to issues in adding and removing services from the environment in a seamless manner. Secondly, as new services are being introduced into the environment, an efficient and timely service discovery mechanism is required. In terms of basic service management tasks such as the provisioning and removal of services, highly dynamic service environments make this a significant management issue in its own right. Ensuring that redundant services are removed in a timely fashion could have significant financial gains for service providers/data-centre operators. Such a dynamic service environment could also lead to significant fluctuations in service demand, as new services are added, become popular and ultimately redundant. Service

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providers need to be extremely agile in adapting to demand, ensuring revenues are not lost through slow response times and service timeouts. Hence services that can scale dynamically over very short time frames become critical to the service provider and operators business. As a result we also need to be able to adequately balance the load generated by varying service demand. While improvements may be made at the Service Management Layer to address the challenges outlined above, we must remain cognoscente of the impact this will have on the underlying communication networks. The original Internet infrastructure was developed for a different purpose and environment (limited services with very static traffic behaviour). However, as services evolve dynamically over short time frames, this will have detrimental effect on the resource management of underlying networks. In particular we must ensure that the routing algorithms can support dynamic traffic, resulting from changes at the service layer, and to perform this new form of routing in a distributed and dynamic manner [20].

Therefore, looking at these various challenges, new service management solutions in the Future Internet will need to be provided in the underlying network as well as at the Service Management Layer, where both operate in a highly cooperative fashion. One possible solution to the challenges described above is through embedding autonomic capabilities into both the services as well as underlying network infrastructure, to minimise human intervention and maximise fulfilment of end user needs [22]. In recent times a number of autonomic solutions have been sought from biological systems [37]. Biological systems have tremendous capabilities in exhibiting autonomy at various levels, ranging from molecular self-organization of organisms to large scale adaptation of animals. In this paper we propose a solution to the *future service environments* challenges outlined above, which addresses each problem individually and combines this into a single solution. While applying biologically inspired solutions to networks has gained tremendous popularity in recent years, a crucial challenge is in the combination of different solutions required for future service environment. The solution proposed in this paper will apply biological mechanisms at the Service Management Layer to allow services to autonomously evolve in an environment, as well as in the underlying communication network layer. In the latter case, a distributed routing solution is proposed that adapts its routes as services evolve and dynamically change. Ultimately our aim is to propose a solution that can contribute to the Service Environments of the Future Internet, where adaptability will be required at various layers and in the co-existence of these layers.

The paper is organized as follows: Section 2 presents the related work. Section 3 presents a high level description of our biologically inspired future service environment, which will be followed by the Service Management Layer in Section 4, and the distributed routing mechanism in Section 5. Section 6 presents a description of the integration of the two layers. Section 7 will demonstrate the validity of the proposed solution through a series of simulations, while Section 8 will present a summary discussion. Finally, Section 9 will present our conclusions.

2. Related work

This section will present reviews of two key areas relevant to the solution presented in this paper, which includes service search/discovery and management, as well as current routing in IP networks.

2.1. Service search/discovery and management

In terms of using biological mechanisms to manage services, there have been a number of solutions proposed for a variety of problems. Miorandi et al. [10] investigated an evolutionary process for autonomic services. The solution developed incorporated an evolutionary algorithm (Genetic Algorithm) that allows services to evolve, based on the demand of the users. The solution also incorporates distributed fitness evaluation, where each service evaluates this individually depending on the demand from the users. Suzuki et al. [11] developed a middleware for autonomous agents that are embedded with content services, which was later extended to incorporate evolutionary behaviour [12]. Carreras et al. [13] investigated bio-inspired approaches to support services in pervasive communication/computing environments, in particular focusing on the heterogeneity, scalability, and complexity requirements of services. Through evolutionary and social interaction mechanisms, the solution supports self-evolving services that can adapt to various environmental conditions. The applications cater towards end users in pervasive computing environments rather than content services of Internet scale systems.

Our fundamental goal of self-managing services shares some common ground with Peer-to-Peer (P2P) based systems and specifically with P2P search mechanisms. In general these can be categorized into two types, structured and unstructured, where unstructured mechanisms suit our approach best, as they are better equipped to handle service transience and have more expressive querying capabilities. There are a plethora of approaches, which address the problem in very varied ways. Most approaches are variations or improvements of the basic flooding technique or random walks. In [4], Yang and Fei propose an approach to uniquely identify each node and using this information can reduce the number of duplicate messages in searches, thereby reducing messaging overhead. In [5], the authors use feedback from previous searches to improve search success rate and reduce redundant messages. Wu et al. [6] developed a somewhat similar approach using the ants model, where nodes on successful paths are aware of the success, and messaging budgets are partitioned based on this success. In [7], the authors semantically group nodes containing related content and then used a two-phase search to first find a relevant group and then to find the exact content within that group. Lin et al. [8] use a hybrid search that integrates flooding with random walk. The main issue with flooding is that it generates an exponentially large number of messages with each hop from the source, so the authors used flooding closer to the source and then random walk as messages moved further away. All of these approaches propose valid search techniques with varying levels of success. One of the strengths of our approach however, is that it could be used to augment all of these approaches.

While a number of different solutions have been proposed for autonomous services, the majority of these solutions have solely focused on the core functionalities of the services, and not from the end user perspective. Firstly, the current approaches do not consider how efficient search processes can cope with autonomous services, as they die, evolve, migrate between different locations. Secondly, most solutions have not considered how the autonomous behaviour may impact on the underlying network, and how the underlying networks can cope and deliver these services to end users in an efficient manner.

2.2. Dynamic routing

In recent years, routing has played a major role in communication network research and various routing algorithms have been proposed, both for fixed networks as well as mobile ad hoc networks [14]. The current approach used for routing in core IP networks is based on the Open Shortest Path First (OSPF) protocol [16]. Although the protocol is distributed, it requires each node to have a full view of the topology. At the same time, when a re-calculation is required, all nodes must coordinate to calculate new routes [18,19], which is not ideal for variable traffic behaviour. A number of approaches have investigated using optimization methods, which besides being similar to OSPF in requiring a central view, the approach also requires pre-knowledge of current traffic demand [17]. Based on these constraints, the communication network research community have also developed distributed solutions for routing. A good example is potential based routing developed by Basu et al. [21], which proposed routing through hop-by-hop discovery. The selection of the next hop is based on the weighted sum of traffic load on the immediate node and the shortest path distance to the destination. The drawback with this technique is that the dynamic change is purely based on the load of each node, which does not provide an accurate view of congestion in the links (e.g. a node with 6 links should not be evaluated in the same manner with a node with 3 links, if both normalized load values are the same). Secondly, the authors mention that the routing technique is not flexible in discovering alternative routes when the sending rates are high compared to link capacities. In [3] Kvalbein et al. proposed a hop-by-hop routing algorithm, where packets can select different paths in the intermediate nodes. However, this could potentially lead to high number of packets arriving out of order at the destination. Another well known distributed routing approach is the Back-Pressure routing mechanism [15], which allows packets to discover paths on a hop-by-hop process by only requiring knowledge of queue lengths in the next hop. However, the drawback of this approach is in the numerous loops that can be encountered during routing.

In order to improve the adaptability of routing, various solutions have looked towards incorporating bio-inspired approaches. For example, social insects [22] have been known to exhibit the coordinated behaviour of self-organisation and can support the design of large scale distributed systems (e.g. communication network routing [23]). Liebnitz et al. [24] investigated the use of bio-inspired techniques for management of overlay networks. The solution was based on the attractor-selection technique, where the condition of a path is monitored and in the event of environmental changes (e.g. congestion or failures) the path will automatically change to the next best candidate. A number of bio-inspired approaches have also been applied to routing in sensor networks. In [31], Iyengar et al. presented a solution towards using ants for mobile wireless sensor networks. In [30], Szymanski et al. developed a self-selective routing protocol that is inspired by pheromone trails similar to ants. In the event that a packet encounters a problem in a node, the packet can take alternative paths. This is not suitable for core network routing, in that routes discovered are usually paths for streaming applications. Although alternative paths can be selected on the fly, this could possibly lead to packet re-ordering at the end buffer. Our approach considers this during discovery, such that a path must first have sufficient resources to support the QoS requirements of the service, and that during the streaming process the paths are not to be disturbed until the service session ends. In the case of wireless sensor networks, traffic can be assumed to be static and periodic (in the case of periodic monitoring). In [32] Selvakenney et al. presented a bio-inspired clustering protocol for wireless sensor networks, in order to allow routing to be performed between cluster heads. Once again this is not appropriate, as we do not aim to have a clustered based solution in core networks, where gradients would need to be formed between cluster heads.

3. Biologically inspired future service environments

Biological systems often exhibit desirable properties for future network services such as scalability, adaptability, and robustness [22]. Biological organisms are autonomous entities and often self-organise without a central controller. Typical life cycles and behaviours of biological organisms include (1) birth and death, (2) migration, and (3) replication (or division) through which a group of organisms can achieve scalable, adaptive and robust behaviours. The biological environment provides a medium that allows biological organisms to interact and mobilise. For instance, bacteria release chemical signals creating chemical gradients in the environment, letting other bacteria know the

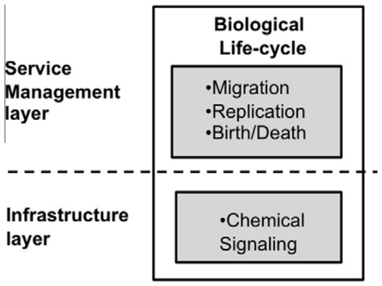


Fig. 1. Mapping of mechanisms from biological life-cycle to service management and infrastructure layers of future service environments.

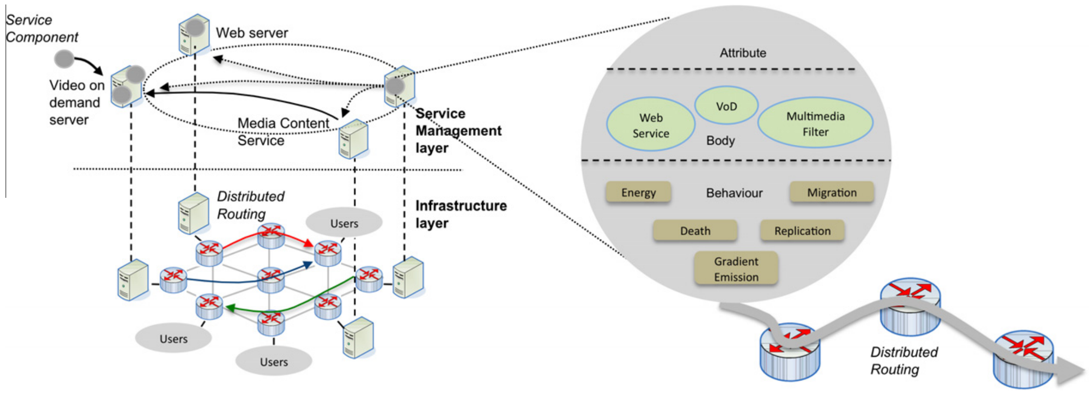


Fig. 2. Proposed two layered solution for future service environment, and internal functionalities of a service agent.

location of the signal-releasing bacteria. This contributes to mechanisms such as chemotaxis, which is a process where microorganisms sniff chemical gradients to mobilise towards a specific food source, for example.

Inspired by the design architecture of biological systems as briefly described above, we envision a two-layered solution for the future services environment. This solution includes the Service Management Layer and the Infrastructure Layer, respectively designed based on observations of biological organisms and the environment. Fig. 1 illustrates the types of biological processes that are mapped from a biological life cycle to each of these layers. In this paper, we use content-based services as a running example, where the service management layer manages services for user's applications (e.g. ranging from composed web services to Video on Demand (VoD) for set top boxes in homes). Example functionalities of the Service Management Layer include composing services to meet user's requirements, or adaptation of service components to suit the end user access network resources or device capabilities (e.g. filtering of multimedia streams). Our vision of the future is that services and the service landscape/environment will evolve quickly, as developers create new services or upgrade existing service functionality. Developers should not have to deal with the mechanisms of how these services are composed, evolve or populate themselves to other Application Servers. Instead all these processes should be performed autonomously. As described in the Introduction, the diversity of services (and compositions) and the dynamicity of the service environment will also lead to very dynamic traffic behaviour, which is not suitable to current routing approaches.

Based on these requirements, our aim is to create a solution that meets the objectives of the individual layers illustrated in Fig. 2. The following two sections will describe the functionalities of each of these layers.

4. Service management

As we have discussed earlier, the future service-oriented environment will see large numbers of services, which enter and leave with great flexibility and are tailored to the users needs. To alleviate the burden this can cause to service providers, we propose an autonomous lifecycle approach where services can be rapidly deployed, act in their own self-interest and eventually remove themselves from the environment when no longer useful. At the same time we describe a discovery approach based on distributed peer services. Fig. 3 illustrates how the Service Management Layer overlays on top of the physical servers (we refer to these servers as Application Server (AS)) that host the services.

The application of the lifecycle mechanisms will enable a more efficient service management process. The approach builds on the previous work of autonomous agents supporting self-organising services [11,12] (this will be referred to as *service agent*), where added functionalities include improved mechanisms to search for these services as they evolve in the environment (e.g. die, replicate, migrate between different AS).

4.1. Service agents

Each service agent contains service content that supports specific user applications. Since each service agent can support diverse content types, we assume that each agent will have varying sizes (e.g. a VoD service agent will be large compared to web-service agent). The service agent consists of three parts (illustrated in Fig. 2), which include: *Attribute*, *Body*, and *Behaviour*. The Attribute contains a description of the service, and performs the matching between the query and service description. Our solution is based on pre-defined mechanisms of service description (e.g. [26–28]). The description reflects on the functionalities of the services and will be determined by the service developers. The Body of the service agent contains the service components, while the Behaviour consists of the lifecycle mechanisms.

4.2. Service lifecycle management

This section will present the processes of the lifecycle management, and their application to the behaviour of the service agent. The service agents that reside in the

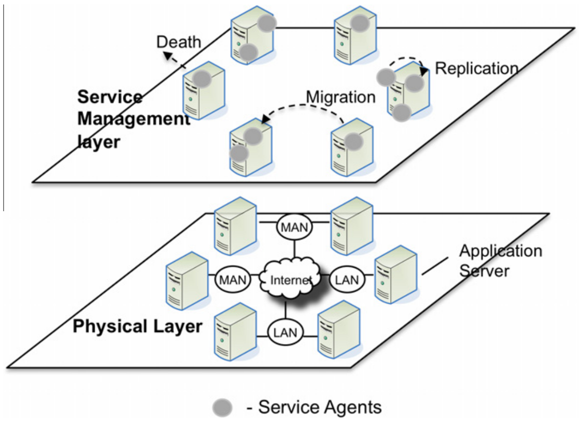


Fig. 3. Service group overlay of service management layer.

service environment share common behaviour throughout their lifecycle (e.g. ability to regulate and manage energy, migration, replication, death).

Energy management and death: each agent contains a quantity of internal energy and is able to manage this energy throughout its lifecycle (total energy of service agent *i* is $E_{T,i}$). When the service agent resides on an AS, it trades part of its energy for utilizing that particular ASs resources (e.g. CPU, memory). At the same time, as the service agent serves user requests, it is able to gain energy for its contribution to the group. In the event that the service agent becomes less popular, it will slowly start to loose energy. If the agent does not serve sufficient requests, its continued energy expended on the AS will eventually result in the agent dying off ($E_{T,i} < 0$). Through this process, service agents are able to live and die depending on the popularity of the service, which creates an evolving environment for services.

Migration: the service agents are able to perform migration by moving between different ASs. The movement is driven by the current load on the AS platform (AS_i). In the event that load on AS_i increases over a certain threshold, the service agent will start to investigate the load of neighbouring AS_j for migration. In the event that load on the neighbouring server is lower than the current AS, and provided the service agent has sufficient energy for migration (migration comes at a certain energy cost), the service agent will migrate to the neighbouring AS.

Replication: service agents are also able to replicate themselves and create clones, in order to handle more requests when the request rate for that particular agent is high. This is due to the fact that each service agent is only able to support a certain number of users. The service agent will consider the number of requests it receives over a period of time, and if the agent contains sufficient energy it will begin replication. The replication process will also lead to the parent service agent providing initial energy for the child (E_{child}) agent to live. Therefore, the energy for replication must consider the energy required for replication as well as energy that is passed to the child ($E_{T,i} > E_{rep} + E_{child}$).

Service gradient search: due to the large number of ASs and service agents, an efficient distributed search technique is required. Our view is that search efficiency can be improved by enabling services to actively attract queries towards the AS on which it resides. Also, by linking this capability to service popularity we can further improve search efficiency by prioritizing frequently used services. This requires that each AS platform maintain a directory of service agents within its vicinity, along with a metric (gradient value) indicating which is the best node to forward the query to in order to reach the required service agent. For a given service, the table/routing entries in each of its neighbouring ASs should be dynamic and change with respect to the popularity of the service. Based on these requirements, we use the concept of simple *Diffusion* of service advertisements to the ASs in close proximity. The diffusion process will in turn create a gradient field that will attract queries towards the AS holding the service agent that the query is searching for. An illustration of this search process is shown in Fig. 4.

Initially, when a service agent is placed on an AS, the agent has a certain amount of energy that is used to propagate the advertisements. The advertisements will be represented as gradient values. As the agent diffuses this value to the neighbouring ASs, the service agent *id* and service description will be entered into the directory, accompanied by the next AS that has a higher gradient value. After entering the information into the directory, the neighbouring AS will deduct the gradient value and continue to diffuse this information to the other ASs. The process will continue until the gradient value reaches zero. An example of this is shown in Fig. 4(a), where SA_3, located in AS 9, diffuses its advertisements to neighbouring nodes. Each neighbouring AS will record the highest gradient value of the next node for the respective service. In Fig. 4(a) AS 8 enters a gradient value of 1 for next AS 9, while AS 5 enters a gradient value of 0.8 for next node 8.

It is important to note that the gradient approach augments the search process rather than actually carrying out search. Therefore a wide variety of unstructured search techniques can be used in conjunction with the gradient

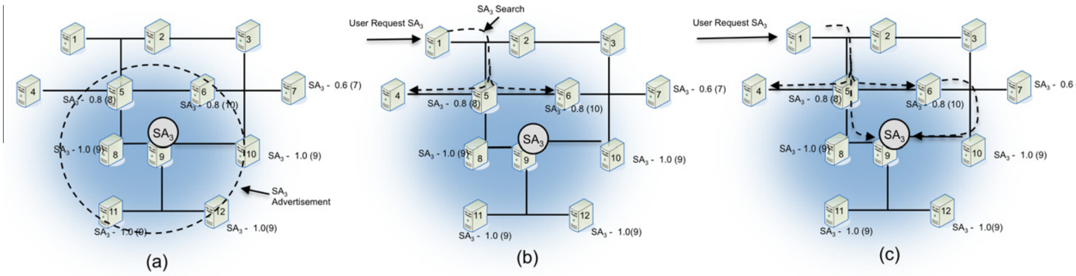


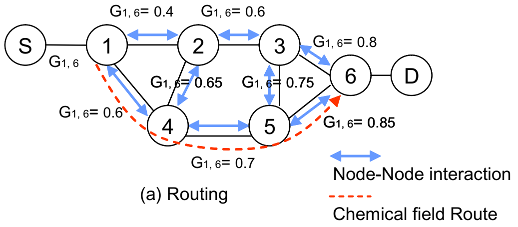
Fig. 4. Gradient based query search.

mechanism proposed in this paper. In this section we use a flooding search as an example to explain the process. During the search for a service agent, a query will be diffused into the environment. When this query approaches an AS, the AS will determine the neighbour AS that has a higher gradient value. Therefore, by moving from AS to AS through a higher gradient value, the query will get attracted to the required service agent. An example of this is presented in Fig. 4(b) and (c), where a query for SA_3 is sent from AS 1. Initially, the query spreads in a diffusive manner. However, once the query enters the gradient field, the query will be attracted to SA_3 in AS 9, through AS 5 and 8. The service agent's gradient value in the neighbouring AS has a certain Time to Live (TTL). After a fixed period of time, the hop count of each entry will be reduced. Therefore, the source service agent will be required to maintain these entries, and this is performed by using a portion of its energy ($E_{GM,i}$) to continually emit and update the gradient values. However, this is also dependent on the amount of energy that the service agent is gaining. In the event that the service agent does not gain high enough energy, this will result in the service agent being able to only contribute a small portion of energy for maintaining the gradient field. In the event that the service reduces in popularity, the gradient emission will reduce, leading to increased resistance for query searches. This creates an automated, distributed, evolving process for discovering services, where new and popular services will flood the AS networks, allowing searches to be easily performed. At the same time, as the service looses popularity, they will slowly disappear.

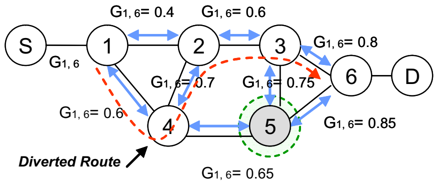
5. Parameterised gradient based routing

As illustrated by the challenges described in the introduction, any future service environment solution will require an adaptive routing process in the underlying network that is closely tied to the services. This section will present our solution for distributed routing in the underlying network which supports the Service Management Layer. The objective of the distributed and adaptive routing mechanism is to support the changing landscape of services resulting from changes in popularity of services or shifting user's requirements. The routing process is known as *Parameterised Gradient Based Routing (PGBR)* and is illustrated in Fig. 5. Although the PGBR routing mechanism is similar to the service query search, the mechanism of forming the gradient field is different. In the case of PGBR it is formed from the environment, unlike the query search in the Service Management Layer where the gradient is only based on the diffusion from the source. The creation of the gradient field is based on the local interactions between the network nodes (shown in Fig. 5). Once a gradient field is set up, the route discovery can be performed between specific source and destination pairs. In the example of Fig. 5, a route is established for $S, D = (1 \rightarrow 6)$, where the flow is routed along the path 1–4–5–6. An example of gradient attraction is at node 1, where node 1 selects the link to node 4 since its gradient is higher than node 2 ($G_{1,6,1\rightarrow 2} = 0.65 < G_{1,6,1\rightarrow 4} = 0.6$).

The advantage of using a gradient field formed by the environment is that it allows the field to adapt and change with respect to the network load change. This is ideal for distributed and adaptive routing, as it allows the route to divert around loaded nodes in the network. An example of this functionality is illustrated in Fig. 5(b), as when node 5 gets congested, new route discovery will automatically divert from link 4–5 to link 4–2 (because $G_{1,6,4\rightarrow 2} = 0.7$ became higher than $G_{1,6,4\rightarrow 5} = 0.65$). In this paper, we will only elaborate on the main functionalities of PGBR, where a full description, algorithm, and performance evaluation can be found in [29].



(a) Routing



(b) Diverted route from increase node load

Fig. 5. Illustrative example of PGBR routing.

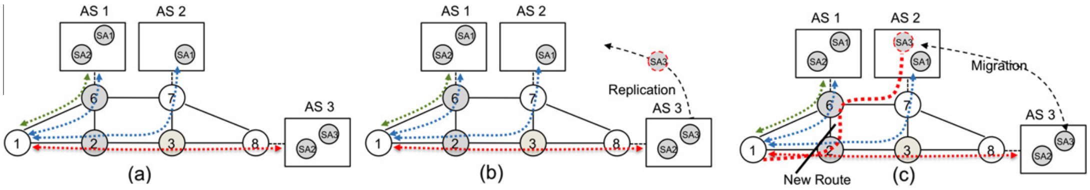


Fig. 6. Dependence between the service management layer and PGBR routing.

As illustrated in Fig. 5, the discovery of the routes is performed in a hop-by-hop fashion, by sniffing the links with the highest gradient for a specific destination. Therefore, the gradient calculation for destination d of node n with link connecting node n to node j is represented in Eq. 1 as,

$$G_{n,d,n\to j} = \alpha\Phi_j + \beta l_{n,n\to j} + \gamma h_{j,d}, \tag{1}$$

where Φ represents the load of neighbouring node j, $l_{n,\ n\to j}$ represents the spare link capacity between node n and j, and h_j represents the normalised hop count of neighbouring node j to destination d. The α is the weighting value for node load, β is the weighting value for link load, while γ is the weighting value for the normalised hop count of the node. The normalised hop count component of Eq. (1) differentiates the shortest hop count distant each node has to a specific destination. The calculation of the hop count (and normalised hop count) is static and is only performed when the topology of the network is formed. Further details of the normalised hop count can be found in [29].

The Φ and the $l_{n,\ n\to j}$ are dynamic values of equation (1), and are calculated periodically. The O value calculates the load of each node based on the ratio of the sum of spare capacity to full capacity of the links attached to the node. The load information is periodically transmitted from each node to the immediate neighbours.

6. Integrated solution

The previous two sub-sections presented solutions for supporting the Service Management Layer and the PGBR routing mechanism. Since our objective is to create a holistic solution to support future service environments, this section will present how the two layers interact and integrate. Firstly, we will illustrate how autonomous services can affect the underlying routing, and the importance of the solution proposed for each layer. Fig. 6 illustrates this example.

Initially, each AS contains a number of service agents, where each agent is served by individual routes in the underlying network (Fig. 6(a)). As the popularity of service agent SA_3 increases, the service agent gains sufficient energy and begins to replicate. After replication, the replicated SA_3realises that the current AS 3 is highly loaded and decides to migrate to the neighbouring AS 2, which is lightly loaded (Fig. 6(b)). As new request for SA_3 arrives, a route through the lightly loaded links and nodes of the underlying network to the new location of SA_3 is selected. Therefore, as we can see, based on the autonomous behaviour of service agents, a more advanced and adaptive routing strategy is required to handle varying loads. This varying load may not only result from user's demand changes, but may also result from changes in service landscape. Using a traditional routing mechanism based on central view, which must coordinate to calculate new routes is not appropriate for such an environment, and this will be validated in the simulation section.

Fig. 7 illustrates the protocol operation for the dual layers, which is a three step process. In step 1 the user requests a specific service by sending out a query message, which is forwarded between different ASs in an attempt to find the service. In this particular example, the query is searching for service agent SA_2. Once the search is complete, the second step begins when the query returns to the origin with the address of the AS hosting the service (*AS-IPaddr*). This address is then passed down to the underlying network, where the PGBR route discovery will begin to form a route to *AS-IPaddr.* One of the important aspects of this integration is that both layers are significantly independent of each other, with the service layer remaining abstracted from the underlying network. This means no additional management is required for the Service Management Layer to interact with the underlying Infrastructure Layer. Simulation results of this concept will demonstrate how the two layers are able to improve the overall performance of the system.

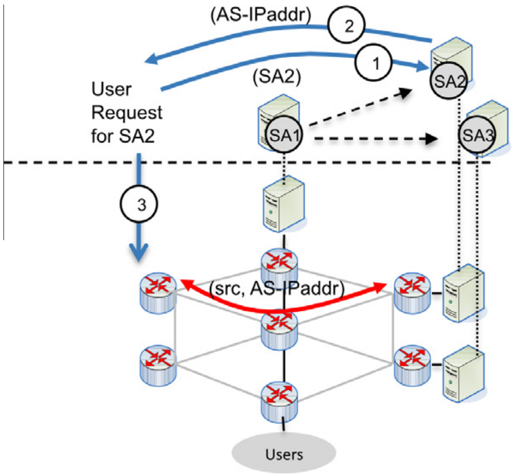


Fig. 7. Protocol for dual layer operation.

7. Simulation

This section presents the results from simulation work performed to validate our proposed solution. Since the systems themselves are quite extensive, for clarity of contribution we have separated the simulations into three subsections. Firstly, we evaluate the operation of the service management solution, specifically the gradient-based search technique, in order to clearly present its advantages. We then evaluate the PGBR routing in order to demonstrate the merits of this routing approach. In the final section, we evaluate the integrated solution in order to demonstrate its advantages and the effects each process has on the other. For each section comparisons were made to existing techniques, in order to validate the advantage of the proposed solution. The service management simulations have been carried out in custom java-built simulators while the routing evaluations were simulated using ns-3.

7.1. Gradient-based service search

In order to assess our approach, we have performed an evaluative case study where we trial our solution in the context of a P2P environment. To do this we selected a recent P2P search mechanism that performed well in comparison to established techniques. The algorithm selected was the DS search algorithm as presented in [8]. There were a number of considerations in selecting this type of search mechanism. Firstly, since the services we consider would be highly transient, more structured search mechanisms (e.g. Distributed Hash Tables) would not suffice as they do not cope well with high churn. Also the lack of expressiveness in search queries would be an issue in performing complicated, non-specific service searches.

One of the advantages of our gradient-based approach is that it can work in conjunction with any underlying search mechanism. As such, we extended the DS algorithm with our gradient-based approach and compared this to the DS search mechanism alone. In DS search, each node checks for the required service and, if not found, forwards the query to its neighbour nodes with a probability of *DSp*, within a selected hop-boundary (*DSn*) of the search source. When a search extends beyond this boundary the forwarding mechanism changes to a random walk, where *DSk* neighbour nodes are selected to forward the query. Our approach augments this by also searching for the relevant gradient value on each node, where if found, the query can follow this directly to the target node. In our simulations, we used a symmetrical grid topology where each node contained 3 services. For search we used a DSn of 3, a DSk of 2 and a DSp of 1.

In Fig. 8 we present the results of our simulation, comparing both the DS algorithm on its own and the DS algorithm employing the gradient approach. We vary two important search parameters, namely the topology size (in terms of nodes) and the TTL (in terms of hops). The

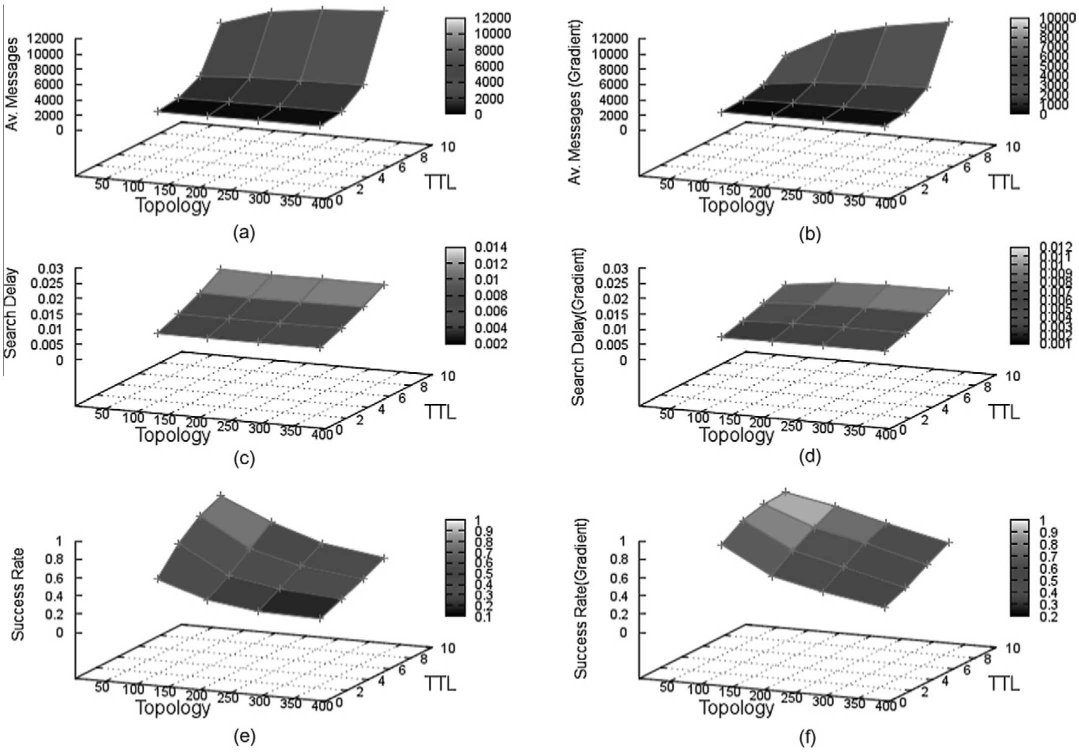


Fig. 8. DS Search vs. DS with gradient.

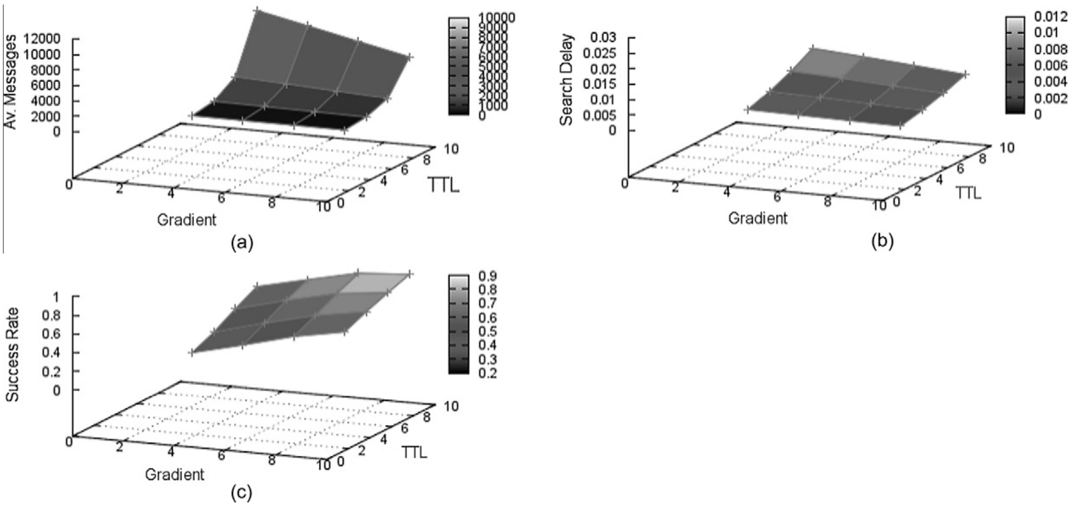


Fig. 9. Effect of varying gradient size and TTL.

key performance metrics that we considered include the success rate in search discovery, the search delay, and number of messages used. The reason that we have selected these performance metrics is because they (or some derivative) are frequently used for service discovery evaluation (e.g. [5,6,8]). Often one of the most decisive metrics for evaluating search in unstructured P2P networks is the number of messages employed. Some search mechanisms are very effective, boasting high success rates but have a major drawback in the additional traffic they generate in the network [9]. Hence search success alone is not sufficient without considering the number of messages generated.

In Fig. 8(a) and (b), we evaluate the average number of messages required per search. We will begin by stating that the gradient approach consistently out-performed the DS algorithm in the number of search messages used. From Fig. 8(a) we can see that as the TTL increases, the number of messages grows at an exponential rate. This is intuitive, as with each hop away from the source the number of nodes reached, and hence messages, grow. In terms of the topology size we see that as the topology increases so too does the number of messages used where this growth is much more pronounced for larger TTLs. The cause of this relates to the relationship between the topology size and the TTL size. In a smaller topology of size 64, a TTL of 10 would allow complete coverage of all nodes, meaning less search messages require the full extent of the TTL and fewer messages are used. However in a topology of size 225 or 324, more searches will require the full extent of the 10-hop TTL, hence more messages are generated.

In Fig. 8(b) we examine the effect of using the gradient approach in conjunction with the DS algorithm. Instantly we can see that the number of messages used in the gradient search algorithm is significantly less. The gains achieved are influenced by both the TTL and topology size. For instance in the 64-node topology the gains achieved for TTLs of 4, 6, 8 and 10 are 43%, 48%, 52% and 56% respectively. In a P2P topology, as you move away from the search source, the number of messages used increases at a growing rate. Using the gradient approach means requests have less distance to travel, hence the number of messages saved is greater at higher TTLs. Also the algorithm can be seen to perform better in smaller topologies. In the 64-node topology the gains are 43–56% (TTL 4-10) whereas for the 324-node topology these values are 9–13%. This is not a reflection on the algorithm but rather the gradient size used for these experiments. Here we used a gradient size of 3 hops which is relatively large in a 64 node topology but small in a 324 node topology. If the gradient had been increased inline with the topology size the gradient effect would be relative, as we will see later (Fig. 9).

In Fig. 8(c) and (d) we compare the search delays. The search delay is simply the time required to locate the requested service and is calculated by assigning each link a uniform delay time. As the TTL increases so too does the delay. This is intuitive as with a greater TTL, services which are further away from the source are found, hence the delay times are higher. In terms of topology size, the delay also increases, as the topology gets larger, especially at small TTLs. This is a result of services being harder to find (potentially further away) and searches spending greater amounts of time searching. As the gradient approach means searches do not need to extend as far, we would expect that services are also found in less time. This can be seen to be true as the search time is consistently smaller in the gradient simulation. Again the effect is more pronounced in the lower topologies, which again relates to the relative size of the gradient to the topology, where in lower topologies the gradient of 3 is quite large.

In Fig. 8(e) and (f), we examine the search success rate associated with each approach. For the DS algorithm we see the success rate increases in line with the TTL. In small topologies the rate of increase is high initially and then decreases slightly. This is because as the TTL increases the search can find more services, however as the topology size is small the success rate peaks earlier and tapers off as the majority of services can be found at a TTL of 8. In contrast, at higher topologies this rate stays linear, as the larger topology size reduces the effects of the TTL. The rate of success decreases as the topology size gets larger, since in larger topologies the TTLs become relatively smaller and so searches less successful. The effect of the gradient is to unilaterally increase the success rate of the searches, where, like in all previous experiments, this is more prominent in smaller topologies for the reasons outlined.

In Fig. 9 we present some experiments in which we alternate the size of the gradient along with the TTL, for a fixed topology size of 324. The effect of an increasing gradient, as we predicted earlier, is to reduce the number of messages. As we progress through gradients of 3, 5, 7 and 9 hops, the number of messages required reduces accordingly. As a comparison, for a fixed topology size of 324 nodes and TTL of 4 hops, the number of messages required at gradient 3 is 119 versus 73 for a gradient of 9, and 131 when no gradient is employed. In terms of search delay and search success, the pattern is the same. As the gradient increases the delay time decreases as services are found more quickly, while at the same time the search success rate increases.

There is however a cost associated with our approach, specifically in updating the gradient field for each service. To help alleviate this we adopted a smart gradient update procedure, where service gradient updates are aggregated at the node and so only one update message is sent per node, as opposed to one per service. In Table 1 we present the data on how the gradient updates scale with increasing average gradient size.

When we consider the update cost, the savings gained using the gradient approach become influenced by a number of factors, such as frequency of search, average gradient size, gradient update frequency, search TTL and the topology size. To demonstrate with an example based on the data above, if the gradient update frequency is set to 5 h, then for an average gradient of size 5 we will generate 116216 update messages in that time period. At the same time we are using 2798 messages less per search. Therefore, we need only perform 41 searches in those 5 h to cover the cost of the updates. On the other hand, if the average gradient size is 9, we need to perform 1323 searches in that same time period. Given that in our simulations we were executing approximately 900 searches per second, these update costs would be insignificant at that update interval. In essence the update costs of our approach can be easily absorbed if sensible parameters are selected. As such we suggest that there is the potential to investigate an extension to the algorithm where the gradient update frequency is scaled automatically in line with the search request arrival rate, the TTL and the average gradient size.

Table 1
Gradient update costs (topology of 324 nodes).

Gradient	Update messages	Messages per search (TTL = 10)
0	0	10931.63
3	14608	9515.884
5	116216	8133.712
7	921576	6705.63
9	7421864	5323.697

7.2. Parameterised gradient based routing

This section presents the simulation results for the PGBR routing mechanism, extended from [29]. The objective of the performance evaluation is to determine the ability of PGBR to route traffic through different size topologies and determine how efficiently resources are being utilized in the underlying network. The topologies we have used for the tests are randomly generated. Tables 2 and 3 present the topology and traffic type parameters.

Table 2 presents the three topologies used in our simulation, including the number of nodes and links, average hop count distance to an AS and number of AS per topology. For all topologies the average link capacities are 1 Mbps. Table 3 presents the types of traffic used in the simulation (HTTP, VoD (L) and VoD (H)).

The key performance metric that is used in this section is packet loss ratio, throughput, and average delay. The packet loss ratio determines the number of successful packets that reach the destination, the throughput reflects the allowed bandwidth of traffic between source and destination, while the average delay determines the delay latency of packets to reach the destination. Once again, similar to the service management, our main aim is to carry out performance evaluations that demonstrate how the end user quality, as well as resource utilization of the underlying network are maximised.

Fig. 10 shows the results from our performance evaluation, which considered three routing algorithms, including: PGBR, Back-Pressure routing (BP), and Shortest Path (SP). The Back-Pressure algorithm that we implemented is from [15]. The Back-Pressure routing algorithm is a distributed routing algorithm, where each node contains a set of queues for each destination. Periodically, the length of each queue is sent to neighbouring nodes. The next node that is selected to transmit the packets, will be the node

Table 2
Topology parameters.

No. of nodes	No. of links	Av. hop count to AS	No. of AS
55	174	4.68	6
120	432	8.06	12
210	796	9.63	21

Table 3
Traffic type parameters.

Traffic type	Average flow quantity (Kbps)	Proportion of total requests (%)
HTTP	20	40
VoD (L)	50	30
VoD (H)	100	30

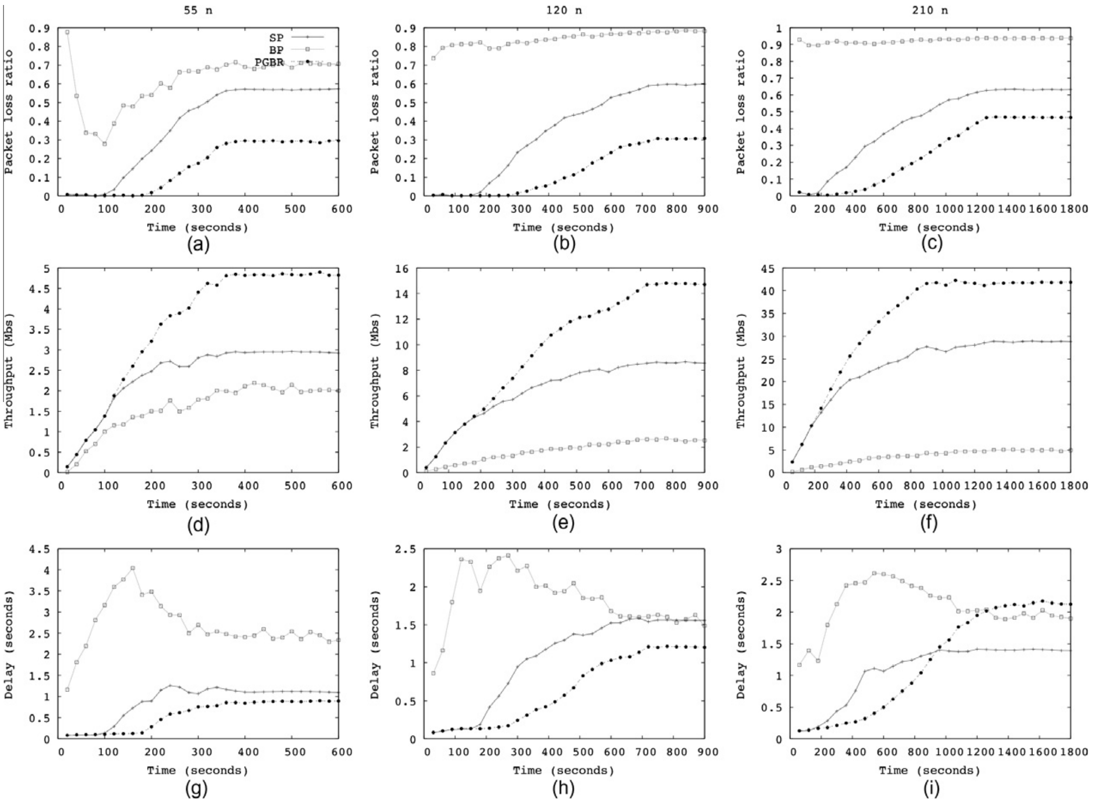


Fig. 10. (a) Packet loss ratio for 55 node topology, (b) Packet loss ratio for 120 node topology, (c) Packet loss ratio for 210 node topology, (d) Throughput for 55 node topology, (e) Throughput for 120 node topology, (f) Throughput for 210 node topology, (g) Delay for 55 node topology, (h) Delay for 120 node topology, and (i) Delay for 210 node topology.

with the lowest queue length for that specific destination. Therefore, this could possibly lead to a considerable amount of looping during the routing process. We can see from the packet loss ratio (Fig. 10(a)–(c)), that Back-Pressure routing algorithm has the worst performance. This is due to two factors, which includes the looping process, as well as TTL that is applied to each packet. Therefore, once the packet reaches its TTL, it is eliminated from the network. We can see that as the topology size increases, the packet loss ratio increases for the Back-Pressure algorithm, as the packets have a higher tendency to get lost. The shortest path algorithm exhibits a similar behaviour, where the packet loss ratio increases with time but then stabilizes after a certain point. This is because once the path is fully loaded the packets are dropped. The PGBR algorithm, on the other hand, exhibits the best performance for packet loss ratio, where we can see that as the topology size increases so too does the packet loss ratio, but not as high as the other two algorithms. The packet loss ratio performance reflects the throughput performance where we can see that for all the topology sizes, the PGBR outperforms the Back-Pressure and the shortest path. In the 55 node topology case, we can see that towards the end of the simulation, the PGBR algorithm is nearly three times better than the Back-Pressure algorithm and nearly twice as good as shortest path. This gap increases as the topology size increases, where in the case of the 210 node topology, the PGBR is nearly eight times higher than Back-Pressure and nearly twice as good as the shortest path algorithm. The delay performance exhibits a very interesting characteristic. We can see that the Back-Pressure initially has a high delay average and this slowly dies off as the simulation progresses. This is attributed to the fact that in the initial stage of the simulation, the packets were successfully reaching the destination. However, as more load is added to the network, the packet loss ratio starts to increase, and the number of successful packets reaching the destination starts to drop. The shortest path on the other hand exhibits a predicted performance, where once the path is loaded the delay starts to plateau and stays constant for the duration of the simulation. The PGBR algorithm exhibits the lowest average delay for the 55 and 120 node topologies. This delay starts to increase towards the end of the simulation, and this is due to the fact that the flows start to take the outer edge of the network topology, leading to longer path lengths. This in turn increases the average delay of the packet. This is also the case for the 210 node topology, where we start to see the delay increase towards the end of the simulation, and actually exhibits worse performance than the shortest path and Back-Pressure algorithm. Once again, this is due to the higher number of flows that are allowed into the network, where the latter flows take longer paths.

7.3. Integrated solution

This section of the simulation will present the results for the combined solution of the Service Management Layer and the PGBR routing in the Infrastructure Layer. The parameters used for the simulation are presented in Tables 4 and 5. The results are presented in Figs. 11–19. The objective of the integrated solution is to investigate the advantages of combining our Service Management Layer and Infrastructure Layer in comparison to standard approaches. In particular, our aim is to evaluate the scenario presented in Fig. 6, where the behaviours of the services are being supported by the PGBR routing. The key performance metrics we investigate are the blocking probability and average throughput. In this case, the blocking probability determines how many services are found in addition to successful routes found (2 step process). The other performance metrics are with respect to the lifecycle service agents (e.g. replication, death, migration), where we aim to demonstrate how the agents behave under changing user demand between different service types. For the non-biological service management simulations no biological behaviours are running, so no gradient search, death, migration or replication is performed. We must point out that the choice of underlying search mechanism (e.g. DS or flooding) is arbitrary, as once the same search mechanism is used for both Service Management – Biological (SM-B) and Service Management – Non-Biological (SM-NB), the improvements gained from using the gradient approach will be relative. The comparisons made for the integrated solution covered the following combinations: biological service management and the PGBR routing algorithm (SM-B:PGBR); biological service management and shortest path (SM-B:SP); non-biological service management with PGBR (SM-NB:PGBR); and non-biological service management with shortest path (SM-NB:SP).

The traffic flow parameters are exactly the same as in Part B. Fig. 11 illustrates the requests pattern for the three different types of services over the duration of the simulation. We have subdivided the simulation duration into 3 zones, where for each zone we bias a particular service type over other services. As shown in Fig. 11, initially zone 1 is biased towards HTTP services, while zone 2 is biased towards video (low) and zone 3 is biased towards video (high).

Our objective is to see how the prioritization of services for each zone impacts on the life cycle of the service agents (e.g. death, replication, migration) and how this in turns affects the underlying routing. We have a flat request rate that does not bias any particular service before zone 1 and after zone 3.

Fig. 12 presents the average throughput measured at the network level for the three different combinations of solutions. This reflects the ability of both solutions working in collaboration to maximise the traffic through the

Table 4
Parameters for topology.

Domain	No. of nodes	No. of links	No. of AS
1	107	360	16
2	103	342	
3	109	386	
4	106	366	

Table 5
Parameters for service management.

Parameter	SM-B	SM-NB
Arrival Rate	16 req./s	
Max. gradient size	14 hops	Flooding search
Replication Threshold	11 requests	–
Migration Threshold	17 agents per Platform	–
Energy To Replicate	200 units	–
Energy to Migrate	300 units	–
Search Timeout (TTL)	4 s	
Agents Per Node	3	
Starting Energy	1500 units	
Energy Per Request	5	
Platform Energy Cost	3	
Execution Time	25 s	

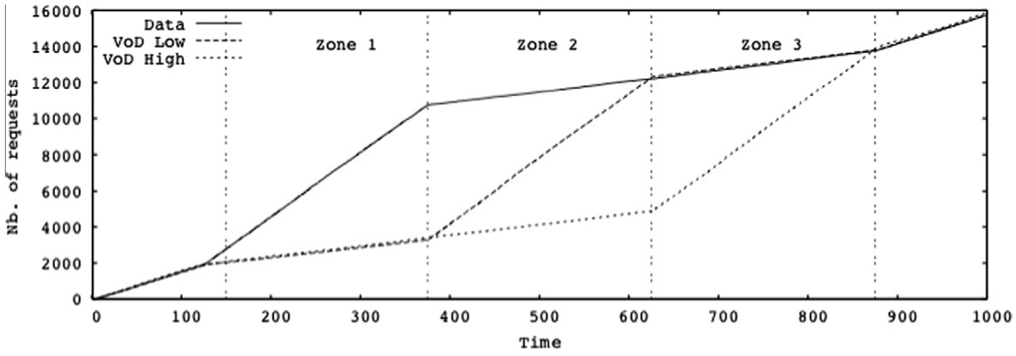


Fig. 11. Requests pattern for simulation.

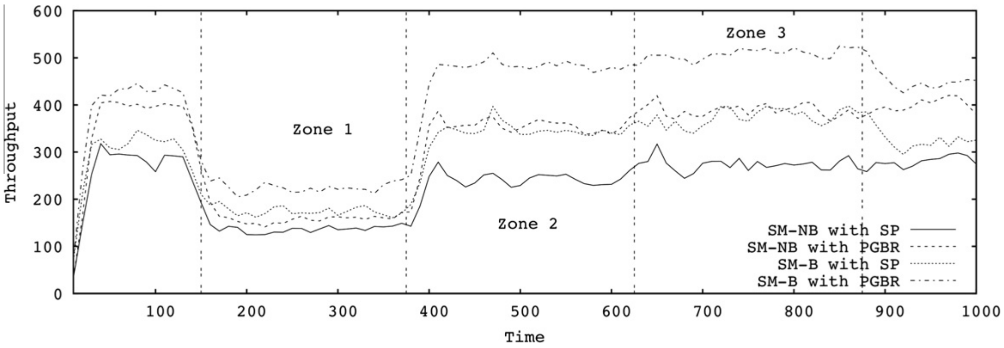


Fig. 12. Average throughput.

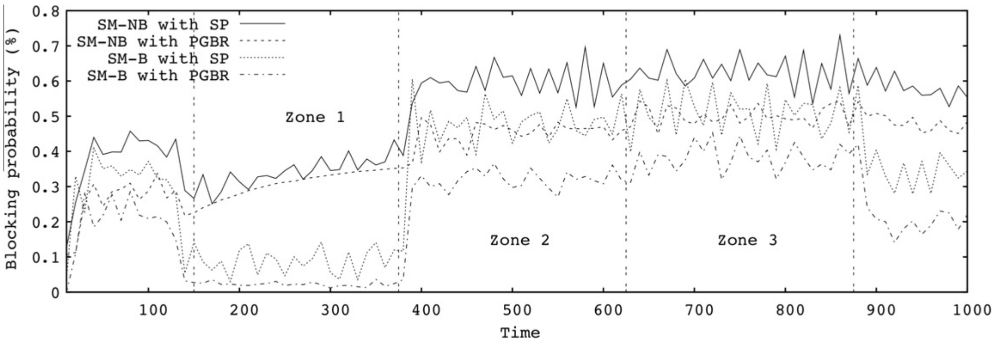


Fig. 13. Average blocking probability.

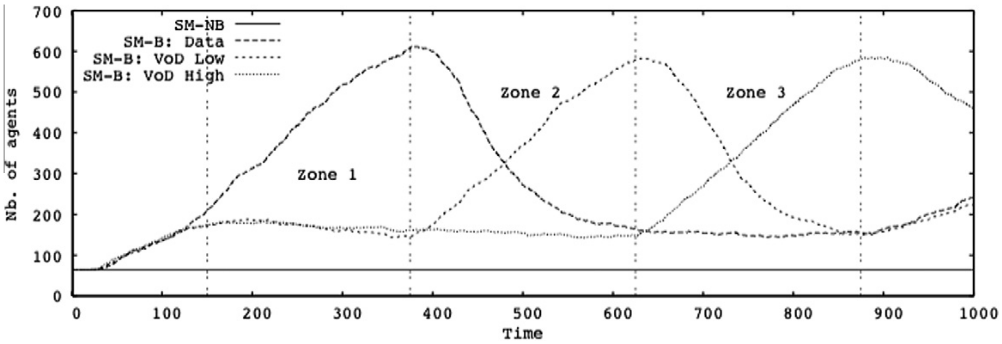


Fig. 14. Number of service agents.

network. As expected, the SM-B:PGBR gave the best performance and was able to provide higher throughput for all the zones. This is made possible by SM-Bs ability to efficiently discover service agents (including replicated service agents) while PGBR was able to efficiently discover the routes at the Infrastructure Layer as the service demand changed between zones. Since zone 1 was biased towards HTTP services, the overall throughput is lower than in zones 2 and 3, which was biased towards VoD (L) and VoD (H), respectively.

The average throughput results also reflect on the average blocking probability (Fig. 13). The blocking probability is the rate of request success for both the discovery of service agents as well as PGBR route discovery. Like throughput above, this is important as it demonstrates the integrated solution's ability to fulfil service requests both

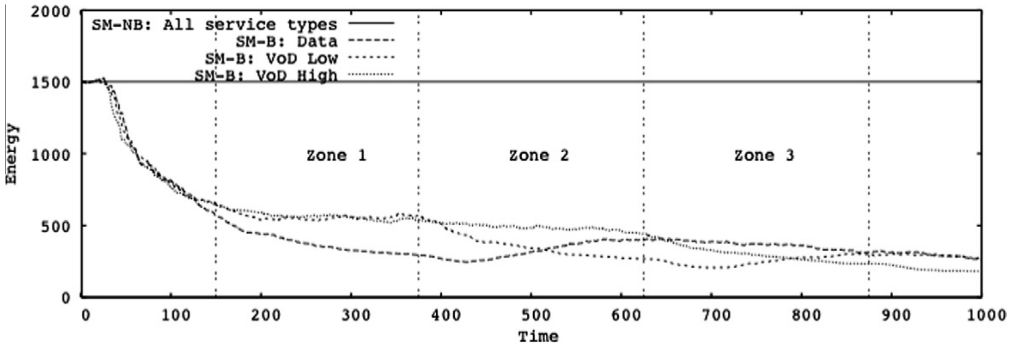


Fig. 15. Average energy for all service agents.

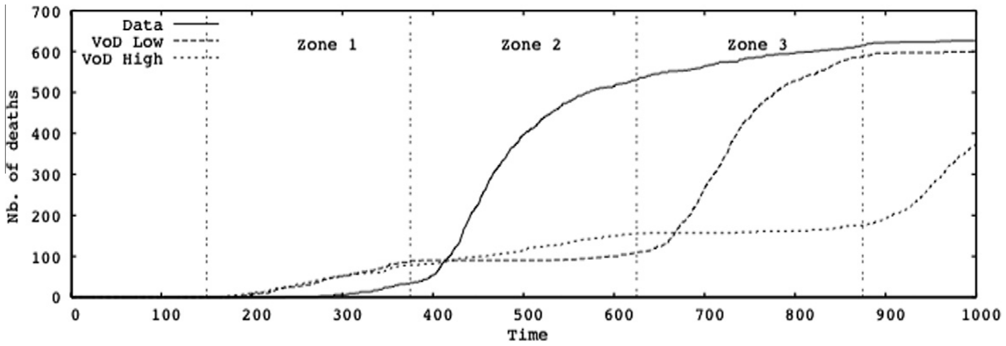


Fig. 16. Average number of agent death.

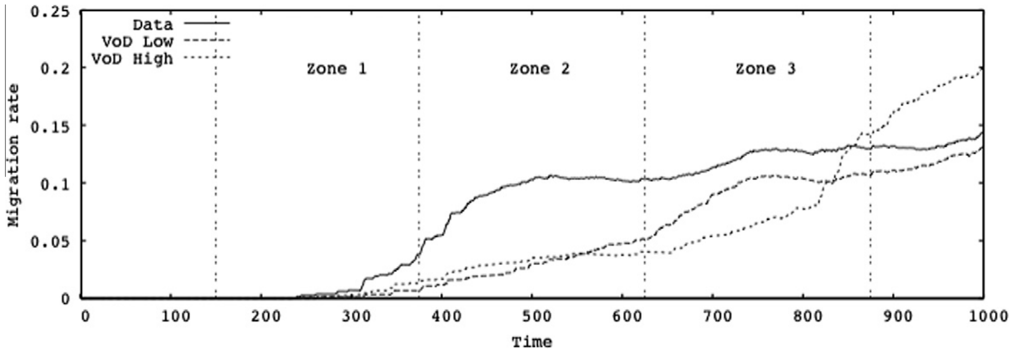


Fig. 17. Average number of migration by service agents.

at the service layer and in the underlying network. The blocking probability in zone 1 was lowest for SM-B:PGBR (0.02) compared to SM-B:SP (0.06) and SM-NB:SP (0.32). For zones 2 and 3, we can see that average blocking probability for SM-B:PGBR was 0.3 compared to SM-B:SP (0.46), and SM-NB:SP (0.56). The results also show the improvement of PGBR routing in comparison to SP for SM-B. Fig. 14 illustrates the number of agents throughout the simulation duration and complies with the biasing of each type of agent for each zone (where zone 1 had the largest amount of replication for HTTP agents, while zones 2 and 3 replicated a large number for VoD (L) and VoD (H), respectively – Fig. 18).

We now examine the service management behaviour in this simulation. These experiments demonstrate the self-regulating properties of the services in action. We monitor

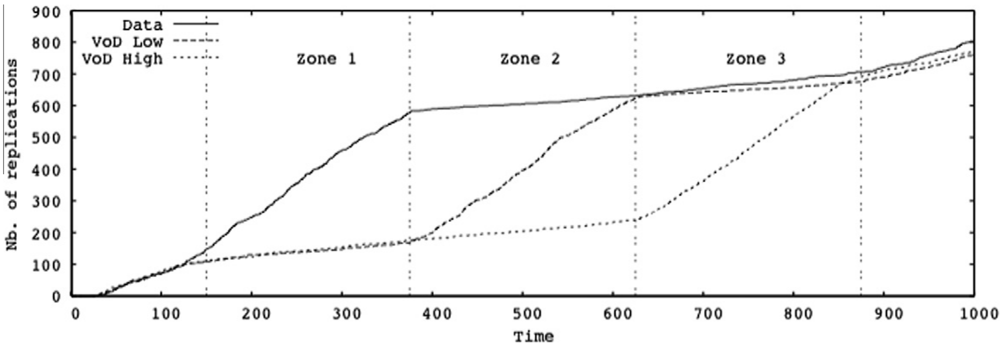


Fig. 18. Number of replication.

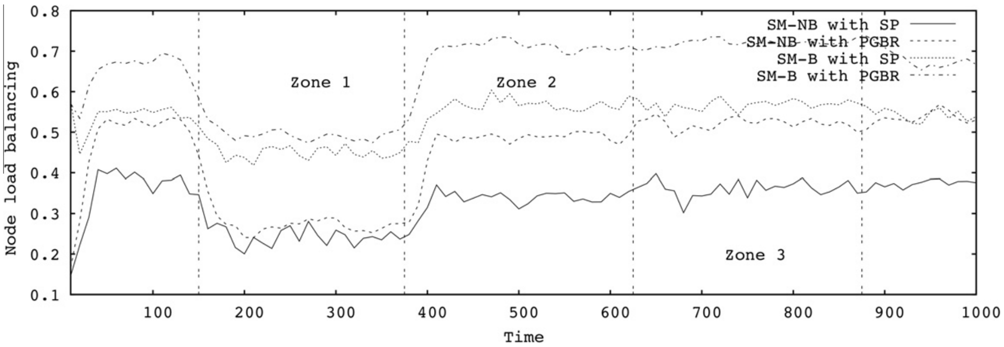


Fig. 19. Average network load balancing.

the number of agents, as well as the replication and migration rates to show how services react to elevated service load. We also show the agent death rates to demonstrate how redundant services are automatically removed, while the average energy shows how equilibrium is achieved by matching agent numbers to demand. Fig. 15 depicts the average energy consumed by the biological service agents and compares this to SM-NB. As shown in the figure, the SM-NB has constant energy consumption for all its service agents (this is due to the constant execution of the service agents on the AS), while for the SM-B the average energy was dependent on their demand and execution. Although there is an increase in the number of service agents in Fig. 14 for zone 1, there is a slow decline of energy in Fig. 15, caused by the parent agents offloading a certain amount of energy to the child (E_{child}) during replication. A similar trend can be observed when VoD (L) and VoD (H) demand started to increase. As zone 1 transitioned to zone 2, we can see a high number of deaths for HTTP service agents in Fig. 15, and this reflects the lower demand for those agents. As the service agent dies, we can also see an increase in energy consumption – since the death of service agent means that the remaining service agents will need to cater for higher number of requests (this can be observed in Fig. 15 zones 2 and 3 where average energy of HTTP service agents increased). Fig. 17 presents the migration number of each type of service agent and shows that in zone 2 there was a high number of migrations for HTTP service agents even though their demand has dropped. The reason for this is because a large number of HTTP service agents replicated in zone 1 were still present in zone 2, and as VoD (L) increased its replication, this started loading the platform and triggered the migration of the HTTP service agents (HTTP service agents actually require less energy to migrate and would be the first to migrate before the multimedia service agents). However, the migration starts to stabilize when the HTTP service agents die off in zone 2. Zone 3 demonstrated a high migration rate for VoD (H) since the demand was the highest.

The results demonstrate how the PGBR was able to adapt to any load resulting from service demand changes (from low load in zone 1 to higher load of VoD services in zones 2 and 3). This has been reflected in the average blocking probability as well as the throughput. Fig. 19 presents the average network load balancing, and shows that the PGBR support for SM-B improves the load balancing over SP. This is also supported by the average link utilization in Table 6, which shows that the SM-B:PGBR utilizes larger amounts of link capacity than other solutions. Therefore, the combined SM-B:PGBR demonstrated the benefits of applying the proposed techniques for the two layers. Even though the two layers are independently functioning, this reflects on the process of co-existence between the two layers, where the changes in the Service

Table 6
Average link utilization.

	SP	PGBR
SM-B	0.169	0.307
SM-NB	0.134	0.239

Management Layer will slowly change the behaviour of the PGBR and cater for varying types of load in the underlying networks.

8. Discussion

As the Internet advances towards the new generation network, one question that arises is *How could the Future Internet support the service needs of today and easily transition to meet the needs of the future?*" Although the roadmap to this question is challenging and full of uncertainties, we believe that the solution proposed in this paper for future service environments, is one foundational step towards answering this question. To make a case for our approach in addressing this question, in this section we discuss possible applications of our solution to support emerging services which we believe will have a big impact on the Future Internet. We would like focus on three main services, which includes: Internet Protocol TeleVision (IPTV), P2P and cloud computing. Cloud computing is an emerging concept that will see computing become a utility, in the same way that we have gas and electrical utilities for example. In the world of clouds, software and various other types of services will be located in high-powered data centres that will be accessed by thin client machines. Essentially clouds are next generation data centres with virtualised nodes [33], where these virtualized nodes are dynamically provisioned on demand. However, these virtualized nodes will essentially execute various software services that once were situated locally in our machine. As the number of these services increases, management will become an issue. Wei and Blake [34], pointed out that the key challenge of cloud computing includes maintaining high availability and managing long standing service workflow. In the first case, discovery of services is a crucial issue, and in the second case, efficient service search in the event of service failure is required to ensure that user's requirements are met. Another challenge in cloud computing is the ability to maintain energy efficient data centres for future green ICT. As cloud computing gains increased popularity, large numbers of services and virtual machines will be executed on data centres. The current agenda for green ICT is the ability for data centres to minimise energy consumption. For the majority of these challenges, our solution provides opportunities to enable the vision of cloud to become a reality. First and foremost, our search discovery mechanism is suitable for cloud computing, in terms of discovering new and popular services that have entered the cloud. This not only applies to services in terms of high availability, but also for managing long standing service workflows, where popular services can autonomously replicate themselves, and through our search technique, ensure that these services are found in a timely manner. In the case of green data centres, the inherent behaviour of migration in the services can provide opportunities for services to consolidate themselves on a smaller number of servers, allowing other servers to be switched off. This could be performed autonomously, where services maybe able to sense the workload of surrounding servers and migrate. In [35], we showed how services are able to migrate between data centres in different countries, when the services discover that a particular country is producing a high quantity of renewable energy. The aim here is to show how services can drive data centres to maximise clean energy usage.

IPTV is a distribution mechanism for digital television over the current IP networks [36,25]. Services offered to users are usually through triple play, which includes data, voice, and video. Video can be streamed either live or on demand. We believe that our solution is most applicable to video on demand. As the volume of video content becomes high, once again managing these and seamlessly moving them between IPTV servers (VSO – Video Serving Offices) will become a challenging task. Therefore, through our solutions, VoD contents can seamlessly replicate and migrate between VSOs as the user demand increases. While they migrate and move between the servers, the PGBR routing in the underlying network can ensure that routes are discovered in a timely manner, and minimise any effects on other on-going flows. Once the video contents become obsolete, they can slowly die off and get taken out of the VSO servers. In many ways, this is also applicable to P2P, in particular the replication process of the contents, and the ability to efficiently search these contents – as we have shown in Section 7.1.

Based on the example case studies discussed, we feel that the solution presented is generic enough to be applicable to various types of services that we will see gain popularity in future service environments.

9. Conclusion

The network research community is currently seeking novel solutions in the development of future service environments, which contribute towards the Future Internet. In this paper we have presented a future service environment solution for the Internet of the future, through a dual layered architecture. These two layers include a Service Management Layer and an Infrastructure Layer. For each layer, new techniques inspired from biological mechanisms have been applied to improve the performance as well as provide additional functionalities. In the Service Management Layer, a lifecycle model is applied to services, allowing services to mimic the behaviour of an organism (e.g. replication, migration, death). Our aim in applying this approach is to enable services to have embedded, autonomous capabilities and to allow services to self-govern themselves with minimum human intervention. The approach also allows services to evolve, as new and more popular services are introduced into the Internet. In tandem to this, we have also developed an adaptive, distributed routing mechanism in the underlying network to deliver these services. The routing mechanism, known as PGBR, adapts its routes irrespective to any traffic demand that may result from changes in service landscape or user demand. We have performed extensive simulation to validate our proposed solution, and performed this in three stages. The first two stages evaluated each layer on its own, while the last stage evaluated the combination of the two layers. Our simulation results have shown that our approach is able to outperform other known techniques. In particular the combined solution shows that, under strong variations in service demand, it can maximise end user satisfaction by better fulfilling requests and reducing delay while maximizing network resources in the process.

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Article III

Julien Mineraud, Sasitharan Balasubramaniam, Jussi Kangasharju and William Donnelly

Fs-PGBR: a scalable and delay sensitive cloud routing protocol

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Contribution: My contribution to this research article is the development of a new normalised hop count metric to enhance the performances of route discovery of PGBR. The contribution includes the writing of the article, as well as performing all the experiments for the evaluation of the new metric.

fs-PGBR: A Scalable and Delay Sensitive Cloud Routing Protocol

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ABSTRACT

This paper proposes an improved version of a fully distributed routing protocol, that is applicable for cloud computing infrastructure. Simulation results shows the protocol is ideal for discovering cloud services in a scalable manner with minimum latency.

Categories and Subject Descriptors

C.2.2 [**Network Protocols**]: Routing Protocols

General Terms

Performance

Keywords

Scalable route discovery, Cloud computing infrastructure

1. MOTIVATION

Cloud computing is recognized as the next generation infrastructure that would revolutionize the way users access services [3]. The driving force behind the concept of cloud computing has been fueled by the growth of computing devices (in particular mobile devices) as well as rich services which execute on power and memory constrained devices. The vision of cloud computing will enable users to offload these services into high powered storage facilities, where users will be able to access infrastructures, platforms, as well as software within the cloud. In essence, the cloud will represent a network of high powered data centers [2] that provides a multitude of services to end users based on a pay as you go model (Figure 1). Although the cloud will enable users to elastically consume resources, this will bring along new challenges for the underlying infrastructure. One of these challenges include a dynamic traffic pattern in the underlying network, which will require more scalable, efficient, and adaptive routing algorithms. In this paper, we propose a scalable routing algorithm called fast search - Parameterised Gradient Based Routing (fs-PGBR) that is fully distributed, scalable and reduces considerable latency during route discovery. The algorithm is an extension to the Parameterised Gradient Based Routing (PGBR) [1], which suffers from scalability performance once the network topology size increases.

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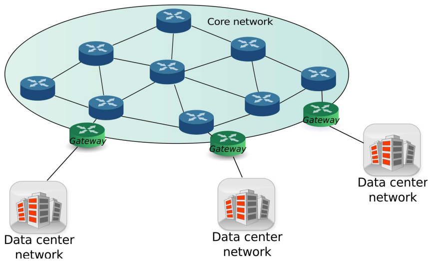


Figure 1: Cloud Computing Infrastructure

2. PROPOSED SOLUTION

2.1 PGBR

The original PGBR algorithm is a bio-inspired algorithm that is inspired from the bacteria motility process known as *chemotaxis*. The process of *chemotaxis*, enables bacteria to mobilize itself towards a destination by sniffing through an attractant gradient field formed in the environment. Mimicking this process, the PGBR algorithm generates an increasing chemical gradient field that attracts packets to a destination node. The equation for generating the gradient field can be represented as:

$$G_i^d(j) = \alpha nl(j) + \beta ll_i(j) + \gamma h_i^d(j) \quad (1)$$

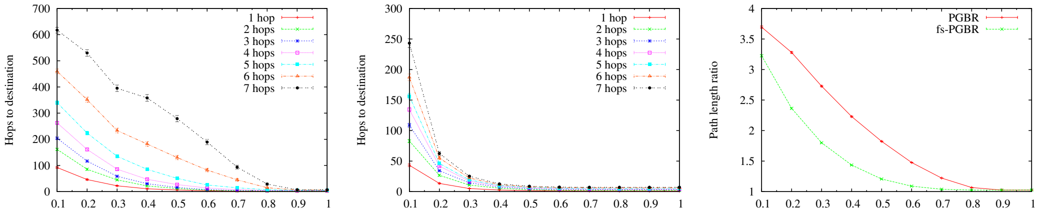
where $G_i^d(j)$ is the gradient value of link $i \to j$ for a packet to destination d, $nl(j)$ represents the node load value of neighbour node j, $ll_i(j)$ is the load value of the link $i \to j$, $h_i^d(j)$ is the normalised hop count neighbour node j of i for destination d, and α, β and γ are weighting parameters. The weighting parameters provides an extra feature of service oriented routing, where different weight sets can correspond to different service types.

The value for $h_i^d(j)$ is calculated during the topology formation, and will remain static. The equation for $h_i^d(j)$ is represented as:

$$h_i^d(j) = 1 - \frac{w^d(j)}{W^d}, \text{ where } W^d = max(w^d(k)), \forall k \quad (2)$$

where $w^d(j)$ is the minimum distance of node j to destination d.

While PGBR provides numerous benefits that are suitable for the underlying network supporting the cloud infrastructure, there is a slight shortfall. This short- fall is in the



(a) No. of hops to destination (PGBR) (b) No. of hops to destination (fs-PGBR) (c) Path length ratio

Figure 2: Performance evaluation of the new metric

approach used to calculate $h_i^d(j)$, which is not scalable once the topology reaches a large number of nodes. In particular, this could be an issue for large-scale cloud infrastructure supported by a network topology with a high number of nodes.

2.2 Hop count value for fs-PGBR

In order to counter the scalability problem, we have modified the $h_i^d(j)$ calculation, and this is represented as:

$$h_i^d(j) = \frac{max(w_i^d(k)) - w_i^d(j)}{max(w_i^d(k)) - min(w_i^d(k))}, \forall k \text{ neighbour of } i \quad (3)$$

This modification enables each node i to compare the shortest path weight of its neighbour k and evaluate it against the maximum and minimum weights of its neighbours. In the case of $max(w_i^d(k)) = min(w_i^d(k))$, the hop count $h_i^d(j)$ is set to 1. Therefore, the new calculation evaluates its hop count not from the relational distance of nodes i and j to the destination d, but rather from the immediate neighboring nodes, and its relation to shortest path. This leads to a perturbation based route discovery process that diverts depending on local conditions of neighboring node (e.g. node or link load).

3. PRELIMINARY EVALUATION

We have evaluated and compared fs-PGBR to the original PGBR discovery mechanism, where simulations were conducted in our custom developed Java simulator. The simulation evaluated two performance metrics based on a real-world large scale topology (i.e. Sprintlink network). The weights that were used to calculate the shortest path were provided by the Rocketfuel project and the load of each link were uniformly selected between 0 and 100% (loads are not symmetric). The simulation scenario generated 100 source-destination pairs for each hop count distance, ranging from 1 to 7 hops. The simulations were reproduced 100 times with different loads, and source-destination pairs selection. For each simulation, we varied the value of γ from 0.1 to 1.0, which is the weighting for $h_i^d(j)$ and reflects the importance of this weight with respect to the shortest path approach. In addition, α and β have similar weights, and set to make the sum of the three weights equal to 1.

As shown in Figure 2, we evaluated the number of hops required to successfully reach the destination as well as the discovered path length ratio (Figure 2 (a) and (b)).

We observed, in Figure 2 (a) and (b) that using the new $h_i^d(j)$ calculation approach leads to minimal discovery time compared to the original approach, in particular for long distance sources. This is due to a number of factors, including minimal discovery rejection that may result from Time-To-Live (TTL) expiration. Consequently, the new extension also enables more diversity in the choice of parameters for fs-PGBR discoveries. Secondly, as shown in Figure 2 (c), the resulting path is maintained under smaller and more reasonable path length ratio compared to the original approach. This demonstrates the effectiveness of fs-PGBR and its suitability towards timely route discovery for cloud computing infrastructures.

4. CLOUD COMPUTING INTEGRATION

Cloud computing requires fast discovery of services that are populated in large scale data centre networks. Once discovered, the paths for the services' must also ensure that Quality-of-Service (QoS) and Quality-of-Experience (QoE) requirements are met. fs-PGBR provides individual routing paths that can adapt to each service's requirements in a fully distributed manner, while minimizing the cost of discovery. In particular, fs-PGBR is ideal for cloud computing infrastructure that are built over large network topologies, and is able to support high service churn rates or varying user demand.

5. ACKNOWLEDGEMENTS

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Article IV

Julien Mineraud, Sasitharan Balasubramaniam, Jussi Kangasharju and William Donnelly

Parameterized Green Gradient Based Routing (PG^{2}BR) for an Energy Efficient Internet

Submitted

Contribution: My contribution to this research article is the development of the PG^{2}BR protocol to efficiently save energy in wired core infrastructure networks. The contribution also includes the writing of the article, as well as performing all the experiments to evaluate the new protocol. These experiments also include a sensitivity analysis of PG^{2}BR.

Parameterized Green Gradient Based Routing (PG^{2}BR) for an Energy Efficient Internet

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ABSTRACT

This paper proposes a distributed routing protocol that minimizes the energy consumption of communication networks. The proposed protocol, called PG^{2}BR (Parameterized Green Gradient Based Routing) contains dual processes, which includes i) a two-phase mechanism that gradually powers devices on/off in a decentralized manner, depending on the traffic condition, and ii) a distributed gradient based routing that quickly adapts to topology changes while maximizing resource usage and maintaining QoS requirements. Simulation work on a number of different types of topologies, have shown that PG^{2}BR is highly adaptive to any traffic and network conditions while proposing the best energy savings-QoS trade-off.

Categories and Subject Descriptors

C.2.2 [**Computer-Communication Networks**]: Network Protocols—*Routing protocol*

Keywords

Energy-aware routing protocol, QoS and energy savings trade-off

1. INTRODUCTION

The growth of the Internet has to led to increase deployments of communication networks in order to maximize connectivity to the end users. The higher reliance to the Internet has also been fueled by more advance and sophisticated services, allowing users to access services from various devices (e.g. multimedia streaming to mobile devices). While this has provided improved connectivity to the end users, this communication infrastructure growth has led to increase energy consumption, which today accounts up to approximately 10% of the world global electricity consumption [5]. This problem is further complicated by the fact that design of communication devices for infrastructure networks (e.g. routers) have not incorporated energy saving capabilities.

Gupta et al. [8] investigated numerous benefits that can lead to a greener Internet by allowing network devices (e.g. line cards in routers) to go to sleep, when under utilized. In particular, the study showed that routers were consuming high quantity of energy, even in idle mode. Chabarek et al. [4] extended the work in [8] to investigate the benefits of energy-awareness while designing networks to save energy. Their study showed that the combination of an energy-aware design and energy-aware routing protocols will lead to tremendous savings of energy.

The solution addressed in this paper focuses on an energy-aware routing protocol that can adapt to varying traffic demand, and minimize energy consumption in the process, without compromising on Quality of Service (QoS). The proposed approach, called PG^{2}BR (Parameterized Green Gradient Based Routing), extends from our original Parameterized Gradient Based Routing (PGBR) [3]. The strength of PG^{2}BR is the ability to adaptively modify the topology without prior knowledge of the traffic demand, by including a new functionality that monitors and powers routers on/off (two-phase mechanism) to adapt to the traffic demand. This provides the capabilities for the network to, (i) maintain sufficient resources required by the traffic demand in order to maintain QoS, and (ii) minimize the energy consumption of the entire network. Furthermore, its fully decentralized two-step mechanism (for uptrend and downtrend traffic demand) enables the savings to be performed at all times and does not require knowledge on traffic pattern or any routing table recalculation to adapt to the topological changes while keeping the impact on QoS extremely low.

We evaluated the PG^{2}BR routing algorithm through a series of simulations, and have compared this with other distributed energy-aware routing protocols. Results from our simulation study, has shown improved performance of the PG^{2}BR routing algorithm for a number of different topologies and traffic traces. As part of our evaluation, we have also conducted extensive sensitivity analysis to determine routing parameters that provide optimum energy savings-QoS trade-off.

The paper is organized as follows: Section 2 presents the related work. Section 3 describes our proposed approach, and this is followed by Section 4, which describes the results of our experiments, and finally, Section 5 concludes the paper.

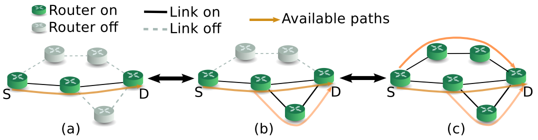

Figure 1: (a) Core topology, (b) Rising traffic demand, (c) Full topology

2. RELATED WORK

Several energy-aware routing protocols have been proposed in recent times to reduce the energy consumption of Autonomous System (AS). These solutions modified existing routing protocols (e.g. OSPF [11], AntNet [7]) to improve the overall energy efficiency.

One example is the work proposed by Cianfrani et al. [6], called Green-OSPF, that modifies the OSPF protocol to save energy of IP networks. To minimize the number of links powered-on in the topology, the authors modified the shortest path calculation of certain routers. In OSPF, each router calculates the Shortest Path Tree (SPT) that defines the shortest routes to all the other nodes. The proposed approach selected a subset of routers, called *importers*, which used SPT of a neighbor router which is called an *exporter*. An *importer* is only connected to a single *exporter*, but an *exporter* could connect to numerous *importers*. Maximizing the number of *importers* reduces the energy consumption of the network considerably. However, the resulting topology may be subject to significant losses of quality. The authors explained their choice by the limited cost of the implementation of their solution, while potentially improving the energy consumption of today's IP networks (e.g. up to 60% of links could potentially be powered-off).

From an adaptive routing protocol perspective, Kim et al. [9] proposed AESR, which is adapted from a well-known bio-inspired routing protocol that uses Ant Colony Optimization (AntNet [7]). The algorithm favors routing along highly loaded links, which could possibly lead to powering off lightly loaded links. The authors coupled the pheromone information collected by ants to a traffic centrality factor that redirect ants to highly loaded links. This technique is able to reduce the energy consumption of real networks by up to 60%, using a single parameter β (factor to weight the traffic centrality). Unfortunately, the choice of β might impact negatively on the network QoS performances.

Several energy optimization techniques such as in [5], use either Integer Linear Programming (ILP) or heuristics to solve the multi-commodity flow problems under certain constraints. These constraints may include maintaing a certain level of traffic throughput and minimization of energy consumption of the network. However, as the Internet continues to increase in popularity, this may lead to varying traffic demand. Therefore, requiring pre-knowledge of traffic demand may not be ideal for managing communication networks of the future.

3. PROPOSED SOLUTION

Our proposed solution extends a fully decentralized flow-based routing protocol with functionalities to save energy. This includes a two-phase mechanism to gradually power devices on or off by reacting to the traffic demand, while ensuring the connectivity of the network's access nodes. In this section, we will present firstly the advantages of using a flow-based routing protocol and secondly the mechanisms that were added to perform energy savings.

3.1 PGBR

3.1.1 Flow-based Routing

A flow-based routing protocol uses routing tables based on flows to forward packets through the network, compared to using only destination information commonly used in current routing protocols. A flow in our solution, is characterized by the 5-tuple (*src*, *dst*, *src port*, *dst port*, *protocol*). Packet differentiation techniques could also be used to separate network traffic into flows, where unique flow id could be selected by the type of service. Therefore, packets from services with similar characteristics (e.g. video) would use the same paths. This is one advantage of flow-based routing, where multiple paths could be set up to satisfy certain service constraints (e.g. delay or capacity). This also enables in-coming new flows to divert traffic to secondary paths in order to avoid certain zones of the network (please note in our solution that on-going traffic paths do not get diverted). In our proposed solution, the avoided zone will be the lightly loaded devices that could be potentially powered-off.

3.1.2 Gradient Search for Routes

An implementation of a flow-based routing protocol is PGBR. The original PGBR is a scalable, distributed, gradient based routing algorithm. PGBR uses one-hop information to compute its gradient field, leading packets through the most appropriated route according to the service's requirements. The gradient is calculated using the following equation:

$$G^d_{i \to j} = \alpha l^n_j + \beta l^l_{i \to j} + \gamma h^d_j \tag{1}$$

where $G^d_{i \to j}$ is the gradient of the link $i \to j$ for the destination d, l^n_j is the load of neighbor node j, $l^l_{i \to j}$ is the load of link $i \to j$ and h^d_j is a normalized hop-count value to the destination. The three-tuple (α, β, γ) enables the gradient field to support various service types. The strength of the algorithm, is in its ability to adapt to varying traffic demand, and at the same time maximizing the use of underlying network resources.

In order to maintain the sanity of their routing table, each router periodically checks flow routing table entries to delete outdated entries. A flow routing table entry is outdated when no packets have been processed over a certain period. In our solution, the protocol will consider switching-off interfaces when the flow routing table does not contain any entry for that interface (in or out) for a period of time. More details on the implementation of PGBR can be found in [10]. The next section introduces the extension made to PGBR to incorporate energy-efficiency awareness.

3.2 PG^{2}BR

The PG^{2}BR, extends PGBR, by incorporating energy efficiency capability. This extension leads to dual processes, which includes : (i) a two-phase mechanism that gradually power-on routers as the traffic demand increases, and power-off as the traffic demand decreases, and (ii) the PGBR routing algorithm that routes and adapts to the changing network topology resulting from (i). In the case of (i), routers will interact with their immediate neighbors, and by inferencing their loads, a decision on powering on/off routers will be made. The following sections will describe the details of these mechanisms.

3.2.1 Core Topology

While our proposed solution enables a dynamic topology to be formed with respect to the current state of the traffic demand, a minimum guarantee is required to ensure that certain nodes are available to support small amount of traffic during off-peak periods. We define this minimal topology as the core topology, and an example of this is illustrated in Fig. 1a. The core topology guarantees that all access nodes are connected at all times, and devices in this topology are never powered-off. Furthermore, the core topology is designed to have minimum energy requirements (this also sets the minimum energy boundary that the network is consuming).

3.2.2 Uptrend Traffic Demand

The decision to switch on/off devices in our proposed approach, is based on a distributed signaling process used in the original PGBR algorithm. In the original PGBR routing algorithm, each node passes its load information to its neighbor, where this information is used to calculate the gradient path. The PG^{2}BR uses this information to analyze its current load to decide when a power on/off operation can be performed. In other words, each router keeps the load information of all its neighbors (node loads) and the loads of the links to the neighbors (link loads). The node load being the average value of all link loads. Another feature has been added to enable the underlying routing protocol to redistribute the traffic: once the configuration changes at a node (power on/off), a lock[1] is applied to the router that forbid any further power on/off operation for a period of time.

The action to power-on a line card is initiated when the node load is over a threshold $\overline{t_{l^n}}$, and the node has at least one interface off and no lock applied. If the conditions are matched, the node looks for the best possible interface to power-on. During this process, the algorithm favors powering-on a line-card connected to a neighbor which is already awake in order to minimize the number of chassis powered-on. For all candidate line cards that are off, PG^{2}BR will estimate the cost of powering each interface, before a specific line card is selected to be powered-on.

The estimated cost of powering the interface $i \rightarrow j$ on for destination d is:

$$EC^d_{i \rightarrow j} = C_{i \rightarrow j}/(h^d_j + 1.0) \qquad (2)$$

where $C_{i \rightarrow j}$ is equal to $2 * LCC$ if the neighbor node j is on, and $CC + 4 * LCC$, otherwise. The $CC(x)$ corresponds to the energy consumption of a router chassis, while $LCC(x)$ corresponds to the energy consumption of a single line card [4].

Therefore, the interface with the minimum cost is selected to be powered-on. The connectivity to the interface of the next router depends on the power state of that router. In the event the neighboring router is on, then the corresponding interface will be switched on. However, if the neighboring router is asleep, the router is first awaken followed by the powering-on of the line card. The neighbor router will also calculates its own $EC^d_{j \rightarrow k}$ in order to select the next best line card to connect itself to the network. This action is repeated until the new path is connected to the network at both ends. Once the router powering-on action has been completed, a lock is applied to all the routers in the path to prevent any further actions to be processed. This, in turn, will provide a short duration of time for the PGBR to correctly re-balance the traffic according to the new topology configuration.

3.2.3 Downtrend Traffic Demand

When the conditions are not satisfied for powering-on an interface, and no locks are applied, the router will look for the best opportunity to power-off in order to save energy. The simple process is based on each router observing the current load on its links. If a link load is below the threshold $\underline{t_{l^l}}$, the router will check its own node load as well as the node load of the next router on that path that could potentially redirect new incoming traffic if that path was shut down (their node loads must be below the threshold $\underline{t_{l^n}}$). If the conditions are met, a flag is set to disable the line card of the link in order to minimize traffic loss, thus becoming unavailable for discovery during a period of time.

This will allow current flows going through this interface to terminate without accepting new flows. In addition, a lock is placed on the corresponding node to ensure that the PGBR mechanisms can re-balance the traffic to fit the new topology, as it does during the uptrend traffic demand. In the event that the interface has not been utilized (i.e. existing flows have been terminated), it will be powered-off after a short duration. Once all the interfaces of a router are powered-off, the whole router will be powered-off.

4. PERFORMANCE EVALUATION

4.1 Simulation Setup

All the experiments are performed using ns-3.14 [1] on a cluster of 240 Dell PowerEdge M610 nodes. Each cluster node has 2 quad-core CPUs, 32GB memory, and runs Ubuntu SMP with 2.6.32 kernel. We conducted two evaluations of PG^{2}BR, which includes sensitivity analysis as well as comparison to Green-OSPF [6] and AESR [9], which are two state-of-the-art energy-aware routing protocols that do not require prior knowledge of the traffic pattern. All the simulations were tested on four topologies (two real and two random topologies). The two real topologies that were selected are the same topologies used in [9] (Ebone (87 nodes, 161 links) and Exodus (79 nodes, 147 links) from the Rocketfuel project [12]). The two random topologies (Brite50 (50 nodes, 150 links) and Brite200 (200 nodes, 600 links)) were generated using the Brite topology generator [2], utilizing the default parameters of the Waxman model with $n = 3$. For simplicity, we have set all topologies with the same link properties, which includes a link capacity of 10 *Gbps* and a delay of 2 ms.

For the four topologies, we evaluated two different scenarios: i) only 40% of the nodes are access nodes, and ii) all the nodes are generating traffic. The aim of evaluating two different configurations is to evaluate the adaptability

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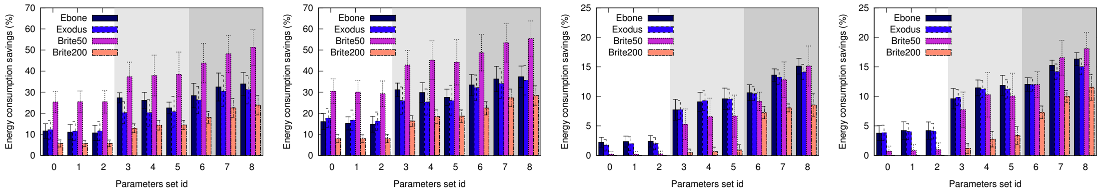
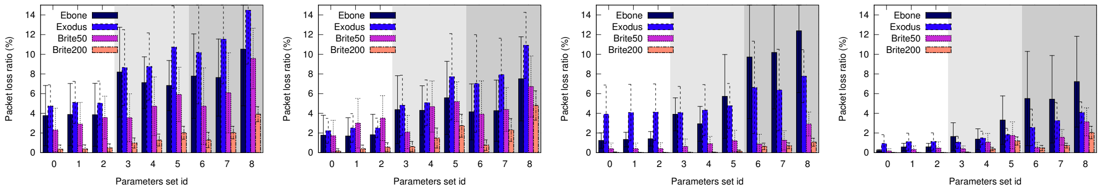
[1] The lock-out period does not provoke any topology oscillations as the PG^{2}BR algorithm does not impact existing flows. The lock-out period is established to ensure PG^{2}BR has sufficient time to balance the new incoming flows into the modified topology. In the worst case scenario, no topological changes would apply.



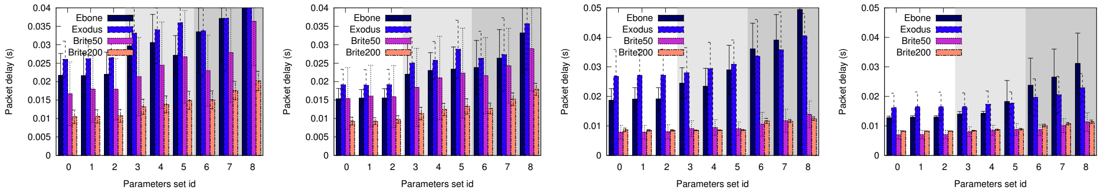
(a) High peak (40%) (b) Low peak (40%) (c) High peak (100%) (d) Low peak (100%)

Figure 2: Sensitivity analysis of PG^{2}BR parameters for energy savings.



(a) High peak (40%) (b) Low peak (40%) (c) High peak (100%) (d) Low peak (100%)

Figure 3: Sensitivity analysis of PG^{2}BR parameters for packet loss ratio.



(a) High peak (40%) (b) Low peak (40%) (c) High peak (100%) (d) Low peak (100%)

Figure 4: Sensitivity analysis of PG^{2}BR parameters for packet delay.

of PG^{2}BR for different environments [2].

In order to achieve realistic traffic patterns, traces from the Totem project [13] were used to generate the traffic matrices at 15 minutes interval, for 24 hours. The resulting 24-hour traffic patterns (one for each source/destination pair) have a diurnal cycle, composed of a low and a high peak zone (e.g. up to 7.6 million flows are generated for a single traffic pattern). The traffic matrices were scaled in order to produce a few congestions when using OSPF alone. This decision was driven by the desire to observe the energy-awareness and its impact on the QoS performance.

The energy consumption of the network devices are identical for all routers and the parameters are set to $CC = 270$ Watts and $LCC = 70$ Watts [4].

4.2 Sensitivity Analysis of PG^{2}BR

		Node load		
		$\underline{t_{l^n}} = 0.1$ $\overline{t_{l^n}} = 0.2$	$\underline{t_{l^n}} = 0.2$ $\overline{t_{l^n}} = 0.4$	$\underline{t_{l^n}} = 0.3$ $\overline{t_{l^n}} = 0.65$
Link load	$\underline{t_{l^l}} = 0.1$	0	3	6
	$\underline{t_{l^l}} = 0.2$	1	4	7
	$\underline{t_{l^l}} = 0.35$	2	5	8

Table 1: Corresponding node and link load thresholds for each parameter sets id.

This section presents the sensitivity analysis of PG^{2}BR, by evaluating different combination of parameters and observing the performance in terms of energy savings, packet loss and delay. In total, we evaluated 27 sets of parameters, and each configuration is defined as a parameter id. As summarized in Table. 1, the parameter ids numbered from 0 to 2 (e.g. white zone) have "low" node load thresholds ($\underline{t_{l^n}} = 0.1, \overline{t_{l^n}} = 0.2$), parameter ids from 3 to 5 (e.g. light grey zone) have "medium" node load thresholds ($\underline{t_{l^n}} = 0.2, \overline{t_{l^n}} = 0.4$) and parameter ids from 6 to 8 (e.g. dark grey) have "high" node load thresholds ($\underline{t_{l^n}} = 0.3, \overline{t_{l^n}} = 0.65$). Finally, within each group of node load thresholds, the link load thresholds are respectively set to "low" ($\underline{t_{l^l}} = 0.1$), "medium" ($\underline{t_{l^l}} = 0.2$), and "high"($\underline{t_{l^l}} = 0.35$). For instance, set id 4 corresponds to medium node load thresholds, medium link load threshold and a lock-out period of 7.5 minutes. We would like to make a note that for all sets we selected a lock-out period of 7.5 minutes. Finally, for each set of parameters, a total of 10 traffic matrices have been evaluated for each topologies (access nodes may differ in the case of 40% access nodes).

Fig. 2, 3 and 4 show the average value of the performance as well as the standard deviation. By analysing the three figures, it is clear that the choice of the node load threshold impact the most on the performances of PG^{2}BR. For instance, Fig. 2b shows the energy consumption savings achieved by each set of parameters, where we can clearly see the three levels of energy savings performances. These levels are not appearing in Fig. 3b and 4b where the impact on QoS in-

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[2] In the case when all nodes are generating traffic, none of the protocols are able to switch devices off, thus putting Green-OSPF on an equal footing.

creases linearly. Fig. 2, 3 and 4 also shows similar behavior for the four topologies, which reassures the flexibility of using PG^{2}BR for different types of topology to achieve the desired energy savings-Qos trade-off.

The choice of middle range $\underline{t_{l^n}}$ holds a good compromise between high energy savings and network QoS performances. For example, the Ebone topology (Fig. 2a) shows improvement by more than 15% for energy savings for low range thresholds compared to 7% for high range thresholds. The choice of the link load threshold $\underline{t_{l^l}}$ and the lock-out duration influences the performance to a smaller extent. As a consequence, Fig. 2, 3 and 4 shows that the combination of a middle range $\underline{t_{l^l}}$, middle range $\underline{t_{l^n}}$, and a long lock-out duration minimizes impacts on the QoS performances while ensuring good energy savings performances.

4.3 Comparison of Energy-aware Routing Protocols

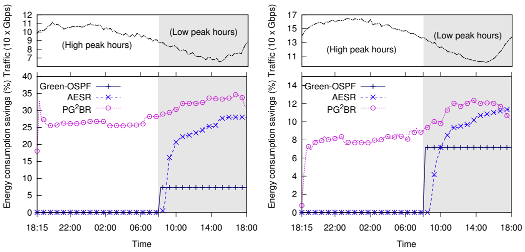
This section compares the PG^{2}BR to the Green-OSPF as well as AESR. Firstly, a description and justification on the selected parameters will be presented. The comparison of the three protocols will be evaluated with respect to time, to demonstrate the performance over a 24 hour period. This will be followed by an evaluation on the energy savings and the resulting QoS degradation during the low-peak period for the three energy-aware routing protocols (metrics evaluated include the packet lost ratio and the average packet delay) .

4.3.1 Simulation Parameters

The parameters for the routing protocols are as follows: Green-OSPF performs its optimization at 8 am (start of the low-peak period) using 5% (as in [6]) of the routers as exporters The value of 5% was used because the number of exporters is relatively low in order to maximize the number of links that can potentially be powered-off. This value is also sufficiently high enough to have a relatively low impact on QoS.

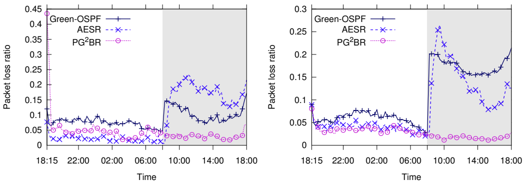
AESR produces an ant agent every 0.1 seconds and uses a centrality factor of $\beta = 0.4$ (as in [9]). Similar to Green-OSPF, the protocol also performs its optimization at 8 am. During down trend traffic, the strategy taken by AESR is to power-off lightly loaded interfaces or routers every 15 minutes. Unlike PG^{2}BR and AESR, Green-OSPF algorithm does not allow any routers to be powered-off.

In the case of PG^{2}BR, neighbor messaging are sent every 0.5 seconds and the parameters (α, β, γ) used for the gradient equation 1 are set to $(0.2, 0.2, 1.0)$. These parameters will lead to path discovery that favor shortest paths with little deviations in order to maximize energy savings. PG^{2}BR powers-off the interfaces when they are inactive (e.g. flow routing tables are empty from this interface) for at least 6 minutes. The energy-aware parameters of PG^{2}BR are selected according to the results of the sensitivity analysis, where we chose the values that optimize the trade-off between energy savings and fulfilling QoS requirements of the network. The selected parameters include: $\underline{t_{l^n}} = 0.2$, $\overline{t_{l^n}} = 0.4$, $\underline{t_{l^l}} = 0.2$, and a lock-out period of 7.5 minutes (i.e. this corresponds to parameter set id 4 as shown in Fig. 2, 3 and 4). We used 80 traffic matrices, where all traffic patterns exhibited similar diurnal cycle over a 24 hour period. Our aim is to develop a number of experimental tests, in order to obtain statistical results. All traffic matrices have similar behavior, and are produced from the Totem traces.



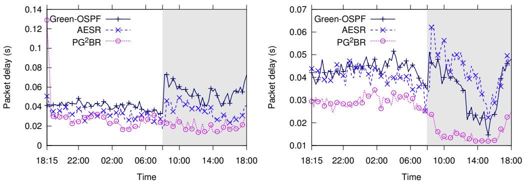
(a) Ebone (40%) (b) Exodus (100%)

Figure 5: Energy consumption performances with respect to time.



(a) Ebone (40%) (b) Exodus (100%)

Figure 6: Packet loss performance with respect to time.



(a) Ebone (40%) (b) Exodus (100%)

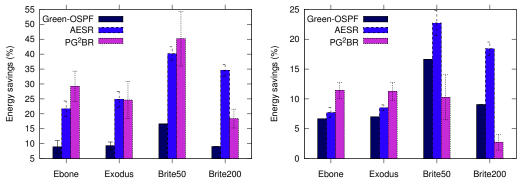
Figure 7: Packet delay performance with respect to time.

4.3.2 Evaluation Over 24 Hour Period

The performance of the three routing protocols over a 24 hour period for both the Ebone and the Exodus topologies are shown in Fig. 5, 6 and 7. We focused on Ebone topology with 40% access nodes and Exodus topology with 100% access nodes. Only a single traffic matrix is shown for each scenario to improve clarity.

As shown in Fig. 5, the traffic demand exhibits two distinct periods; the first period (High peak) lasts 14 hours between 6 pm and 8 am, while the second period (Low peak) represents the remaining 10 hours. For Green-OSPF and AESR, the optimization is executed only during the low peak hours as set out in [6,9]. However, PG^{2}BR is performing energy savings throughout the entire 24 hour period. due to the dual process, which dynamically reacts to traffic pattern changes.

In Fig. 5a, PG^{2}BR is able to dramatically decrease the energy consumption of the network by up to 34.6%. During the day, the protocol reduces the energy consumption by over 25% due to redundant paths in the networks. In the case of Exodus topology with 100% access nodes (Fig. 5b), Green-OSPF removes most of the redundant paths and have similar energy savings as PG^{2}BR (this is during the transi-



(a) 40% access nodes (b) 100% access nodes

Figure 8: Comparison of energy savings during the low peak hours.

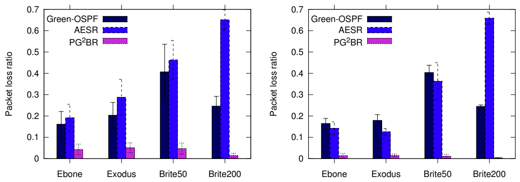
tioning period between high to low-peak zones). However, PG^{2}BR can dynamically improve the energy savings by up to an extra 10%. During high peak, PG^{2}BR topological changes are minimal but ensure good performances. The gains obtained by Green-OSPF are the lowest in both 40% and 100% access nodes configurations. However, as shown in Fig. 5b, the difference is reduced as the number of access nodes increases. On the Exodus topology, PG^{2}BR improves the energy savings by up to 5.1%. In Fig. 5a and 5b, AESR is slowly converging to an optimal solution. Regrettably, this shows that AESR is unable to cope with dynamic traffic pattern, thus resulting in degradation of QoS performances. In addition, AESR does not have a two-phase mechanism to switch network devices on when resources are missing. Green-OSPF exhibits simple behaviour with very low dynamics, and is inefficient compared to the other two routing protocols. AESR exhibits higher dynamics but is very slow to converge compared to energy saving performances of PG^{2}BR. However, PG^{2}BR with its dual process is able to dynamically react to traffic pattern changes to save energy, and at the same time maximize available resources. This energy saving process also continues into the high-peak traffic period.

In Fig. 6 and 7, we compare the QoS performances of the three energy-aware routing protocols during the 24 hour period. As previously mentioned, the performances of AESR are the most unreliable. They fluctuate greatly depending on the topology size as well as varying traffic conditions. This is particularly the case for the packet lost ratio (Fig. 6), where the algorithm is not able to adapt to the new traffic conditions resulting in poor packet loss ratio performances. Similar performances are also observed for the packet delay (Fig. 7).

Green-OSPF presents a solution to keep stable QoS performances, which only fluctuates slightly with the traffic pattern. Fig. 6b and 7b shows that this behavior is noticeable when there are 100% access nodes. However, PG^{2}BR demonstrates the best packet loss ratio and delay performance. In comparison to PG^{2}BR, AESR has a lower packet loss ratio and delay only on the Ebone with 40% access nodes during high-peak period. However, this difference in QoS is relatively negligible.

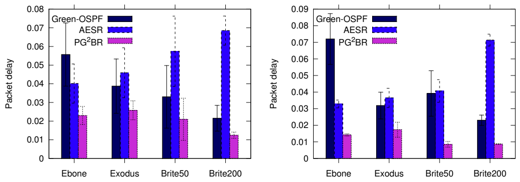
Therefore, the hourly details of Fig. 5, 6 and 7 show that PG^{2}BR is the most stable protocol to maintain QoS requirements, while greatly reducing the total energy consumption of the network. However, the Ebone topology was the only topology to exhibit a small disadvantage for PG^{2}BR during the high-peak hours.

4.3.3 *Impact of Energy Savings on QoS during Low-Peak Hours*



(a) 40% access nodes (b) 100% access nodes

Figure 9: Comparison of packet loss ratio during the low peak hours.



(a) 40% access nodes (b) 100% access nodes

Figure 10: Comparison of packet delay during the low peak hours.

Fig. 8, 9 and 10 show the differences of performance between Green-OSPF, AESR and PG^{2}BR on the four topologies, each evaluated with 10 traffic matrices during the low peak hours. These figures show respectively the average energy savings, packet loss ratio and packet delay and their standard deviations. Fig. 8 shows the energy savings performance of the three energy-aware routing protocols on the four topologies. As shown in the results, PG^{2}BR exhibits the best performance on the three smallest topologies (Ebone, Exodus and Brite50). For instance, with the Brite50 topology, the average energy savings is 45.2%.

Green-OSPF performs similarly in both configuration because its energy savings does not rely on the traffic but only on the number of exporters. However, the performance of AESR and PG^{2}BR dramatically increase when only 40% of the nodes are generating traffic (e.g. Fig. 8a) as they are able to power-off devices. Fig. 8b shows the possible energy savings that can be obtained when no router can be powered-off (100% access nodes), putting Green-OSPF on an equal footing with other routing protocols. In this configuration, the performance of Green-OSPF improves, but still lower compared to the other two routing protocols. As predicted, the energy savings are much lower when all the routers are powered-on. On the Brite50 topology, the energy savings using PG^{2}BR with 40% access nodes are more than 4 times greater than with 100% access nodes. The energy savings result, as seen in Fig. 8, confirms that AESR has very good energy saving performances due to its capability to also power-off devices. Unfortunately, no mechanism in the protocol have been designed to power-on devices when the resources of the network become limited. As a consequence, AESR does not cope well with QoS requirements when the traffic demand fluctuates. Since the routing algorithm maximizes centralization of the traffic (using parameter β), it leads to high packet loss ratio and delay, especially for the Brite200 topology. Furthermore, the swarming intelligence of ants is lost because insufficient number of ants reaches their destinations on topologies where the average node degree is high (Brite50 and Brite200).

Reducing energy consumption of the network automatically results in the degradation of the QoS performances. Fig. 9 shows the comparison of performances for packet loss ratio. The results also comply with the patterns observed over a 24 hour period (Fig. 6). The results have shown that for Green-OSPF and AESR, the packet loss ratio degradation is proportional to the energy savings. The only exception is for AESR on the Brite200 topology, which does not follow this pattern. However, this is due to slow convergence of the ants in large topologies. On the other hand, PG^{2}BR maintains low average packet loss for all topologies, including 40% and 100% access nodes. The greatest advantage of PG^{2}BR is the adaptability of its underlying protocol PGBR, which aims to maximize the use of network resources. This is also reflected in the delay performances presented in Fig. 7, which shows PG^{2}BR outperforming Green-OSPF and AESR for all topologies and access node configurations.

In summary, PG^{2}BR is able to maintain QoS performance for all topologies in comparison to Green-OSPF and AESR. This is particularly the case for packet loss ratio. At the same time, PG^{2}BR is able to successfully maintain the highest energy savings for all topologies, as well as access node configurations.

We can summarize characteristics of each protocols as follows:

- **Green-OSPF**:
  - Simple algorithm but performs poorly in terms of energy savings, due to the limitations that only links can be powered-off.
  - Degrades the QoS performance of the network proportionally to the energy savings.
- **AESR**:
  - Overall QoS performance fluctuate severely and is highly dependent on the topology and access node configuration.
  - Slow convergence time towards high energy savings.
- **PG^{2}BR**:
  - Exhibits good QoS performances for both packet loss and delay, even during high-peak traffic period.
  - Highly dynamic and adaptable to changing traffic conditions.
  - Demonstrates the best energy savings-QoS tradeoff.

5. CONCLUSION

In this paper, we introduced a novel routing protocol that dynamically adapts the network topology to reduce the overall energy consumption. The protocol, called PG^{2}BR, allows each router to autonomously power on/off depending on the traffic demand of the network. The strength of the proposed approach is the ability to eliminate prior knowledge of traffic demand, as the topology changes shapes, while respecting QoS constraints. Through simulations, we show that our protocol outperforms current state of the art energy-aware routing solutions and saves up to 45.2% in electricity consumption, while ensuring good QoS performances.

6. ACKNOWLEDGMENTS

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Appendix B: Energy Management using PGBR

Article V

Julien Mineraud, Liang Wang, Sasitharan Balasubramaniam and Jussi Kangasharju

Reducing Data Center Energy Use Via Renewable Energy Aware Routing and In-Network Caching

Submitted

V

Contribution: My contribution to this research article is the development of the rePGBR protocol that favours routes with highest green renewable energy usage. The contribution also includes the writing of the article but the sections related to content caching, while the experiments were collected cooperatively with PhD student Liang Wang.

Reducing Data Center Energy Use Via Renewable Energy Aware Routing and In-Network Caching

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***Abstract*—The ICT industry today is placed as one of the major consumers of energy, where recent reports have also shown that the industry is a major contributor to global carbon emissions. While renewable energy-aware data centers have been proposed, these solutions have certain limitations. The primary limitation is due to the design of data centers which focus on large-size facilities located in selected locations. This paper addresses this problem, by utilizing in-network caching with each router having storage and being powered by renewable energy sources (wind and solar). Besides placing contents closer to end users, utilizing in-network caching could potentially increase probability of capturing renewable energy in diverse geographical locations. Our proposed solution is dual-layered: on the first layer a distributed gradient-based routing protocol is used to discover the paths along routers that are powered by the highest renewable energy, and on the second layer, a caching mechanism will pull the contents from the data centre and place them on routers of the paths that are discovered by our routing protocol. Through our experiments on a testbed utilizing real meteorological data, our proposed solution has demonstrated increased quantity of renewable energy consumption, while reducing the workload on the data centers.**

I. INTRODUCTION

The current global energy depletion is a widely debated topic, due largely to the increasing population which has fueled massive industrial growth in the last few decades. Paralleled to the pressing problem of energy depletion, is the increase in CO_2 emission which has affected the environment in the form of global warming. These problems have largely been attributed to the poor planning process and short term goals that we as humans have taken in utilizing natural resources, over the years. The growth of the Internet is slowly moving up the ranks as a major source for energy consumption (10% of the world global energy consumption [1]), which is close to other established industries (e.g. airline industry). The wide spread popularity of the Internet has led to an increasing number of deployed communication networks (e.g. WiFi, WiMAX) providing rich services (e.g. Multimedia contents) to end users' devices. These rich services are usually represented through contents that are placed in high powered data centers, which today is one of the major source of energy consumption in the whole Internet infrastructure.

This new landscape has shifted ICT researchers towards developing solutions that can improve energy consumption of communication networks, and at the same time minimize CO_2 emissions [2]. In particular, as we witness increasing developments in renewable energy infrastructure, ICT researchers are pursuing new solutions where clean energy could be used as an energy source for the Internet infrastructure (e.g. designing energy efficient networks). While new solutions have been proposed for increasing renewable energy sources for data centre networks, the limitation of these solutions are the fact that the number of data centers are only localized in small number of locations, which also minimizes the probability of meeting high quantity of renewable sources (e.g. as we know, renewable energy is highly dependent on the weather patterns as well as location). However, compressing the size of data centers and increasing their distributed locations, will require a brand new design, which will incur high infrastructure costs. Therefore, a more feasible and practical solution is required for distributing the source of content storage, that is flexible, highly dynamic and reactive to the changing weather patterns.

In this paper, we propose a solution that meets this objective, by utilizing content routers as a distributed source for content storage. Storing contents on the routers provides a number of appealing benefits. Firstly, storing contents within the network provides an opportunity to bring the contents closer to the clients, which minimizes the need to re-fetch the content from end data centers. Secondly, the lower costs of storage prices, means that changes in the infrastructure costs would be minimal in order to enable content caching within the network. However, the main benefit that also suits our proposed solution, is the fact that contents can be stored in a distributed manner and increases the distribution of location and access to wider renewable energy sources (we assume that each router is powered by renewable energy infrastructure, which could be a combination of wind turbines and solar panels). Therefore, by pulling contents out from the data centers and placing them on content routers which are powered by renewable energy, we will have an opportunity of accessing higher quantity of renewable energy to power the content, which in turn can allow us to power-off certain servers in the data centers that may utilize brown energy.

The novelty of our work lies in the ability to maximize source of renewable energy to power storage points for contents. Our solution is dual-layered:

- The first layer uses a gradient-based routing algorithm to discover paths along the routers that have access to high renewable energy.

- The second layer uses a CCN-like [3] in-network caching to cache the contents along the discovered paths.

A thorough evaluation has been conducted using real renewable energy data, on a real network topology. The evaluation was validated using an experimental testbed. Our key findings can be summarized as follows:

- The combination of our routing and caching is very effective at both increasing use of renewable energy as well as reducing traffic in the network (by up to 35%) even when the renewable infrastructure differ greatly (each geographical location has its own optimal combination of wind turbine or solar panel infrastructure depending on availability of sunlight and wind).
- Increased use of renewable energy in the network is equivalent to reduction of brown energy; our solution was able to save brown energy usage between 10-55%.
- We identify trade-offs between the amount of renewable energy and caching performance and show how they interact with each other.
- Content traffic to data centers can be reduced by 24–53% using the adequate caching strategy which directly translates into energy savings at the data center.

The paper is organized as follows: Section II presents the related work. Section III clearly defines the objectives of our solution, and this is followed by Section IV which describes our proposed approach. Section V describes the results of our experiments. Section VI summarizes the paper, and finally, Appendix A describes the meteorological background used for our study, and the mechanisms of converting renewable energy to consumable power.

II. RELATED WORK

In this section, we will present related work in green Internet and information-centric caching, as these are most closely related to our proposed solution.

A. Greening the Internet

Developing ideas for a greener Internet has been investigated for a number of years [4], where proposed solutions include new routing approaches as well as considering renewable energy as a possible source of power.

1) Energy-aware protocols: Bolla et al. [5] developed a new approach for next-generation backbone network devices that have smart stand-by primitives through virtualization of the physical network infrastructure. Their evaluation showed the ability to manage hardware wakeup and standby events transparently from the network-layer protocol. Cianfrani et al. [6] investigated a simple modification of a link-state routing protocol to minimize the number of links powered-on in a topology. This led to traffic being redirected to a small number of nodes, yielding reductions in energy consumption. Solutions based on energy optimization techniques have also been proposed. In [1], an optimization approach was proposed to minimize the traffic and energy consumption of the network. However, these problems are NP-complete which makes them unrealistic solutions for large-scale network. An important requirement is to have more adaptive power-aware routing technique that constantly follow the traffic behavior, while reducing the energy consumption without disrupting the QoS requirements of the network.

2) Renewable energy: Liu et al. [7] proposed the use of renewable energy for powering data-centers, including an optimal mix of renewable sources of energy, using a 30 kW wind turbine and a 4 kW solar panel. The authors found the optimal energy proportion to be 80% wind and 20% solar, which is mainly due to the extra power than can be generated by a 30 kW wind turbine compared to a 4 kW solar panel. Unlike [7], we do not focus on a single data center; instead our goal is to maximize the use of renewable energy to power the routers within the network.

B. Content Caching Strategies

Information-centric networking (ICN) [3], [8]–[10] has emerged as a general, network-wide caching solution. In ICN the contents are cached in the network (e.g., in routers), where they are able to serve requests that pass through the routers.

A number of research works have investigated and analyzed the performance of ICNs. In [11], Carofiglio et al. provided an analytical model for data transfers in ICN. Muscariello et al. [12] analyzed the ICN performance by taking into account different bandwidth and storage limits. The solution proposed by [13] evaluated the ICN performance with realistic traffic mix, showing there is significant difference between different traffic types (Web, file sharing, UGC, VoD, etc.). In all these solutions, only simple Least Recently Used (LRU) approach was used as a caching strategy. Age and popularity-based methods have also been investigated, where solutions have been developed to placing contents closer to the edge caches [14], [15]. In [16], an investigation was conducted on the allocation of cache sizes across the ICN, where results from the analysis showed that the node's cache size should be proportional to its degree. In our previous work [17], we investigated effects of cache admission policies and cooperative caching and found them to be crucial towards good caching performance. The variant of ICN that we consider in this paper is based on [17], which bears a close resemblance to CCN/NDN [3], in that any router on the path of a request may answer it, if it has the content cached.

Our work in this paper differs markedly from the work above. Our focus is not on optimizing caching performance, but instead we combine caching with renewable energy-aware routing and evaluate the combined solution in terms of its ability to exploit renewable energy available at different routers in the network, as well as having a positive influence on the data centers' energy savings.

III. PROBLEM STATEMENT

We now define our problem statement, and models that we use to represent the renewable energy consumption by the routers of the network. We consider an Internet Service Provider (ISP) network (such as Fig. 1), in which nodes may be powered partially from renewable energy sources, where this source could be a combination of wind and solar. The ISP

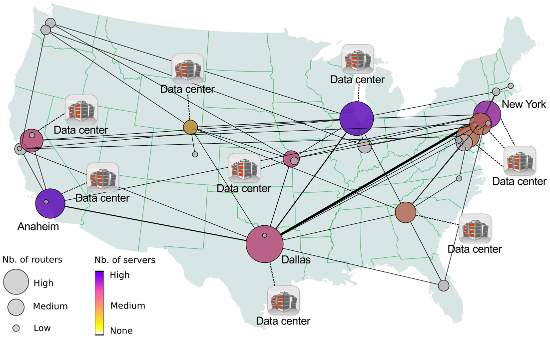


Fig. 1. Sprintlink USA mainland network. The figure shows the network links and the size of the bubbles indicates the size of the POP. The placement of data centers is explained in Section V.

network connects the data centers and the users access points, which serve as the source and destination points for traffic in the network. The remaining routers in the ISP network serve as transport nodes that form the ISP's mesh topology.

An informal description of the design problem we consider is the following:

> [**Given**] (i) a realistic ISP network topology composed of routers and bi-directional links, (ii) an infrastructure for renewable energy for each router, (iii) the power consumption of all devices in the networks besides data centers, and finally (iv) a model for content popularity in function of time.
>
> [**Objective**] is to (i) determine the impact of integrating renewable energy awareness on the network and the data center performance, and (ii) if needed, determine the best trade-off to maximize the reduction of brown energy for the ISP networks and the data centers, while maintaining satisfactory content delivery performance for the end users.

The energy consumption model of the ISP's network devices is derived from the study of Chabarek et al. [18], which was extended from the model proposed initially by Gupta and Singh [4]. The model proposed by [4] was developed by empirically monitoring the energy consumption of chassis and line-cards in two Cisco routers (*Cisco GSR 12008 and 7507*) under various traffic loads. Results from the experiments showed that the chassis is the biggest consumer of energy while the line-cards consume less.

In this paper, a new energy consumption model for routers has been developed to incorporate use of renewable energy. [18]. The general energy model for a router's power consumption is represented as:

$$PC(X) = CC(X_0) + \sum_{i=1}^{N} (TP(X_i) + LCC(X_i)) \quad (1)$$

where X is the vector of chassis and line-cards energy models, as well as the traffic configuration of the router. $CC(X_0)$ is the energy consumption for the chassis, N is the number of line-cards of router X, $TP(X_i)$ is the energy consumption due to traffic on the line-card i, and $LCC(X_i)$ is the line-card energy consumption.

Since the impact of traffic load on the routers does not fluctuate significantly, the $TP(X_i)$ can be omitted in equation 1, leading to:

$$PC(X) = CC(X_0) + \sum_{i=1}^{N} LCC(X_i) \quad (2)$$

In our energy consumption model, we assume that a router has the ability to power-off line-cards, and the entire router will be powered-off when all its line-cards are off. Therefore, the power consumption model at time t can be represented as follows:

$$PC(X,t) = x_{0,t}CC(X_0) + \sum_{i=1}^{N} x_{i,t}LCC(X_i) \quad (3)$$

where

$$x_{0,t} = \begin{cases} 0 & \text{if } \sum_{i=1}^{N}(x_{i,t}) = 0 \\ 1 & \text{otherwise} \end{cases}$$

$$x_{i,t}, i > 0 = \begin{cases} 0 & \text{if } X_i \text{ is powered-off at time } t \\ 1 & \text{if } X_i \text{ is powered-on at time } t \end{cases}$$

Consequently, the configuration of each $x_{i,t}$ is added to the vector X. Let X^0 be the vector of chassis and line-cards models, where all $x_{i,t} = x^0_{i,t} = 1$.

Let us assume that each router X would have a source of renewable energy $rePC(X,t)$ at time t:

$$rePC(X,t) = P_w(X,t) + P_s(X,t) \quad (4)$$

where $P_w(X,t)$ and $P_s(X,t)$ are respectively the power generated from wind and solar energy at time t. More details can be found in Appendix A on the methods used to calculate $rePC(X,t)$ using real meteorological data.

By subtracting $rePC(X,t)$ from $PC(x)$, we obtain $brPC(X,t)$, the brown energy consumed by router X at time t.

$$brPC(X,t) = PC(X^0,t) - rePC(X,t)$$
$$\text{with } brPC(X,t) = 0, \text{ if } rePC(X,t) \geq PC(X^0,t) \quad (5)$$

Our aim in this paper is to analyse the impacts of favoring routers powered by renewable energy in order to facilitate the powering-off of the unused routers that may be powered by brown energy. Therefore, we can formulate the brown energy reduction of the entire network σ_n at time t by calculating the total brown energy consumption of the network when unused devices are powered-on or off.

$$\sigma_n = 1 - \frac{\sum_{\forall X}\sum_{\forall t} brPC(X,t)}{\sum_{\forall X}\sum_{\forall t} brPC(X^0,t)} \quad (6)$$

Let α, $\alpha \in [0,1]$ be the factor that favor renewable energy, and where $\sigma_n(\alpha)$ and $\sigma_d(\alpha)$ are respectively the brown energy reduction utility functions of the network and the data centers derived from the choice of α. In the subsequent sections we will show how α is used in our renewable energy aware gradient-based routing algorithm. While our paper does not focus on the utility function of the data centers, we discuss the trade-off that can be obtained by changing α and show that the α value can be optimized according to seasonal changes.

To conclude, we want to maximize $\sigma_n(\alpha) + \sigma_d(\alpha)$, while minimizing the impact on the performance for the end users.

IV. PROPOSED SOLUTION

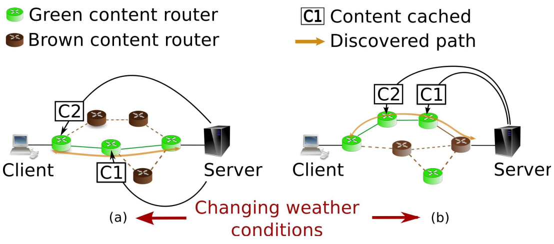
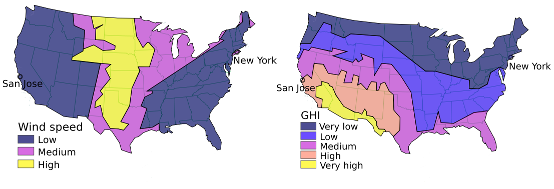


Fig. 2. Illustration of proposed approach, demonstrating path discovery as weather condition changes ((a) to (b)). Once paths are discovered, contents C1 and C2 are cached on routers along the discovered paths.

Fig. 2 shows an example of our proposed approach, where routes are discovered via routers with access to high renewable energy. Once the paths are discovered, contents will be pulled from the data centre and populated along the discovered paths. However, these paths will change as the weather pattern changes, which implicitly moves the contents to new locations that have access to high renewable energy. At the same time, certain routers that are powered by "brown" energy maybe unused, which could lead to a situation where we can power-off these routers to minimize overall brown energy. Therefore, as shown in Fig. 2, the proposed approach is dual-layered.

Firstly, a gradient-based routing protocol discovers the path of routers powered by the highest amount of renewable energy, and secondly a CCN-like [3] caching approach populates the routers of the discovered path with contents based on a caching strategy. Therefore, the approach maximizes the dynamic properties of caching, where contents can be moved to different locations, and in this particular case to locations that provide the highest amount of green energy.



(a) Wind speed

(b) GHI

Fig. 3. Average annual wind speed and Global Horizontal Irradiance in USA. Brighter colors indicate higher availability.

An important factor that affects the performance of renewable energy production is the location. For instance, Fig. 3 shows the average annual wind speed and Global Horizontal Irradiance in the USA. As shown by these two figures, the available energy sources greatly differ depending on the locations of routers. Cities such as New York or San Jose exhibits dissimilar weather conditions, including predictability in the weather patterns. More detailed information can be found in Appendix A which discusses the quantity of wind and solar energy for specific cities. While the production of renewable energy fluctuates for different locations, this is most ideal for our gradient-based routing protocol. The gradient-based routing protocol, which is highly scalable and distributed, can discover routes by adapting to these weather conditions in order to maximize the renewable energy.

The metric used to determine the greenest router is based on the highest ratio of renewable energy consumed compared to total energy requirements of the router $g(X,t)$ (this is also termed *green ratio*). This ratio is calculated according to equation 7:

$$g(X,t) = \begin{cases} 1 & \text{if } rePC(X,t) \geq PC(X,t) \\ \frac{rePC(X,t)}{PC(X,t)} & \text{otherwise} \end{cases} \quad (7)$$

Examples of the variations of the green ratio for different locations are presented in Fig. 14i-14l. Every router in the network locally broadcasts messages to its one-hop neighbors regarding the ratio of renewable energy that it has available. The greenest routers, will in turn maximize the production of packets processed with renewable energy (*green packets*).

The subsequent sections, we describe our routing protocol and caching strategies in more detail.

A. *Routing*

Our routing protocol, called *Renewable energy-aware Parameterized Gradient Based Routing* (rePGBR), is extended from our original *Parameterized Gradient Based Routing (PGBR)* protocol [19]. The original PGBR is a fully distributed bio-inspired routing protocol, that is inspired by the *Bacterial Chemotaxis* [20] process. Through the process of *Chemotaxis*, bacteria are able to mobilize themselves towards a destination point by sniffing a chemical gradient emitted from the destination node. This same bacteria motility principle is used for the rePGBR routing algorithm, where the routes are discovered by hopping from node to node along the path with the highest gradient, until it reaches the destination. The benefit of the rePGBR algorithm, includes (i) high scalability, (ii) no requirements for pre-knowledge of the traffic demand, and (iii) the ability to efficiently discover paths to contents favoring the usage of renewable energy.

The gradient field equation is represented as follows:

$$G_i^d(j) = \alpha g(j) + (1-\alpha) h_i^d(j), \quad 0 \leq \alpha \leq 1 \quad (8)$$

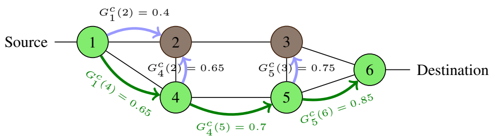
where $G_i^d(j)$ represents the gradient value of the link $i \to j$ for a packet to destination d, $g(j)$ (e.g. equation 7) represents the green ratio value of neighbor node j, and $h_i^d(j)$ represents the normalized hop count value of neighbor node j of node i for destination d. The α, as specified in Section III, represents the weighting parameter between the shortest path and the greenest path to the content location, and is a key parameter in evaluating the trade-off between maximizing green energy and maximizing caching performance. Unlike the normalized hop count value used in [19], where the equation for $h_i^d(j)$ is $h_i^d(j) = 1 - \frac{w^d(j)}{W^d}$, with $W^d = max(w^d(k)), \forall k$, the new normalized hop count value of *re*PGBR provides fast destination discovery in a scalable manner [21]. The modified $h_i^d(j)$ is represented as:

$$h_i^d(j) = \frac{max(w_i^d(k)) - w_i^d(j)}{max(w_i^d(k)) - min(w_i^d(k))}, \forall k \text{ neighbours of } i \tag{9}$$

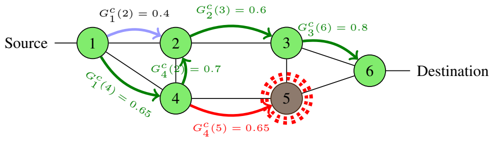
where $w_i^d(k)$ represents the weight of node k in the shortest path tree for root d, the destination.

Algorithm 1 Selection of next hop during discovery

```
Require: Destination $d$, incoming neighbour $iN$
 1: $u \leftarrow$ current node
 2: $qIn \leftarrow$ list of incoming neighbours
 3: $qOut \leftarrow$ list of outgoing neighbours
 4: if $iN$ is not nil then
 5:     $qIn \leftarrow qIn + iN$
 6: end if
 7: $nextHop \leftarrow nil$
 8: $bestG \leftarrow -1$
 9: for neighbor $v$ of $u$ do
10:     if $v \notin qIn \cup qOut$ and $G_u^d(v) > bestG$ then
11:         $bestG \leftarrow G_u^d(v)$
12:         $nextHop \leftarrow v$
13:     end if
14: end for
15: if $nextHop$ is nil then
16:     repeat
17:         $nextHop \leftarrow last(qIn)$
18:     until $nextHop \notin qOut$
19: end if
20: if $nextHop$ is not nil then
21:     $qOut \leftarrow qOut + nextHop$
22: end if
23: return $nextHop$
```



(a) Discovery of paths along gradient field formed by routers with high renewable energy.



(b) Gradient field modification due to changes in renewable energy performance.

Fig. 4. Route discovery process for *re*PGBR.

Routing is performed by first discovering the path between a source-destination pair, by sending a discovery packet that migrates hop-by-hop, selecting the link with the highest gradient value. Algorithm 1 describes how to choose the next hop during discovery. Unlike the original PGBR where the path was stored in the discovery packet, *re*PGBR stores local information in routers. This local information enables the discovery to avoid loops (i.e. using list of incoming and outgoing neighbours, line 10) and performs back-tracking (i.e. lines 15 to 19) in a fully and efficient distributed manner.

Furthermore, this discovery process is depicted in Fig. 4a and Fig. 4b illustrates the discovery process dynamically changing to avoid brown hot-spot areas (e.g. discovery avoids brown node 5 due to the gradient field changes). Once the weather conditions change, a new discovery is issued. However, during the discovery process, the existing path remains stable until the new discovered path is adopted sequentially as the discovery message backtracks to the source using the local information described in Algorithm 1.

The utilization of the weighting parameter α provides *re*PGBR with robustness in supporting multiple objectives. For instance, when α is set to a low value (e.g. 0.2), the discovered path is biased towards the shortest routes (more weight is attributed to the hop count) while a larger value would tend to favor greener routes. As a result, the gradient field equation of *re*PGBR is flexible and can exhibit multiple behaviors by only manipulating one parameter to provide the desired green performance of the network. This paper aims to investigate the most optimum α, that could maximize the savings of brown energy usage of the full network, as well as having a positive influence on the data centers' energy savings.

B. *Caching*

This section will describe the second component of our solution, which is the caching process of contents along the paths discovered by *re*PGBR. We used three caching strategies described in [17]. The work in [17] focused on evaluating these strategies purely on caching performance across a wide range of networks. In this paper, we focus on using these caching strategies to maximize the use of renewable energy for specific points of storage, and the suitability of these strategies in combination with the adapted *re*PGBR routing algorithm. Below we describe the three strategies and briefly recap the main results from [17]. In terms of different information-centric architectures, our caching strategies would be most suitable for a CCN/NDN-like architecture [3].

ALL: ALL is the simplest caching strategy, where each router tries to cache all the packets that passes through, and uses LRU algorithm to evict packets if the cache is full. There is no cooperation between the routers.

Cachedbit: Cachedbit uses one bit in the packet header to indicate whether the packet has already been cached by a router along the path. If the bit is not set, a router decides locally whether to cache the packet or not, with a probability of $1/n$ where n is the length of the path from the client to the server (or ingress router to egress router for an intermediate network). As discussed in [17], the length of the path can be determined by observing packets that pass through a router;

global knowledge is not required. In this case, the caches use LRU as a replacement policy for evicting the contents. Algorithm 2 describes the admission policy for the Cachedbit strategy.

Algorithm 2 Admission Policy in Cachedbit Strategy

```
Input: Data chunk $C_i$
Output: Caching decision
if $C_i$ is not cached and $cached\_bit$ not set then
    Draw a random $x$ uniformly from $(0, 1)$
    if $x < 1/n$ then
        if Cache is full then
            Evict entry based on LRU
        end if
        Add data chunk $C_i$
        Set $cached\_bit$
    end if
end if
Forward chunk to destination
```

Neighbor Search (NbSC): NbSC is otherwise similar to Cachedbit, except that routers periodically send Bloom filters of their contents to their neighbor routers. When a router experiences a miss, it can check if any of its neighbors has the requested packet. If there are multiple matches, the request will be redirected to a random neighbor. We also investigated a variant which redirects requests to the greenest neighbor.

The results in [17] showed that a Cachedbit-like admission policy is needed to get good caching performance, but that the addition of NbSC reduces network traffic considerably.

Algorithm 3 describes the cooperation policy in the algorithm that implements NbSC.

Algorithm 3 Cooperation Policy in NbSC Strategy

```
Input: Data request $R_i$
Output: Response decision
if $C_i$ is cached for $R_i$ then
    Reply with $C_i$
end if
if $C_i$ is not cached for $R_i$ then
    if Neighbor $N_i$ cached $C_i$ for $R_i$ then
        Redirect $R_i$ to $N_i$
    else
        Forward $R_i$ to next hop
    end if
end if
```

V. EXPERIMENTATION

In order to validate our proposed approach, we have conducted experiments on a testbed using the weather data described in Appendix A. The network evaluated on our testbed is based on the Sprint router-level topology from the Rocketfuel project [22]. The Sprint network consists of 278 routers geographically distributed in 27 cities in U.S. mainland (meteorological data from [23] is available only for the U.S. mainland locations). For the experiment, the top 40 highest degree nodes are connected to content servers, while the 80 routers with the lowest degrees are connected to the clients. Fig.1 shows the resulting topology where routers located in the same city are grouped (i.e. the size of the city increases with the number of routers). For instance, Anaheim, Chicago, New York and Dallas are the cities with the highest number of routers. The color of the cities, on the other hand, represents the number of servers (e.g. nodes which have the highest connectivity). A total of 10 cities have servers resulting in 10 data centers that are interconnected through the ISP network. Once again, Anaheim, Chicago and New York are the three cities with the highest number of servers.

The remaining routers are used as intermediate nodes for the routing algorithm. In our experimental setup, the clients will continually request data from the servers (request rate depends on the traffic pattern). While tests have been conducted for three different traffic patterns, which includes (i) real trace from the TOTEM project [24], (ii) trace from the gravity model [25], and (iii) constant traffic pattern (600 pkts/s), there was no significant difference between these traffic patterns in terms of performance. Therefore, we only show the results of our experiments based on a constant traffic pattern.

The request trace for each client is generated from a real DNS trace of a university lab. We sorted the requested DNS names according to their popularity and removed the top 20 entries. The request pattern from this trace follows a Zipf distribution with parameter 0.9, which is very close to real-life distribution shown in [26]. Our trace requests chunks of content, which are assumed to be independent of each other. We assigned each router with a storage capacity of 128 chunks.

The power requirements of every router has been set using the measurements of a Cisco 7507 [18]: the basic chassis requiring 210W and each line-card an additional 70W (i.e. a router with 4 line-cards consumes $210 + 4 * 70 = 490\ W$).

We investigated two scenarios: In scenario A, the renewable energy infrastructure of the routers are set to supply twice the energy required by the router (i.e. $rePC(X, t) = 2PC(X^0, t)$) at most. Therefore, the changes of weather conditions greatly modify the green ratio $g(X, t)$. This scenario is defined as the static capacities scenario. In scenario B, the infrastructure supplies up to three times the energy required by the routers. The different size of infrastructures implies that some routers are mostly fully brown and others mostly green, which will better represent a realistic scenario where green renewable energy farms are built gradually (to limit the cost of installation). More details on the settings can be found in Appendix A.

The following metrics have been used to evaluate our proposed solution for the two scenarios previously described:

- **Hit Rate:** Determines the fraction of requests that are served by the content routers. Since all objects are of the same size, the hit rate is also the byte hit rate. Hit rate shows how much external traffic is saved by caching, thus leading to potential energy savings for the data centers.
- **Footprint Reduction:** Network footprint is the product of the amount of content and the network distance from which the content was retrieved. It measures the amount of internal traffic reduction, where a smaller footprint (larger reduction) means less traffic within the network.

- **Green/brown ratio:** Proportion of the packets by the router within an hour that has been processed using renewable energy to the packets that has been processed using fossil fuel energy.
- **Reduction of brown packets:** Reduction of brown packets that has been processed within an hour using fossil fuel energy.
- **Brown energy savings:** The amount of brown energy that has been saved by powering-off unused routers. In the case of a neighbouring router being unused, the line-card connecting the two routers is considered to be powered-off. The brown energy savings is calculated using equation 6.

While hit rate and the footprint reduction are mainly caching metrics, the green/brown ratio, eduction of brown processed packets and the brown energy savings are representing the performances of the solution to successfully address the energy efficiency requirements. Hit rate also represents the reduction on traffic towards data centers and, therefore, indicates potential energy savings at the data center.

A. Testbed setup

All the experiments are performed on a cluster of 240 Dell PowerEdge M610 nodes. Each node has 2 quad-core CPUs, 32GB memory, and is connected to a 10-Gbit network. All the nodes run Ubuntu SMP with 2.6.32 kernel. The experimental platform we used in the evaluation is capable of simulating realistic routers, and allocating necessary physical resources according to the simulated network size. In the event that the network size is larger than the actual number of nodes in the cluster, multiple routers will be multiplexed onto one node.

B. Network performance

As described earlier, the benefit of the rePGBR routing algorithm is in the ability of manipulating α to suit any particular objective. In our scenarios, we would ideally like to select an α that provides the greenest routes, without compromising on the caching performance. Therefore, we have conducted tests to select the most appropriated α for different seasons in the year. In total, we investigated 4 weeks throughout the year, and the periods of these weeks are as follows (Winter: 1st - 7th, January; Spring: 6th - 12th, April; Summer: 11th - 27th, July; Fall: 21st - 27th, October). The weeks of Spring and Fall have been selected at different times to ensure that the weather patterns would not be similar. Fall is on the verge of Winter while Spring is slightly milder.

We first evaluate the different caching strategies with respect to varying α values for scenarios A and B. Below we will look more closely at performance of rePGBR in these conditions.

We begin first by evaluating the different caching strategies with respect to varying α values. As previously mentioned, we focused on 5 metrics including footprint reduction (e.g. Fig. 5 and 6), hit rate (e.g. Fig. 11), green/brown ratio and the reduction of brown processed packets (e.g. Fig. 7), as well as the brown energy savings of the network (e.g. Fig. 8 and 9). All the results are shown using 5 kW wind turbines, but with the nodes having different renewable energy architectures (scenarios A or B). Below we will look more closely at the performance of the solution in these conditions.

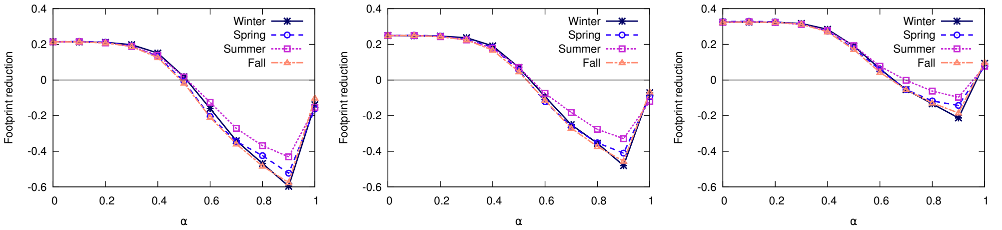
1) Footprint reduction: We previously mentioned that the footprint reduction is a relevant metric for the ISP, showing the improvements in its internal traffic. Fig. 5 shows the footprint reduction as a function of α for the four seasons and for each caching strategies. For all the caching strategies, we see that as α increases, the footprint reduction decreases. First the degradation is limited (when $\alpha \leq 0.3$). The reason for this positive correlation is because higher α value leads to longer paths along routers with high green ratio, which further increases the footprint of the network. The results also show NbSC is far more superior than Cachedbit and ALL. The same behavior is observed for scenario B and Fig. 6 confirms this.

In particular, after α reaches 0.4, the footprint reduction drops significantly. When the footprint reduction reaches zero, this means the paths are so long that caching strategies can no longer reduce intra-network traffic. Obviously, caching still happens, but the net benefit is zero. From the figure, we can see this threshold is about 0.8 for NbSC (e.g. Fig. 6c) and lower for the others (e.g. Fig. 6a and 6b). The degradation of the footprint reduction varies with the seasons but the behavior is similar. Although the behaviour is similar, we can see that for all caching strategies there are improvements in footprint reduction in the warm seasons. This improvement is visible when α is greater than 0.6 and 0.4 for scenario A and B, respectively. An increase of the footprint reduction happens when $\alpha = 1$, due to inefficient route discoveries that are not able to update routing table information with the latest renewable energy values. As a consequence, requests are served using outdated paths increasing slightly the chances of a cache hit.

As we mentioned before, we considered a variant of NbSC which selects the neighbor router with the highest green ratio, instead of a random neighbor when multiple matches are found. However, we found out that this modification has no visible effect on the performance. This is mainly because routers are co-located at POPs and thus share the same weather pattern among many (but not all) neighbors.

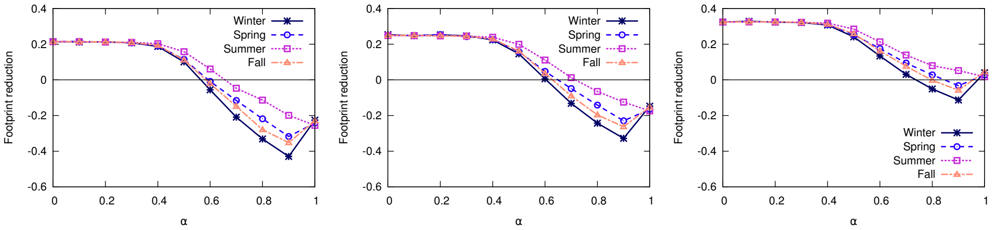
We observe a large performance difference between NbSC and the others even when using only the shortest path (with $\alpha = 0$; ALL and Cachedbit has a footprint reduction of 21% and 25%, respectively, while NbSC has a footprint reduction of 32% for the static and random scenarios). The advantage of NbSC is at least 7% higher than Cachedbit and increases with α, up to 23% and 18%, respectively for scenarios A and B.

2) Improving network's greenness: Fig. 7 shows the ratio of green/brown packets and the reduction of brown packets as a function of α for scenario A. In particular, Fig. 7a - 7c show a difference between the seasons for the green/brown ratio but very little between the caching strategies. This is due to the importance of rePGBR route discovery to enhance the green processing of the packets. In addition, we can see that the ratio is greater for the warm seasons (i.e. Summer and Spring) than for the cold seasons. One can see that the performance of the warm seasons are quite similar compared to those for the cold seasons. As explained in Appendix A,



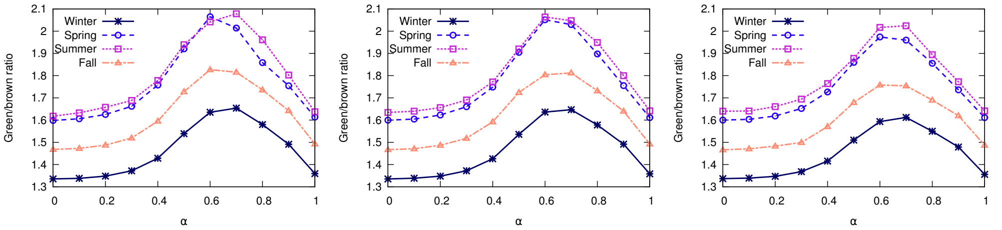
(a) ALL (b) Cachedbit (c) NbSC

Fig. 5. Varying α of rePGBR routing and evaluating its impact on footprint reduction for scenario A.

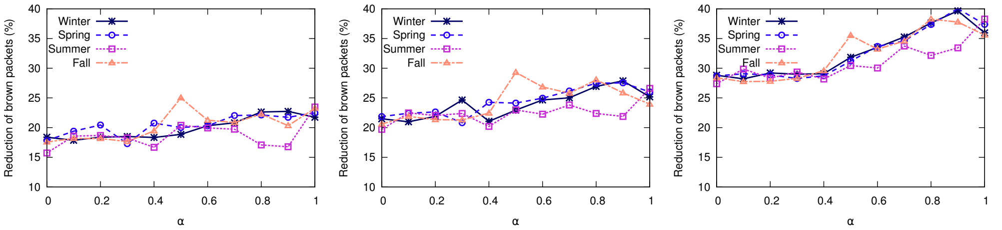


(a) ALL (b) Cachedbit (c) NbSC

Fig. 6. Varying α of rePGBR routing and evaluating its impact on footprint reduction for scenario B.



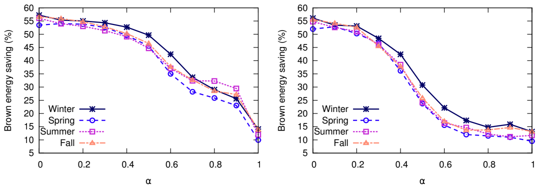
(a) ALL - Green/brown ratio (b) Cachedbit - Green/brown ratio (c) NbSC - Green/brown ratio



(d) ALL - Reduction of brown packets (e) Cachedbit - Reduction of brown packets (f) NbSC - Reduction of brown packets

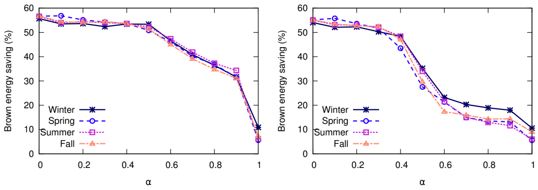
Fig. 7. Varying α of rePGBR routing and evaluating its impact on green/brown ratio and reduction of brown packets for scenario A.

the warm seasons tend to be more reliable (the impact of the solar energy is higher than the wind energy) and predictable (diurnal phases) which leads the routing protocol to maximize the discovery of highly green routes. Fig. 7a - 7c show that the ratio of green/brown packets slowly increases with α. As shown in the figures, the significant improvement (peak) starts at approximately 0.4 and ends at 0.9. Therefore, this is the range of α values that maximize the green processing of packets in the network. However, the ratio of green/brown packets is insufficient without showing the reduction of brown packets as a function of α, which are shown in Fig. 7d - 7f. The results show that the number of brown packets almost linearly decreases as α increases, which comforts the fact that the network's greenness increases when $0.4 \leq \alpha \leq 0.9$.



(a) No caching / ALL / Cachedbit (b) NbSC

Fig. 8. Varying α of rePGBR routing and evaluating its impact on brown energy savings for scenario A.



(a) No caching / ALL / Cachedbit (b) NbSC

Fig. 9. Varying α of rePGBR routing and evaluating its impact on brown energy savings for scenario B.

Finally, the results also show that NbSC outperforms other caching strategies for every α.

Experimental results show similar trends for scenario B, that differ only from the green/brown packet ratio induced by the scenario definition. In Appendix A, we described how the capacities influence on the greenness of the routers, where certain routers are more green that others irrespective of the weather conditions. This in turn limits the variety of routes discovered by rePGBR.

Using the ability of rePGBR to maximize the discovery of green routes, could leave to a number of routers left unused. Fig. 8 and 9 shows the brown energy savings that could be achieved if these routers were powered-off. The best savings are obtained when rePGBR goes for the shortest routes, and decreases as α increases. The performances of ALL, Cachedbit and no caching are similar because all the routers discovered by decreasing α are used independently of the caching strategy. However, NbSC presents a significant disadvantage where the brown energy savings are reducing much faster with regards to α. For Cachedbit, the brown energy savings are quite stable until α reaches 0.4, while NbSC maintains high energy savings only until 0.2. To summarize, the brown energy savings of the network varies between 10% and 55% which could lead to significant improvement of the network's greenness. For scenario B, the values of α that maintain high energy savings are larger than for scenario A. For instance, Cachedbit is able to maintain brown energy savings over 50% when α is lower or equal to 0.5 and NbSC to 0.3 for all seasons. As shown in Fig. 8 and 9, the impact of seasonal weather conditions is not significant on the brown energy savings, because these savings are highly dependent on rePGBR route discoveries.

3) Hourly performance: Fig. 10 shows the 4 metrics described above for Cachedbit and NbSC as a function of time for the first 48 hours of Spring for scenario B. The α values used for each caching strategy correspond to the greenest α maintaining brown energy savings above 50%, which are respectively 0.5 and 0.3 for Cachedbit and NbSC (Fig. 9).

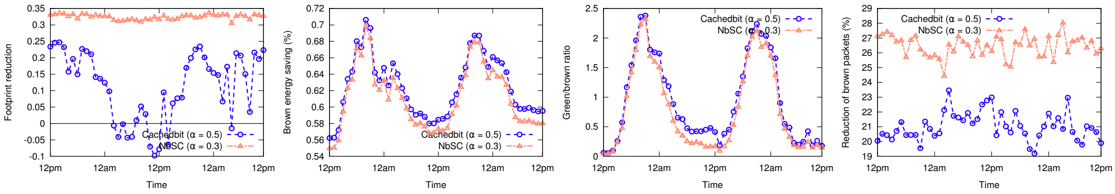
In detail, Fig. 10a shows the footprint reduction of Cachedbit and NbSC. The results of ALL behave similarly to Cachedbit's, although yield less gains, and as a consequence have been omitted. The results are showing the high stability of NbSC which maintains a high footprint reduction of 32% while Cachedbit's performance are highly variable throughout the days. The performances of the two caching strategies are similar for the brown energy savings (e.g. Fig. 10b) and the green/brown ratio (e.g. Fig. 10c) and distinctively show a trend that maps to the sun pattern (e.g. Appendix A). In other words, the performances of the caching strategies drastically increase during the sunny hours. As previously mentioned, the sunny hours bring stability in the route discovery, thus improving the solution's performances. Lastly, Fig. 10b shows the reduction of brown packets as a function of time, where the daytime pattern is not visible, and performances of Cachebit and NbSC are fluctuating respectively around 20.5% and 26.5%.

C. Impact of the solution on data centers

In order to improve energy savings in the data centers, we assume that a non-negligible improvement could be obtained by reducing the number of requests directly served by the servers of the data centers. Unlike the routers' energy consumption where the workload induced by traffic does not modify the energy consumed, the data centers energy consumption are known to *vary with their workloads*. Our solution, combining the energy savings at the ISP using greener routes and efficient caching strategies, could greatly improves the workload of the data centers by serving content cached in the ISP's routers, thus reducing their energy requirements (i.e. maximizing $\sigma_d(\alpha)$ defined in Section III).

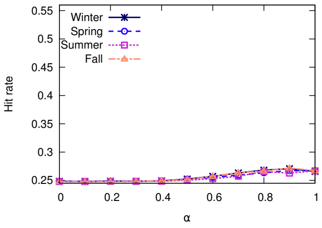
We see that as α increases, the hit rate also increases, as shown in Fig. 11. The reason for this positive correlation is because higher α value leads to longer paths along routers with high green ratio, which further increases the possibility of cache-hit along the path. The results also show NbSC is far more superior than the Cachedbit and ALL, with a respective gains of over 15% and 20% improvement for scenario B. Experiments for scenario A have shown similar gains and, thus have been omitted. Furthermore, the seasonal differences are also negligible, which shows that the effectiveness of the caching strategies defined by α would deliver predictable performances.

The hourly performances of Cachedbit and NbSC to improve hit rate are depicted in Fig. 12 for a selection of α values on the two first days of Spring. The α values have been selected to show the hit rate performances when (i) the greenness of the ISP network is at its peak (where α equal to 0.3 and 0.5 for NbSC and Cachedbit, respectively) or when (ii) the hit rate performance is at the maximum (with $\alpha = 0.9$ for both strategies). Fig. 12 shows that hit rate



(a) Footprint reduction (b) Brown energy savings (c) Green/brown ratio (d) Reduction of brown packets

Fig. 10. Performances of Cachedbit and NbSC with respect to time during the two first days of Spring for scenario B.



(a) ALL (b) Cachedbit (c) NbSC

Fig. 11. Varying α of rePGBR routing and evaluating its impact on hit rate for scenario B.

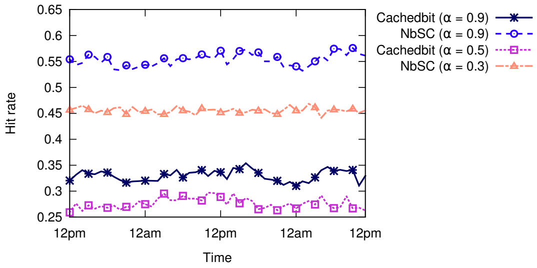


Fig. 12. Hit rate performances of Cachedbit and NbSC with respect to time during the two first days of Spring for scenario B.

performances are very stable and do not vary according to the weather conditions. However, one can observe that Cachedbit is constantly performing worse than NbSC with a loss of 20% on average in both cases (i and ii).

As a result, increasing renewable energy awareness in routing enhances caching performances of the network, thus resulting on a positive impact on the data centers' workload. This in turn could lead to data centers reducing their energy consumption for unused servers that hold contents which are already cached within the network.

D. Discussion

As stated in Section III, the aim of the paper is to demonstrate that using renewable energy awareness in routing at the ISP's network could reduce the energy consumption from fossil fuels of the network and the data centers serving user's requests. The network operator, could with the choice of a single parameter α and a caching strategy, maximize the brown energy savings of the network from an end-to-end perspective (i.e. including data centers), without compromising the performance of end user's access to contents.

- **User-observed content delivery performance:** In this paper, we assume that delivery performance is positively correlated with footprint reduction. Fig. 5 and 6 showed that the performance would decrease as the renewable energy awareness increases, and this is observable for all caching strategies. There are even α values where the performance is worse than not using any caching (i.e. footprint reduction below 0). For all caching strategies, the delivery performance is maximal when the energy awareness is nil. Fortunately, the performance is maintained for lower α values, and using NbSC further maximizes the delivery performance.
- **Network greenness:** Maximizing network's greenness includes minimizing use of brown energy by powering-off unused routers and reducing the number of brown packets. Unfortunately, these performances are not achievable using the same α values and caching strategies. On the one hand, in order to maximize the brown energy savings of the network, the smallest α values and Cachedbit are preferable. On the other hand, maximal reduction of brown packets is obtained with high α values and NbSC. Depending on the requirements of the network, the operator would have to carefully choose the appropriate combination to best fulfill the network's objectives.
- **Data center greenness:** Improving caching performances also improves the hit rate and thus helps reduce the workload on data centers. Increasing α improves the hit rate, while using NbSC always increases the performances by

an additional 20%.

Therefore, the choice of the caching strategy and α value could produce a positive trade-off, where benefits would be maximized.

VI. CONCLUSION

The popularity of the Internet today has led to widespread deployment of ICT infrastructures, which is consuming considerable quantity of energy. In recent years, a new research initiative towards enhancing renewable energy aware ICT infrastructure has been proposed. In this paper, we propose a renewable energy aware CCN, where routers are powered directly by wind and/or solar energy. The proposed approach is composed of two components, which includes a novel gradient-based routing algorithm that discovers paths along routers powered by high renewable energy, followed by a caching strategy that stores contents along these discovered paths. This enables the routing protocol as well as caching strategy, to adapt to varying weather patterns that may affect energy that is used to power the routers. The results from an experimental testbed using real meteorological data, has shown that using the combined approach has resulted in increased consumption of renewable energy, where a combination between high renewable energy consumption and caching strategy can minimize the need of fossil fuels energies of the network and the data centers without compromising the users' experience.

APPENDIX A
RENEWABLE ENERGY BACKGROUND

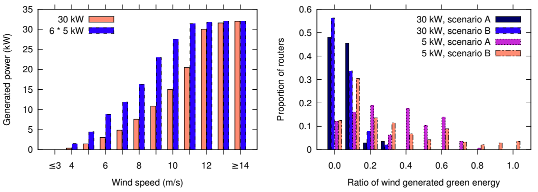
We use publicly available data from the National Renewable Energy Laboratory [23] to estimate the availability of wind and solar power in different parts of the U.S. Below we describe our weather data and present the methodology used to convert the meteorological wind and solar data, to power.

A. Wind energy profile

Fig. 3a shows a simplified version of the annual wind speed in the U.S. The darker zones have an average wind speed between 4 - 6 m/s, the average wind speed for the medium zones are between 6 - 8 m/s, and in the brighter zone, the average speed is greater than 8 m/s.

We consider two wind turbines produced by the Huaying company [27]. The two models are "HY30-AD11" which is a 30 kW wind turbine, and a smaller model "HY5-AD5.6" which produces energy up to 5.4 kW (the larger turbine has a similar size to the turbine investigated in [7].)

Fig. 13a presents a plot showing the relationship of wind speed to generated power that can be achieved by the two different turbines. As we can see, six 5 kW wind turbines produce more power than a single 30 kW turbine at a low wind speed (e.g. at 6 m/s, the ratio is 2.9). However, the type of turbines could be decided on the space restrictions and the cost of the infrastructure.



(a) Wind speed to power conversion (b) Optimal mix distribution

Fig. 13. Wind energy profile for different turbine types (5 kW and 30 kW), as well as distribution of routers with optimal ratio of wind and solar energy sources.

B. Solar energy profile

The Global Horizontal Irradiance (GHI) is used to estimate how much power could be generated by photovoltaic solar panels. A 4 kW photovoltaic solar panel that is needed to produce 4 kW of power, will require a GHI of 1000 W/m^2. As shown in Fig.3b, the GHI is usually stronger in the south west of the U.S. For example, in the brigther zone (very high GHI), the estimated energy is greater than 6000 kWh, while the estimated energy is only 3000 kWh in the zone with the lowest GHI.

C. Renewable energy calculation

In this section, we describe two calculations that determine the required renewable energy infrastructure to provide adequate renewable energy (the infrastructure refers to the number of turbines or size of photovoltaic panels). Calculation 1 will be used when the proportion between wind and solar power is predefined. Calculation 2 will determine the optimal proportion of wind and solar power that maximizes the green ratio of the router.

Calculation 1: Given a proportion β, a capacity c and $PC(X^0, t)$ the energy required by the router X, we intend to determine the renewable energy infrastructure, such that:

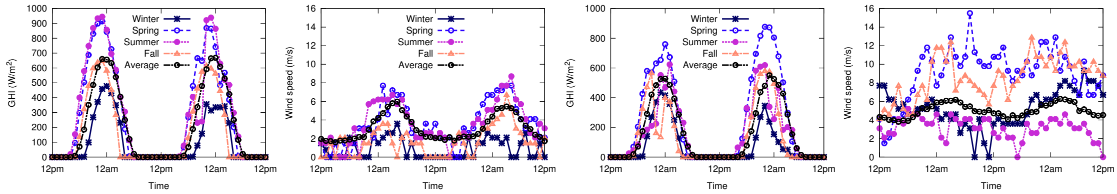
$$rePC(X,t) = P_w(X,t) + P_s(X,t), \qquad \text{where } P_w(X,t) = \beta rePC(X,t) \tag{10}$$

In this case, $P_w(X,t)$ is the energy provided from wind infrastructure, while $P_s(X,t)$ is the energy provided by the solar panels. Therefore, $rePC(X,t)$ is the total renewable energy that can be provided to router X. At the same time we also consider cases when a large quantity of renewable energy is produced. In such situation, the capacity c is set to satisfy $max(rePC(X,t)), \forall t = cPC(X^0, t)$.

Calculation 2: In order to maximize the green ratio of the router, we decided to find the optimal β that would maximize the average $g(X,t)$ $(avg(g(X,t)))$, for a typical year. The $avg(g(X,t))$ is calculated as follow:

$$avg(g(X,t)) = \frac{\sum_{t=1}^{24*365} g(X,t)}{24 * 365} \tag{11}$$

where $g(X,t)$ is the green ratio of router X at time t defined by equation 7 (time has been shifted to match the PDT time zone of Los Angeles, CA). We will do this calculation for all

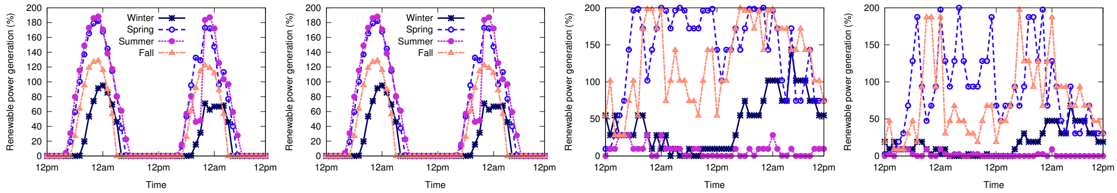


(a) San Jose, CA - GHI

(b) San Jose, CA - Wind speed

(c) NYC, NY - GHI

(d) NYC, NY - Wind speed

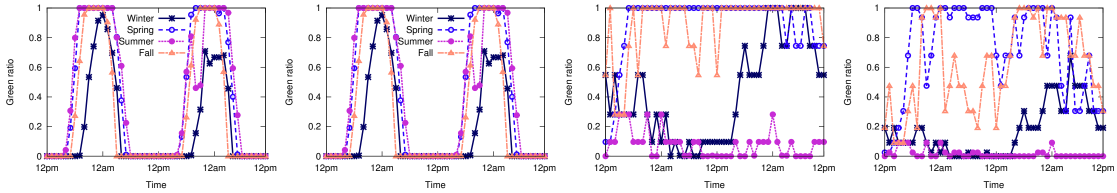


(e) San Jose, CA - Percentage of power generated (with 5 kW turbine)

(f) San Jose, CA - Percentage of power generated (with 30 kW turbine)

(g) NYC, NY - Percentage of power generated (with 5 kW turbine)

(h) NYC, NY - Percentage of power generated (with 30 kW turbine)



(i) San Jose, CA - Green ratio (with 5 kW turbine)

(j) San Jose, CA - Green ratio (with 30 kW turbine)

(k) NYC, NY - Green ratio (with 5 kW turbine)

(l) NYC, NY - Green ratio (with 30 kW turbine)

Fig. 14. Weather profiles and power generation performance for San Jose, CA and New York City, NY (The number of turbines has been optimized by calculation 2).

β between 0.0 to 1.0. Therefore, the optimal β will be the value with the best $avg(g(X,t))$.

Fig. 13b shows the distribution of routers for the Sprint network topology as a function of the optimal β. For example, in Fig. 13b, when no wind energy are considered in the ratio (i.e. $\beta = 0.0$), for a maximum $c = 2$ for 30 kW wind turbine, we can see that only 47% of the routers will have this configuration. Fig. 13b shows the optimal mix for both types of turbines for two different types of capacities. The two different capacities, includes a fixed capacity $c = 2$ (also referred to as constant capacity for the scenario A) and random capacity that is uniformly selected between 0 and 3 for the scenario B. As shown in Fig. 13b, selecting the 5 kW turbine will lead to a better distribution of routers with mixed sources of wind and solar (where β goes up to 1.0). On the other hand, the 30 kW turbine will only lead to low ratios of wind energy (e.g. $0.0 \leq \beta \leq 0.3$).

We now show an example of the optimization process for two routers, one in San Jose, CA, and the second in New York City, NY. Fig. 14a and 14c show the GHI and wind speeds for these three locations over a period of two days, for each season. Fig. 14e, 14f, 14g and 14h show the power generated at these two locations for wind energy using either 5 kW or 30 kW turbines, after the optimization of ratio between wind and solar energy. Recall that the optimization is performed over the whole year by picking out the peak periods of high wind and solar performance, and the figures presented only show performance for two days. Interestingly, the router in San Jose gets all of its renewables from solar and ignores the weak wind performance, even though this means that during night time the router must be powered with brown energy. In contrast, the router in New York uses only wind energy as its renewable source (although not clearly visible in Fig. 3a, New York is in the medium wind zone). Fig. 14g and 14h, shows that using 5 kW wind turbines produces better energy performance than 30 kW wind turbines. As a consequence, only experiments using 5 kW wind turbines have been presented in this paper.

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Appendix C: Bandwidth Management via BiRSM

Article VI

Sasitharan Balasubramaniam, Dmitri Botvich, Julien Mineraud, William Donnelly and Nazim Agoulmine

BiRSM: bio-inspired resource self-management for all IP-networks

In *IEEE Network*, vol. 24, no. 3, pp. 20–25, May 2010

Contribution: My contribution to this research article was the development and the implementation of the bandwidth management protocol, as well as conducting all the experiments and collecting the results. I also took part in writing some parts of the paper, as well as proof reading.

BiRSM: Bio-inspired Resource Self-Management for All IP Networks

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Abstract

The increased complexity of communication systems has led to new challenges in network management and more specifically, efficient mechanisms to manage communication resources. The vision of autonomic networking aims to overcome these challenges by incorporating self-governance into communication network devices, in order to improve overall efficiency and minimise human intervention. Since biological systems exhibit properties that meet the requirements of self-governance, this paper proposes a bio-inspired approach to efficiently manage resources in IP based core networks, called Bio-inspired Resource Self-Management (BiRSM). The approach aims to provide a holistic solution for ISPs to manage their resources at different time scales as well as automating the interactions with underlying carrier network operators for dynamic resource provisioning. The implemented solution in a simulator, has shown improved performance compared with traditional approaches.

Keywords: Resource Management, Autonomic, Bio-inspired, Blood Glucose Regulatory Process

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Introduction

The development of communication networks in recent years has led to large-scale, heterogeneous networked systems that transports multitude of services to various end user devices. With deregulated telecommunication market, the end-to-end communication has to traverse a multitude of horizontal and vertical domains. In this case, the horizontal domains are ISPs, while the vertical domains are the chain of operators going from the carrier to the Internet access provider. This communication network structure as well as various supporting technological developments have led to increase complexities in efficiently managing the end-to-end services, which has inspired researchers to seek and develop new approaches to improve management capabilities. One of these approaches is known as *Autonomic Communication,* which enables network devices to cooperatively exhibit self-governance (e.g. self-management, self-organisation, self-learning), in order to minimise human intervention, operation costs, while maximising efficiency in the process. Autonomic was first proposed in [4] to enable more efficient management of computer systems, and later this concept was extended to communication networks. One key application that can benefit from self-governance is the *self-management* of communication network resources. It is anticipated that efficient management of communication resources will require immediate attention in the very near future, due largely to: (1) increase in variety and number of network devices, (2) increase in number and variety of traffic types, and (3) highly dynamic traffic behaviour resulting from increase in services (e.g. IPTV, P2P multimedia streaming). ISPs have to face a number of challenges to fulfil the requirements of their customers. Firstly, they should be able to efficiently manage the distribution of resources to their customers, and secondly, they should accurately calculate the quantity of resources to purchase from its carrier operators. The latter is very crucial, since the ISPs have to ensure its subscribed resources meet its customer's demand to minimise any service degradation, and at the same time avoid expensive over provisioning of resources. This balancing process can only be achieved with some form of vertical regulatory process of provisioning and releasing of resources between the ISPs and the underlying carriers. Unfortunately, the existing technical solutions and contractual relationships between these operators make this task very difficult to fulfil. At the same time, human administrators are always in the loop, making it very challenging to manage communication systems in a dynamic, flexible, and cost effective way.

To address these challenges, we propose in this paper an autonomic bio-inspired self-management solution for ISP operators to efficiently manage their communication network resources in coordination with underlying carrier network operators. The proposed solution autonomously fine-tunes resources at various time scales (short, medium, and long term), and enables automated interactions between the ISP and the underlying carrier network. The motivation behind using bio-inspired techniques is because a number of autonomic characteristics can be found in biological systems and as such meet the requirements of self-governance. Nature has shown, through thousands of years of evolution, that living organisms are able to exhibit a high degree of adaptation. This evolutionary process has led to the development of various complex mechanisms that allow living organisms to adapt as individuals or in groups in face of any environmental changes (e.g. scarcity of food, change in weather conditions). For this reason, biological processes and systems are a source of inspiration for future communication system developments [9].

In this work, we have applied a specific bio-inspired resource self-management approach (Blood Glucose Regulatory process) to improve the capacity of IP networks, which support multiple traffic types. Validations have also been conducted to compare with standard approaches.

Classical Resource Management Strategies

Before, going into the details of our proposed solution, we will first describe how standard approaches address the management of resources. These standard approaches will be used as benchmark comparisons to our proposed solution. Standard approaches for resource management includes static provisioning (*Static – RM*) and *Weighted Fair Sharing* (*WFS*). The example traffic pattern used for the illustration is presented in Fig. 1. The figure also shows cases where collision can occur when two different traffic types compete for limited resources. Static – RM provisioning sets a fixed boundary between different resource types, where traffic is only confined within the boundary. In the event that traffic exceeds the boundary, the request will be rejected. Unlike Static – RM, WFS aims to maximise resource usage by allowing certain traffic types to cross the boundary, in order to use under utilised resources. However, this resource could be claimed back in the event that the original traffic type requires that resource, which could lead to high number of flows being interrupted.

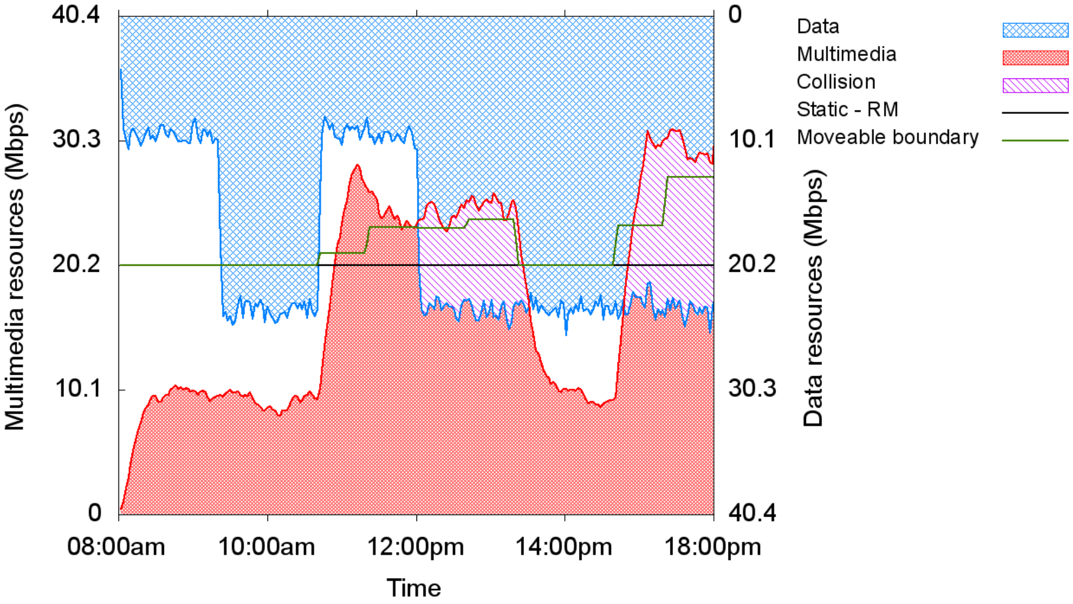


Fig. 1 Example illustration of Static – RM and moveable boundary of BiRSM.

Proposed Solution

Our proposed solution, illustrated in Fig. 2, is called *Bio-inspired Resource Self-Management* (*BiRSM*). Fig. 2 also presents a high level illustration of the internal functionalities of BiRSM. For each source and destination pair, the ISP will subscribe the required resources from the carrier through BiRSM, and this is the allocated path capacity (C_T) (each of these path maps to routes that are discovered at the carrier layer). For each C_T, the BiRSM performs call admission by managing resources for multimedia (high priority) and data traffic (low priority). The self-management process observes patterns in the traffic behaviour and self-tunes and manages the resources at different time scales to optimally maximize call admission. The short, medium, and long term resource management is performed by the BiRSM using the Blood Glucose Regulatory process, where the details of the process will be described in the next section.

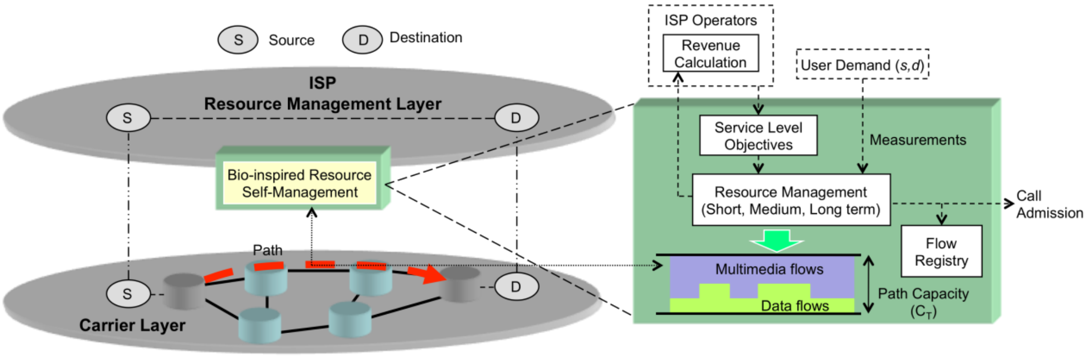


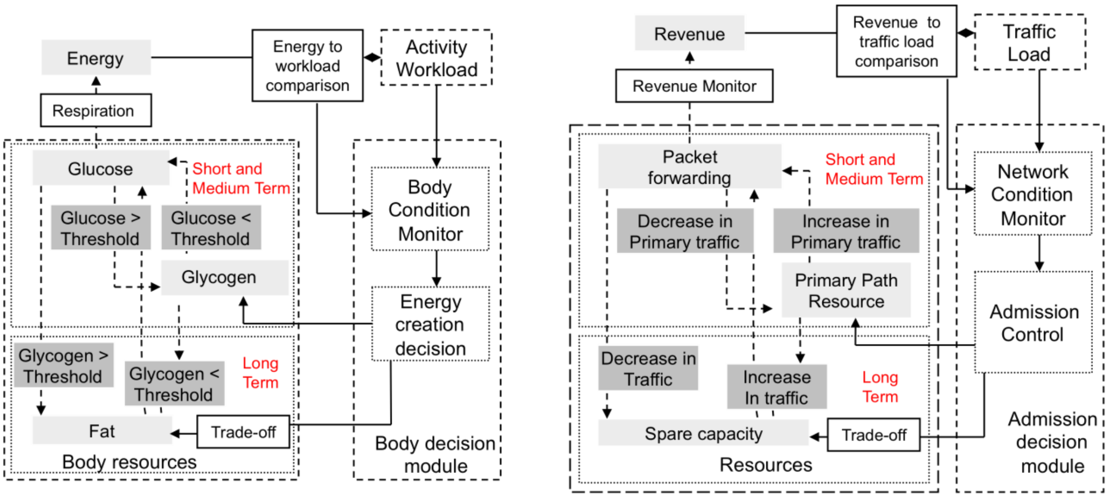
Fig. 2 Bio-inspired Resource Self-Management.

Blood Glucose Regulatory Process

The resource self-management process requires a regulatory mechanism that regulates and manages the system's resources autonomously. Besides regulating and adapting resources at different time scales, the regulatory mechanism should be intelligent enough to adapt resources by considering the degree of changes in traffic pattern as well as the state of the network (e.g. if the initial change is large, the system should adapt differently to when the change is small). Due to these requirements, we have studied different regulatory mechanisms in the human body and we have selected the *Blood Glucose Regulatory Model* [1] [2], since the regulatory mechanism exhibits the closest similarities with the problem we want to solve.

In the human body, the blood glucose regulatory process aims to balance the glucose supply with respect to the energy expenditure required to perform a certain workload [2]. The mechanism is based on concentric feedback loops, which refines the resource usage to suit the body's activity and workload patterns for different time scales. The blood glucose regulatory process is shown in Fig. 3 (a), and consists of three main processes; each corresponding to adaptation at different time scale.

In the medium term, the body breaks down glucose to create energy. In the event that the glucose supply is depleted, the body turns towards glycogen and breaks this down to create glucose for further energy production. The interchange between the glucose and glycogen breakdown usually supplies sufficient energy to support the average daily workload, where the process refines the amount of glycogen to suit the average workload pattern. The second process occurs when the body is faced with short unexpected (e.g. different from usual routine pattern) high intensity workout. Although there is a certain quantity of glycogen to support medium term workload, the body could be pushed to create *extra energy*. This process only occurs at very short time scales, and can only be performed at limited capacity. The third process occurs when the workload increases and the glycogen becomes depleted. At this point the body turns to fat breakdown to create glucose. This rarely occurs, except when the body is undergoing a new and heavier workload pattern that is different from the routine workload, and over a longer period of time. In this process there is a trade-off, as the body can only produce a certain amount of energy to burn the fat initially. However, if this routine continues to occur, the fat breakdown becomes easier and will build extra resources for energy production.



(a) (b)

Fig. 3 (a) Blood Glucose Regulatory Process, (b) Mappings of Blood Glucose Regulatory Process to BiRSM resource self-management.

BiRSM Internal Functionalities

Fig. 3 (b) presents the concept mappings of the blood glucose regulatory mechanism (Fig. 3 (a)) to BiRSM to enable resource self-management. Similar to the human body being able to utilise blood glucose for energy output at varying activity loads, the resource self-management process will manage and adapt resource utilisation for the different time scales to cope with varying intensity of traffic. Since the human body is able to manage the blood glucose system by conforming to certain goals (e.g. maintain fitness at a certain level), we use the same process for ISP operators to define the goals the system should achieve. These goals are defined through *Service Level Objectives (SLO)*, shown in Fig. 2.

The analogy comparisons of the blood glucose model to the network model are: (1) the total amount of glycogen that is used to support human daily routine activity, is similar to combination of path resources (C_T) which the ISP purchased from the carrier to manage the daily demand traffic, (2) the way in which the body can refine and cope with varying intensity of workload, is the same way that the network must be able to cope with changing traffic behaviour at different times of the day, (3) the technique the body uses to exert extra effort to create extra energy during peak work load is used by the network to relinquish traffic resources with lower priority (in this case the extra energy is equivalent to extra revenue) during scarce resource situations, and (4) when the glycogen is depleted due to the body pushing its limit, the body seeks glucose from fat breakdown. This fat breakdown analogy is used by the ISP to interact with the carrier network to purchase spare capacity that is used to support extra traffic intensity. Our central objective in all these processes is to maximise revenue by self-tuning call admission to suit changing traffic behaviour. The revenue maximization is through prioritizing certain traffic types when traffic behaviour changes (in this paper we have prioritised multimedia over data traffic). The following sub-sections will illustrate how we perform the process of fine-tuning the resources for different time scales, where each time scale will correspond to a specific mechanism of the blood glucose regulatory process. Our solution for resource self-management is based on extending the WFS solution.

Medium term resource allocation strategy

Although the WFS resource management approach provides flexibility, the boundary is not set for different traffic load at different time periods and could lead to unnecessary claims of resources during bursty periods. Based on the traffic pattern of Fig. 1, we can see the number of interrupted flows in Fig. 4 for WFS at approximately 12:00 and 15:00. We can also see that there is equal disruption for both data and multimedia flows. Since traffic intensity will be different for different times of the day, we created a *time zone* based moveable boundary strategy. This strategy moves the boundary for different time zones, by following the average multimedia traffic load. However, allowing the boundary movement to follow the average multimedia traffic could lead to full depletion of resources allocated for data traffic. To avoid this problem, we have set a minimum quantity of resource for data traffic, which is specified through a SLO. The approach used to tune the boundaries is based on a prediction process, which predicts the multimedia capacity required for a specific time zone on the next day. Therefore, the movement of the boundary is re-configured at the end of each day. Fig. 1 illustrates the moveable boundary that has settled on day 3, and shows that each time zone has a boundary at different position. As shown in the figure, the boundary converges closer to the multimedia traffic demand.

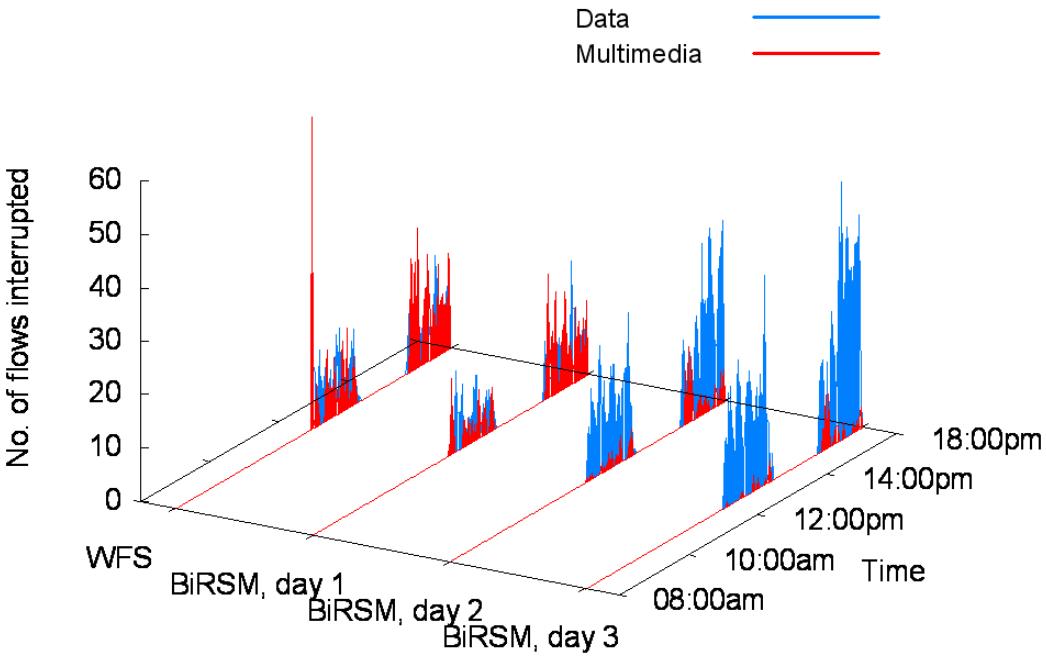


Fig. 4 Comparison of number of interrupted flows between WFS and BiRSM (day 1 – 3).

The prediction of resource requirements for the following day is calculated using Simple Exponential Smoothing, which uses measured information of multimedia traffic on the current day as well as history of traffic prediction. This measurement information is collected from multimedia traffic entering the ingress router.

The analogy of the body predicting the amount of glycogen required to create energy for the daily workload is adopted in predicting the average amount of resource required for multimedia traffic on the next day. This process is comparable to the training process that self-tunes the body to suit the intensity of daily activities.

Short term resource allocation strategy

The next concept that is taken from the blood glucose regulatory process is for obtaining extra resources in scarce resource situations. Such situations will occur when the multimedia traffic has been settled to a particular boundary for the specific time zone, but random burst of multimedia traffic may occur. In such cases, the multimedia traffic may exceed the boundary if there are under utilised reserved resources for data traffic. However, in the case that the data traffic increases and would like to reclaim its resource back, the process will only allow a certain portion of the resource to be claimed back. The prioritisation of multimedia traffic in such situations is driven by higher revenue that multimedia traffic can offer. To ensure a certain degree of fairness, we propose a resistance-based mechanism for resource reclaim. Initially, when this situation occurs, the resistance of the multimedia traffic will be high, allowing minimum data requests to reclaim back its resources. However, if this situation repeats itself, the resistance decreases. We base the resistance on a probability function, known as resistance probability. This resistance probability is a ratio of the number of reclaim attempts for data traffic, to the total amount of data traffic that is allowed to reclaim resources (the latter can be set by the ISP provider through a SLO).

As described earlier, this process is analogous to the body pushing to create extra energy when the body has reached peak capacity during high intensity workout and is in a fatigue state. This process can only be performed for a short period of time and limited number of times, depending on the state of the body's fatigue level. Therefore, this analogy is compared to communication network during peak hour period which would have used most of its resources, but is able to prioritise and push certain traffic type to gain extra revenue. The objective of using this process is two folds: (1) to gain extra revenue for the operators in a manner that is autonomous and depending only on the current state of the system, and (2) to perform this process only within limits and not to compromise too much multimedia traffic.

Fig. 4 illustrates this process based on the traffic pattern of Fig. 1. On day 1, the boundary was configured equal between data and multimedia resources for all time zones (exactly the same as Static – RM). During periods of unused data resources, multimedia traffic that over exceeds its own allocated resources will use the data resources. At 12:00, new data traffic has entered and would like to reclaim its resource back. However, due to high resistance from the multimedia resource, a large number of data traffic was rejected, and this is shown between 12:00 - 13:00. This resistance was lowered in the late evening. Due to this effect and the fixed boundary of the first day, we can see a reasonable quantity of multimedia and data traffic rejected on day 1. On day 2, the boundaries start to move closer towards the average multimedia traffic. Therefore at 12:00, we can see that less number of multimedia traffic are rejected, but higher data traffic rejection due to the initial high resistance. Day 2 also shows that due to the higher priority of multimedia traffic, there were higher data flows interrupted to make space for multimedia traffic. However, towards the evening (16:00 – 18:00) we can see higher rejections for multimedia traffic as the resistance is lowered to make way for new data requests. A similar trend could be observed on day 3 as the boundaries start to settle.

Long term resource allocation strategy

The next process of BiRSM is the ability for the ISP to purchase spare capacity from the underlying carrier when C_T is depleted. The extra resources required maybe due to an increase in overall traffic intensity entering the network. The process from the blood glucose regulatory model used to inspire this mechanism, is the process of burning fat to obtain more glucose to create energy. As described earlier, the process of burning fat is based on a trade-off process, where a certain amount of heat must be produced before fat breakdown can occur. This process is highly dependent on the frequency of workload pattern changes.

We use this analogy to determine whether the ISP is willing to purchase the extra capacity from the carrier to avoid customer service degradation resulting from under provisioning. The mechanism assumes that the carrier sells the resource only in bulk quantity, and this is referred to as Δ (e.g. Δ = 10Mbps). Different quantities of Δ will have different price settings, where the higher the quantity purchased, the cheaper each unit of Δ will be. Therefore, based on the blocking probability of data traffic, and the minimum quantity of revenue that must be generated (set by the SLO), a trade-off strategy can be made by the system to determine if spare capacity should be purchased. At the same time, the strategy can also support releasing resources back to the carrier. This will be indicated to the ISP provider through low revenue turnout. The analogy comparison to the human body is when excessive fat is stored in the body resulting in lowered fitness.

Evaluation and Comparison

We have performed simulations to evaluate the benefit of BiRSM solution. The solution has been developed in Java as part of our custom developed bio-inspired simulator for a larger research program [3]. The traffic pattern used for our simulation is based on the same traffic pattern used in Fig. 1. In the simulations, the data flow has a duration between 2 to 8 seconds and a payload ranging from 20 to 60 kbps, while the multimedia traffic has a duration of 20 to 80 seconds with a payload ranging between 54 and 74 kbps. The pricing scheme for revenue calculation is based on data costing 1 €/Mb, multimedia costing 1.5 €/Mb, C_T costing 0.2 €/Mb, single Δ (10Mb) costing 0.35 €/Mb, and double Δ (20Mb) costing 0.30 €/Mb. The initial C_T is set to 40.4Mbps.

Short and medium term resource allocation

Table 1 presents the comparison between WFS, Static – RM, and the short and medium term resource allocation of BiRSM (between days 1 – 3 only; on day 4 long term strategy was applied). As predicted in the results, the WFS out perform the static boundary for both blocking probability of data and multimedia traffic. This is also reflected in the achieved throughput where WFS is able to achieve substantially higher throughput for both data and multimedia traffic. In the static boundary case, no traffic was interrupted and this is due to the fact that no reclaim of traffic was performed by other traffic types, while WFS showed a certain degree of interruption. In the case of BiRSM, the data blocking probability, increases from day 1 to day 3. This is due to the autonomic boundary movement, which results in continuous reduction of multimedia traffic blocking rate from day 1 to 3. This is also reflected in the average throughput, which shows that data traffic in BiRSM is lower than WFS, but in reverse, the multimedia traffic increases from day 1 to 3. From the operator's perspective, our solution leads to increase in revenue by allowing higher revenue traffic to be accepted, without completely jeopardizing the low priority traffic. Therefore, through the BiRSM medium term boundary movement and short term resource reclaim, higher revenue can be generated compared to WFS and static approaches, while minimizing interruptions for ongoing multimedia traffic.

Long term resource allocation

While the movement of the boundaries will satisfy the resource required for multimedia traffic, and in turn increase the overall revenue, this has come at a cost of lower throughput for data traffic. As described earlier, the purchase of spare capacity to increase total path capacity is based on a trade-off strategy. The trade-off strategy monitors the degree of boundary changes from day 1 to 4. Although the boundary change is the highest on day 1, this decreases on subsequent days. Finally on day 4, the boundary movement is very small, and is below the threshold. This threshold indicates that the boundary change has converged, and it is now impossible to optimize the resource allocation using only the short and medium term strategies, and if data traffic rejection continues, then the strategy for spare capacity purchase is required. As described earlier, different Δ quantity of spare capacity has a different price. Based on our example scenario, when a single Δ is purchased, the revenue increases to 39, 025 Euros. When 2Δ of spare capacity is purchased, this leads to the ISP operators with higher quantity of resources, but the revenue drops to 38, 775 Euros. Therefore, if a single Δ is purchased, the operator can still maintain a decent margin of revenue. By considering the revenue targets set by the SLO, the BiRSM can autonomously determine a suitable quantity of Δ that needs to be purchased. The increase in revenue for combination of short, medium and long term resource allocation strategies is shown in Table 1 (BiRSM day 4). The improvement from perspective of blocking probability, throughput, as well as number of interrupted multimedia flows, has also shown the benefits of using all three strategies of BiRSM. While the solution presented in the paper only shows refinement for 4 days, the solution can be extended to multiple boundary refinements in cases where there are different traffic patterns within the week. Such cases may occur when one traffic pattern represents the weekdays, while a different traffic pattern represents the weekends.

	Static - RM	WFS	BiRSM Day 1	BiRSM Day 2	BiRSM Day 3	BiRSM Day 4
Data Blocking Probability	0.12	0.06	0.06	0.10	0.11	0.08
Multimedia Blocking Probability	0.18	0.13	0.13	0.08	0.05	0.02
Data Throughput (Gbps)	19.9	21.5	21.4	20.5	20.0	20.9
Multimedia Throughput (Gbps)	18.0	18.8	18.9	20.0	20.6	21.4
Data Throughput Interrupted (Gbps)	0.0	0.10	0.07	0.21	0.28	0.22
Multimedia Throughput Interrupted (Gbps)	0.0	1.85	1.26	0.45	0.23	0.07
Revenue (Euros)	35, 332.27	38,099.90	38,215.25	38,608.19	38,794.92	39,024.43

Table 1 Performance evaluation comparison between Static – RM, WFS, and BiRSM.

Related Work

Although a number of different solutions have been proposed to manage resources adaptively [6] in recent years, these solutions do not address the challenges in a holistic manner proposed by BiRSM. In particular, previous solutions do not consider the vertical provisioning of interactions between ISP and the carrier operators for autonomic resource purchase and allocation. The Quasi-Dynamic Resource Management [5] proposes flexible boundary resource management for DiffServ-based networks on specific paths. However, the solution does not support dynamic resource preemption for prioritised traffic during peak periods. In [7], a self-optimisation based QoS resource provisioning for DiffServ networks using reinforced learning techniques was proposed. Although the solution allows learning of variations in traffic pattern, the reinforced learning process requires a large data set, which could lead to lengthy periods before boundary convergence. In particular, the training process can be complex for varying traffic pattern for specific times of the day that is considered in BiRSM. The Traffic Engineering Automated Manager (TEAM) automates resource management for DiffServ-based MPLS networks [8]. The solution is very similar to BiRSM, where LSP paths can be dynamically created and torn down depending on changes in traffic patterns. At the same time, preemption of low priority LSPs is also permitted to create extra bandwidth when resources are scarce. The proposed approach employs cost and objective functions for decision making strategies. The drawback with this approach occurs with frequent changes in traffic pattern, which can lead to frequent re-calculations of the optimisation functions. Burst in traffic pattern changes that leads to re-calculations may also lead to possible oscillations. However, in the case of BiRSM, oscillations are avoided where short time scale resource allocation could be initially performed before medium term boundary movement is triggered. The TEQUILA project [10], proposed a Policy Based Management System to manage resources in DiffServ networks. The proposed solution aims to program network elements to adapt to changing environments. Unlike TEQUILA, BiRSM leverages the automation process by only allowing limited number of policies to operate in tandem with the blood glucose regulatory model. This will minimise any requirements for frequent policy changes by the administrator to change the behaviour of the communication networks when changes in traffic patterns are encountered.

Conclusion

Future communication networks will face increase challenges, some of which includes dynamic changes in traffic behaviour due to introduction of new services (e.g. P2P streaming), as well as new emerging resource sharing structures between carrier and ISP operators. In the latter case, solutions are being sought to enable vertical resource provisioning between the ISP and carrier network to improve overall resource management. In recent years, communication network researchers have been investigating autonomic solutions to meet the ongoing challenges resulting from ever increasing complexities. One source of inspiration for autonomic solutions is from biological systems and processes, which exhibits characteristics similar to self-governance requirements of autonomic communications. To address the challenges described above, we propose BiRSM, which focuses purely on self-management of communication resources in all IP networks, through a single holistic solution. The analogy used to inspire the solutions in BiRSM is based on the blood glucose regulatory system. Our motivation in selecting this specific mechanism for resource management is in its ability to fine tune resources at short, medium, and long time scales, which fits very well to requirements for resource management in IP networks. Evaluations have also been presented to compare the proposed solution to standard approaches used to manage communication network resources.

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Appendix D: Management of Multiple Providers

Article VII

Sasitharan Balasubramaniam, Julien Mineraud, Patrick Mcdonagh, Philip Perry, Liam Murphy, William Donnelly and Dmitri Botvich

An Evaluation of Parameterized Gradient Based Routing With QoE Monitoring for Multiple IPTV Providers

In *IEEE Transactions on Broadcasting*, vol. 57, no. 2, pp. 183–194, June 2011

Contribution: My contribution to this research article is the development of the PGBR routing protocol. In order to evaluate the routing protocol, I also implemented a well-known bio-inspired routing protocol known as Ants. I was responsible of the full evaluation of the routing protocol, as well as the integration to the complete solution. Quality-of-Experience results where obtained in cooperation with PhD student Patrick McDonagh. Finally, parts of the contribution also include the writing of some parts of the paper, as well as proof reading.

An Evaluation of Parameterised Gradient Based Routing with QoE Monitoring for Multiple IPTV Providers

Sasitharan Balasubramaniam, Julien Mineraud, Patrick McDonagh, Philip Perry, Liam Murphy, William Donnelly, and Dmitri Botvich

***Abstract*—Future communication networks will be faced with increasing and variable traffic demand, due largely to various services introduced on the Internet. One particular service that will greatly impact resource management of future communication networks is IPTV, which aims to provide users with a multitude of multimedia services (e.g. HD and SD) for both live and on demand streaming. The impact of this will be higher, when we consider multiple IPTV services overlaid on the same network. In this paper we propose a resource management scheme for a network provider that supports multiple IPTV providers. The proposed solution incorporates a new distributed routing mechanism in the underlying network that incorporates QoE monitoring. Through this monitoring process, network providers are able to provide timely updates of quality of flows for each IPTV provider. Simulation work has been conducted to validate the efficiency of the proposed solution in comparison to standard approaches.**

***Index Terms*—Quality of Experience, Distributed Routing, IPTV**

I. INTRODUCTION

THE network research community is currently pursuing new solutions to enhance the communication systems supporting the Future Internet. It is anticipated that the Internet of the future will incorporate a multitude of services, in particular high bandwidth services including multimedia content. One such multimedia service that has attracted attention in recent times, is IPTV [1] (Internet Protocol TeleVision), which is often regarded as a distribution mechanism for digital television services over a dedicated and controlled IP network. A number of solutions have been proposed for IPTV networks to co-exist and be managed with traditional IP networks, for example a proposed solution for IPTV and Next Generation Networks was presented by [2]. IPTV was developed to compete against the growth of Cable and Satellite providers, thereby providing customers with greater value through the triple play service offering that includes broadband internet access, VoIP, as well as digital TV services [3]. The video services will include both Video on Demand (VoD in High and Standard definition), as well as live streaming of traditional broadcast content. Due to its increased popularity, and the potential for high revenues, it is anticipated that numerous IPTV service providers will emerge. While the opportunity for choosing between a number of IPTV service providers will enable competitive offerings and pricing to end users, this will bring new challenges to the deployment of IPTV services on the existing Internet infrastructure. The increase in the number of IPTV service providers, augmented with other additional services will lead to higher traffic volumes and increase the variability of the traffic load. This stems from the fact that multiple service providers will be consuming resources from the same underlying infrastructure. These challenges not only impact on the underlying infrastructure in ensuring that sufficient resources are provided to the IPTV Service Providers, but also for the providers to ensure that high quality IPTV content is provided to subscribers [4].

Due to these foreseeable challenges, one research area that is currently being pursued by Future Internet researchers are new, adaptive and robust routing mechanisms. As service traffic diversifies and increases in the future, routing in communication networks will be required to be more scalable, adaptive, robust, and efficient [5]. In particular, the routing protocol should be able to support: (i) a high number of nodes in the infrastructure networks, (ii) routing processes that cope with highly dynamic traffic, (iii) the ability to improve resource usage in the networks, and (iv) ensure that the improvement in quality is provided to end users for various types of services. In this paper, we present a new resource management scheme for network providers supporting multiple IPTV service providers. The proposed solution incorporates a new routing mechanism, known as Parameterised Gradient Based Routing (PGBR) [6], that addresses the requirements (i) - (iv). In particular we show how PGBR is able to support a dynamic traffic profile that may result from multiple IPTV providers sharing the Internet infrastructure. PGBR is a distributed routing technique for core and metro networks that is inspired from biological processes. The routing algorithm is based on gradient route attraction for flows between a specific source to destination pair, where the gradient is calculated from local interactions between neighbouring nodes. In order to support (iv), the proposed resource management scheme also incorporates Quality of Experience (QoE) monitoring, where regular updates are provided to IPTV providers to ensure maximum quality. Evaluation through simulation work will show how PGBR is able to ensure a high degree of QoE for subscribers, irrespective of the current load within the networks.

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This paper is organised as follows: Section II presents the related work on current approaches used for QoE monitoring as well as routing. Section III presents the proposed solution, and section IV describes the PGBR routing algorithm. Section V presents the simulation results, and lastly, section VI presents the conclusion.

II. Related Work

The related work is subdivided into two sections, which include current approaches for QoE for IPTV services and routing.

A. QoE for IPTV services

Since IPTV will directly compete with existing digital TV delivery mechanims (e.g. satellite and cable networks), IPTV providers must ensure that customers are guaranteed a high and consistent QoE. QoE is a measure that combines user's expectation and perception and is usually represented through a non-technical description (e.g. a form of ranking) [7]. In order to assess QoE, a number of factors must be considered, which includes dependability and control responsiveness in order to maximise Audio-Visual (A/V) quality [8]. These factors are strongly linked to Quality of Service (QoS) parameters in the network and any variation in these QoS parameters caused by congestion or other factors, can lead to a decrease in QoE. In [9], Fiedler et al developed a generic solution for the relationship between QoE and QoS. The unified solution is based on an exponential dependency relationship between QoE and QoS, and has been tested for three different applications. In order to accurately monitor QoE, an efficient monitoring methodology is required. A number of methods exist to measure video quality using either subjective or objective metrics. Subjective tests involve the rating of video quality by viewers through active participation. However, this technique is not feasible for a deployed service. Objective methods involve the use of empirical values to provide a rating of video quality and can be integrated as part of a service deployment. The Video Quality Experts Group (VQEG) provides guidelines on undertaking both subjective and objective measurements [10]. One popular example of an objective method is the Peak Signal-to-Noise Ratio (PSNR), which is calculated based on the differences between the original, reference signal, and the received signal. It has been noted that this method does not mimic perceptual features and thus should not be taken as a measure of perceptual quality [11]. As a result, new objective metrics have been developed which more closely mimics user perception through integration of factors derived from analysis of the human visual system [11].

Through efficient monitoring approaches, service providers can deduce the root causes of QoE degradation, such as factors affected by dependability or requirements for control responsiveness. Control responsiveness allows QoE monitoring to enable corrective actions at the source in order to minimise QoE. In [12], Muntean et al developed a client software to monitor the service quality which reports to the server, in order for the server to select the most appropriate level of compression for a given user, and optimise network utilisation. This allows the adjustment of the bit rate of the video stream as an effort to ease congestion, rather than the random dropping of packets in the network which will have unknown impact on the perceived quality at the client.

Although corrective actions can be made at the source, the effect in Quality of Service degradation (e.g. delay, jitter, and Packet Loss Ration (PLR)), can lead to errors during content playback in the form of visual or audio distortion, blocking, loss of A/V synchronisation and perhaps loss of playback due to buffer starvation. A method for classification of service quality through the examination of PLR is provided in [13]. In [8], further research has been carried out, detailing constraints on latency, jitter and PLR to ensure satisfactory levels of QoE for video streams encoded at differing bit rates and using differing encoding techniques. Jitter and latency can usually be constrained through buffering in the end devices leading to smooth playback. However, the main challenge is to keep packet losses to a minimal level. Another issue that affects the QoE in IPTV streaming is the channel switching time for VoD contents. Example solutions to mitigate this problem is insertion of additional I-frames into the video stream to minimise the time between selection of a new stream and the initialisation of playback [14], or pre-loading of contents to minimise the delay incurred as a result of channel change [15]. However, a major factor that affects QoE from lengthy channel switching is also excessive congestion and/or packet losses in the underlying network.

In summary, scalable, real-time monitoring of QoE is essential for IPTV providers to ensure that guaranteed quality is delivered to their customers. Therefore, a relationship is required to map between IPTV providers and underlying network providers for monitoring QoE. At the same time, the underlying networks will require efficient resource management and routing mechanisms to minimise packet loss, which in turn will minimise QoE degradation.

B. Communication Network Routing

In recent years, research in communication network routing has been investigated extensively. A number of research initiatives of the Future Internet have specified the need for more efficient, scalable, and adaptive routing mechanisms in order to support diverse services of the future. The routing mechanisms of the future will need to satisfy a number of objectives, where examples include: maximising resource usage of the underlying network in line with traffic demand, ensure dynamic resource provisioning for multiple providers, and as mentioned in the previous section, maximising end user's QoE. Current routing techniques use IGP routing protocols such as OSPF [16], [17] in IP based networks. Although OSPF is a distributed routing algorithm, the solution requires each node to have a global view of the network. Therefore, in the event of changes (e.g. traffic demand change or failures), coordination is required by all nodes to re-configure routes. This coordination can allow OSPF to reconfigure routes dynamically based on various objectives (e.g. throughput on links) [18], [19]. However, this is not suitable for dynamic traffic demands that may require frequent re-routing. For dynamic traffic this can lead to route instability and a lengthy re-routing process in the event of network failures. A number of solutions have also proposed using optimization approaches, but this requires pre-knowledge of traffic demand, and a centralised view of the topology (e.g. Genetic Algorithms solutions in [20]) [21], [22]. Applegate and Cohen [23] took a slightly different approach to determining routes, where OSPF was used with minimal knowledge of the traffic demand.

Therefore, an alternative is to propose a hop-by-hop distributed routing approach. While distributed routing ensures, scalability and robustness, there are also inherent risks (e.g loops during route discovery [24], [25]). In [26] Gohmerac et al investigated adaptive multipath routing for dynamic traffic engineering and proposed a distributed routing algorithm that takes load balancing into consideration. The re-routing mechanism, however, is not load sensitive and is only appropriate for managing inter-domain routing (with few links) rather than intra-domain routing. The concept of gradient based anycast routing in wireless networks has been investigated by Lenders et al [27], and is inspired by concepts of potential fields. The mechanism is largely based on opportunistic routing and does not cater for supporting QoS for different traffic types. Bio-inspired adaptive routing has also been investigated, and most recently by Leibnitz et al [28]. The solution is, however, based on a central processing solution that calculates the predefined routes and thus is not suitable for large-scale networks with numerous nodes. A hop-by-hop load-adaptive routing was proposed in [29], where traffic can be streamed along multiple paths. Each node will perform the decision on splitting the traffic based on local node load information. However, this could possibly lead to high number of packets arriving out of order at the destination, which could lead to high requirements of re-ordering at the destination node.

Therefore, as discussed, there are a number of challenges to address in routing for networks of the future. In particular to satisfy a number of objectives that includes, scalability, robustness, adaptiveness, and maximising QoE of end users. Our objective is to propose a routing solution that addresses these challenges, in particular to support load that will be placed by multiple IPTV providers where each will have varying traffic demand.

III. PROPOSED SOLUTION

A. *Objective and Proposed Solution*

The proposed scenario is illustrated in Fig. 1 and assumes a number of IPTV providers that have virtual overlays on the underlying network infrastructure. IPTV architecutures usually consists of VSOs (Video Serving Offices) and VHOs, (Video Head Offices) that help distribute contents to end users in residential areas. As shown in Fig. 1, as the number of IPTV providers increases, this could potentially lead to highly dynamic traffic in the underlying network. Fig. 2 illustrates the proposed resource management scheme for multiple IPTV providers. The proposed scheme consists of a Service Provider Monitoring Interface that interfaces between the IPTV providers and the network provider. As discussed in section II-A, there are a number of different QoE measurement methodologies. In order to enable flexibility in our proposed scheme, we allow each IPTV provider to load their own QoE measurement mechanism into the Provider QoE Measurement Module. Each IPTV provider maintains a relationship with the network provider through SLA agreements (IPTV-SLA). Let the set of IPTV providers be $IPTV = \{IPTV_1, IPTV_2, \ldots, IPTV_j\}$, where j is the total number of IPTV providers. During each SLA request, the IPTV provider k specifies the required bandwidth $(BW_{C,k})$ for the VoD content $(VoD_{C,k})$, expected quality $(EQ_{C,k})$, as well as frequency of monitor reports $(t_{C,k})$. The module will in turn subscribe to specific QoS parameters for the specific content $(QoS_{C,k})$ from the Network Provider. Once a request is submitted to the network provider, a flow id of the new flow is recorded in a registry. During the streaming process, the network provider will record the QoS measurements, and this will be used to calculate the QoE metric. In this particular solution, the QoE is based on a Mean Opinion Score (MOS), which gives an indication of user's perception of the content. The Network Provider will in turn, provide the calculated MOS to each IPTV provider, to allow each provider to monitor the quality of the streaming content ($MOS_{C,k}$ for content c of IPTV provider k). This entire process is reflected in the algorithm presented in Fig. 3.

TABLE I
SUMMARY OF KEY NOTATION

Notation	Meaning
$IPTV_k$	IPTV provider k
$VoD_{C,k}$	Video on Demand content C for IPTV Provider k
$BW_{C,k}$	Required bandwidth for $(VoD_{C,k})$
$EQ_{C,k}$	Expected quality for $(VoD_{C,k})$
$t_{C,k}$	Frequency of update between the MOS calculator and the IPTV Provider k
$QoS_{C,k}$	QoS parameters subscribed by IPTV Provider k for $(VoD_{C,k})$
$MOS_{C,k}$	Mean Opinion Score for $(VoD_{C,k})$
$G_{n\to m,d}(t)$	Gradient between node n and m for destination d at time t
Φ_m	Load of neighbouring node m
$l_{n\to m}$	Link load between node n and m
$h_{m,d}$	Normalised hop count of node m to destination d
α, β, γ	Weight values for $G_{n\to m,d}$
$p_{d,(s\to d)}$	Discovery packet for route discovery
PLR	Packet Loss Ratio

As described earlier, our proposed resource management scheme incorporates the PGBR routing algorithm to deliver the stream from each IPTV provider through the underlying network. Therefore, our proposed solution can provide a mechanism that can enable network operators and service providers to federate and provide improved service to the end customers [30].

IV. PARAMETERISED GRADIENT BASED ROUTING

PGBR is located at the underlying network layer, as illustrated in Fig. 1. As described in the related work section, current routing approaches are not suitable for dynamic traffic that has the tendency to fluctuate or change frequently. This motivates us to pursue a new routing process at the underlying network that will form routes through self-organisation of network nodes. Through the self-organisation process, a gradient

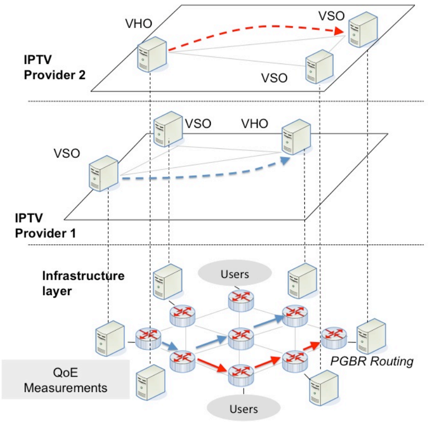


Fig. 1. Federated IPTV providers over a single underlying infrastructure

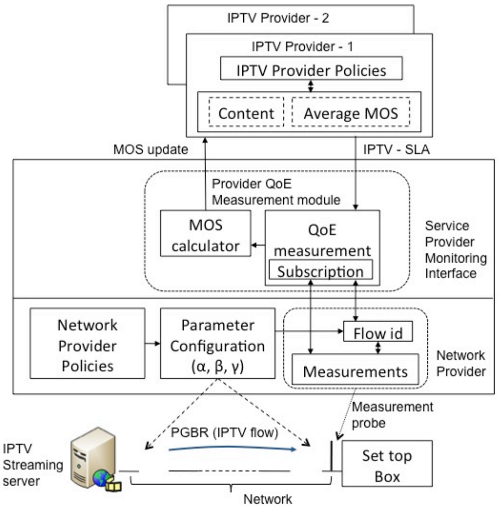
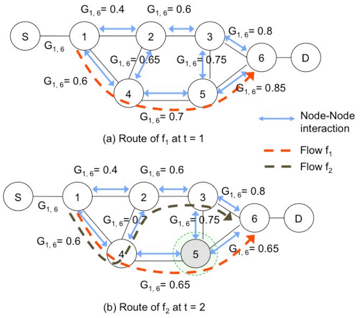


Fig. 2. Multiple IPTV Resource Management Scheme

based route will form for each source (s) and destination (d) pair. The self-organisation process is based on local neighbourhood interaction, where each node is able to sense the load of the neighbouring node and determine the most appropriate gradient value. Once the gradient values are calculated for each node, the route discovery is based on selecting the highest gradient from the source to destination. Fig. 4 (a) illustrates the local node to node interaction, as well as the route formation. Through local node to node interaction, route $1 \rightarrow 4 \rightarrow 5 \rightarrow 6$ (Fig. 4 (a)) is initially formed for flow f_1 that is streamed at time $t = 1$. At time $t = 2$, a new flow f_2 is streamed and takes on the path $1 \rightarrow 4 \rightarrow 2 \rightarrow 3 \rightarrow 6$ (Fig. 4 (b)), in order to avoid the highly loaded node 5. Therefore, the route discovery process automatically adapts as the network load changes, and is able to react to changes in a timely manner, which is crucial for IPTV multimedia flows. Fig. 5 presents the route discovery from a 3 dimensional perspective and shows how the route discovery changes as new load are added to the network. The figure shows different paths taken as flow f_1 (Fig. 5 (a)), flow f_2 (Fig. 5 (b)), and flow f_3 (Fig. 5 (c)) are added to the network, and also shows how the gradient field in the network changes as each streaming session is established.

```
for $IPTV\ Provider\ k,\ k \in IPTV_j$ do
    for all $VoD_{C,k}$ do
        SUBSCRIBE TO NP($BW_{C,k}, EQ_{C,k}, t_{C,k}$)
        NP monitors $QoS_C$
        for all $t_C$ do
            NP calculates $MOS_{C,k}$ for IPTV Provider $k$
        end for
    end for
end for
```

Fig. 3. Federated IPTV Provider Resource Management algorithm



(a) Route of f_1 at t = 1

(b) Route of f_2 at t = 2

Fig. 4. Diagram of PGBR routing

A. Parameter definition

This section will present the various parameters of the PGBR route calculation. Before routing is performed between a source and destination pair, a hop-by-hop route discovery process is initiated. This is accomplished through the use of a discovery packet ($p_{d,(s \rightarrow d)}$) that migrates from hop to hop, selecting the link with the highest gradient value.

In order to support this process, the nodes must periodically calculate the gradient $G_{n \rightarrow m,d}(t)$ for the link between node n and m for destination d as follows:

$$G_{n \rightarrow m,d}(t) = \alpha \Phi_m(t) + \beta l_{n \rightarrow m}(t) + \gamma h_{m,d} \qquad (1)$$

where Φ_m represents the load of neighbouring node m, $l_{n \rightarrow m}$ represents the link load between node n and m, and $h_{m,d}$ represents the normalised hop count of node m to destination d. The α, β and γ are weight values for each respective variable.

Hop Count: The hop count value (h_j) determines how far each node is from a specific destination, and is stored in a table. The values are static, and only calculated during the formation of the topology. The process is never performed again unless the network topology is restructured (e.g. addition of new nodes). All the hop count values are normalized

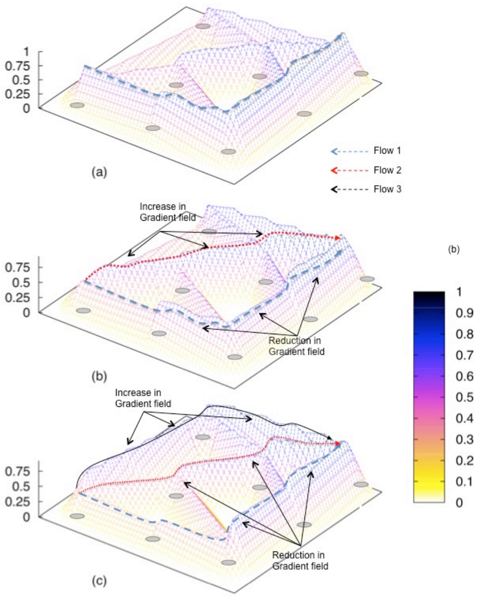


Fig. 5. Chemical gradient formation for route discovery

```
for node $n$ do
    if detect current load $> Threshold_{\Phi}$ then
        calculate $\Phi$
        emit $\Phi$ to neighbours
    end if
end for
```

Fig. 6. Algorithm of the node load calculation

between 0 to 1. We have developed an automated mechanism for creating the normalized hop count values during topology formation, and a full description can be found in [6].

Node load: The next component of the gradient equation 1, is the load of the neighbouring node (Φ). The load calculation is the ratio of free capacity to total capacity of outgoing links from the node, and is represented as,

$$\Phi_n(t) = \frac{\sum\limits_{n \to m} (l_{n \to m,F} - l_{n \to m,C}(t))}{\sum\limits_{n \to m} l_{n \to m,F}} \tag{2}$$

Each node contains i number of links. The full capacity of the link between node n and m is represented as $l_{n \to m,F}$, while the current load of the link is represent as $l_{n \to m,C}(t)$. The calculation of the load is based on a threshold, where once the load changes over a certain threshold, the node will calculate its load and emit this to its neighbour. The algorithm for this process is illustrated in Fig. 6.

The gradient is calculated based on the current link value, node load and hop count of neighbouring nodes. Therefore, the gradient value will dynamically change as the load of the link as well as the load of neighbouring node changes.

```
1:  for node $n$ do
2:      if receive $\Phi$ from neighbour $m$ then
3:          calculate $G$, $\forall\ l_{n \to k}$
4:      end if
5:      if link load change then
6:          calculate $G$, $\forall\ l_{n \to k}$
7:      end if
8:  end for
9:  for discovery packet $p_{d,(S \to D)}$ do
10:     $n$ receives $p_d$
11:     $n$ determines address $d$ for $p_d$
12:     $n$ selects highest $G$ to forward $p_d$
13:     $p_d$ records $n$ as $FN$
14:     if $p_d$ arrives back to n ($n \in FN$) then
15:         $p_d$ backtrack one hop to node $e$
16:         $e$ forward $p_d$ to next best $G$
17:     end if
18:     if $p_d > PL_T$ then
19:         route discovery is null
20:     end if
21: end for
22: if $p_d$ is successful then
23:     route stream
24: end if
```

Fig. 7. Algorithm for de-centralised routing

B. Routing algorithm

Our routing algorithm is illustrated in Fig. 7. Lines 1 - 8 (Fig. 7) describe the calculation of the gradient, which results from receiving information of node load changes from the neighbouring nodes or from link load changes in its own link. Lines 9 - 21 (Fig. 7) describes the path discovery process. As p_d traverses from node to node by hoping through the highest gradient link of each node, the packet records all the nodes during the path. The risk with the hop-by-hop transmission is when packets get caught in loops [31]. In order to eliminate this risk, the PGBR incorporates a mechanism to eliminate loops during the discovery process. During discovery, the p_d records all nodes into a Forbidden Node (FN) list. If p_d hops to a node that is already recorded in FN, the p_d will backtrack one hop and select the second highest gradient. In the event that another loop is encountered, then the third highest gradient will be selected. Fig. 8 illustrates an example of backtracking mechanism, where the p_d initially discovered path $1 \to 4 \to 5 \to 3 \to 2 \to 4$. Since node 4 has already been recorded into the FN, the p_d backtracks one node and selects the next highest gradient at node 2. Therefore, this leads to route $2 \to 6 \to 7 \to 8 \to 11$. The final route will be $1 \to 4 \to 5 \to 3 \to 2 \to 6 \to 7 \to 8 \to 11$.

The p_d will continue to discover new routes while the path length is below threshold PLT. Once the path length is beyond this, the route discovery is abandoned (Line 18 - 19: Fig. 7). Line 22 - 23 (Fig. 7) describes the mechanism when the route

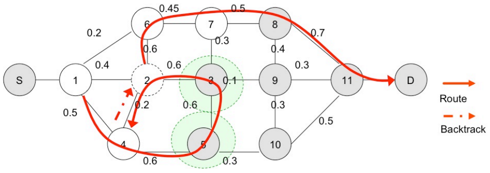


Fig. 8. Loop eliminating routing

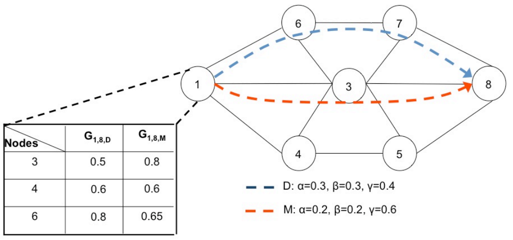


Fig. 9. Multi-traffic PGBR routing

is successfully discovered, where p_d will return to the ingress router, and route the new stream. The back tracking process is enhanced from the original PGBR algorithm [32], which allowed loops to occur during the discovery process.

C. Multi-traffic PGBR

In real deployment of IPTV contents, each content will have different QoS requirements (e.g. Standard Definition content may be different from High Definition content). Therefore, for the various different types of content stream, a different set of α, β, and γ should be applied to equation 1. An example is presented in Fig. 9. As shown in the figure, there are two different streams, where one is for multimedia and other for data. Each node contains a table with the gradient value of the next node with respect to the traffic type. As shown in Fig. 9, the multimedia stream, which has a higher weighting for hop count (γ) will tend to take the shorter path (which will lead to lower delay), while the data traffic will concentrate on even weighting of the link load and node load, leading to the paths on the outer-edge of the network. Therefore, this mechanism enables network providers to re-configure weightings depending on the type of contents, which in turn will lead to change in routing behaviour of the traffic stream.

In this section, we have described the PGBR distributed routing algorithm. The main functionalities of the PGBR routing algorithm is the local view taken by each node in creating the gradient formation for route discovery. Before streaming is performed, a route discovery is performed from source to destination, where the route discovery process has the ability to eliminate loops through a backtracking mechanism. Once the route is discovered, streaming will be performed. The main advantage of the PGBR routing algorithm is in its fully distributed operation, and capabilities to balance the network. At the same time, flexibility in routing behaviour can be modified by only adjusting α, β, and γ of equation 1. These capabilities will be evaluated in the simulation section.

TABLE II
TOPOLOGY PARAMETERS

No. of nodes	Connectivity	Avg. link capacity
20	0.1	100 Mbps
100	0.0198	100 Mbps
200	0.010	100 Mbps

TABLE III
DURATION AND PAYLOAD PARAMETERS

	Data	Multimedia
Duration (seconds)	2-8	20-80
Payload (kbps)	20-60	54-74

TABLE IV
PARAMETERS FOR ANTS ALGORITHM

Parameters	Value
Interval creation ants per node	50 ants/sec.
Initialisation period	10,000 ants/node
Source selection	Random (uniform)
Destination selection	Random (uniform)
Maximum age of an ant	255 hops

TABLE V
PGBR PARAMETERS

	α	β	γ
Data	0.2	0.4	0.4
Multimedia	0.2	0.2	0.6

V. SIMULATION

This section will present our simulation of the proposed solution. Section V-A presents the performance evaluation of the PGBR routing, while Section V-B presents the QoE evaluation comparison between PGBR and Shortest Path (SP) for multiple IPTV providers.

A. PGBR routing

This section presents the performance evaluation of the PGBR distributed routing algorithm. Table II presents the topology parameters, while Table III presents the traffic types parameters. In total, three different random topology sizes were used for the testing (20, 100, and 200), and the topologies are shown in Fig. 10. The simulation tests of the PGBR routing algorithm were compared to the SP and ANTS algorithm. The parameters used for the ANTS algorithm is presented in Table IV. Our simulation work performed in this section is extended from the work in [6].

The ANTS algorithm uses swarm intelligence to find the best route and also uses gradient based routing, where the gradients are set through pheromone trails. We used an ANTS version which modifies the pheromone table using age and delay based on the link load [33]. The parameters used for the PGBR data and multimedia flows are shown in Table V. Fig. 11 presents the performance evaluation comparison between the three algorithms. The performance metrics evaluated during the experiments include the average blocking probability, path length ratio, and network load balancing. The tests were performed by increasing the load on the network, where the traffic generated was based on a Poisson process. For the 20 node topology, a small variation in the blocking rate can be seen between the different algorithms, compared to the 100 and 200 node topology. This is due to the fact that PGBR has less maneuverability with small topologies, since one of the main advantages in PGBR is the ability to use both link and node load information which increases diversity in route discovery. However, we can still see that the blocking rate for the PGBR is lower compared to ANTS and SP as the number of requests rate increases. For the 100 node topology we can see a greater variation in the blocking probability, where the other solutions start blocking at approximately $40 - 50$ requests/s, compared to the PGBR (for both multimedia and data), which started at approximately 80 requests/s. When the network is highly loaded (at 100 requests/s), we can observe that the PGBR will have a maximum blocking probability of 0.15, while the other solutions will have a blocking rate of approximately 0.30. Fig. 11 (c) presents the blocking rate of the 200 node topology, and we can see that PGBR has a much lower blocking probability at very high load (0.05).

This shows that as the topology gets larger, the PGBR is able to utilize the spare capacity of the links much more efficiently during the route discovery process. Once again, this is due to higher maneuverability in discovering routes when number of nodes and links are high. This is also reflected in the ability of PGBR to make quicker local movements based on link load changes, as well as node load changes. At 200 nodes, the ANTS algorithm performed the worst, and the reason is because most of the ants will get lost during the route discovery process. Therefore, for both small and large topologies, we can see that the PGBR algorithm is able to utilize the resources in the network more efficiently.

The average path length ratio for the different algorithms is presented in Fig. 11 (d) - (f). This is calculated by finding the ratio between the actual length of the discovered path to the minimum hop count between the source and destination (minimum hop count is the ideal shortest path). The aim of this experiment is to observe the degree of deviation from the ideal length. We can see that as the load increases for all topology sizes, the average path length of the data flows gets larger (at 100 requests/s, the 100 node topology had 2.4 while for the 200 node topology this was 3.5). This is because the hop count value (γ) is set at 0.4, which results in most data flows concentrating on the less loaded parts of the network (e.g. outer edge of the topology), while the multimedia stream will concentrate on shorter routes in the centre of the topology ($\gamma = 0.6$). The objective of the PGBR algorithm is to allow the routes to use resource differently depending on their QoS requirements (e.g. data can have longer delay, while multimedia should have high capacity and small number of hops). In the 100 and 200 node topology case, we can see that PGBR (multimedia), SP, and ANTS algorithm loaded the network mostly in the centre parts of the topology (with the shortest routes) leading to path length ratio that is quite similar Fig. 11 (g) - (i) presents the network load balancing results for the three topologies. The approach used for computing the network load balancing is the ratio of the average loads in each node to the average load of the whole topology (therefore, for optimum load balancing, the value should be as close as possible to 1). As shown in the figures, the average network load balancing for PGBR improves the balance as the load increases for all topology sizes, where at the highest load (100 requests/s), we are able to achieve close to 0.87 network load balancing, compared to ANTS and SP. We can see that for SP, at 100 node topology, the network load balancing was approximately 0.4, while for the 200 node topology that value dropped to 0.2. In the case of ANTS algorithm, for the 100 node topology the average network load balancing was 0.3 and for the 200 node topology, this value dropped to 0.1. This means that for both these algorithms, as the topology gets larger the concentration of routes are in the centre of the network, which reflects the reason why the blocking probability increases as the load increased. On the other hand, the PGBR is able to adaptively discover new paths and balance the network in the same process leading to lower blocking probability and better network load balancing. Simulation tests have also been performed on the overhead of the PGBR routing algorithm, in particular the searching process. The results is presented in Fig. 12, where the tests were performed for different source - destination pairs (number of hops). The calculation includes calculating the sum of the number of hops in searching the paths S_{PGBR} and the backtracking path P_{PGBR} (please note the backtracking path

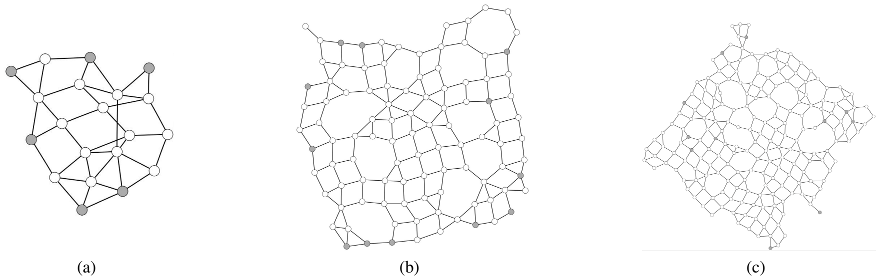
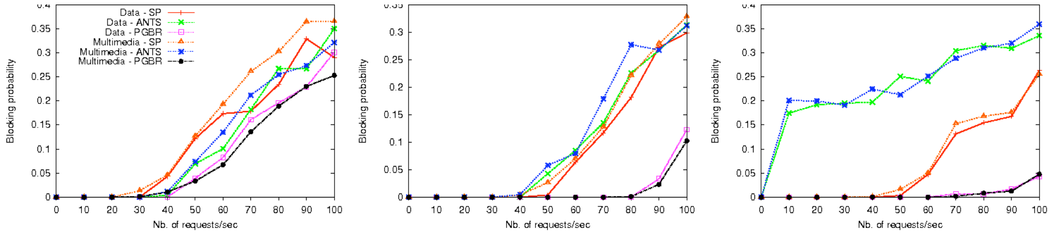
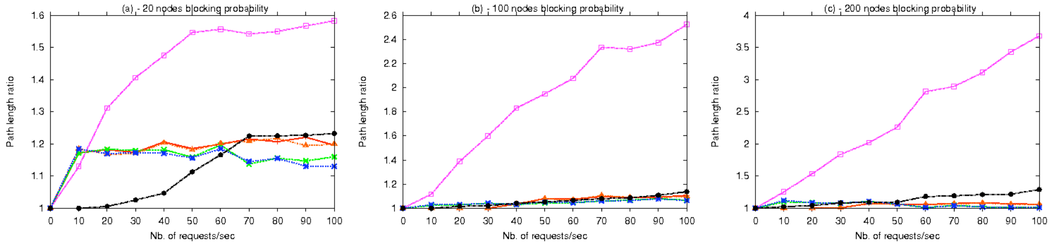

(a) (b) (c)

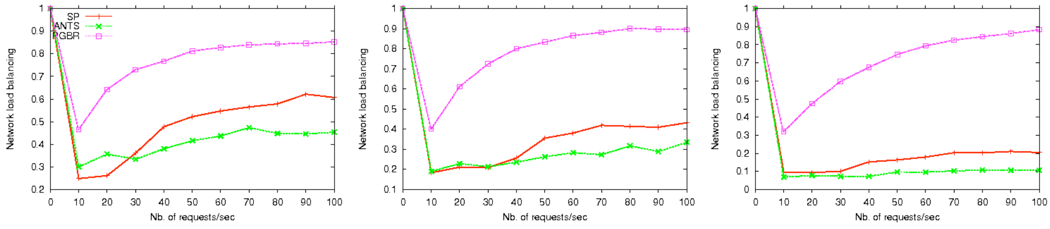
Fig. 10. Topologies used for simulation (a) 20 nodes, (b) 100 nodes, (c) 200 nodes



(a) - 20 nodes blocking probability (b) - 100 nodes blocking probability (c) - 200 nodes blocking probability



(d) - 20 nodes path length ratio (e) - 100 nodes path length ratio (f) - 200 nodes path length ratio



(g) - 20 nodes Network balancing (h) - 100 nodes Network balancing (i) - 200 nodes Network balancing

Fig. 11. Performance Evaluation between ANTS, Shortest Path and PGBR

is the path used for streaming, as this path eliminates all loops during discovery). The ratio of the sum to the shortest path ($(S_{PGBR} + P_{PGBR})/SP$) of that source - destination pair, will therefore give the overhead signalling of PGBR over SP. The ideal value is 2, which means that the sum of S_{PGBR} and P_{PGBR} is twice the hop count of SP. This value increases as the load of the network increases. However, we can see that this correlation value is relatively small at very high network load (e.g. 2.16 for average network load of 0.8). This indicates that the PGBR has a certain degree of directionality in the searching process, and does not lead to random route discovery when the network load is high.

The simulations tests performed here are different from the work presented in [6]. In the case of [6], we tested a single parameter sets for the two traffic types. However, in this paper we have applied different parameter set for the two traffic types for the same simulation scenario (but in [6] the two parameter sets were performed for different simulation scenario), and our aim is to show the impact of one traffic type over the other as we increase the load on the network. We can see that the blocking probability of data traffic is higher than multimedia traffic, but this gap is reduced as we increase the topology size. This is also reflected in the path length ratio, where we can see longer paths for the data traffic of PGBR compared to the multimedia traffic. Therefore, this shows that tuning the parameters can allow the different traffic types to automatically use differents parts of the networks but at the same time balancing the network in the process.

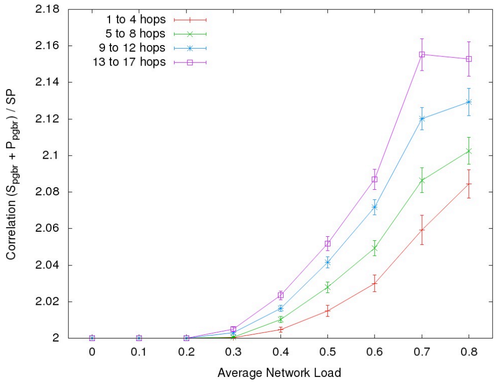


Fig. 12. Overhead of PGBR routing algorithm

B. *Shortest Path vs. PGBR for IPTV service distribution*

This section presents the performance evaluation of our Federated IPTV provider over a single network provider network described in Section III. Based on our algorithm in Fig. 3, the

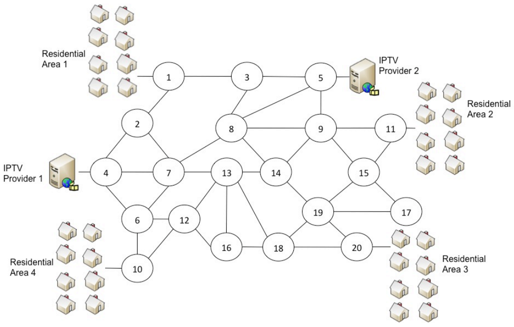


Fig. 13. Simulation Network Topology

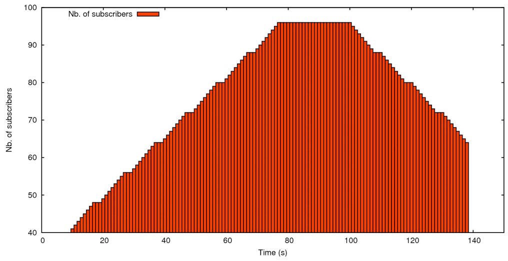


Fig. 14. Subscribers levels throughout simulation

number of IPTV providers j is two. Our scenario for this case study is a number of residential areas that contains customers subscribing to a service from one of the two IPTV providers. The purpose of the simulation was to carry out a comparison of the QoE between SP and PGBR when introducing additional flows to a network where the QoE of existing customers must be maintained, through avoidance of large scale packet loss. This process represents the MOS calculator of the resource management scheme in Fig. 2. The MOS calculator uses the QoE measurement that is monitored for each flow.

The network topology used in the simulation is shown in Fig. 13, indicating the location of the IPTV providers and residential areas within the network. As the simulation progresses and additional streams are introduced to the network, the majority of additional streams were those from the IPTV provider 2 to residential area 4. The purpose of this was to introduce additional traffic in a particular region of the network. As a consequence, certain links within the network will begin to approach their capacity and packet loss will occur. As additional streams are introduced, PGBR will be able to accommodate more of these additional streams than SP by using PGBR's route discovery process, while maintaining the QoE of the existing subscribers. This allows IPTV providers to increase revenues by allowing additional subscribers to access to their offered services, while ensuring that existing subscribers do not suffer any degradation in their service, thus affecting their QoE.

Two forms of video traffic were used for the simulation corresponding to two different video bit rates, 5Mbps and 4Mbps. Initially, the traffic load on the network was established using the 5Mbps flows and, as the simulation progressed, additional video flows were added in the form of the 4Mbps flows to emulate a higher level of compression for these flows. Video flows were modelled as constant bit rate flows. The flows are modelled using the MPEG Transport Stream (TS) format with an application layer payload of $1,316$ bytes per IP packet, corresponding to 7 TS packets each containing 188 bytes as is typically found in IP packets over Ethernet with a Maximum Transmission Unit of 1500 bytes. Links in the network were modelled as having a fixed bandwidth of 100Mbps, with the exception of the links directly from the IPTV provider into the network, which were given 1Gbps links so they could adequately support as many video flows as required by the simulation. These link rates coincide with the likely existence of Fast Ethernet and Gigabit Ethernet links in a real network. We believe that the results are scalable to larger bandwidths using either leased or dedicated links. Further work will be required to validate the approach in the face of contention with TCP based traffic to assess its "TCP friendliness" in an "over the top" deployment scenario.

As discussed above, the flows for the initial set of subscribers were established in the network at the outset of the simulation. As the simulation progressed, additional flows were added in a round-robin fashion to the residential areas. As discussed previously, in order to ensure that parts of the network were congested more than others, the following loading pattern was adopted. For each new set of flows originating from IPTV provider 2 (corresponding to new sets of subscribers), two of these flows would be delivered to residential area 4, two additional flows were also added alternating between residential areas 1 & 2 and 3 & 4.

Throughout the simulation, for each IPTV provider/residential area pair, network performance metrics for the video flows were monitored. In each residential area, two subscriber flows were monitored, one for IPTV Provider 1 (SP1) and one for SP2. The network metrics monitored were jitter, end to end delay, and PLR. From related work [8] it is known that once jitter and end to end delay were kept within a fixed range, as dictated by the size of the playback buffer, the effect of quality degradation was minimal. As a result, the primary factor affecting the video quality, and therefore QoE, is packet loss [34].

As the simulation progressed and packet losses began to occur, it was found that PLR experienced by subscribers were enough to disrupt the service to an extent where video playback became impossible to maintain. The histogram in Fig. 14 shows how the total number of IPTV subscribers in the network is increased during the simulation. The corresponding PLRs, calculated on a per second basis and video quality measurements are presented for monitored subscribers. Note that not all monitored subscribers experienced packet loss, due to the network topology and asymmetric load profile. As a consequence, results are only presented for monitored subscribers who experienced losses. The simulation was conducted using the Qualnet Network Simulator developed by Scalable Network Technologies [35].

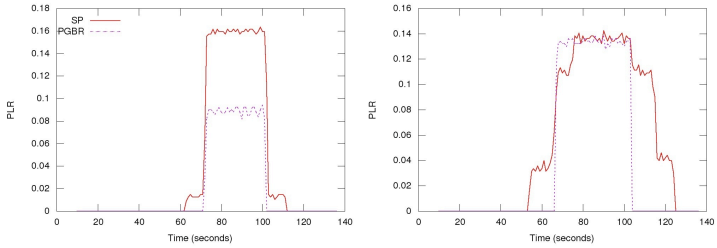
In order to measure video quality based on our Multiple IPTV Resource Managemen scheme (Fig. 2), a simplified version of the video quality metric presented in [36] is used for the Service Provider Monitoring Interface. Our evaluation is concerned with the analysis of simply the number of seconds where a Packet Loss Event (PLE) and thus video quality degradation occurred, within a given time. The reason for this simplification is two-fold;

- Once an error has occurred, the system will require some time to recover so that monitoring on a sub-second basis is not required.
- By simply flagging each second as containing an error or not simplifies the calculation so that a real time monitor could be embedded in a network node carrying a large number of streams and still be able to make a quality assessment for each stream.

For the purpose of our simulation the specified timeframe was 10 seconds as in [36]. The equation for the calculation of QoE at time n on a scale between 1 and 5 is presented below;

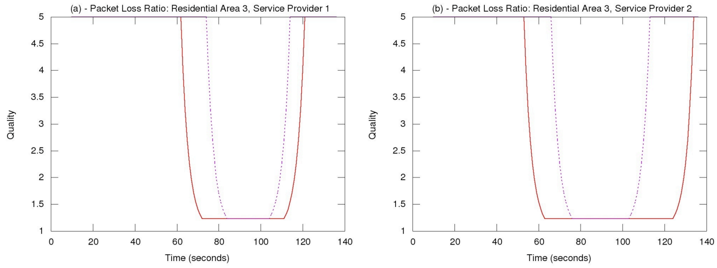
$$Q(n) = 1 + 4e^{-\frac{\sum_{n}^{n-9} PLE}{3.5}} \tag{3}$$

where PLE represents a boolean value indicating whether



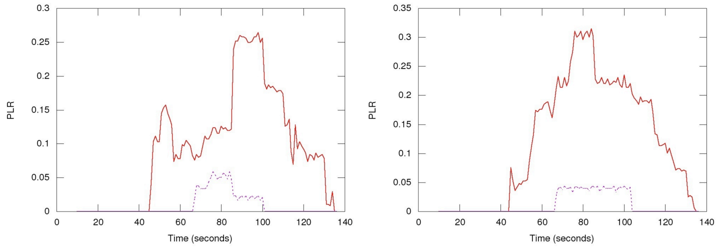
(a) - Packet Loss Ratio: Residential Area 3, Service Provider 1

(b) - Packet Loss Ratio: Residential Area 3, Service Provider 2



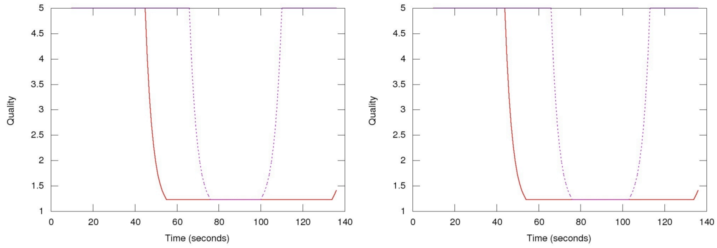
(c) - Video Quality: Residential Area 3, Service Provider 1

(d) - Video Quality: Residential Area 3, Service Provider 2



(e) - Packet Loss Ratio: Residential Area 4, Service Provider 1

(f) - Packet Loss Ratio: Residential Area 4, Service Provider 2



(g) - Video Quality: Residential Area 4, Service Provider 1

(h) - Video Quality: Residential Area 4, Service Provider 2

Fig. 15. Packet loss rate and video quality measurement results

TABLE VI
Additional Subscribers Supported

Residential Area	Service Provider	Additional Subscribers	% Increase over SP
3	1	1	9%
3	2	1	14%
4	1	5	25%
4	2	5	25%
total		6	17%

a packet loss event occurred for a given second. As packet loss events occur in succession, video quality and thus QoE decreases rapidly. The value of 3.5 used in the formula is used to represent the expected quality ($EQ_{C,k}$ from algorithm in Fig. 3) video stream as our scenario is not able to discern whether content is fast moving action content or footage with low spatio-temporal variation. Applying a weighting of 4 to the exponential, means that any encoder related imperfections are disregarded, so the MOS score relates purely to the network impairment. The histogram in Fig. 14 shows the piecewise linear increase in offered load measured as the number of subscribers admitted above the baseline of 40 subscribers. As can be seen in Fig. 15 (a) - (h), as the number of subscribers increases, certain links within the network become congested leading to losses of video content being delivered to subscribers.

We can see that using PGBR and it's route discovery process, the IPTV providers are able to add more subscribers to their services before PLE occurs. This benefits IPTV providers, while ensuring the QoE of existing subscribers is unaffected. This allows IPTV providers to maximise revenues through increased subscriptions without the need to lease additional bandwidth on existing links. Table VI summarises the additional number of subscribers that could be added using PGBR before PLE began to occur.

VI. Conclusion

As the Internet of the future moves towards service oriented environments, new challenges are emerging in efficiently managing communication systems. IPTV, in particular, is emerging as a popular service with its main focus of delivering various types of multimedia content (VoD and live streaming) to end users. As the IPTV market becomes increasingly competitive with multiple service providers operating over a common network infrastructure, new resource management challenges will emerge for the underlying network providers. This paper proposes a new resource management scheme that allows multiple IPTV providers to interact with the network provider, while ensuring that quality is maximised for end users. The scheme incorporates a new gradient based routing mechanism, PGBR, to deliver IPTV content over an IP network. A QoE monitoring mechanism is also incorporated into the solution to allow network providers to periodically update the IPTV providers to ensure that quality is maintained. The proposed solution has been validated through simulations, showing that the proposed solution outperforms other approaches, and in the cases reported here, can accommodate 17% more IPTV customers in the congested parts of the network when compared to shortest path routing.

Acknowledgment

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Appendix D: Management of Multiple Providers

Article VIII

Sasitharan Balasubramaniam, Julien Mineraud, Philip Perry, Brendan Jennings, Liam Murphy, William Donnelly and Dmitri Botvich

Coordinating allocation of resources for multiple virtual IPTV providers to maximize revenue

In *IEEE Transactions on Broadcasting*, vol. 57, no. 4, pp. 826–839, December 2011

Contribution: My contribution to this research paper is the adaptation of the Lotka-Volterra inter-species competition model to the allocation of resources for multiple service overlays sharing common resources. I was also responsible of conducting the experiments for the evaluation of the model. I also took part in the writing of that article.

Coordinating Allocation of Resources for Multiple Virtual IPTV Providers to Maximize Revenue

Sasitharan Balasubramaniam, *Member, IEEE*, Julien Mineraud, Philip Perry, Brendan Jennings, *Member, IEEE*,
Liam Murphy, *Member, IEEE*, William Donnelly, and Dmitri Botvich, *Member, IEEE*

***Abstract*—Network virtualization is seen by many as a key technology to help overcome some of the constraints of the current Internet architecture and help build a "human centric" Future Internet. As IPTV gains popularity, creating virtual networks for IPTV Service Providers can allow them to deploy specific protocol suites, routing algorithms and resource allocation strategies without affecting other IPTV providers that share the same underlying infrastructure. However, from the perspective of the underlying networking infrastructure provider (the "carrier") virtualization presents new management challenges, in particular how to efficiently and fairly allocate available resources to multiple virtual networks. In this paper we describe a framework in which management systems associated with virtual IPTV provider networks communicate with the management system of the carrier to provide coordinated resource allocation. The proposed approach allows policy-based management systems to control a bio-inspired resource management mechanism, based on species competition for biological systems, that a carrier can use to allocate resources to competing IPTV providers in a manner that maximizes the carrier's revenue. Results of a simulation study are presented, which show that this approach outperforms uncoordinated virtual network management approaches.**

***Index Terms*—Virtualization, Overlay Networks, Bio-inspired Approaches, Network Management, Service Management**

I. Introduction

Over the years, the Internet has continually attracted users through innovative and diverse services. One particular service that has gained tremendous popularity in recent years is IPTV [1], [2], [3], [4], [5], [6], [7]. For the purposes of this paper we consider the use of IPTV technology to provide a digital multimedia stream over the Internet through triple play, which includes data, voice, and video. The video streaming portion comes in a number of versions, ranging from standard definition to high definition for both video on demand as well as live streaming. The EU's "Digital Agenda" [8] predicts that, as the popularity of IPTV services grows, many small providers will enter the market to offer either specialist content or geographically relevant content. To lower the barrier to entry for such service providers the Digital Agenda expects to see an increased sharing of network resources which, in turn, will require low cost management systems to enable such services to be delivered effectively over these shared networks. Therefore, we will start to witness individual providers creating overlay networks on top of the carrier network. The carrier typically manages most of the resource management and routing control on behalf of the IPTV providers. However, in the days before IPTV, when traffic patterns were less dynamic, carriers were able to carry out these management tasks on a medium to long term basis, at minimal cost, and in a manner that provided adequate Quality-of-Service (QoS) levels.

As the number of IPTV users as well as the diversity of content increases, network operators will see significant increases in the volume and heterogeneity of traffic carried on their networks. One hugely significant trend is the growing volume of peer-to-peer [5] video streaming traffic, which many predict will soon become the dominant traffic type on the Internet. This is further exacerbated when the number of IPTV providers increases. For carriers, these trends mean it will be no longer tenable to employ only traditional medium to long term management techniques to support resource requirements of IPTV. They must augment these with techniques for dynamic allocation of resources to each IPTV provider (from here onwards IPTV service provider will be referred to as an IPTV-P) together with techniques to more frequently reconfigure the networking infrastructure (for example to support better routing plans for the current traffic demands).

Although a number of solutions have been developed for QoS-based routing (for example MPLS path management [9]), these solutions require modifications to underlying routers and are not suitable for frequent route re-configurations. Given this, a de-coupling approach is required to remove the management burden from the carrier network, whilst offering IPTV providers the ability to have much more control over how they deliver their services to their customers. This de-coupling approach is nowadays termed "network virtualization," with current virtualization techniques building on previous work on virtual local area networks (VLANs), virtual private networks (VPNs), active/programmable networks and overlay networks.

An illustration of virtual IPTV overlay networks is provided in Fig. 1, which shows two virtual IPTV overlays, one (IPTV 1) spanning more than one carrier network domain and the other (IPTV 2) spanning a single carrier network domain and sharing some of the underlying routers and links with

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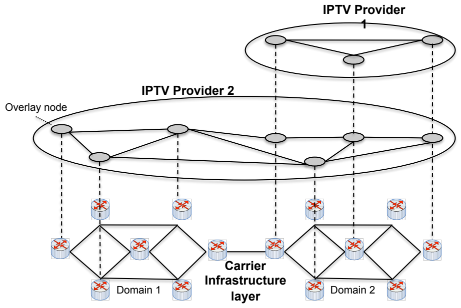


Fig. 1. Virtual IPTV-P overlay networks deployed over two carrier domains.

IPTV 1's virtual overlay. The creation of virtual IPTV overlay networks allows IPTV-Ps to deploy management systems that directly control path selection between specific source and destination pairs in order to satisfy particular sets of QoS metric targets relevant for the particular content. In times of high load the IPTV-P's dedicated management system can enforce differentiated flow admission control based on subscription profiles. For example, users subscribing to a "gold" package could be prioritized over users subscribing to "silver" or "bronze" packages.

Although a number of studies have investigated dual management of a single overlay and its underlying carrier network, investigation into management of multiple overlay networks sharing a common carrier is still in its infancy, and poses a number of research challenges [10], [11]. In this paper we focus on the following issues:

- How a carrier should allocate its resources to multiple IPTV-P overlays in a manner that:
  - ensures that the IPTV-Ps have sufficient resources to meet requirements; and that
  - maximizes the revenue generated for the carrier?
- How to supply IPTV-Ps with knowledge of the amount of resources (bandwidth) the carrier is allocating on a given path so that they do not over-use resources?
- How can IPTV-Ps request additional resources for paths when traffic demands increases?

We describe a framework, based on the policy-based network management paradigm [12], in which the management systems associated with IPTV-P overlays can communicate with the management system of the carrier to exchange such information, thereby collectively providing coordinated resource allocation for the overall system. We also specify and evaluate an approach based on the Lotka-Volterra species competition model, used in ecology to model the dynamics of resource consumption, in which the carrier allocates resources to competing IPTV-Ps in a manner that maximizes its own revenue.

The paper is organized as follows: §II reviews relevant related work on IPTV service provision and overlay network management. §III discusses IPTV-P overlay network deployments and highlights resource allocation issues. §IV provides an outline of our framework for coordinated IPTV overlay network management, describing how policy based network management systems can be federated to facilitate exchange of management information, and presents the Lotka-Volterra based coordinated resource allocation technique. §V describes the results of a simulation study that compares the proposed coordinated management approach with independently managed and unmanaged alternatives. Finally, §VI summarizes the paper and outlines areas for further work.

II. RELATED WORK

In this section we will discuss two key research areas that are relevant to the solution proposed in this paper, which are IPTV and overlay networks.

A. IPTV

As IPTV moves further towards the mass market, a number of different research domains have formed. An example of this is the work that interlinks IPTV to standardization activities outlined by Maisonneuve et al. [6]. These standardisation activities cover a wide range of aspects including approaches for service level monitoring that combines Quality of Service dimensions from the network and human perception of the delivered services. Lee et al. [4] presented an architecture for IPTV that has proved to be useful in enabling the research community to target outstanding issues with a common purpose.

Besides standardization and architecture development, a body of research work has also looked at network protocols and algorithms to support IPTV. Asghar et al. [1] minimizes the effects of congestion in IPTV networks using a connection admission control mechanism in the core combined with a real-time signalling mechanism to provide effective quality monitoring. The bandwith reservation protocol (RSVP) maximizes the resources usage while protecting the Video Quality Experience (VQE) of accepted users. When congestion occurs, incoming streams will be rejected so that existing streams will be preserved. The limitations of this mechanism is the unfairness of bandwidth sharing in the event of multi-class traffic or multiple IPTV-Ps coexisting in the network.

One major challenge that remains is the question of opening the use of IPTV beyond controlled network domains to bridge across administrative boundaries and still maintain control of service quality. The approach proposed by Kim et al' [3] is to use a service policy function to enable service quality monitoring data to adjust the routing and transportation of the IPTV stream. Davy et al. [13] describe two admission control algorithms based around estimating the effective bandwidth required to satisfy QoS targets for admitted IPTV flows. The approach employs a revenue-maximising algorithm that utilizes information relating to the price, duration and request frequency for different content items to make profit-optimal admission control decisions.

Other techniques have been developed to reduce bandwidth utilisation in parts of the network where the popularity of Video on Demand (VoD) content is high. For instance, De Vleeschauwer and Laevens [2] enhanced a caching technique by migrating copies of the content closer to future users based on the content's popularity. Lee et al. [5], used knowledge of network performance to optimize content caching location.

End to end quality adaptation techniques have also been developed so that the server can adapt the bit rate per VoD stream to improve network utilization without unduly sacrificing picture quality [7].

Therefore, as we can see that there are various approaches that can be adopted to improve the quality of delivered IPTV streams, whether this may include route adaptations or migration of contents between servers. However, if each IPTV-P adopts different approaches for managing resources, and in particular if these providers overlay on each other, this could create unbalance resource consumption, which in turn could affect the underlying carrier network. The solution presented in this paper addresses this potential problem, in particular from perspective of revenue.

B. Overlay Networks

In this section we review a number of studies that have investigated issues relating to management of both single and multiple overlay networks. One of the earliest works on overlay networks, was the Resilient Overlay Networks (RON) [14] approach. The objective of RON is to create a fault tolerant network that can route around failures with minimal disconnection time. The approach targets inter-domain network solutions, relying on underlying network routing protocols and providing QoS support for overlay paths.

Koizumi et al. [15] investigate the use of a three-layered overlay network, consisting of an overlay layer, a virtual network topology (VNT), and an optical layer. The authors investigate the effect changes at the VNT layer will have on the optical layer, looking in particular at link utilisation. The proposed solution introduces hysteresis to improve the stability between the two layers. Stability is improved by minimising the interactions between the layers so that the only interactions permitted have a significant impact on improving performance. Although this is shown to improve link utilisation in the optical layer, the technique would lead to high blocking rates for customers, which was not addressed in the study.

Chun et al. [16] evaluated the characteristics of overlay network routing using selfish nodes playing competitive construction games. In particular this is applied to multi-domain overlay networks, where nodes in each domain want to selfishly behave to maximize resources for its own domain. Keralapura et al. [17] investigate the co-existence of overlay ISPs network and underlying IP networks, in particular during network failures. The authors point out key challenges for multiple overlay routing. One such challenge is minimising physical link overload when simultaneous overlays perform re-routing. At the same time, the authors also discuss overlays for multiple domains, where route oscillations in a specific domain can affect and lead to oscillations of entire overlay paths.

Liebnitz et al. [18] propose a self-adaptive overlay network solution based on bio-inspired techniques. The mechanism is based on attractor-selection algorithm that considers the path quality. In the event of quality degradation, the path will automatically change to improve the application QoS. Liu et al. [19] investigate the effects of dual routing for overlay and underlay networks. The mechanism used is a two-player non-cooperative non-zero sum game with two separate objectives for each layer, where the overlay objective is to try to minimize delay of its traffic and the native layer's objective is to minimize network costs. Their results indicate that, in some circumstances, the interaction between the dual layers can lead to performance degradation due to conflicting objectives.

While numerous studies have investigated the stability of dual routing, including for multiple overlays, to our knowledge no studies have addressed techniques for managing the allocation of resources to multiple overlays so that carrier resources are utilized efficiently and overlay QoS targets can be met.

III. Multiple ISP Overlay Deployments

The basic deployment scenario for IPTV-P overlay networks is depicted in Fig. 2. The carrier owns and operates the underlying physical network infrastructure, selling resources (bandwidth between endpoints) to independent IPTV-Ps, who in turn sell triple play packages to their customers. Each IPTV-P consists of video servers that house VoD content, where these servers are linked to a router of the carrier network (e.g. a Video Serving Office (VSO) may be connected to router 1 of the carrier network, which is represented as $1'$ in the $IPTV\text{-}P_1$ overlay of Fig. 2). Each IPTV-P will have specific delivery points, and this is shown for example in Fig. 2 as $6'$ in the overlay layer, which represents egress router 6 of the underlying carrier. Therefore, for each of the overlay nodes, the IPTV-P can perform virtual overlay routing to deliver contents to the various egress points. Individual IPTV-Ps perform their own route calculation (for example using a link state routing protocol) in accordance with their measured or estimated traffic demand matrix. Since routing can be performed in the overlay layer, routes for the same source/destination pair may take different overlay logical link(s) as well as physical links. For example in Fig. 1, the overlay path of $IPTV\text{-}P_1$ from overlay node $1'$ to $6'$ may take path $O_{IPTV\text{-}P_1}(1',6')$, which could map to carrier path $P(1,6)$, while $O_{IPTV\text{-}P_n}(1',6')$ for $IPTV\text{-}P_n$ may take overlay paths $O_{IPTV\text{-}P_n}(1',4')+O_{IPTV\text{-}P_n}(1',6')$, which maps to carrier path $P(1,4)+P(4,6)$. In Fig. 2, IPTV-Ps do not deploy management systems for their overlay network, thus they are not able to perform prioritized admission control of traffic flows in high load conditions. In the paper we refer to this as the "unmanaged" IPTV overlay approach, or as "solution 1" ("S1").

Given that IPTV-Ps are not aware that the logical paths of their overlay are mapped to carrier paths that are potentially shared with traffic from other IPTV-Ps, there is a risk of over utilisation of the carrier links [10]. If the carrier has dimensioned the network properly this would usually not be a significant problem, however during link failure or high load conditions the operation of carrier and overlay routing algorithms can easily lead to oscillatory behavior known as route flapping, which significantly degrades customers QoS

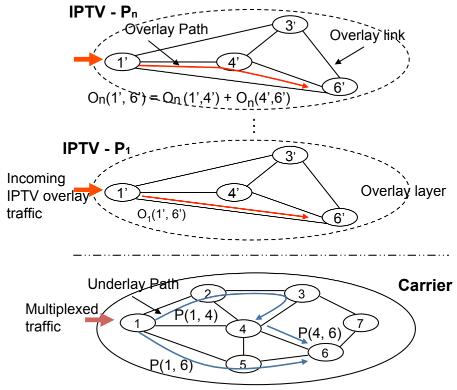


Fig. 2. IPTV overlay deployment with no management.

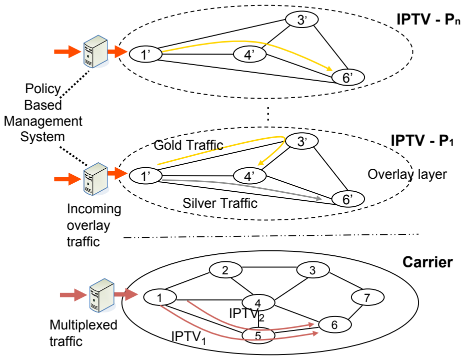


Fig. 3. Independently managed IPTV-P overlays.

[17]. From the perspective of the IPTV-P, the fluctuating availability of carrier resources can be mitigated through deployment of resource allocation techniques at the overlay layer. For example the deployment of a Policy-based Management System (PBM) [12], as depicted in Fig. 3 can allow each IPTV-P to deploy their own policies, where these policies may incorporate flow admission control which ensures that when demand outstrips the availability of resources, flows associated with more valuable customers are prioritized over flows associated with less valued customers [20]. For example in Fig. 3, $IPTV\text{-}P_1$ can use PBM to determine which overlay route a the traffic of a gold customer should take as opposed to traffic from a silver customers. In the event that load on the overlay links start to increase, then policies may indicate that traffic flows from silver customers should be throttled in order to ensure that gold customers' traffic continues to receive acceptable QoS. In the case of $IPTV\text{-}P_n$, a different overlay route may be taken for their gold customers.

In this paper we refer to this as the "independently managed" solution, or a "solution 2" ("S2"). A clear shortfall with this approach is that IPTV-Ps are limited to managing their own overlays only, they do not have visibility of the degree to which the underlying carrier resources they use are shared with other IPTV-Ps. On the other hand the carrier does not have the ability to adaptively allocate resources to individual IPTV-Ps so that the they can use its links without overloading them.

IV. COORDINATED MULTI-IPTV OVERLAY MANAGEMENT

In this paper, we seek to provide a solution for coordinated management of multiple ITPV-P overlays [21], [22]. The coordinated management proposed here is between the IPTV-Ps and the carrier, whereby the carrier allows IPTV-Ps to dynamically change the level of resources leased from the carrier. This offers the carrier the opportunity to maximize its revenue, whilst simultaneously ensuring that the collective behavior of the overlay networks does not lead to sub-optimal performance for any of the IPTV-Ps. To achieve this there must be communication between the management systems of the IPTV-Ps and the carrier, as depicted in Fig. 4. This communication would take the form of requests from an IPTV-P to the carrier for additional resources on a specified overlay path to meet changing customer demands for that IPTV-P's services. Following such requests the carrier may reallocate its resources between the IPTV-Ps it supports and will then inform them of the new allocations. This must be done within the constraints of the physical bandwidth available:

$$CP(a,b) \leq \sum_{n} CO_n(a',b') \qquad (1)$$

where $CP(a,b)$ is the capacity of the physical link between nodes a and b, while $CO_n(a',b')$ is the capacity of the overlay link for $IPTV\text{-}P_n$ between nodes a' and b'.

We assume that carrier and IPTV-P management systems use the policy-based network management paradigm, in which the behavioral rules for network management are separated from the code that realizes the functionality of given network devices. Policies are typically formulated as event-condition-actions tuples with the semantics of *"on event(s), if condition(s), do action(s)."* These rules can be specified by network administrators and deployed directly onto network devices (via configurations applied typically through command-line interfaces), or are maintained by independent *Policy Decision Points*, which specify actions to be enforced when notified of events by the network devices. Examples of the application of the policy based management paradigm in single administrative domains are discussed by Zhuang et al. [23] and Agrawal et al. [24].

In our framework we create a federated policy based management system, in which the actions resulting from policies triggered in the IPTV management system are interpreted as events which trigger policy evaluations in the carrier management system and *vice versa*. Policies allow system administrators to easily configure management system behavior; for example, an IPTV-P policy may contain a condition clause that indicates that the action of requesting additional resources from the carrier should only be executed if a certain threshold percentage of traffic flows for "silver" customers have been rejected by an admission control process within a given elapsed time interval. As depicted in Fig. 5 policies can

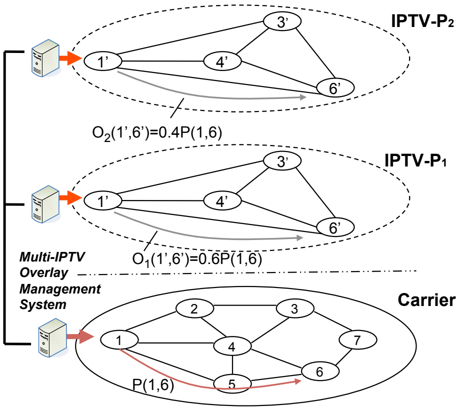


Fig. 4. Coordinated multi-overlay management system for overlay and carrier.

be separated into "internal" policies and "federated" policies, where the latter control interaction between the management systems. The internal policies can be tailored to suit each IPTV-P's objective (e.g. call admission), and this could be linked to federated policies (e.g. request for resource of a certain quantity). The federated policies govern when requests for additional resources are fowarded to the carrier.

In this paper we assume that all policies are specified in a single language and are related to a single information model, such that the syntax and semantics of the policy actions exchanged between the systems are interpreted correctly. However, incorporating policies that have different syntax and semantics for each IPTV-P is also possible, but semantic mappings between the systems will be required. This topic is out of the scope of this paper, but further discussion of how this can be achieved can be found in van der Meer et al. [25]. The next sub-sections will present details of our proposed solution. Initially we describe the process of resource allocation between the carrier path and the overlay virtual links. This will be followed by description of internal operations within the IPTV-P based on the resources allocated from the carrier, and the last sub-section will present the Lotka-Volterra competition model that is used to distribute resources between the physical path in the underlying network, and the overlay links.

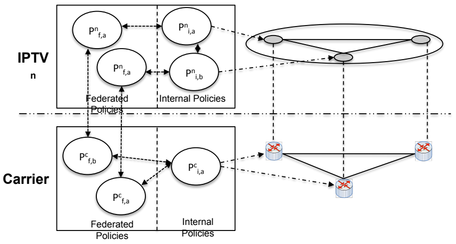


Fig. 5. PBM support for multiple IPTV overlay networks.

A. Carrier Path Resource Mapping to Overlay Virtual Links

As described in the introduction, one of the objectives of our solution, is to allow the carrier to allocate resources to each ITPV-P, so that each ITPV-P will be able to perform operations (e.g. re-routing at the overlay layer) without affecting the performance of other IPTV-Ps. In order to allow this level of stability, the carrier must have an accurate picture of each IPTV-P resource requirements, and accurately distribute the resources from the physical path in the underlying network to the virtual overlay links of the IPTV-Ps. We will explain this concept through an example presented in Fig. 7(a). In this example, there are two IPTV-P overlay networks sharing resources from a single carrier. Initially, the carrier determines the optimum path between different pairs of nodes in the carrier network. In this example, the optimum path of $P(1,3) = P(1,4) + P(4,3)$, and $P(1,2)$ and $P(2,3)$ are direct links between the nodes. This is then followed by each IPTV-P requesting resources between its overlay nodes from the carrier. For example if we have a particular link with $1 Gbps$ of capacity and two possible IPTV-Ps competing for resources, the bandwidth may be allocated at a ratio of 20:80 at some given instant of time. Therefore, for both $ITPV\text{-}P_1$ and $ITPV\text{-}P_2$, the carrier will map $O(1',3')$ to $P(1,3)$, $O(1',2')$ to $P(1,2)$, and $O(2,3)$ to $P(2,3)$ (this is triggered by $Policy\, P4$) shown in Fig. 7(a). Once the resources have been allocated, each overlay network determines the optimum routes at the overlay layer, as shown in Fig. 7(b) (dashed lines). Based on the resources allocated to the virtual links of each IPTV-P, $ITPV\text{-}P_1$ found the optimal path for $O(1',3')$ to be the direct virtual link between nodes $1'$ and $3'$, while for $ITPV\text{-}P_2$ the optimal path for $O(1',3')$ is $O(1',2') + O(2',3')$.

In this sub-section, we have only presented the process of mapping and allocating resources between the paths in the carrier layer and the overlay virtual paths. The mechanism of dividing the resources for each IPTV-P's overlay virtual link is based on the Lotka-Volterra model, which will be presented in Section IV-C.

B. IPTV-P Internal Operations

Once resources are allocated to the IPTV-Ps, each IPTV-P will be able to manage the resources according to its revenue objectives and users' service requirements. As described in the previous sub-section, each IPTV-Ps will be able to perform routing at the overlay layer. Therefore, if congestion is encountered on an overlay virtual link, the IPTV-P will be able to perform re-routing based on the resources allocated to it by the carrier, without having to be concerned that such operation may affect the performance of other IPTV-Ps. The decision to perform re-routing rather than purchase more resources could be based on some knowledge of the traffic behavior. The IPTV-P could evaluate the traffic pattern, and find that the resource previously purchased from the carrier is sufficient and does not require to bid for further resources. This also enables the carrier to maintain a certain degree of stability in the system, where the carrier is likely to configure its policies so that it will not immediately trigger a re-allocation

```
1: for all $IPTV\text{-}P_i$ do
2:     Update $CO_i(a',b')$ every $T_{ProbeIPTV}$
3:     if $CO_i(a',b') < C'_T$ then
4:         Recalculate overlay paths $O_i(a',b')$
5:     end if
6:     for incoming flow request $t_{c,i}$ do
7:         if $C_{IPTV_i} < Th_{IPTV_i}$ then Accept $t_{c,i}$
8:         else Accept $t_{c,i}$ with probability $P(c)$
9:         end if
10:    end for
11: end for
```

Fig. 6. Algorithm for internal IPTV-P Operation.

of resources every time it receives a request from an IPTV-P. Instead it could trigger re-allocations based on all requests received within a given interval—for example over the course of a day or a week. At the same time, if an IPTV-P has gold, silver, and bronze subscription packages (or similar) for their customers, prioritized admission control can be made for different subscription packages when resource become scarce. An algorithm to show the internal operation of the IPTV-P is presented in Fig. 6.

Initially, each $IPTV\text{-}P_i$ checks the current available capacity of its overlay links ($CO_i(a',b')$) every $T_{ProbeIPTV}$ seconds. In the event that an existing overlay path capacity $CO_i(a',b')$ between overlay nodes a' and b' is below a threshold C'_T, the IPTV-P will recalculate the path for $O(a',b')$.

Each $IPTV\text{-}P_i$ will calculate the load on the overlay network, and when the load exceeds the $Th_{IPTV\text{-}P_i}$ threshold, the $IPTV\text{-}P_i$ will select incoming traffic based on probability values for each subscriber package class c (lines 6-9). Fig. 7(c) presents an example of this process. The figure shows that each ITPV-P has performed a re-route for $O(1',3')$, which is triggered by the internal $Policy\ P_1$ of each IPTV-P. In this example, $Policy\ P_1$ triggers a re-route when the threshold of the overlay path approaches a certain threshold of the total overlay path capacity.

C. Lotka Volterra Model

Section IV-A presented the allocation of resources from the carrier path to the overlay virtual links. This section will describe the process of distributing the resources to each IPTV-P depending on their demand. This mechanism is through the Lotka-Volterra competitive symbiosis model [26]. We will first describe the Lotka-Volterra model, and describe how this model is used to coordinate resource management between the different IPTV-Ps.

The Lotka-Volterra model was developed to model the competition between multiple species competing for a fixed set of resources. Our application is inspired by the work of Kodama et al. [27], who applied it to management of TCP congestion. The Lotka-Volterra competition model is represented as:

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} = \varepsilon_i \left(1 - \frac{N_i + \gamma_{ij} N_j}{K_i}\right) N_i \tag{2}$$

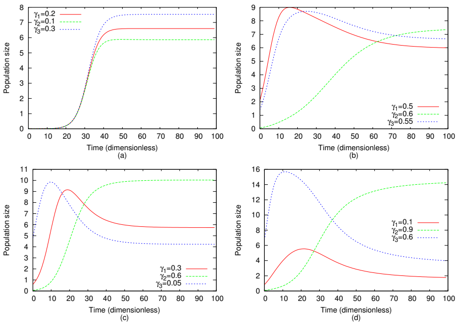


Fig. 8. Effect of varying competition in the Lotka-Volterra modes.

where N_i represents the type of species i, ε_i represents the growth rate, γ_{ij} represents the ratio of competition between species i and j, whilst K_i represents the carrying capacity of the environment. The species j could represent a total aggregate aggressiveness from the remaining species in the competition. Therefore, the model is not only limited to a single species, where Eq. 2 could represent the competition between species i and the total aggressiveness of remaining species, represented as j. The model represents the consumption of resources by different species depending on their aggressiveness. For species that are highly aggressive, the consumption of resources will be high compared with less aggressive species. However, the species are still able to co-exist symbiotically. Fig. 8 illustrates an example of how resources are being consumed for different competition (values of γ) between different species. In Fig. 8(a), when all species have low competition values, each consumes very similar quantities of resources. Similarly this could be seen in Fig. 8(b), where all species have medium aggressiveness. Fig. 8(c) shows a slightly mixed strategy, where low aggressive species will consume less compared to species with high aggressiveness. Fig. 8(d) shows this more clearly with wider range in aggressiveness between the different species. While the model shows transients behaviors, we only consider the final resource consumption once the model approaches steady-state.

In our application, the competition between the IPTV-Ps is analogous to the environment of competing species. IPTV-Ps must continually evolve to improve sustainability and meet continually changing environments (e.g. user demand). This is analogous to species that must survive and evolve by consuming resources in order to maintain survivability in face of any changes from the environment. We, therefore, express the competition models for virtual overlay link as:

$$\frac{\mathrm{d}IPTV\text{-}P_{CO_i(a',b')}}{\mathrm{d}t} = \varepsilon \left(1 - \frac{IPTV\text{-}P_{CO_i(a',b')} + \gamma_i P_{SC}(a,b)}{P(a,b)}\right) IPTV\text{-}P_{CO_i(a',b')} \tag{3}$$

where $IPTV\text{-}P_{CO_i(a',b')}$ represents the amount of capacity the carrier allocates to $IPTV\text{-}P$ from capacity of carrier path

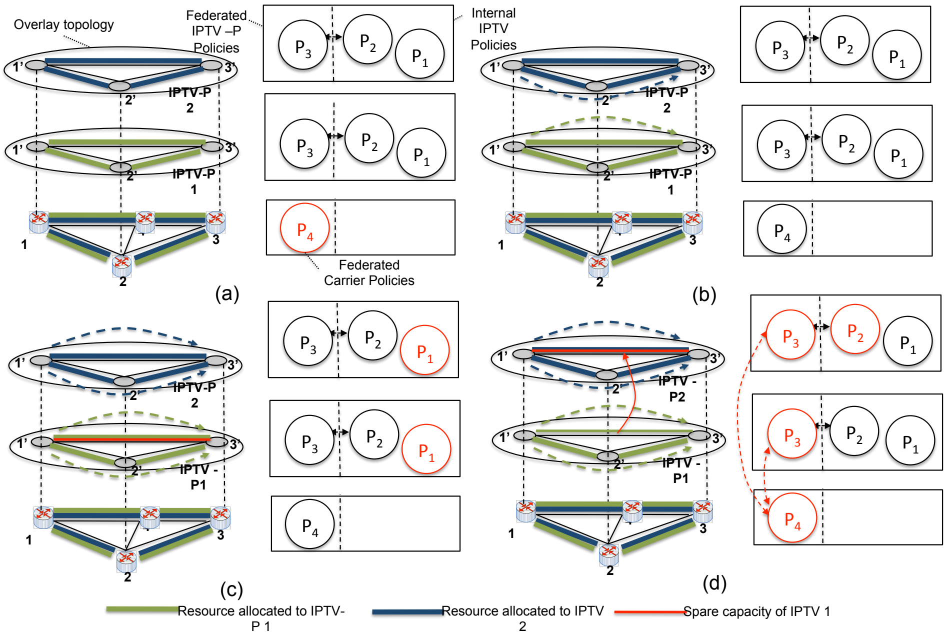


Fig. 7. Example of coordinated management of multiple overlay IPTV-Ps.

$P(a,b)$ for source-destination (a,b), $P_{SC}(a,b)$ the spare capacity of $P(a,b)$, and γ_i represents the competitiveness of $IPTV\text{-}P_i$. We assume a constant adaptation rate ε for each IPTV-P. The γ is dependent on a number of factors, which includes the demand from users and the amount of revenue (R_{G_i}) generated by the IPTV-P.

Fig. 9 presents the algorithm for the carrier resource management. Initially, the carrier calculates the optimal path between the nodes in the underlying network. The carrier is responsible for recalculating paths for all source and destination pairs when a certain path is loaded. Based on the overlay link $O(a',b')$ for $IPTV\text{-}P_i$, the carrier will distribute resources from the physical path $P(a,b)$ depending on the competition value $\gamma_{IPTV\text{-}P_i}$ of $IPTV\text{-}P_i$. All resource distribution is synchronously performed every T_{Car_update} seconds. Each IPTV-P is also not confined to their original competition status of resources from the carrier, where each IPTV-P can change their competition value $\gamma_{IPTV\text{-}P_i}$ to obtain new resources. The carrier will charge the IPTV-P a certain amount ($COST_{CH\_carrier}$) when the IPTV-P changes the $\gamma_{IPTV\text{-}P_i}$.

Through this approach, IPTV-Ps who wish to selfishly hold back unused resources will have to pay a higher price when the demand is high, leading to lower revenue. This solution provides scalability to large numbers of IPTV-Ps and also allows resources to be dynamically requested when the demand changes in accordance with IPTV-P policies. At the same time, the framework affords carriers the opportunity to minimize overloading physical links that are shared by overlay links of different IPTV-Ps.

```
for all carrier nodes do
    Calculate optimal routes
    for all $IPTV\text{-}P_i$ do
        if $IPTV\text{-}P_i$ changed its $CompStatus$ then
            Submit $\gamma_{IPTV\text{-}P_i}$ to carrier
        end if
        if $T_{Car\_update}$ timer expires then
            for all $O(a',b')$ from $IPTV\text{-}P_i$ do
                Determine $IPTV\text{-}P_{i,O(a',b')}$
            end for
        end if
    end for
end for
```

Fig. 9. Algorithm for carrier resource management.

Fig. 7(d) shows the federated operation of resource request. In this example $IPTV\text{-}P_2$ triggers *Policy P*2, which evaluates the historical traffic pattern and determines that extra resources is required from the carrier. Therefore, *Policy P*2 determines the amount of resources required and invokes *Policy P*3 which subscribes the resource from the carrier. The carrier notes that $IPTV\text{-}P_1$ is not fully utilising its resources, and since $IPTV\text{-}P_2$ is offering a higher bid (through $\gamma_{IPTV\text{-}P_2}$), decides to recall the unused resource from $IPTV\text{-}P_1$ and allocate this to $IPTV\text{-}P_2$.

V. SIMULATION STUDY

The simulation is divided to two sections: §V-A presents performance evaluation between three management approaches for the multiple overlay networks (unmanaged IPTV-P overlay (S1), independently managed IPTV-P (S2), and

TABLE I
Simlation parameters.

Parameter	Value
Network Topology	
No. Carrier Nodes	101
No. IPTV-P overlays	10 (6 moderate, 3 high intensity, 1 very high intensity)
No. nodes/IPTV-P overlay	15
No. source/destinations	28
Traffic Parameters	
Traffic Rate	80 requests/s (8% moderate, 12% high intensity, 16% very high intensity)
Average Service Time	$300s$
Flow Payload	$200\ Kb/s$
Selection Policy	
Selection Threshold	65% ISP load
Price (€$/Mb/s$)	Bronze: 0.07; Silver: 0.085; Gold: 0.11
$P(c)$ [moderate]	Bronze: 0.5; Silver: 0.6; Gold: 0.8
$P(c)$ [high intensity]	Bronze: 0.3; Silver: 0.6; Gold: 0.8
$P(c)$ [very high intensity]	Bronze: 0.5; Silver: 0.7; Gold: 0.95
Competition Model	
γ [moderate]	0.8
γ [high intensity]	0.5
γ [very high intensity]	0.5
Intensity Rate Charges (€$/Mb/s$)	
Moderate	0.025
High intensity	1.2 × moderate
Very high intensity	1.4 × moderate

Coordinated Multi IPTV-P Overlay Management system (S3); and §V-B investigates how adaptive changes of IPTV-Ps competition affect the revenue of other IPTV-Ps. The traffic parameters used for the simulation are created synthetically to simulate extreme conditions that IPTV-Ps of the future may encounter.

A. Static Competition

The parameters used for the simulation are shown in Tables I. We simulate three types of overlay IPTV-Ps, based on the number of requests generated by users in each, where the lowest traffic rate is categorized as *moderate*, medium traffic rate is *high intensity*, and very high traffic rate is *very high intensity*; this is also reflected in the ratio of incoming traffic, where out of 80 $requests/s$, 8% are allocated to each moderate IPTV-P, 12% to each high intensity overlay IPTV-P, and 16% to the very high intensity overlay IPTV-P. The selection policy parameters are based on the traffic rate intensity that is measured on each overlay network. In the event that the load reaches 65% of the capacity allocated by the carrier, the IPTV-P will begin admission control of incoming request based on probability $P(c)$. Also provided are the parameters for the competition model, where we allocated a range of load for each parameter range (e.g. light load as 0.8).

The simulator is implemented as a discrete time event simulation written in Java. The results shown in Fig. 10, indicate that the carrier gains the largest revenue using S3. Fig. 13 shows the very high intensity overlay IPTV-P gains the highest revenue with S3 compared to S2 and S1 (for Euros/sec earned). This is mainly because the IPTV-P has been allocated resources based on its requirement and therefore is able to maximize the resources subscribed to suit its requirements. This is also reflected in the throughput shown in Fig. 15, where S3 resulted in the highest throughput, followed by S2 and S1. At approximately time $t = 80s$, S1 has higher throughput than S2 and S3, and this is because of the selection process used by S2 and S3, which leads to limiting the amount of traffic admitted into the network. Since S1 indiscriminately allowed all traffic into the network early, this leads to higher loading of the overlay network. However, after $t = 150s$, S3 was able to admit more traffic, and this is due to the higher capacity allocated by the carrier.

The advantage of the competition model is also illustrated in Fig. 16, which shows the spare capacity of overlay path for a specific source-destination pair of very high intensity overlay IPTV-P. The graph shows the reduction in spare capacity as the path is loaded with respect to time. The load is the number of incoming requests for a specific overlay source and destination pair. The fluctuations indicate new path calculation events, when the old path is loaded to a certain threshold (in this case 90%). As shown in the figure, the use of competition model provides the resource that suits the intensity of the IPTV-P's traffic demand. In this case, the very high intensity overlay IPTV-P had the highest share, compared to the other IPTV-Ps at the initial stage of the simulation.

Fig. 12 shows that one of the high intensity overlay IPTV-Ps (all behave similarly) has a similar behavior to the very high intensity IPTV-P, although the revenue gained is not as high. The average throughput is shown in Fig. 14 and, as expected, the S3 throughput is less than S1 at $t = 80s$, again because of the selection process. However, as the network slowly gets loaded, S3 is able to gain higher revenue compared to S2 and S1. However, this behavior is not present in moderate overlay IPTV-Ps (Fig. 11), where the competition does not result in higher revenue compared to even distribution of resources provided by S2.

B. Adaptive Competition

This section will evaluate the performance of overlay IPTV-Ps when they adaptively change their competitive status. The scenario for the simulation is based on changes in traffic pattern, and the ability for the IPTV-P to change its competitiveness. The performance evaluation will compare the situation if the IPTV-P had adaptive competitive status compared to constant status (e.g. moderate or very high intensity), to measure the gain the adaptability provides. The change in

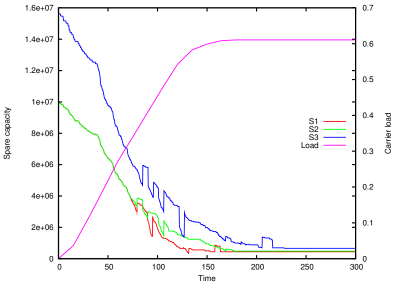


Fig. 16. Path capacity comparison between solution 1, 2 and 3.

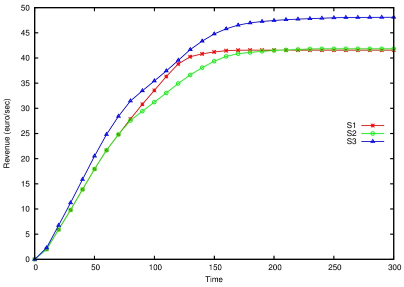


Fig. 10. Carrier revenue.

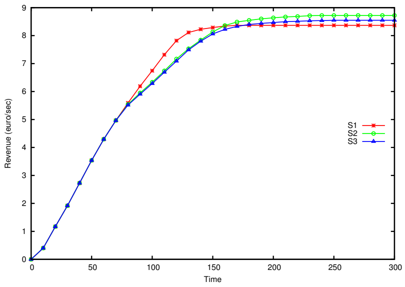


Fig. 11. Moderate intensity IPTV-Ps' revenue.

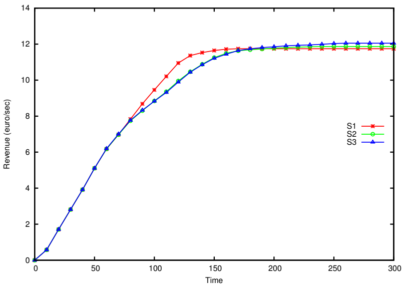


Fig. 12. High intensity IPTV-Ps' revenue.

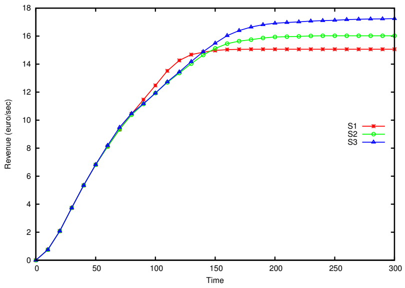


Fig. 13. Very high intensity IPTV-Ps' revenue.

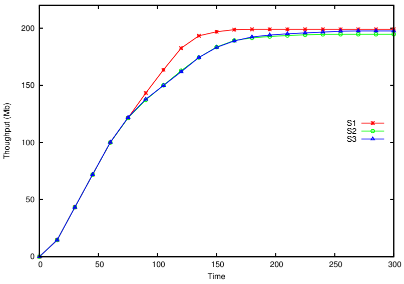


Fig. 14. Average throughput of high intensity IPTV-Ps.

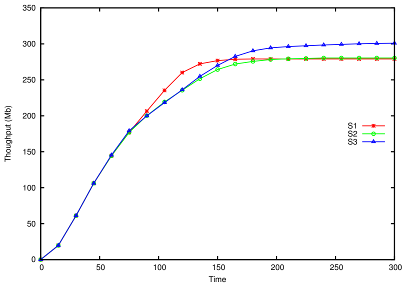


Fig. 15. Average throughput of very high intensity IPTV-Ps.

traffic pattern will be performed based on time zones, where a certain request rate stays constant during the time zone, but changes as it transitions between the time zones. For scenario A there are three time zones, while scenario B has 6 time zones. Scenario A will evaluate the effect a single IPTV-P (IPTV-P 7) with adaptive competitive status will have on other IPTV-Ps which have constant competitive status. Scenario B will evaluate the effect of the system when there are multiple overlay IPTV-Ps adaptively changing their competitive status. The internal policies of the IPTV-Ps are as follows:

- **Policy$_{1,\textbf{IPTV-P}}$**: When the measured load of the IPTV-P reaches a certain threshold, trigger prioritized call admission (call admission is based on probability presented in Table I).
- **Policy$_{2,\textbf{IPTV-P}}$**: When the measured path load of the IPTV-P reaches a certain threshold, if traffic pattern is stable, then re-route.

The federated policy for the IPTV-Ps is as follow:

- **Policy$_{3,\textbf{IPTV-P}}$**: In the event of changes in traffic demand, determine new resources required and submit new $\gamma_{IPTV\text{-}P,i}$ value to the carrier.

As described earlier, the carrier is responsible for determining the most appropriate resources for each IPTV-P using the Lotka-Volterra model. The methodology is based on dynamically changing prices for the resources, depending on the competitiveness and demand of resources from all IPTV-Ps. Therefore, during peak periods, resources will be charged higher as the demand increases. The internal policy for the carrier is as follows:

- **Policy$_{1,\textbf{Carrier}}$**: If underlying network path load reaches a certain threshold, perform re-route calculation.

The federated policy for the carrier is as follows:

- **Policy$_{2,\textbf{Carrier}}$**: Every T_{Car_update}, recalculate the resources

TABLE II
Number of requests/second for each IPTV-P (scenario A).

	Zone 1:0-150s	**Zone 2:150s-300s**	**Zone 3:300s-450s**
IPTV-P 1	12.8	19.2	12.8
IPTV-P 2	9.6	12.8	9.6
IPTV-P 3	9.6	12.8	9.6
IPTV-P 4	9.6	12.8	9.6
IPTV-P 5	6.4	11.5	6.4
IPTV-P 6	6.4	11.5	6.4
IPTV-P 7	6.4	19.2	6.4
IPTV-P 8	6.4	11.5	6.4
IPTV-P 9	6.4	11.5	6.4
IPTV-P 10	6.4	11.5	6.4

for each ISP depending on their latest $\gamma_{IPTV\text{-}P,i}$ value.

1) Scenario A: This scenario uses the same topology and payload configuration detailed in Table I , but with average service time of $20s$ and request arrival rates for the individual IPTV-Ps as shown in Table II.

The simulation is separated in three time zones, where each zone shows the traffic rate (requests/second) for each IPTV-P.

The scenario starts in zone 1 ($t = 0 - 150s$) with IPTV-P 1 having very high intensity status, IPTV-Ps 2, 3, and 4 having high intensity, and the other 6 IPTV-Ps having moderate intensity. At zone 2 ($t = 150 - 300s$), IPTV-P 7 changes its status to very high intensity; it then changes its status back to moderate in zone 3 ($t = 300 - 450s$).

Fig. 18(g) shows the gain of IPTV-P 7 when it is in adaptive status compared to constant very high intensity and moderate intensity. Therefore, this illustrates the improvement adaptive status has over constant status when the traffic behavior changes between zones. Fig. 17 presents the progressive revenue with respect to time for IPTV-P 7. As shown in the figure, the total revenue of the adaptive status gives the highest revenue compared to constant moderate and very high intensity. The performance of this adaptive regime is compared to two static regimes, one where IPTV-P 7 adopts a moderate intensity state and the other where IPTV-P 7 adopts a very high intensity state for the duration of the simulation. Results of these simulations are shown in Fig 17. They all show a loss of revenue compared to when the IPTV-P 7 adopts a static moderate state.

Fig. 18 also presents the results of revenue comparison between the adaptive, constant moderate, and constant very high intensity status of IPTV-P 7, and its effect on the performance of other IPTV-Ps. The green shaded areas in Fig. 18 shows the gain each IPTV-P makes when IPTV-P 7 has a adaptive competitiveness compared to constant very high intensity, and the red area shows the gain each IPTV-P makes when IPTV-P 7 has an adaptive competitiveness compared to constant moderate status. For example in Fig. 18(a), IPTV-P 1 (with constant very high intensity status) shows that in zone 1 and 3, it is able to receive higher revenue if IPTV-P 7 had an adaptive status. Although zone 2 would yield higher revenue if IPTV-P 7 had a constant moderate intensity, the overall revenue gain is higher if IPTV-P 7 is adaptive. Fig. 18(b)-(d), shows the impact of IPTV-P 7's adaptive status to the IPTV-P's 2, 3, and 4's high intensity status. Similar to IPTV-P 1's performance, the overall revenue is high when IPTV-P7 has an adaptive status, even though zone 2 showed a higher revenue gain if IPTV-P 7 had a moderate status. Fig. 18(e)-(f) and Fig. 18(h)-(j) shows that if IPTV-P 7 had an adaptive status, the moderate IPTV-Ps benefit with higher revenue overall only in zones 1 and 2.

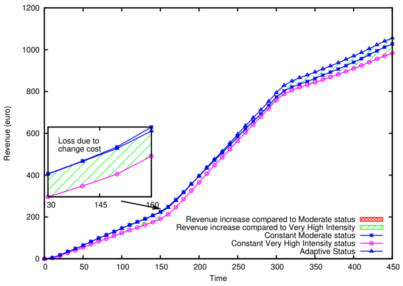


Fig. 17. Progressive Revenue comparison between adaptive status to constant moderate and very high intensity status.

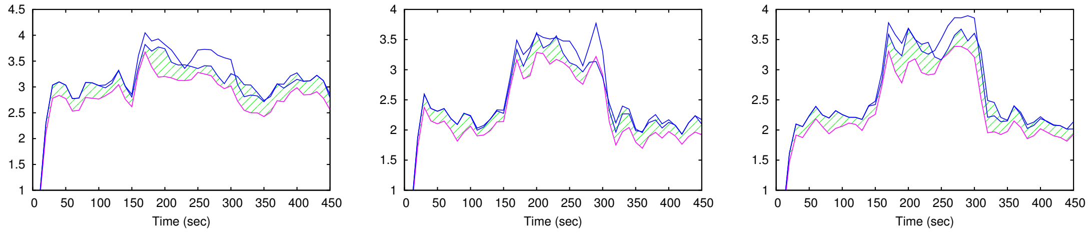
All results in Fig. 18 show reduced revenue if IPTV-P 7 adopts a very high intensity state as the red line is always lower than the blue. The adaptive regime reduces this loss and increases the revenue for IPTV-P 7.

2) Scenario B: Unlike the previous scenario, where only a single overlay IPTV-P changed its status, this scenario considers a number of overlays changing their status through 6 time zones. The number of requests for each zone for each IPTV-P is shown in Table III. The scenario for the multiple IPTV-Ps changing their status is based on IPTV-Ps 1-5 increasing their traffic demand at different rates (IPTV-P1 increases at the highest rate, followed by IPTV-P2, and IPTV-P3, 4, and 5 increases at a lower rate). IPTV-Ps 6-10 had a reasonably constant traffic pattern. Fig. 17 shows the revenue performance of all the IPTV-Ps., whilst Fig. 19 shows the revenue performance of individusl IPTV-Ps. As shown in the figure, IPTV-P 1 which had the highest aggressiveness, yields the highest revenue with the adaptive status, compared to constant high intensity and moderate intensity.

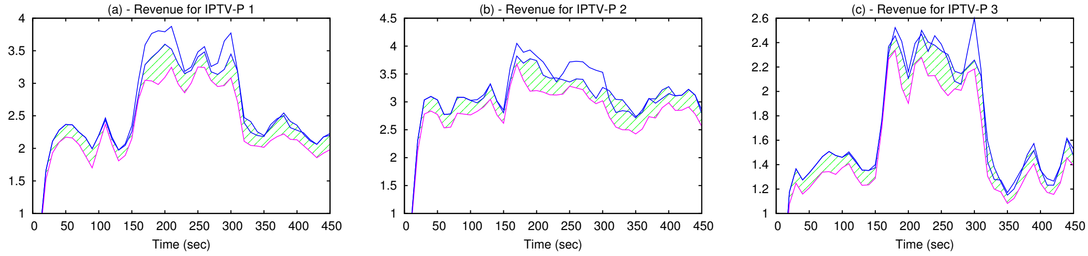
As shown in the figures, IPTV-P 2-5 also benefit from adaptive status as their traffic rate increases from zone to zone. This is especially shown towards the latter zones (e.g. zone 5-6). IPTV-Ps 6-10 demonstrate with a relatively constant revenue rate due to the relatively constant traffic pattern throughout all the time zones (as shown in Table III). The initial time zones, show that the IPTV-Ps benefit from the adaptive status (although the performance fluctuates tremendously). The most significant result is that the resources have been shared in a way the yields good revenues by using the policy driven species competition model.

VI. Conclusion

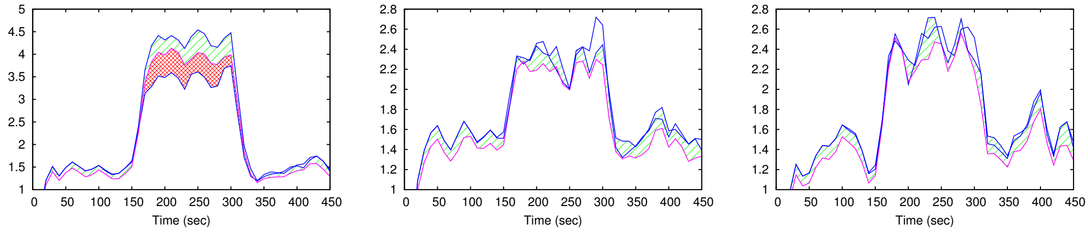
As the popularity of IPTV increases, the underlying communications infrastructure of the Internet will see an increase in virtual IPTV-Ps sharing resources over the carrier networks. This paper has presented a framework, based on the policy-based network management paradigm to manage coordinated



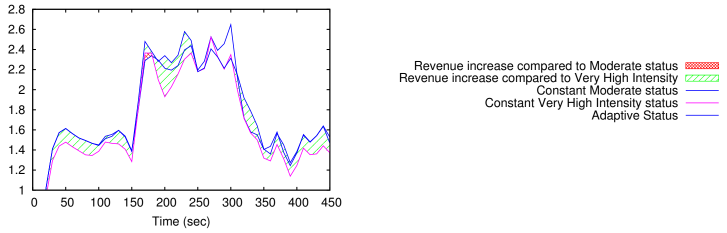
(a) - Revenue for IPTV-P 1 (b) - Revenue for IPTV-P 2 (c) - Revenue for IPTV-P 3



(d) - Revenue for IPTV-P 4 (e) - Revenue for IPTV-P 5 (f) - Revenue for IPTV-P 6



(g) - Revenue for IPTV-P 7 (h) - Revenue for IPTV-P 8 (i) - Revenue for IPTV-P 9

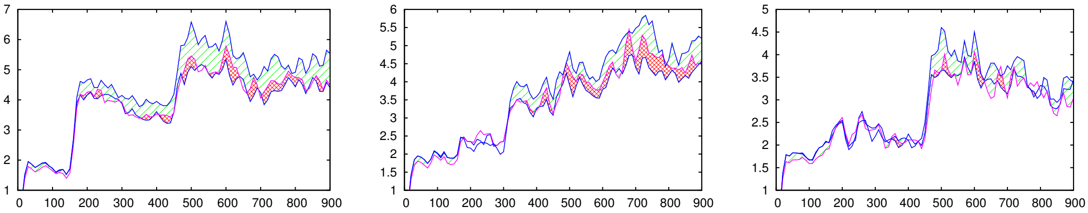


(j) - Revenue for IPTV-P 10

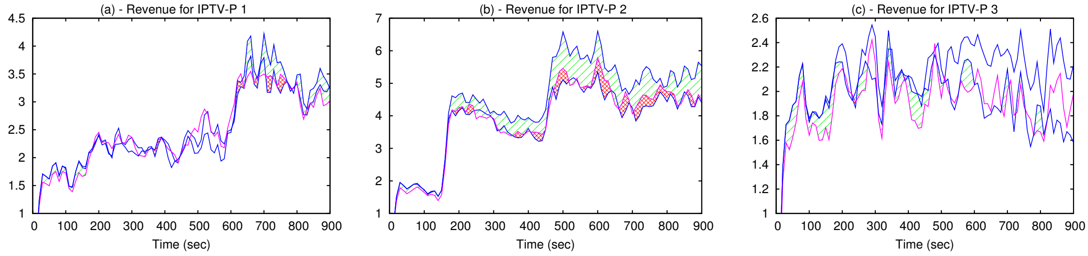
Fig. 18. Revenue for Scenario A (y-axis is €/s).

TABLE III
Number of requests/s for each IPTV-P (Scenario B).

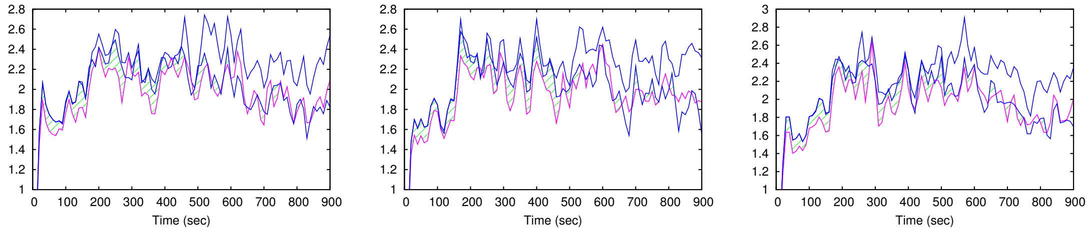
	Zone 1: 0–150s	**Zone 2: 150s–300s**	**Zone 3: 300s–450s**	**Zone 4: 450–600s**	**Zone 5: 600s–750s**	**Zone 6: 750s–900s**
IPTV-P 1	12	18	16.8	27.2	24.8	24
IPTV-P 2	12	11.3	16.8	20	24.8	24
IPTV-P 3	12	11.3	13.3	20	18.4	17.6
IPTV-P 4	12	11.3	13.3	13.3	18.4	17.6
IPTV-P 5	12	11.3	13.3	13.3	12.27	17.6
IPTV-P 6	12	11.3	13.3	13.3	12.27	11.84
IPTV-P 7	12	11.3	13.3	13.3	12.27	11.84
IPTV-P 8	12	11.3	13.3	13.3	12.27	11.84
IPTV-P 9	12	11.3	13.3	13.3	12.27	11.84
IPTV-P 10	12	11.3	13.3	13.3	12.27	11.84



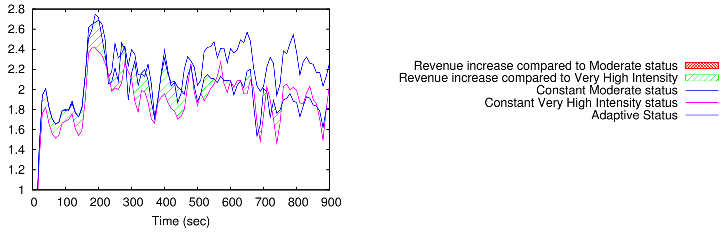
(a) - Revenue for IPTV-P 1 (b) - Revenue for IPTV-P 2 (c) - Revenue for IPTV-P 3



(d) - Revenue for IPTV-P 4 (e) - Revenue for IPTV-P 5 (f) - Revenue for IPTV-P 6



(g) - Revenue for IPTV-P 7 (h) - Revenue for IPTV-P 8 (i) - Revenue for IPTV-P 9



(j) - Revenue for IPTV-P 10

Fig. 19. Revenue for Scenario B (y-axis is €/s).

multi-IPTV-P overlay networks. The proposed solution allows the carrier to fairly distribute resources to individual IPTV-Ps based on their demand and competitiveness with respect to other IPTV-Ps. Through the environment of competitiveness, the system shows improved revenue for the carrier and for the IPTV-Ps with high and very high traffic intensity. At the same time, the coordinated resource distribution, allows each IPTV-P to efficiently manage resources without affecting the performance of other IPTV-Ps. A simulation study was conducted to compare the superiority of the coordinated management systems with unmanaged and independently managed overlay IPTV-Ps. At the same time, the study also evaluated the effects of IPTV-Ps changing their competitive status, and the impact this has on other IPTV-Ps.

The results show that the proposed framework can use a bio-inspired species competition approach to implement policy driven resource management. This approach shows a robust method to enable network virtualization and federated network management. While the solution presented in this paper is only limited to a single carrier domain, the solution can definitely be extended to multiple domains through federated management systems as outlined in [28].

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Appendix E: Simulation Environment

Article IX

Julien Mineraud

An implementation of Parameterised Gradient Based Routing (PGBR) in ns-3

In the proceedings of the *Network Operations and Management Symposium Workshops (NOMS Wksps)*, 2010 IEEE/IFIP, pp. 63–66, April 2010

Contribution: I was the only contributor of this research paper.

An Implementation of Parameterised Gradient Based Routing (PGBR) in ns-3

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***Abstract*—This paper presents an implementation of the PGBR routing protocol within the ns-3 simulator. Broadband convergence networks can offer a solution for multiple service classes through integrated heterogeneous networks. However, to prepare this for the future variability in traffic demand, a dynamic routing protocol that enhances scalability, QoS awareness, and easy roadmap to deployment if necessary. The implementation using ns-3 simulator can ensure this capability.**

I. INTRODUCTION

Future broadband convergence networks will see integration of multiple communication systems (e.g. WiFi, core networks), supporting various traffic types that are managed by different providers (e.g. service providers, network providers). This will lead to highly complex network architectures that must be able to support increasing number of services while ensuring that resources of the network are managed efficiently. The Future Internet research is seeking new solutions that address a new Internet architecture that can meet these requirements and allow flexible support for future expectations of the Internet. In particular, one of these requirements that requires attention is a new routing algorithm for the Future Internet that can implicitly minimise network management overhead while ensuring sufficient resources to meet growing end-user's needs. An autonomic, scalable and distributed routing technique is needed to have access to the full capacity of the network resources.

Balasubramaniam et al [1] defined a routing technique that fulfill these requirements while offering support for different traffic types through flexible parameter configuration. This routing solution is known as Parameterised Gradient Based Routing (PGBR) protocol which is a flow-based routing protocol. A flow represents a sequence of packets which belong to the same service request, and a flow generates a certain bitrate, has a specific duration and belongs to certain traffic types, such as those defined by DiffServ [2]. Several studies has been done in the area of flow awareness, but the focus is only on queueing management and/or control admission [3].

Balasubramaniam et al explored the PGBR solution by building a flow-based routing algorithm. They designed a flow-aware discrete-event routing simulator in Java that handles a sequence of traffic requests events. The simulator and PGBR are not accessible to the wider research community desiring to use the capabilities offered by PGBR. In order to create a good impact of PGBR for future networks, implementing this in a suitable simulator is necessary. Ns-3 [4] is a new open-source project, under GNU GPLv2 license [5], and represents the next generation of communications network simulator, and has been designed to facilitate the use of code for simulation and experimentation. The simulator, which is not compatible with ns-2 [6], has been inspired by many advantages of several open-source simulator, and uses the experience gained from their development to build a robust architecture. This paper will present a development implementation plan for the PGBR routing algorithm.

The next section presents a comparison overview of the ns-3 to other standard network simulator. Section III presents a short description of the PGBR routing algorithm, and this is followed by a description of the PGBR implementation architecture in ns-3. Lastly, section V presents the conclusion.

II. COMPARISON OF NS-3WITH OTHER NETWORK SIMULATORS

The development plan for PGBR is to implement the algorithm in an open-source simulator. Therefore, commercial simulators, such as OPNET [7] (even though, research licences are available), were not considered for the implementation of PGBR.

Weingärtner et al [8] compared five different open-source simulators: ns-2, ns-3, OMNet++, SimPy and JiST/SWANS [4], [6], [9]–[11]. The authors describe ns-2 as a network simulator with large number of models available, but is not scalable, presents memory usage inefficiency and extensive simulation run-time. The memory usage problem has been investigated with the concept of parallelisation. Similarly, SimPy is not efficient when it comes to scalability. Since PGBR is aiming to be a scalable routing protocol solution, it will not be appropriate for ns-2. JiST is a Java-based simulator and has the best simulation run-time results, but poor memory management as the topology's size increases. OMNet++ represents a good solution with good performance results, and provides large number of models with a GUI.

Ns-3's architecture has been designed to allow easy transition to real network deployment, which is not supported with many existing network simulators. According to the ns-3 manual, the benefits of ns-3 includes:

- minimises changes to the core of the simulator, which allows easy extensions for new types of packet headers or trailers

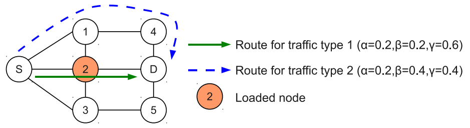
- maximises the ease of integration with real-world code and systems
- improves scalability for simulating large number of nodes
- improves memory management
- implementation in pure C++ provides an easier debugging
- allows easy transition to real testbed implementation

One feature of ns-3 is the ability to tag packets, which allows cross layer information without modifying the current packet header. As an example, if additional information is needed for a future version of PGBR, the use of tags on the packet will allow the future implementation of PGBR to be aware of those cross-layer information without disrupting the current architecture. Emulation allows ns-3 simulation to send data to a real-world network device, and as described earlier, allows easier integration into testbed and virtual machine environments. An example test-bed used by ns-3 project to test the integration of ns-3 into real network equipment is the ORBIT test-bed [12].

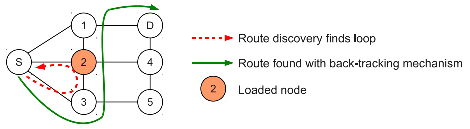
III. PARAMETERISED GRADIENT BASED ROUTING

This section will present a short summary of the PGBR algorithm, where the details of the algorithm can be found in [1]. An illustration of the PGBR routing algorithm is shown in Fig. 1. The routing protocol is based on attraction from a source to destination, where the packets of flows would migrate from node to node, sniffing the link with the highest gradient. There are two processes to the PGBR routing process. First is the discovery process, where a discovery packet is sent from a specific source to destination to discover the path. Once the packet discovers a suitable path to the destination, it will return back to the source. This will then lead to the second process which is the routing of the flow. The flow will then follow the path that was discovered by the discovery packet. The calculation of the gradient is based on a function that consider three components: (1) the load of the link to the neighbour node, (2) the relative distance of the neighbour node to the intended destination (this is a normalised value and is static, where it is calculated only when the topology is built), and (3) the load of the neighbour node. By combining these three components through a weighted sum, a gradient value is obtained. The node load information of the neighbour is not accessible directly, where a local communication has to be established between neighbours. Nodes which aggregated the PGBR discovery technique broadcast periodically one hop messages to their neighbours about their current node load.

The back-tracking mechanism (e.g. Fig. 1b) is another feature of PGBR, and is necessary due to the probability of the gradient based routing creating loops when the network is subject to heavy load. A PGBR node must be able to analyze the content of the discovery message (containing the visited hops and identification number of the discovery packet). If the discovery message is processed for the second time by a node, it will direct the message to the second highest gradient. In the event that the message is processed for the third time, the third highest gradient will be chosen to forward the discovery message. To achieve that, a PGBR node has a table with limited number of entries that keeps track of processed discovery messages and the number of time they have been processed. The PGBR mechanism assumes that gradient will not change dramatically between two processings of a discovery message.



(a) Gradient search



(b) Back-tracking

Figure 1: PGBR mechanisms

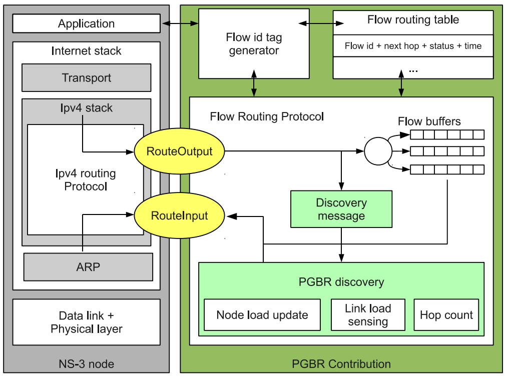


Figure 2: PGBR contribution to ns-3

IV. IMPLEMENTATION OF PGBR IN NS-3

A flow-based routing protocol consists of a few procedural steps, and this is the extension contribution we have made to ns-3 (which is illustrated in Fig. 2). Firstly, a module should be aggregated to the node to separate flows (ns-3 has a functionality of module aggregation instead of extending classes). To make the flow-based routing possible, the internal process required is to calculate the *flow id* of a packet, which consists of a five-tuple `(SA, DA, SP, DP, P)`[1], such as in [13]. Currently, it is possible to extract a flow id of an IPv4 packet in any circumstances. The ns-3 API also provides the concept of tagging packets, which allows tags to be generated, added and removed from packets easily (the payload of the tag will increase the size of the packet transmitted) and enable configuration and inter-layer communications without

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[1] SA is the source address, DA is the destination address, SP is the source port, DP is the destination and P is the protocol number

modifying headers. A tag can then be generated by the flow-based routing or upper layer applications and be identified by the flow-routing protocol. Secondly, when the source is processing the first packet of a new flow, a discovery process is initiated. The flow-based routing protocol uses a discovery technique which is also an implementation of a IPv4 routing protocol. The decision of having such an implementation has been driven by the necessity of the flow-based routing protocol to be as generic as possible. Thirdly, a technique has to be used to buffer packets of a flow during the discovery without breaking the synchronous aspects of the `RouteOutput` function of `IPv4RoutingProtocol` that expects instantaneous information of the next hop. Finally, processes has to be implemented to use flow-based information to forward packets through the network (discovery packets or flow packets) and to delete obsolete flow-based information.

A. *Discovery message*

Discovery messages are the core message signalling of the flow-based routing protocol. As described earlier, the mechanism is used to keep trace of the discovered path to the destination and the process is required to remove loops during path discovery.

0 1 2 3
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1

Packet length		Packet Sequence Number	
Packet Type	Reserved	Time To Live	Hop Count
Source Address			
Destination Address			
Hop Address			
...			
Hop Address			

Figure 3: Discovery packet header

As shown in Fig. 3, the discovery packet header contains fields necessary to process flow discovery information. The *Packet length* field represents the packet length in bytes. *Packet sequence number* field is used to keep track of discovery messages. The field *Packet Type* contains the message type (`DISCOVERY` or `RETURN`), *Time To Live (TTL)* keeps the message alive until the values goes down to zero. Usually the *TTL* value for a discovery message is set to 255 but may be set by the user. The *Hop Count* records the number of hops the discovery messages went through. The *Source Address* and *Destination Address* are 32 bytes IPv4 addresses of the source and destination, respectively. The *Hop Address* fields contains the IPv4 address of the visited hops by the discovery messages.

B. *RouteOutput*

The `RouteOutput` function is usually called by the transport layer protocol as a lookup for the next hop to forward the outbound packet (e.g. Fig. 2). It is similar to the `ip_route_output()` function of the linux IP stack. Fig. 4 shows how the flow-based routing handles an outbound packet.

The first procedure is to check if the packet is tagged; a tagged packet can only be generated by a flow-aware application. If the packet is not tagged, the packet will be sent to the local loopback (IPv4 address “127.0.0.1”) where the flow id calculation mechanism would be invoked. Sending a packet to the local loopback will results in the packet being checked by the `RouteInput` function which is asynchronous with full IPv4 header information.

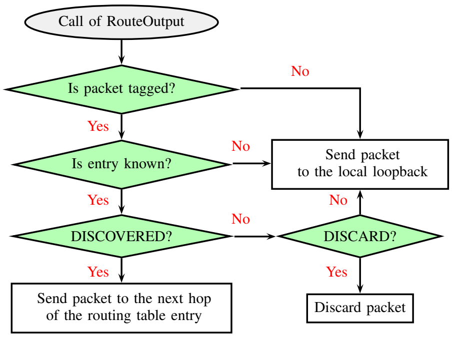

Figure 4: Mechanism of flow routing protocol on call of `RouteOutput`

If the packet is tagged, the routing protocol will check if an entry exists in the flow routing table. A flow routing entry is similar to a usual routing table entry with a difference in the information required for the next hop (which is different from standard routing tables that are based on destinations). It also provides information on the status of the flow, such as `DISCOVERY`, `DISCOVERED` and `DISCARD`, and also a timestamp of the last packet using the flow information (used to remove obsolete flow routing table entries).

C. *RouteInput*

The `RouteInput` function, similar to the `ip_route_input()` of the IPv4 linux stack, have a more complex behaviour than the `RouteInput`. This is due to the asynchronous behaviour that enables the flow-based routing protocol to buffer packets during discovery and because IPv4 header contains enough information to process the packet as part of a flow. When a packet is received by the routing layer of the node from a lower layer, it calls the `RouteInput` function.

As shown in Fig. 5, when a packet is from the local loopback, the process checks if the packet is tagged. If not, the flow-routing protocol will generate a flow id. Then it has to check if a flow routing table entry exists for this flow. If not, the flow routing protocol creates an entry in the flow routing table, starts a discovery, and buffers the packet. If the entry exists, the process checks if the packet has to be discarded, otherwise the packet would be buffered or forwarded to the next hop, as unicast, depending on the status of the flow routing table entry (`DISCOVERY` or `DISCOVERED`).

On the other hand, if the packet is not coming from the local loopback, the packet could be an existing flow packet or

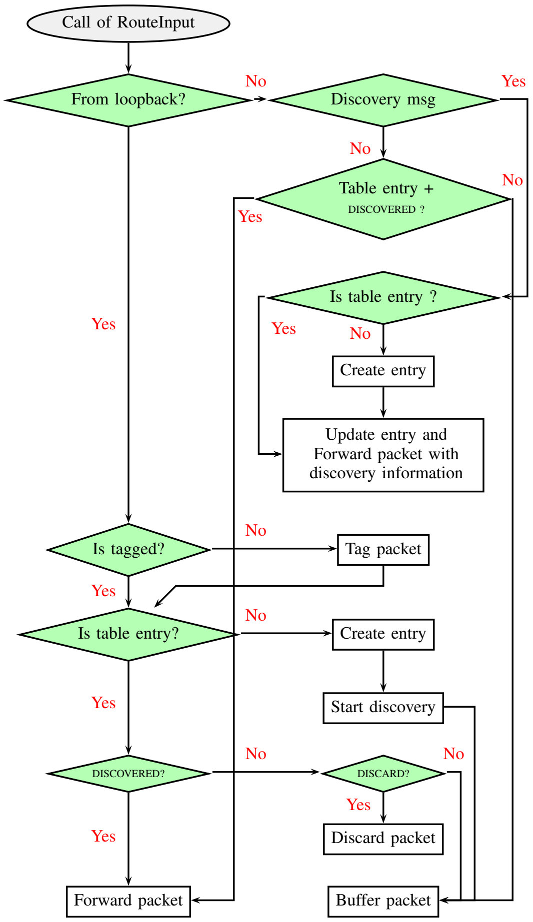

Figure 5: Mechanism of flow routing protocol on call of `RouteInput`

a discovery message. If the packet is a discovery message, a flow routing table entry has to be created if needed and the discovery routing protocol will be invoked to get information on the next hop. The kind of discovery message (`DISCOVERY` or `RETURN`) determines how the entry will be updated. If the message is a discovery message, only the timestamp is updated, and the flow routing table entry will remain as `DISCOVERY` status. The next hop to forward the message will be determined by the discovery protocol. In the event that the discovery message is a `RETURN` message, this means the packet is returning back to the source, the next hop would be in the header as the packet back tracks. When the `RETURN` packet arrives at the source of the discovery process, all the packet buffered for this flow will be flushed and forwarded into the network following the information of the routing table entry. The flow routing table entry will be kept for a period of time (using another timer) to route packets of existing flows. If the source received a `RETURN` packet and the discovery timeout has occurred, the admission control will block the request (this means that the time took to discover the packet was too long and would reflect on the high load of the network).

Finally, if the message is not a discovery message then it is a packet from an existing flow. A flow routing entry must exist with a status set to `DISCOVERED` and the packet is routed according to the routing table entry's information.

V. CONCLUSION

PGBR is a distributed, scalable and QoS aware routing protocol that enhances all features required for next generation networks. PGBR's implementation in an open-source environment is part of the development plan of this routing protocol. In order to create high impact in the Future Internet research community and also allow quick deployment process, this paper presents how ns-3 simulator can support the implementation of the PGBR flow routing protocol.

ACKNOWLEDGEMENT

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