Outdoor-Indoor Wireless Sensor Communications in a modern Building Management System
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Abstract

Outdoor environmental monitoring will be used to enhance future BMS performance, from video surveillance applications and security (UWB wireless sensors), to monitors to respond to cold snaps, daylight monitoring, etc (typically using narrowband ISM sensors). However, the modern buildings also have a strong heat control requirement, realised using metal-coated insulation in the cavity or building cladding and also using metal oxide coating on the inner leaf of double glazed windows. The latter has excellent reflection properties (bi-directional) for electromagnetic wavelengths from Infra Red upwards, which has significant consequences for communications (reflecting typically more than 90%), but means shorter wavelength radiation (especially the visible spectrum), passes relatively well. This work presents measurements at frequencies relevant to ISM band and UWB wireless sensors and highlights the significant losses incurred in communicating to or from an external sensor. We were recently funded (TSR Strand 1) to carry out further work to examine means of improving wireless penetration into energy efficient buildings.

Introduction

Low emissivity glass reflects longer wavelength (typically above 1 μm), in order to help control building temperature. The low emissivity is achieved by adding metal oxide coatings, usually to the inside of one or both of the panes in a double glazed window. The coating thickness varies from about 10–400 nm and has good electrical conductive properties. Low electrical resistivity (10^{-4} ohm cm) yields low thermal emittance, ideal for window insulation and prevention of radiative cooling, but bad for electromagnetic propagation. The coatings typically behave like a metallic coating to light of wavelength above 1 μm. The work described here looks at propagation reduction in some frequency ranges of interest to present and future wireless sensors. It will be shown that the extra coating reduces the transmission by up to about 30 dB across all frequencies.

Experimental Set-up

The experiment was carried out indoors, in a corridor in the cellar of the University of Applied Sciences and Arts in Hannover, which was well shielded by thick walls, so that broadcast services had no major influence on the experiment. The window under test was placed in a specially constructed wall between the transmitter and receiver. The rest of the wall consisted of a timber frame and foil-backed insulation, similar to wall construction in a timber framed house. Thus, a majority of the test signal is transmitted directly through the window and not by other propagation paths. A diagram of the wall is illustrated below. The measurement series include both linear polarisations.

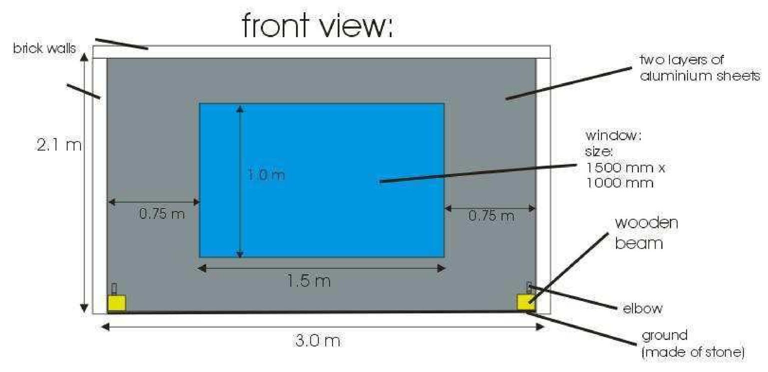

FIGURE 1: Wall construction and dimensions to test both standard and low emittance window types.

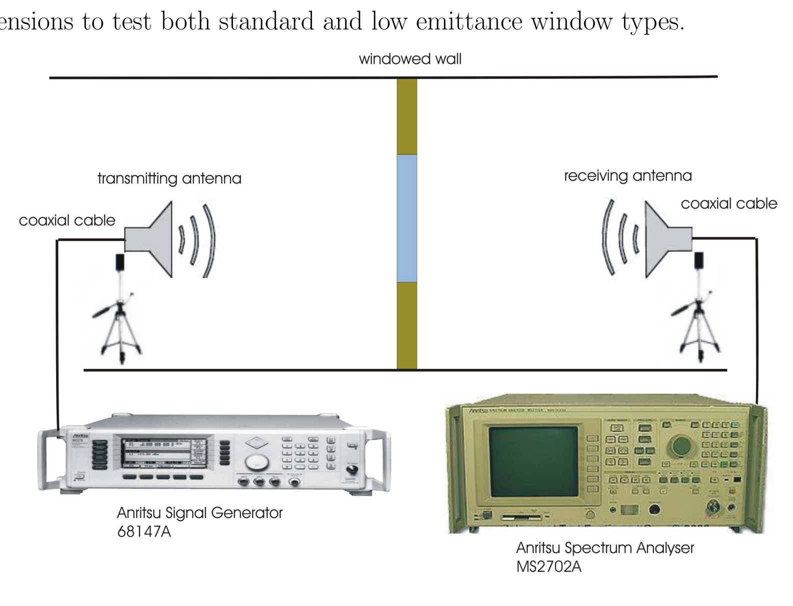

FIGURE 2: Experimental test set-up for both window types using X-band horn antennas.

Windows

Two types of windows, with identical dimensions, 4 mm thick glass with a 12 mm air-gap, were investigated with this setup. The first window is double glazed with standard float glass and the second window is also double glazed, but with a low emissivity layer on the inside pane on the vacuum side.

Procedure

First of all, the measurement system was characterised with no window present, over the whole frequency range. This means that the antenna frequency dependency parameters, such as the gain, directivity, radiation characteristic and input impedance may be characterised, as well as the attenuation of coaxial cables. Then a measurement series is carried out with windows present. The differences of the detected signal strengths may then be attributed directly to the poorer propagation caused by the actual window under test.

Measurement Results

As mentioned earlier, the results are measured relative to the losses incurred when no window was installed in the wall. The results are presented in the following graphs and for the standard isolation window can be compared with trends identified in previous work, such as by the NIST (National Institute of Standards and Technology). But the losses for both window types are worth examining. Inaccurate measurements, unexpected or abnormal wave propagation are unlikely to be the reason for this result, because the horn antennas utilised were very close to the window (0.5m). Therefore the transmission line between transmitter and receiver is very short and only obstructed by the window itself. Also, horn antennas have narrow lobes, resulting in a very good directivity. The explanation lies more likely in constructive and destructive interference patterns due to the 4 mm glass pane window thickness and their 12 mm separation. This is analysed in more detail in the next section, where the dielectric constant of glass is also taken into account.

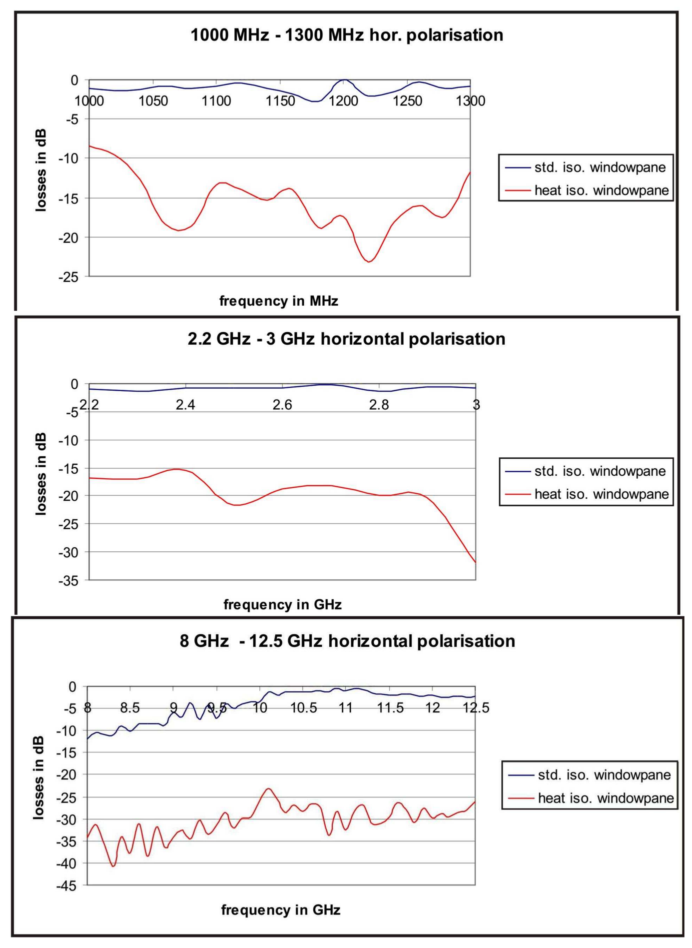

FIGURE 3: Relative propagation performances of both standard and low emittance window types.

A similar effect is visible in the case of the heat isolation window, but the analysis (later) is slightly different, due to the dominant reflection and transmission coefficients on the coated glass–air interface. The incident angle is normal, so reflected waves (especially in the case of the low emissivity window, where more than 99% is reflected) will propagate directly back to the signal source and influence new radiated waves coming from the transmitting antenna. Note that multiple reflections occur, because the complete window has four boundaries (albeit one dominant reflecting boundary, in the case of the coating in the Low Emissivity case) and reflected waves will be generated on each of them. Destructive superposition of this cluster of reflected waves would effect the overall transmission of energy through the window. This is the reason proposed for the oscillatory trend in the heat isolation window, compared with the standard window.

Analysis

Low Emissivity Case

The periodic element in the heat isolation window attenuation may be partly explained as follows. Let T_1, T_2, Γ_1, Γ_2, be the transmission and reflection coefficients for the first and second panes respectively (for simplicity, it is assumed that the reflection only occurs at one of the panes interfaces, but it is easy to extend the analysis to both interfaces). It can be seen from comparison with that the standard float glass panes that $T_1 >> T_2$, and $\Gamma_1 << \Gamma_2$. Also, the low emissivity coating is assumed to be on the inside of pane 2 (propagation path is outside to inside the building). Let the test signal be represented by $e^{j\omega t}$. After propagation through pane 1, the signal may be represented by $T_1 e^{j\omega t}$. A significant part of this signal $\Gamma_2 T_1 e^{j\omega t}$ will be reflected back by the low emissivity coating, but some, $T_2 T_1 e^{j\omega t}$, will propagate through the glass. The reflected portion will be incident on pane 1 and the major part of this ($\Gamma_2 T_1 2 e^{j\omega t}$) will propagate back through the pane and be lost. The remainder ($\Gamma_1 \Gamma_2 T_1 e^{j\omega t}$) will reflect back to pane 2 and ($T_2 \Gamma_1 \Gamma_2 T_1 e^{j\omega t}$) will propagate through. It is possible to follow this argument through for more reflections from panes 1 and 2, but as the reflection coefficient for pane 1, Γ_1, is small, these are neglected here. The two signals incident on the receiver after pane 2 are then given by: $T_2 T_1 e^{j\omega t} + T_2 \Gamma_1 \Gamma_2 T_1 \mathrm{e}(e^{j\omega t + \phi})$ Where ϕ is used to denote the phase difference due to the extra path (equal to two times the pane separation or 24mm) traversed by the second part of the signal. This expression may then be written as: $T_2 T_1 e^{j\omega t}\ (1 + \Gamma_1 \Gamma_2 e^{j\phi})$ The $e^{j\omega t}$ term is fixed for any given wavelength, but will vary as the wavelength varies, defined by the fraction of wavelength remaining in the 24 mm traversal. This variation can be seen in the l ow emissivity measurements, but, as expected, not in the standard float glass.

Standard Window

A similar analysis may be applied to the standard glass, although in this case there is no dominant reflection or attenuation interface, i.e. $T_1 = T_2 = T$, and $\Gamma_1 = \Gamma_2 = \Gamma$. This analysis only includes paths with double or no reflections and treats reflections at both glass-air interfaces on each pane. Paths with higher numbers of reflections should contribute a negligible effect. It is easy to see then that the received signal, r(t), is given by r(t)=$T_2 e^{j\omega t} + T_2 \Gamma_2 (e^{j\omega t + \phi_1}) + T_2 \Gamma_2 (e^{j\omega t + \phi_2}) + T_2 \Gamma_2 (e^{j\omega t + \phi_3}) + T_2 \Gamma_2 (e^{j\omega t + \phi_4})$
So the path may be described by h(t)=$T_2 (1 + \Gamma_2 (e^{j\phi_1}) + \Gamma_2 (e^{j\phi_2}) + \Gamma_2 (e^{j\phi_3}) + \Gamma_2 (e^{j\phi_4})$
where ϕ_i denote the phase differences due to the extra paths of 8mm, 24mm, 32mm and 40mm, traversed by the reflected parts of the signal. The $e^{j\phi_i)}$ term is fixed for any given frequency, but will vary as the frequency varies.

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