Effect of Frequency Selective Surfaces on radio wave propagation in indoor environments

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Abstract **This paper investigates the deployment of Frequency Selective Surfaces (FSS) in an indoor environment and their impact on radio wave propagation. In this work, FSS are used to either isolate certain indoor areas by increasing the loss of the interfaces or as a way to passively amplify the reflected signals. Simulations at two different frequencies highlight the frequency selectivity behaviour of the deployed FSS.**

1. Introduction

Radio signals generally propagate through reflections, transmissions, diffraction and scattering. Radio waves can arrive to the point of interest from many different directions with random phases. Typically, the instantaneous received signal can vary by as much as 30 to 40 dB over a fraction of a wavelength due to constructive and destructive contributions. In an indoor environment the received signal is mainly attenuated due to reflection and transmission through building materials. Building penetration loss depends on different variables associated with the building architecture, including but not limited to the geometry of the building structure, the material-interface composition, the angle of incidence etc [1], [2].

Depending on the application, there are cases where one would like to confine the signal in order to reduce interference or increase wireless security by reducing the spillover of radiowaves outside designated areas i.e. in WLAN. On the other hand there would be cases where the propagated radio signal will need to be amplified in order to increase coverage and reliability.

The literature includes various methods that can be used to increase coverage. These include increasing the transmitted power, using active and passive repeaters, distributed antennas, leaky feeders etc. The details of these can be found in [3], [4]. Each method has its own advantages and disadvantages. For example, the transmitted power cannot be increased beyond a certain range, as it will cause interference, licensing problems and health and safety issues. Active repeaters require power and good isolation between antennas [5], otherwise the system can become oscillatory. Usually distributed antenna systems or directional antennas are connected to the inputs and outputs of repeaters for localized spot coverage, particularly for improving coverage in buildings and in tunnels. Leaky feeders can be also used in tunnels or in areas difficult to access. In order to reduce interference, various techniques can be used, including: relocating the devices or systems to a distance that minimises interference, reducing the transmitted power, but this affects coverage and performance etc.

The technique investigated in this paper is to utilise Frequency Selective Surfaces (FSS) as passive repeaters or isolators to either increase or retain the radio signal. The passive repeater concept is based on the assumption that the mean signal received due to a reflected contribution from an FSS will be higher than the one received from any other object/material that does not produce a strong reflection. Alternatively, Frequency Selective Surfaces can be used to provide isolation by selectively rejecting a frequency range, thus reducing interference or increasing wireless security by minimising the spill over of radiowaves outside the designated areas. Similar behaviour can be achieved if instead of a FSS, a metallic surface is used as the reflecting interface. The disadvantage of using such a surface over FSS is that it will unselectively block all radio signals, where depending on the design of the frequency selective surface, signals can be selectively reflected or transmitted through.

Section 2 of this paper highlights some of the FSS behaviour issues related to this work, including the effect on the transmission and reflection characteristics of a FSS due to an impinging wave with a variable incident angle. Typical modelled and measured responses are also provided. Section 3 investigates a typical indoor scenario through a custom written ray tracing algorithm, by incorporating the FSS interface/facet behaviour. This section highlights how the FSS can be used for signal isolation or amplification purposes.

2. Frequency Selective Surfaces

One of the most important factors regarding the response of a FSS is the element shape. Different shape of elements will cause different performance in handling polarisation, angular sensitivity and bandwidth [6], [7]. Apart from the element shape, the dielectric material also plays an important role in the FSS response [8]. The element size is affected by the permittivity and thickness of the substrate, and the gaps between elements. Various approaches have been developed for analysing the behavior of FSS. Examples include the equivalent circuit method, the method of moments (MoM), the Finite Difference Time Domain method (FDTD) and the Conformal Finite Difference Time Domain method (CFDTD) [9], [10].

Figure 1 and 2 present the reflection (S11) and transmission (S21) loss characteristics for a typical Cross Dipole FSS design, at two different incident angles (0° and 37°). Simulations were performed utilizing the Conformal Finite Difference Time Domain method [10]. Measurements were also performed in an anechoic chamber measuring the S21 response at 0° incident angle (Figure 2). The substrate used was FR4 having a thickness of 1.6mm an ε_r of 4.55 and a tanδ of 0.0175.

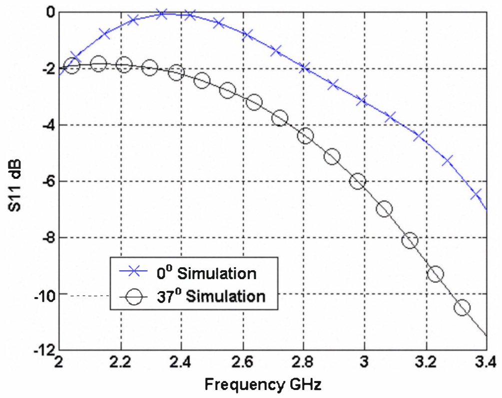

Figure 1: Reflection Loss

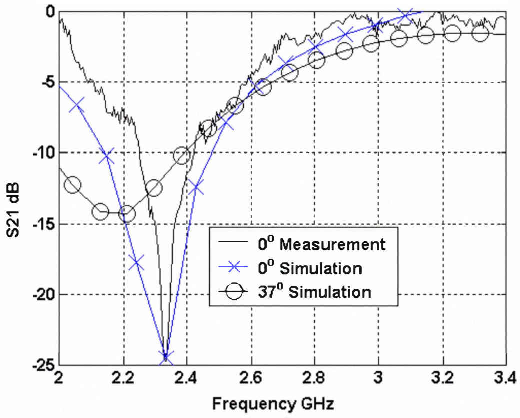

Figure 2: Transmission Loss

It is clear from Figures 1 and 2 that as the angle of incidence is varied, the transmission and reflection loss characteristics will vary as well. Furthermore, different FSS designs will result in a different transmission and reflection behavior. When designing a FSS for a particular scenario, this angular sensitivity has to be taken into account. This is necessary in order to correctly model the appropriate radiowave propagation interaction in the modeled environment.

To practically show the reflection gain and respectively the possible isolation that can be achieved, measurements were carried out in an anechoic chamber. For this purpose a brick wall was constructed in the anechoic chamber of the Centre for Communication Systems Research at the University of Surrey. Horn antennas were used for transmission and reception, with antenna gains of 9 dBi and 14.4 dBi respectively at the frequency of interest. A network analyser was used to sweep the antenna frequency range. The angle of incidence was 37° and the FSS was placed in the far field of the transmitting and receiving antennas. After performing the reflection measurement with only the brick wall, the FSS was then attached to the brick wall and the reflection characteristics were measured again. Results obtained are shown in Figure 3, highlighting the typical reflection advantage of the deployed FSS.

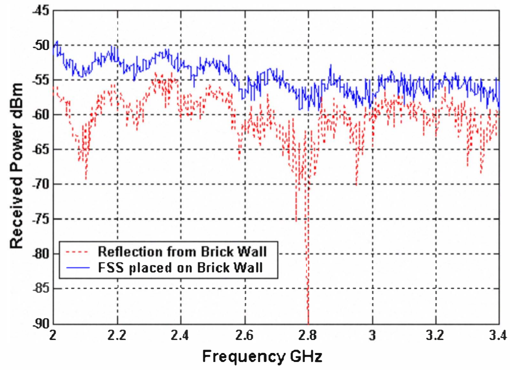

Figure 3: Measured reflection response of a deployed FSS

3. Impact of Frequency Selective Surfaces

In order to study the effect of deploying Frequency Selective Surfaces (FSS) in an indoor environment, a 3D ray tracing model was developed to simulate a simple scenario with and without FSS. The application of ray tracing falls into the category of deterministic or Site-Specific modelling [11], [12] which is very well suited for this work. Ray Tracing is based on Geometrical Optics (GO) and is used to identify all the possible ray paths between the transmitter and the possible receiver locations. Typical algorithms for the implementation of Ray-Tracing include the shooting and bouncing ray (SBR) and the image method.

During this work, a ray tracing algorithm was first implemented in MATLAB. This algorithm is based on the image method, where for a given source point and a facet, the reflected rays in the facet can be considered as being directly radiated from a virtual source called the image source, which is symmetrical to the source with respect to the facet [11], [12]. The first step, during the implementation of the algorithm is to unambiguously define the environment under investigation in terms of its geometrical and morphological characteristics. These two descriptions are integrated into the faceted model where every building interface is represented by a polygon-shaped facet, which geometrically and morphologically describes the interface.

In order to test the basic ray tracing algorithm prior to the investigation of the effect of the FSS, a real scenario (second floor of the Centre for Communication Systems Research, CCSR, University of Surrey) was simulated and some radio measurements were performed along the measurement route depicted in Figure 4. The basic ray tracing modelling approach was also compared with results obtained from a commercial ray tracing simulator. The simulator used was Wireless Insite from REMCOM, which was utilising a shooting and bouncing ray algorithm. The electrical parameters of the scenario's interfaces, used in both simulators, are tabulated in Table 1. Typical constitutive parameters for different materials can be found in [2].

Interface Type	Material	Electrical Permittivity	Conductivity σ (Siemens/m)	Thickness (metres)
External Wall	Brick	5.5	0.018	0.30
Floor & Ceiling	Concrete	8	0.01	0.40
Internal Wall	Plaster	3.5	0.015	0.15
Door	Wood	2	$8x10^{-3}$	0.10
Window	Glass	5.2	$3.5x10^{-3}$	0.02

Table 1: Electrical parameters used for CCSR interfaces

Figure 4 shows the measurement route used for comparison purposes, which consisted of 51 (both LOS and NLOS) averaged measurement points. Measurements were carried out through the use of a portable spectrum analyser from Rohde and Schwarz (FSP30). The transmitter used was a Rohde and Schwarz signal generator (SMT 06) transmitting a 10 dBm CW signal at a frequency of 2.4GHz. Dipole antennas were used for transmitting and receiving purposes at the frequency of operation. Figure 5 shows the comparison of the theoretical predictions and the measurement set.

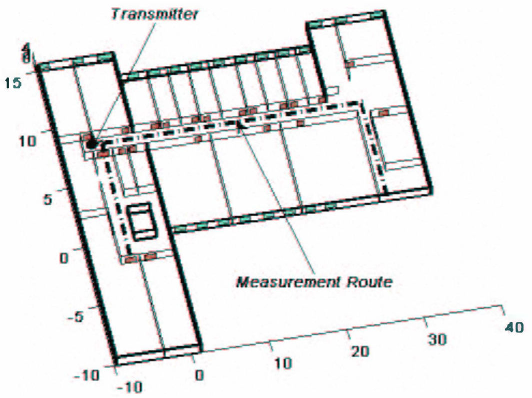

Figure 4: Measurement route

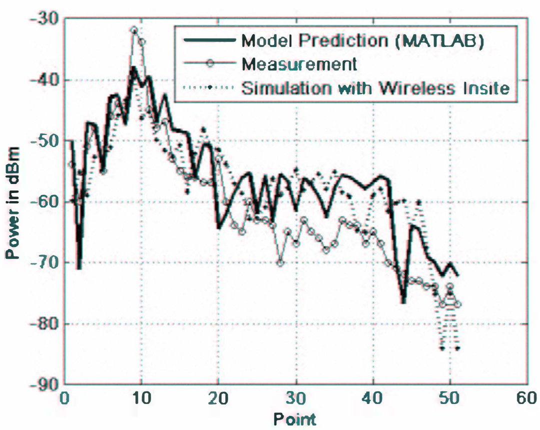

Figure 5: Comparison between measurements and modelling

The recorded set of measurements indicated a mean model error of around 4dB and a model error standard deviation of around 5dB, which are considered to be reasonable. One reason for the minor differences between the theoretical predictions and the measurements is the possible inaccurate use of the constitutive parameters [1], [2].

After the basic algorithm was verified, a smaller scenario was developed (Figure 6). The facets in the simulated environment were also described in such a way in order to incorporate the theoretical behaviour of the FSS, under different angles of radiowave incidence, as suggested by the CFDTD method. In this case the FSS that was simulated was a square-loop design assumed to be constructed on FR4 dielectric. This scenario consisted of 14 brick 30cm-thick walls (including floor and ceiling) as shown in Figure 6, having a relative permittivity $\varepsilon_r = 5$ and conductivity $\sigma = 0.1$S/m. The transmitter power was set to 1mW and the transmitter-receiver antenna gain to 0dBi.

The first case under investigation examined the effect of deploying the FSS, designed at 2.4GHz, on the four external walls as shown in Figure 6. Results obtained along the estimation route are shown in Figure 7.

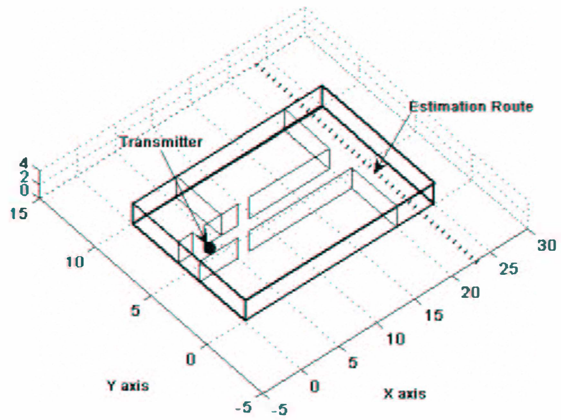

Figure 6: Scenario under investigation

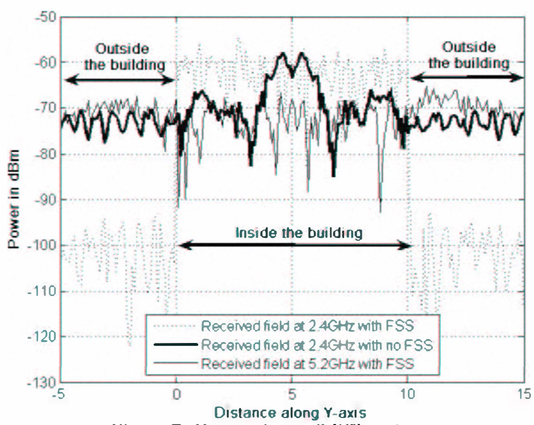

Figure 7: Comparison of different cases

It is obvious from Figure 7 that the field strength inside the building is increased where as the one outside the building is decreased. The power outside the building is reduced by roughly 25dB and effectively reduces the interference to any other wireless systems operating at the same frequency outside the external containing walls, whereas the power inside the building is increased by 5 to 10 dB depending on the position of the receiver.

To simulate the effect of the deployed FSS on a system operating at another frequency, 5.2GHz was used. Figure 7 also shows that the FSS has very little effect on the propagation characteristics at this frequency since the FSS is not tuned at 5.2GHz. This effectively means that another wireless system operating at a frequency other than the FSS design frequency, can be used without any significant effect on its radio propagation characteristics. A specific example could be the confinement of WLAN signals within a building for security or interference reasons, without obstructing transmission of cellular signals through such a frequency selective building.

Figure 8 investigates the radio coverage scenario where FSS are used on the internal walls of Room 2 and Room 3. It is obvious from the results presented in Figure 9 that the received signal in rooms 2 and 3 is attenuated where as the signal along the corridor is increased and channelled through multiple reflections. The presented received power in Figure 9 does not show the expected fast fading effect because the calculated field by the ray tracing algorithm at the reception points was calculated at in-between distances greater than a wavelength. This was done in order to speed up the MATLAB calculations. The presence of FSS on the internal walls significantly reduces the amplitude of the rays transmitted into Room 2 and Room 3, while simultaneously these rays are channelled along the corridor, which acts as a waveguide. Results suggest that in certain scenarios FSS can be used as passive repeaters by channelling the signal into areas of interest.

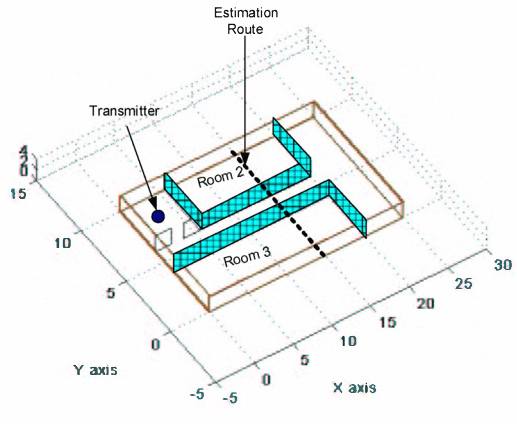

Figure 8: FSS added internal walls

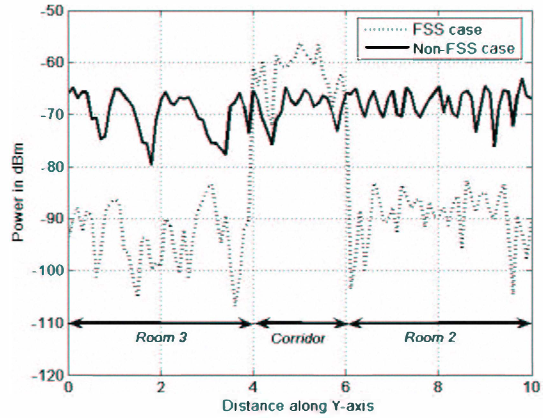

Figure 9: Signal amplification/reduction in different areas

4. Conclusions

In this paper the basic isolation and passive amplification capabilities of Frequency Selective Surfaces were demonstrated through the use of a specially modified ray tracing tool. Based on this tool, a simple scenario was simulated, highlighting typical isolation and amplification figures that can be obtained. These figures will depend on the specific type and setup of the FSS used.

5. References

[1] Stavrou S., Saunders SR., "*Factors influencing outdoor to indoor radio wave propagation*", 12th International conference on Antennas and Propagation ICAP 2003, Vol. 2, 31 March - 3 April 2003, (Conf. Publ. No. 491), pp. 581-585.

[2] Stavrou S., Saunders S.R., "*Review of constitutive parameters of building material*", 12th International conference on Antennas and Propagation ICAP 2003, Vol. 1, 31 March - 3 April 2003, (Conf. Publ. No. 491), pp. 211-215.

[3] Yang R., "*Passive repeater using double flat reflectors*", IRE International Convention Record, Vol. 5, Mar 1957, pp. 36-41.

[4] Hristov H.D., Feick R., Walter G., "*Improving indoor signal coverage by use of through-wall passive repeaters*", Antennas and Propagation Society International Symposium 2001, IEEE, Vol. 2, 8-13 July 2001, pp. 158-161.

[5] Daniel J.P., "*Mutual coupling between antennas for emission or reception application to passive and active dipoles*", IEEE Transactions on Antennas and Propagation, Vol. 22, No. 2 , Mar 1974, pp. 347-349.

[6] Gregorwich W., "*The design and development of Frequency Selective Surfaces for phased arrays*", IEEE Aerospace Conference Proceedings 1999, Vol. 5, 6-13 March 1999, pp. 471-479.

[7] Munk B.A., "*Frequency Selective Surfaces, Theory and Design*", John Wiley & Sons, 2000.

[8] Luebbers R.J., Munk B.A., "*Some effects of dielectric loading on periodic slot arrays*", IEEE Transactions on antennas and propagation, Vol. AP-26, Issue 4, July 1978, pp 536-542.

[9] Mittra R., Chan C.H., Cwik T., "*Techniques for analyzing Frequency Selective Surfaces – A Review*", IEEE Proceedings, Vol. 76, No. 12, December 1988, pp. 1593-1615.

[10] Yu W., Mittra R., "*A conformal FDTD Software Package for modeling of antennas and microstrip circuit components*", IEEE antennas and propagation magazine, Vol. 42, No. 5, October 2000, pp. 28-39.

[11] Athanasiadou G.E., Nix A.R., "*A Novel 3-D Indoor Ray-Tracing Propagation Model: The Path Generator and Evaluation of Narrow-Band and Wide-Band Predictions*", IEEE Transactions on Vehicular Technology, Vol. 49, No. 4, July 2000, pp. 1152-1168.

[12] Ji Z., Li B., Wang H., Chen H., Sarkar T.K., "*Efficient ray tracing methods for propagation prediction for indoor wireless communications*", IEEE antennas and propagation magazine, Vol. 43, No. 2, April 2001, pp. 41-49.