Bio-inspired Policy Based Management (bioPBM) for Autonomic Communications Systems

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Abstract

The tremendous development of Internet infrastructures as well as communication technologies has led to an increase in network management complexity. Autonomic control is one way to manage complexity. Policy Based Management Systems (PBMS) provide a consistent model for decision making using a set of abstractions (i.e., to manage the system in a manner that is independent from the complexities of low level network technologies). In this paper, we develop a hierarchical bio-inspired PBMS based on mechanisms for organism regulation that supports self-organisation and self-management at different levels of the hierarchy. We employ this mechanism towards network management of autonomic communications systems.

1. Introduction

In recent decades, the Internet has witnessed tremendous growth, evolving from a research network to a global information exchange architecture. The current Internet architecture spans a variety of access and core network types (e.g. wireless, ad hoc, MPLS) and device technologies, supporting users with a variety of services and computing applications. As the complexity of the Internet infrastructure grows, there is a need for autonomic functionality to efficiently manage, configure, and maintain the networks supporting these infrastructures. Traditionally, these functionalities have been performed in a largely manual fashion and controlled by humans, particularly in the core networks that make up the backbone of any global network. This manual management leads to high maintenance cost and frequent errors causing failure in some cases. In order to counter these drawbacks, autonomic functionality in communications networks is required to reduce human control whilst dealing with associated network complexity.

The requirements for autonomic communication systems is motivated by the need for self-governing behaviour (e.g. self-learning, self-optimising, self-organizing [10], self-healing), which will dynamically adapt and configure communication systems to meet changes in the computing environment (e.g., network failures, service provider requirement changes). Although there is current research work in the area of autonomic computing, the current disparate solutions only provide particular functions for specific applications and are not applicable to a wide range of communications systems. One possible solution towards integrating these disparate solutions is through the use of bio-inspired techniques (e.g. self-healing and self-learning for individual elements that contribute to self-organising and self-managing behaviour for systems), where communications systems are modelled as living organisms that adapt to a dynamic environment. Fundamental biological traits, realised as a set of hardware and software mechanisms, would enable autonomic systems to integrate various microbiological characteristics, such as: (i) the ability for cells to recognise other compatible cells of the same type and self-organise as a tissue, or (ii) the ability for a physiological system to maintain system equilibrium through self-management.

In order to counter the inherent complexities required by autonomic communications systems [1], a PBMS is integrated into the communications network management architecture. To support the requirements for autonomic communication systems, we believe that a policy framework should be modelled after biological systems, which have comprehensive capabilities to detect changes and adapt to the environment to maintain equilibrium. Bio-inspired Policy Based Management (bioPBM) allows organisational personnel to specify policy at a level of abstraction that complements their specific (but different) needs, vocabulary and understanding. This results in a *Policy continuum* [1, 11], where different constituencies are aggregated into different layers of the continuum. This enables business level policies to be refined into device level enforceable policies that together represent the user-specified business level policies on the underlining network infrastructure.

This paper presents a specific feature of bioPBM – homeostasis inspired PBM – to decrease reconfiguration complexity and the related cost for self-configuration of autonomic communication. Self-organistaion techniques found in tissues are also captured by the bioPBM. Cell recognition via tissue-specific identity markers (called Major Histocompatibility Complex (MHC) proteins) is used as the motivation for self-organisation of new devices entering into the communications network.

This paper is organised as follows: Section 2 presents related work on bio-inspired systems and current PBMSs. A short background on molecular biology is delineated in Section 3. Section 4 outlines our autonomic communications architecture, while section 5 presents the organism regulation hierarchy that was used as a guide to develop the bioPBM Policy continuum. Section 6 details a case study to demonstrate the application of bioPBM. Lastly, section 7 presents conclusions and future work.

2. Related Work

2.1 Policy based management

Policy-based Network Management is a concept developed originally to reduce the administrative complexity of reconfiguring a device and/or a network to respond to the changing conditions of the business and infrastructure. This concept corresponds to the vision of self-governance innate in autonomic communications.

IBM's Policy Technologies group has recognised this link and has developed Policy Management for Autonomic Computing (PMAC). An 'autonomic manager' tool can make decisions based on policies, specified with Simplified Policy Language (SPL) or Autonomic Computing Policy Language (ACPL) to facilitate self-managing and self-configuring applications [16].

Motorola's autonomic networking for seamless mobility responds to changing conditions in the business and in the network infrastructure with self-awareness and business-driven adaptation with the Policy continuum [11]. Motorola's autonomic system is self-governing. The system senses changes in itself and its environment, determines the effect of the changes on the business policies, executes changes to be made if business policies are violated and subsequently observes the results [13]. However, it currently does not use the bio-inspired mechanisms described in this paper.

2.2 Bio-inspired systems

Bio-inspired mechanisms have been applied to various disciplines of science (e.g. genetic algorithms) and engineering (e.g. digital electronics [6]). Suzuki and Suda [2] developed the Bio-networking Architecture that supports autonomic applications using group of distributed and autonomous objects known as Cyber Entities (CE). Each CE supports various types of applications and at the same time contains different behaviour policies supporting each application. The CEs are based on observation of bee colonies and provides capabilities such as migration, reproduction, pheromone emission and energy exchange.

Dressler [5, 15] observed cell characteristics when reacting to pathological situations, such as inflammations and virus attacks and applied those observations to autonomic network security systems. The analogies used from cell biology include (i) comparing tissues to network domains, where tissues contain various cell types similar to network domains composed of different network elements, and (ii) external signaling pathways of cellular systems that are used to trigger immune systems by cells affected from inflammation are mapped to network domains where a system that suspects suspicious traffic can contact its management system to enforce countermeasures. However, only the security aspects of a communications networks were considered in this work.

Mark Burgess has embraced immune system principles to tweak the conventional structure of PBMSs that statically specifies what may be done, under particular circumstances by whom or what. He endeavors to augment the ability of PBMS so that configuration integrity is maintained in the face of change, including random unplanned change [7]. Changes that do not conform to policies are defined as sickness and are attacked, so that the system state will continually converge to a dynamic equilibrium.

Likewise, researchers at the University of New Mexico have used the natural immune system as motivation for a proposed computer security architecture [12]. The premise is that the immune system while incomplete and flawed works efficiently primarily because of the flexibility it tenders and the manner in which it adapts to change. The researchers draws on a number of the immune systems principles not least its ability to recognise self (molecules and cells of the body) and non-self (foreign molecules) to defy viruses that may attach static data and also the lymphocyte process to slow, suspend, kill or restate misbehaving processes. They do not suggest that mimicking the immune system would provide a complete security architecture, rather they highlight the limitations of the analogy when considering correctness and confidentiality. However, similar to Dressler they concentrate solely on security concerns.

Although we have only described a few examples of bio-inspired systems, majority of these current systems only address limited autonomic capabilities and are not suited for overall requirements of autonomic communications systems.

2.3 Policy Continuum

Personnel play different roles in an organisation, but work together to build a product or solution. The goals these personnel aim to achieve via policies appear as diverse as the roles of the personnel, but these goals and hence their policies are intrinsically linked. Therefore, since there are multiple constituencies (e.g., business analysts, system architects and network engineers) that use policy, the notion of a "single" policy is limited. The Policy continuum [11], depicted in Fig, 1, uses five different abstractions (Business, System, Network, Device and Instance) to address this concern.

The Business View is employed by business users; therefore, at this abstraction, policies are specified using vocabulary native to business professionals. The business view provides a description of business objects, such as customer, service and Service Level Agreement (SLA). As a simple example, consider the business definition for Quality of Service (QoS) in a communications network, "Customers who purchase an internet service package with Gold Level QoS get preferred access to and usage of network resources." There is no mention of any technology or any particular device.

The System view uses the same objects as defined in the Business View, but adds further objects and detail that correspond to concepts and terminology that are not appropriate at the Business view. For example, QoS as defined at the System view includes detail pertaining to data throughput capacity (bandwidth), latency variations (jitter) and delay information. However, the System view is still device and technology independent; thus, a user who defines policy at the System view, such as a systems engineer, does not refer to any particular technology or vendor device

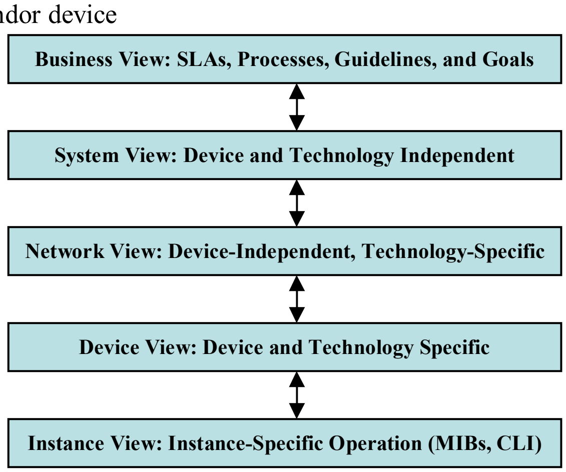

Fig. 1 Policy continuum

Reference to specific technology is introduced at the Network view. The Network view is device independent but technology specific. QoS policies defined by a network architect will include reference to QoS technologies including Differentiated Services (DiffServ), Integrated Services (IntServ) and MultiProtocol Label Switching (MPLS) for traffic conditioning and RSVP signaling for bandwidth reservation.

Reference to specific device features is introduced at the Device view. Thus, the Device view is device and technology specific. For instance, policy for QoS defined by a network administrator will include reference to queuing, scheduling and dropping algorithms for a particular type of router using a particular version of a vendor's operating system. The Instance view includes device and technology specific commands to implement the device level policies for a specific vendor device. For example, in Cisco IOS 12.x, one would specify ACLs, policy maps and service policies.

The Policy continuum represents an important milestone in enabling business goals to drive the services and resources provided by a network. In order to harmonise between multiple layers of the continuum, we have used the organism regulation analogy.

3. Molecular Biology

In this section, we will briefly discuss core molecular biology principles that will be used as a conceptual guide towards modifying the Policy continuum for our needs. All organisms are composed of one or more cells, in which the vital functions of an organism are performed. The key characteristics of molecular cell biology behaviour that we believe can contribute towards autonomic networking includes (i) the translation of DNA sequences to protein in cells to perform specific types of functionalities, (ii) the ability for tissues to maintain homeostatic equilibrium to support survivability, and (iii) the capabilities for cells to self-organise in tissues [8, 9].

Each cell contains hereditary information in the form of DNA that is necessary for regulating cell functions and for transmitting genetic information to enable self-replication. Apart from maintaining the identity of an organism, DNA also has the responsibility of determining functionalities of the cells through protein production. Protein production is essential for maintaining the functionalities of the cells, transportation of other molecules, and supporting activities of other proteins.

Homeostasis, the property of an organism to regulate its internal environment to maintain a stable condition in order to live, is achieved in living organisms by making dynamic adjustments through various mechanisms to maintain equilibrium. Examples of homeostasis are the ability to regulate the amount of water and minerals in the body (also known as osmoregulation), removal of metabolic waste, regulation of blood glucose level, or regulating body temperature (mainly done at the skin). In the event of changes that may lead to instability, the system will react to two types of feedback, negative and positive. An example of this is thermoregulation, where the tissue receptors in the skin detect an increase in body temperature and notifies the brain to perform functions that lead to reduction in body temperature.

Cells that are similar in structure and functionalities are grouped into tissues. Cells have a process of determining the tissues to which they belong. This process of cell recognition is through tissue-specific identity markers. These markers are usually located on the cell surface and serve as cell tissue-specific identity. The cells that belong to the same tissues have the same self-markers that are known as MHC protein. During tissue formation, cells of compatible types come together and join to form tissues.

Cells also have the capacity to communicate with other cells through cell-cell signaling mechanism. The surface of each cell contains a classification of receptors, whereby each type of receptor will only respond to a specific signal. Upon receiving the signal, the receptor translates the signal strength to specific internal signals to readjust the internal functionalities of the cell (e.g., protein production). This allows all cells within a tissue to function in a uniform manner to achieve the goal of the tissue.

4. Autonomic Communications Architecture

Our proposed autonomic communications architecture uses four distinct architectural constructs: shared information/data model, virtual software, infrastructure, and policy [4].

4.1 Shared Information/Data Model

The Information model used in our architecture is based on the Shared Information/Data model (SID) of the TeleManagement Forum. The SID is a subset of the Directory Enabled Network – next generation (DEN-ng) initiative. DEN-ng is based on UML, and uses abstraction mechanisms and software patterns to provide an extensible structure that can integrate other models (whether or not they are UML compliant) and technologies as appropriate. Object-oriented information modeling provides a common language for representing the characteristics and behavior of entities in the managed environment in a single, extensible *lingua franca*. This extensibility is provided through patterns [17], roles, and various other abstraction mechanisms. The SID is a backbone framework and is used as a reference model and common language for representing the business objectives and technology-neutral definition of entities within a system. Therefore, the shared information and data model is used to translate and support refinement of business policies to device level network element policies, and supports the formation of the context data model for the virtual software layer.

4.2 Virtual Software Layer

The purpose of the virtual software layer is to support autonomic capability for heterogeneous networks in different administrative domains. This capability achieves governance through (intelligent) decision-making. This layer contains a model of the ***desired behaviour*** as well as the ***deduced current behaviour*** of the system or component being managed. The virtual software layer supports autonomic capabilities by monitoring the deduced current behaviour of the systems and aligning this towards the desired behaviour in the event of any disruptions due to environment changes.

One solution towards achieving governance and intelligent decision making is through a combination of ontological engineering and information modeling to enable semantics to be added to facts and knowledge based reasoning techniques to develop a representation of behavioural orchestration. The context data model within the virtual software layer contains information that is relevant to the current activities, including the device and vendor specific managed elements as well as the user profiles/preferences. The context information is evaluated by the active set of policies that are required in response to environmental, business, and/or technological changes.

4.3 Infrastructure

The infrastructure layer includes network elements and other computing devices within a specific administrative domain. The type of protocols and adaptability mechanisms used depend on the current context as well as the type of behaviour that is being orchestrated.

4.4 Policy

Policy plays a central role in an autonomic architecture as it formalises the concept of decision-making. This architecture element is based on the DEN-ng policy model, which enhances the IETF and DMTF policy architecture by extending their definition of policy to include events as well as architectural patterns [11, 14].

Our policy framework uses the DEN-ng Policy continuum, with some slight modifications which will be described in section 5.3. The different levels of abstraction of the Policy continuum are refined using a combination of information modeling, ontological engineering, and knowledge-based reasoning for each level of the continuum. The information model is used for two distinct purposes: (1) to represent policies at each level using the same set of building blocks, and (2) to explicitly define which set of managed entities are the subject and target of the policy.

5. Organism regulation

In this paper we concentrate solely on the Policy continuum and integrating knowledge from biological models as possible reasoning techniques. This reasoning technique will help create a platform for ontology reasoning between the various layers of the continuum. Our objective is to create a modified Policy continuum that our architecture can use to create a layered policy hierarchy. The Policy continuum can be compared to a hierarchical organisation of regulation rules in living organisms. In this section, we will describe the organism regulation hierarchy, which will be used to develop the Policy continuum.

5.1 Organism regulation hierarchy

Organisms have hierarchy layered architecture for adapting to changes and maintaining regulation. This structure is illustrated in Fig. 2. The structure, which is predominantly rule based, is composed of inter-layer and intra-layer rules, which together constitutes the relationship levels. The intra-layer rules are self-contained regulation rules that are local within each layer and are independent from other layers. The inter-layer rules between the layers govern the relations and at the same time transform the requirements between the layers.

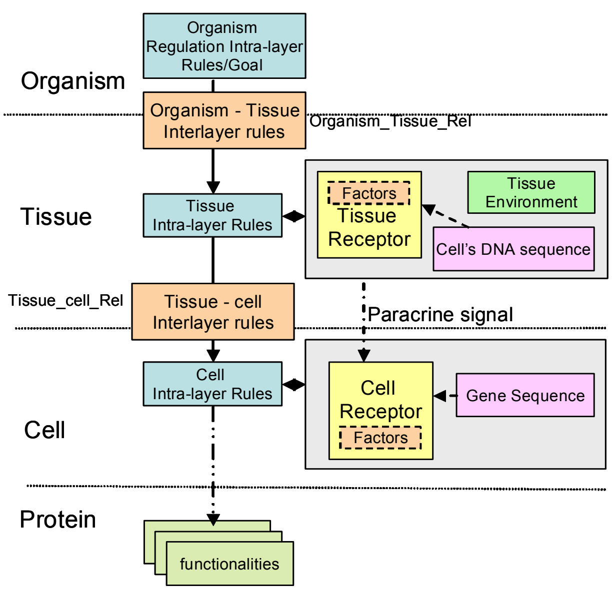

Fig. 2 Organism regulation hierarchy

The layers, which include organism, tissue, cell and protein, are organised hierarchically. The organism layer, which is the highest layer, specifies high level regulation rules/goals that are required for survivability. Examples of these rules include maintaining the overall organism temperature (Thermoregulation), blood glucose, and water level (Osmoregulation).

The organism level links to the tissue level through a relationship known as the *Organism_tissue_Rel*. This relationship associates the corresponding high-level organism goal to the specific tissues. For example, the goal for maintaining Osmoregulation is associated to the different kidney tissues that are required to maintain the equilibrium. The tissues will associate to the different cell types that are required to perform cell functionalities through the *Tissue_cell_Rel* relationship. As illustrated in Fig. 2, the cells will produce different kinds of proteins to reflect the specific functionality.

5.2 Organism Regulation Rules

Our organism regulation rules model is based on the work by Schober [3], who has defined an ontology model for signal transduction in molecular biology to maintain homeostatic environments. Fig. 3 describes the class hierarchy and relationship between the different classes for each level of the organism regulation process. In the organism level, the *Homeostatic_goal* presents a condition that is required for survivability of an organism.

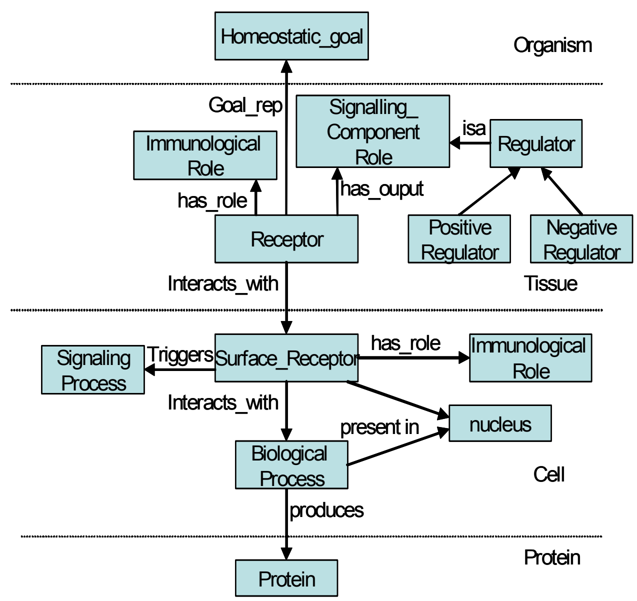

Fig. 3 Organism regulation rules

In the tissue level, the *Receptor* class specifies the type of receptors that are crucial in determining when the stability of the systems has been affected. The *Receptor* class forms relationships to a number of classes that capture the behaviour of the specific receptor. These relationships that reflect the characteristics of the receptor includes, the role of the receptor and types of signals they respond to (*Immunological_Role*), the signaling process that the receptor triggers (*Signaling_Component Role*), and the interaction that the receptor has with the specific type of surface protein (*Surface_receptor*).

The surface protein transforms the Paracrine signal to an Autocrine signal, which directs the production of the appropriate type of protein. The surface protein signals the nucleus to perform protein production (*Biological_process*). The protein produced will, therefore, reflect the functionality of the particular cell.

5.2.1 Organism Inter-layer rules. The relationships established between the layers are composed of two rules. **Rule 1** specifies the relationship of components between layers. **Rule 2** specifies the transformation relationship of quantitative parameters between the layers.

Rule 1 (component relationship):
$\{layer_{n-1a}, layer_{n-1b} \ldots\} \in layer_n$ (where a and b represent different components in layer n-1)

Rule 2 (parameter transformation relationship): $f: A \rightarrow B$ where
$$\forall x \in A, \forall y \in B, f(x) = f(y) \Rightarrow x = y$$

Examples of the organism-tissue interlayer rules for the *Organism_Tissue_Rel* relationship includes:

Rule 1$_{Organism\_Tissue\_Rel}$: $\{ Tissue_{renalcortex}, Tissue_{renal\ medulla}, \ldots\} \in Organism_{Thermoregulation}$

Rule 2$_{Organism\_Tissue\_Rel}$: f: organisms→Renal Cortex where
$\forall x \in$ organism, $\forall y \in$ rental cortex, renal medulla…, $f(x) = f(y) \Rightarrow x = y$

The parameter transformation in this particular case involves transforming quantitative values between the layers using injective mappings. Injective mapping involves a one-to-one function mapping that maps parameters between domains. These rules are applied to all inter-layer relationships. For example, between the goals specified at the organism level and the receptors at the tissue level, the parameter is transformed to a set point at the receptors. The set point values at receptors provides threshold to trigger feedback (positive or negative) Paracrine signals to the cells to readjust their protein productions. In the case of tissue to cell parameter transformation, the Paracrine signal translates the intensity of the signal to a calculated intensity of the Autocrine signals to determine the required volume of protein production (which is done internally in the cell). Therefore, the right set of protein as well as the volume of production of protein will depend on the intensity of signal mapping as well as the relationships established between the tissue and the cells.

5.2.2 Organism Intra-layer rules. The Intra-layer rules perform specific tasks that are required to maintain stability within the layer based on translation of quantitative parameters from inter-layer rules. Description of the rules that are embedded into each layer includes:

Organism: Specify the goals that provide overall system equilibrium.

Tissue: (i) Rules are required to organise and classify receptor categories for tissues. The categorisation provides the ability to classify the types of signals that are associated to the receptors as well as factors that can lead to de-stabilisation of equilibrium. (ii) Using the metric parameters translated from the organism level, the tissue employs rules to self-manage at the tissue level. The self-management rules include evaluating the current condition of the tissue and invoking negative or positive feedback in response to factors that may affect overall equilibrium. Factors that may affect overall equilibrium includes: parameter changes that are translated from organism level or the addition or removal (due to death) of cells in tissues that can affect overall work rate of the tissue.

Cells: (i) Rules to cooperatively self-heal tissue when damage (ii) produce proteins corresponding to the signal intensity from the tissue level (evaluating signal intensity from external Paracrine signals and translating to internal Autocrine signals) (iii) rules for receptor and signal classification within the cells, and (iv) ability to self-organise through MHC interactions.

5.3 Policy continuum hierarchy

Through the observation of organism regulation process and their hierarchy structure, we extract the various processes and techniques used in organisms regulation and map this to the Policy continuum. The process of using molecular cell biology as an analogy and mapping to communications systems is based on a cell representing a device and the collection of cells forming a tissue represents a communications system. By using the organism hierarchy as a guide, we derived the class diagram for the Policy continuum, shown in Fig. 4. We have modified the System and Network layer of the Policy continuum to a combined Architecture/System layer, where this new layer introduces new concepts and technology specific rules that is more suitable to the organism hierarchy.

Similar to the organism hierarchy, we model the Policy continuum as a hierarchy and organise the policies relevant to each layer to be independent from other layers, where the policies that govern the behaviour of each layer are called intra-layer policies. At the same time, we are able to link between the layers using the inter-layer policies. At the Business level, similar to the organism, we specify high level requirements. Examples of this may include specifying the right package of content service for a particular customer. The Business view links to the Architecture/System view through the *Bus_Arch_Rel*. For example, the goal of maintaining gold service for a customer will be associated to a Diffserv network that the user is currently subscribed. The inter-layer policies will be described in detail in the next section.

The Architecuture/System layer establishes a relationship to the device layer through the *Arch_Dev_Rel*. As illustrated in Fig. 4, the different devices will create different instances of the policies specified at the device layer.

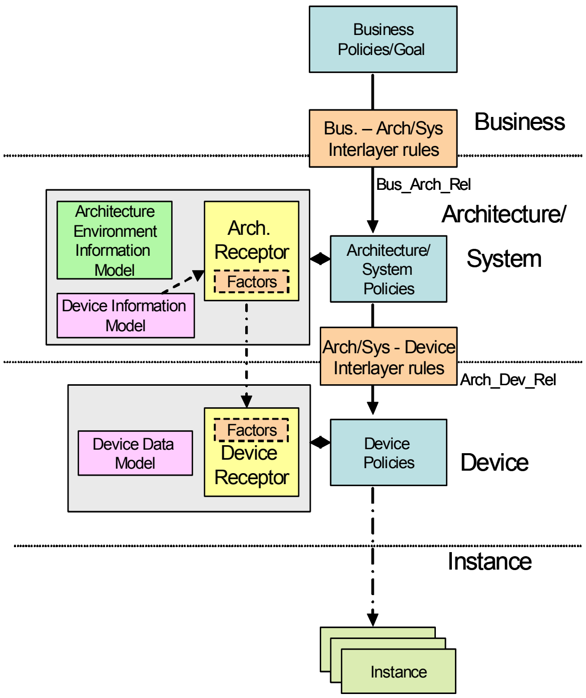

Fig. 4 Policy continuum hierarchy

5.4 Policy Continuum Regulation

We adopt the organism regulation for the Policy continuum. Fig. 5 illustrates the class hierarchy and the relationships between the classes.

As described in the previous section, the Business layer is used to specify high level goals. In the architecture level, the stability control class specifies the different sensor classes that are used to detect any instability (e.g., rise in congestion of particular links, link failures). The stability control class forms relationships to the *Signaling_Component Role* that acts as a regulator for reacting to any factors that may lead to instability. The output of the receptors will be in the form of weights, which is similar to signal intensity used by cells to evaluate changes in stability. The stability control also specifies the role and types of sensory signals that it responds to (e.g., the role may include managing DiffServ resources for the class based on monitoring the traffic of different classes). The device interface class transforms the signals and interacts with the functionality process by evaluating the weights and at the same time, evaluating the functionality that must be manipulated. In turn the functionality process will invoke the functionality at the instance layer.

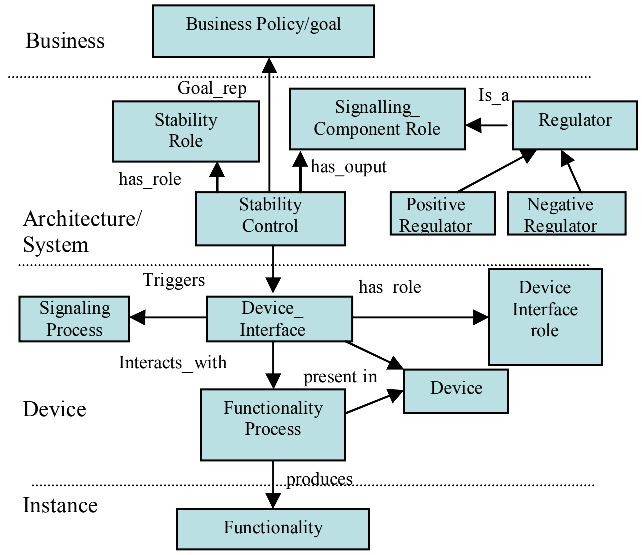

Fig. 5 The regulation process of Policy continuum

5.4.1 Policy Continuum Inter-layer policies. The Policy continuum inter-layer policies are mapped from the organism inter-layer policies, where two rules are specified, see section 5.2.1. Similar to the organism inter-layer policies, **Rule 1** will determine the different component relationships between the layers, and **Rule 2** performs quantitative transformation of parameters between the layers using injective mapping.

Examples of the Business-System/Network interlayer policies for the *Bus_Arc_Rel* relationship includes:

Rule 1$_{Bus\ Arch\_Rel}$: $\{$ Network/System$_{DiffServ}$, Network/System$_{WLAN\ access\ network}$, …$\}$ $\in$ Business$_{Preferred\ access\ for\ Gold\ QoS}$

Rule 2$_{Bus\ Arch\_Rel}$: f: Business→Network/System, where $\forall x \in$ Gold QoS, $\forall y \in$ DiffServ traffic class, $f(x) = f(y) \Rightarrow x = y$

5.4.2 Policy Continuum Intra-layer policies. Similar to the intra-layers of the organism hierarchy, the intra layers of the Policy continuum contain policies required for internal regulation of the layers. The description of policies for each layer includes:

Business: Defining the overall goal specified by the service providers or customers.

System/Network: (i) Policies are required to organise and classify the sensor categories for the network. The classification will also include the types of signals that are associated to the sensors as well as factors that can disrupt network equilibrium. (ii) The translation of parameters from the business level is used by the network level to self-manage resources, admission control, etc. The self-management rules include evaluating the current condition of the traffic flow for each class and invoking negative or positive feedback in response to factors that may affect the network equilibrium. For communications systems, the factors that may affect resource equilibrium includes: parameter changes that are translated from business level or the addition or removal of network elements from the network (removal of network elements includes link or node failures and managing path restorations).

Device: (i) Invoking the correct functionality of the device to suit the task requirements by the communications environment (ii) manipulating functionality in response to signal intensity from the System/Network level (iii) rules for receptor and signal classification within the devices, and (iv) ability to self-organise through device interactions by determining if devices contain same or compatible configuration setups. The manner in which cells detect other cells of the same type with MHC recognition is used as an analogy for devices; where devices can detect and cross check compatibility of their functions before setting up connections between the devices.

6. Case Study

We present a case study of molecular regulation model and then map to a case study of applying Policy continuum for Diffserv network.

6.1 Molecular Regulation Model

The case study scenario for the molecular regulation model depicts self-organisation of new cells joining an existing tissue, and the ability for the tissue to regulate this process, taking into account the addition of new cells to maintain homeostasis. Section 3 described mechanisms of cell organization, using tissue specific identity markers on the surface (MHC). Once the markers come into contact with cells that are already adhered to the tissue, the marker negotiation has the capability to reject incompatible cell types that do not belong to the specific tissue and accept compatible cells. The process of maintaining homeostasis is also described in section 3. In this case study, we particularly focus on maintaining osmoregulation homeostasis and self-organisation of cells, which is illustrated in Fig. 6. The process of maintaining osmoregulation in organisms is through regulators of water receptors in the tissue. The regulators trigger a positive or negative feedback when the fluid level in the kidney increases or decreases respectively. A notification is transmitted to the surface of the kidney cell, which translates the signal and invokes a biological process. In this particular case, the process is to decrease the production of Vassopressin (ADH). Vassopressin is used to increase permeability of cells to absorb water.

As shown in Fig. 6, the organism level specifies a high level goal for osmoregulation homeostasis, which maintains the overall water level of the body. The association to the tissue level translates the requirements of the organism goal to the threshold limits at the regulator. The positive and negative regulators will then evaluate the kidney tissue environment and measure against the threshold before triggering a positive or negative feedback to re-stabilise the system.

Fig. 6 also shows the MHC association to the specific cell. One association to the MHC is the *Interact_with* association, which determines if cells are compatible when the MHCs of cells come into contact with each other. In the event that the MHCs are compatible, the cells start performing a cell-cell adhesion process, which is then followed by inter-cell communication setup. Once the cell adhere to other cells and receives the signal from the neighboring cells to produce the ADH protein, this will lead to excess production of ADH. After a short period, the negative regulator at the water receptor will detect this and recalculate the signal intensity to the surface cells to limit the protein production to maintain stability.

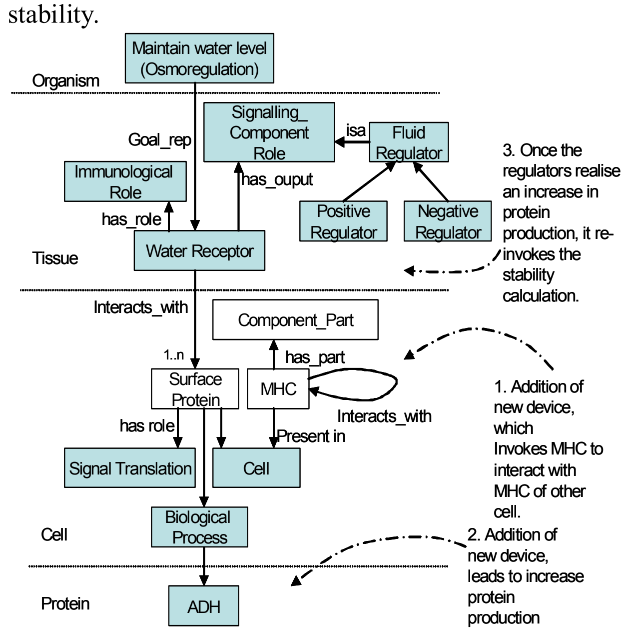

Fig. 6. Molecular regulation case study

Therefore, this case study has demonstrated the capability for cells to self-organise at a particular level of the organization hierarchy. At the same time, the self-management of the overall tissue was detected and stabilised, independent of the activity at the cell level. Once the instability is detected at the tissue level, the cells are notified and informed of the changes.

6.2 Policy Continuum supporting Network QoS

In order to correlate the mechanism of self-organisation and configuration described in section 6.1 to networks, this section will describe a case study in which the Policy continuum is applied. The case study will employ techniques from molecular cell biology, to achieve self-organisation of new devices joining a communications network and self-management to maintain an overall network state that adheres to the business policies (goals). This case study is illustrated in Fig. 7.

In our case study example, we describe a self-organisation process by adding a new core router that offers a 1 Gigabit line into a Diffserv network. Each device is equipped with a Local Policy Decision Point (LPDP) that can make basic policy decisions for the device. Once the router enters the communications network, its LPDP negotiates directly with the LPDP of its adjacent devices that operate within the network to determine whether or not the new router may also operate within that network. The more general case of a device becoming (for example) a border device that facilitates communication between heterogeneous devices requires a higher level *policy broker* [11] to be used. However, due to space limitations we will only assume that each of these LPDPs is in a common administrative area. Data model pattern matching is completed by the LPDP and if compatible the router is accepted into the network. The self-organisation process is equivalent to the MHC association with a specific cell, which are used to determine if cells are compatible for a tissue. The data model of the device mimics the MHC of the cell.

Once the router is proven to be compatible and is integrated into the network, intercommunication between the router and the other devices in the network is established. The router then receives a signal from the adjacent devices to maintain QoS with DiffServ, where Gold service customers get traffic marked with two DiffServ Code Point (DSCP), one corresponding to Expedited Forwarding (EF) for their voice traffic and a different DSCP corresponding to Assured Forwarding class AF11 for data traffic. The average rate inbound IP traffic is set to 3Mbps and an average rate outbound IP traffic is set to 3Mbps. Silver service customers get traffic marked with a DSCP for EF that has been rate limited on the ingress and shaped on the egress, along with a DSCP for AF21 for data traffic. The average Inbound IP traffic for silver services is set at 2Mbps and an average rate outbound IP traffic of 2Mbps.

Therefore, the difference at the business layer between Gold and Silver service is that for Gold service, the customer gets better quality and a greater bandwidth for a higher cost. This is translated to the network layer into different device configurations (for Gold vs. Silver), which use the same QoS technologies to provide different forwarding treatments (and hence different end-user behaviour) for Gold vs. Silver service.

The addition of new devices will lead to excess bandwidth where the resources available in the network as a whole are under utilised and maximum revenue potential is not realised because of the inability to use all of the capacity of the 1 Gigabit line that the new router offers.

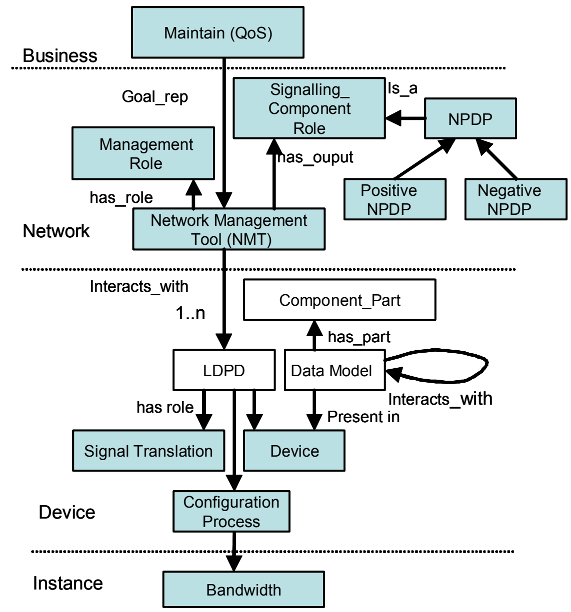

Fig. 7. Policy continuum case study

Consequently, the network management tool, for instance SNMP, will detect the under-utilisation of resources and send a positive signal to the Network Policy Decision Point (NPDP). The NPDP establishes the capacity rate in accordance with one or more high level business goals and the communications network capabilities. If the business goal states that 'gold service customers get 50% of network resources and silver service customers get 30% of network resources', then the NPDP must determine the bandwidth rates for gold and silver services based on the bandwidth availability in the network. Once the bandwidth rate is calculated, the NPDP informs the network receptor which in turn sends a signal to the devices in the network to increase input and output IP traffic in accordance with the new calculated bandwidth ratio. Using this approach, self-management of network resources is achieved in a similar way to homeostasis in an organism.

7. Conclusion and Future Work

The complexity of future communications systems requires autonomic functionalities (self-organising, self-managing, etc.) to help alleviate manual control which are costly and error prone. Investigating these autonomic functionalities, we find that a number of these characteristics can be found in nature itself and one distinct example is biological systems.

Now that we have established a mapping of biological systems to PBMS, for future work we will formalise the generation of inter-layer rules in a dynamic system, supporting environments that may change indeterminately. Information models, including non-deterministic state machines, and ontological engineering will be further investigated and applied to define the relationship of components between layers, so that new policy and states can be dealt with in an autonomic fashion. Additionally, the concept of maintaining stability within a layer must be considered. A process of altering and diffusing intra-layer rules to maintain stability derived from osmosis and active transportation will be explored.

In this paper we apply molecular cell biology principles towards achieving autonomic capabilities for communications systems. The paper has analysed core molecular biology principles and the organism hierarchy and used this as a guide towards developing the Policy continuum hierarchy. The key principles of molecular cell biology that have been applied towards the policy continuum include self-management mechanisms in tissues as well as self-organisation techniques used by cells to form tissues. A case study comparison has also been presented to demonstrate the application of these principles.

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