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Special Issue

Radio propagation in frequency selective buildings

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SUMMARY

This work proposes the deployment of frequency selective surfaces (FSS) in indoor wireless environments and investigates their effect on radio wave propagation. FSS could be used to isolate coverage in indoor areas by increasing the transmission loss through the interfaces. At the same time they can channel the signals into other areas of interest. Simulations have been carried out at two frequencies in order to verify the frequency selectivity of FSS. Copyright © 2006 AEIT.

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 30–40 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 reflections and transmissions 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. [1–4].

Depending on the application, there are cases where one radio signals have to be confined in order to reduce interference or increase wireless security. 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 active and passive repeaters, distributed antennas, leaky feeders etc. The details of these can be found in References [5, 6]. Each method has its own advantages and disadvantages. For example, active repeaters require power and good isolation between antennas [7] otherwise the system can become oscillatory. Also with active repeaters the received noise and interference is also reradiated on both the forward and reverse link. Leaky feeders can be used in tunnels or in areas difficult to access.

The technique investigated in this paper is to utilise frequency selective surfaces (FSS) as passive repeaters or isolators, in order to either increase or retain the radio signal [8]. 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, FSS 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 [9] as the reflecting interface. The disadvantage of using the latter method is that it will unselectively block all radio signals.

Section 2 of this paper highlights some of the FSS behaviour issues related to this work. These include the effect of the angle of incidence and the effect of typical building materials when placed at various distances behind the FSS, on the transmission and reflection characteristics of FSS. Typical modelled and measured responses are also provided. Section 3 investigates a typical indoor scenario

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through a custom written ray tracing algorithm, which incorporates 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 influencing the response of FSS is the element shape [10, 11]. Also, the dielectric material plays an important role in the FSS response [12]. The frequency response is affected by the element size, the permitivity and thickness of the substrate, and the gaps between the elements. Various approaches have been developed for analysing the behaviour 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) [13, 14].

For the purpose of this investigation a cross-dipole FSS was designed and fabricated on FR4. To characterise the transmission and reflection from FSS, measurements were carried out in the anechoic chamber of the Centre for Communication Systems Research at the University of Surrey. Horn antennas were used for transmission and reception and a vector network analyser (Rohde and Schwarz VNA ZVCE 20 KHz–8 GHz) was used to sweep the frequency between 1–4 GHz. The measurement setup is shown in Figure 1.

The measured and simulated results are presented in Figures 2, 3 and 4. The simulations were performed utilising the CFDTD method [14]. For simulation purposes, the FR4 effective dielectric constant was set to 2.775 [15, 16].

Figure 2 presents the transmission characteristics of a cross-dipole FSS at normal incidence. The measurement result is in close agreement with the simulation performed, which verifies the validity of the CFDTD simulator. Figures 3 and 4 present the transmission (S21) and the reflection (S11) loss characteristics for a typical cross-dipole FSS design, at four different angles of incidence (0°, 15°, 30°, 53°).

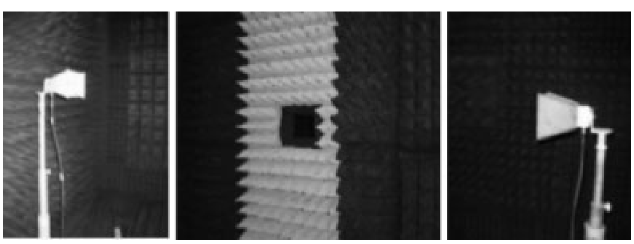

Figure 1. Measurement setup.

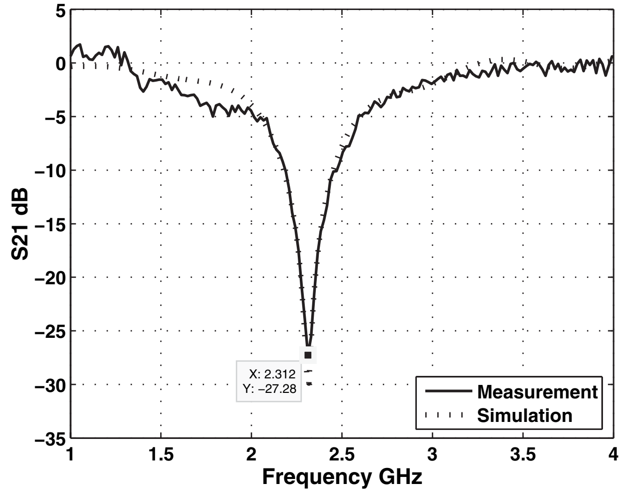

Figure 2. Transmission through FSS at normal incidence.

It is clear from Figures 3 and 4 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 behaviour. 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 modelled environment.

It has also been reported in the literature that when a FSS is placed on a dielectric medium the frequency response changes [11, 16]. For this reason the interaction of FSS with building materials such as wood, plaster and brick was investigated.

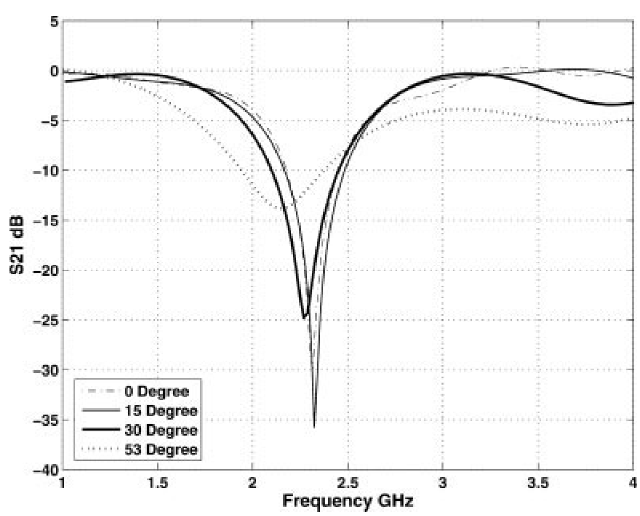

Figure 3. Transmission through FSS at various angles.

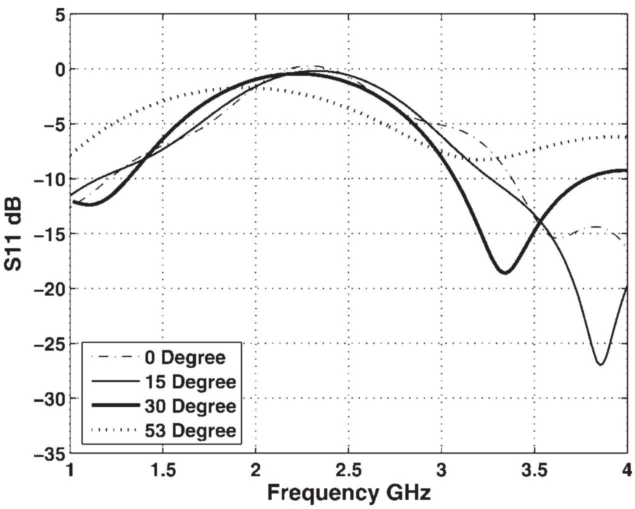

Figure 4. Reflection from FSS at various angles.

Figure 5 shows the building materials effect on the frequency response of FSS. The results indicate that there is a shift on the tuning frequency of the FSS when the latter is attached on a building material which seems to depend on the properties of this material. To further investigate this effect, measurements were also performed by varying the distance between the FSS and the material. The results are presented in Figures 6, 7 and 8.

The distance between the FSS and the plaster wall was gradually increased up to 125 mm. The results tabulated in Table 1 suggest that when an FSS is deployed on typical building materials its tuning frequency changes. Initial investigations indicate that as the distance between the FSS and the building wall material is increased, the tuning frequency is restored back to the case when there is no material present behind the FSS.

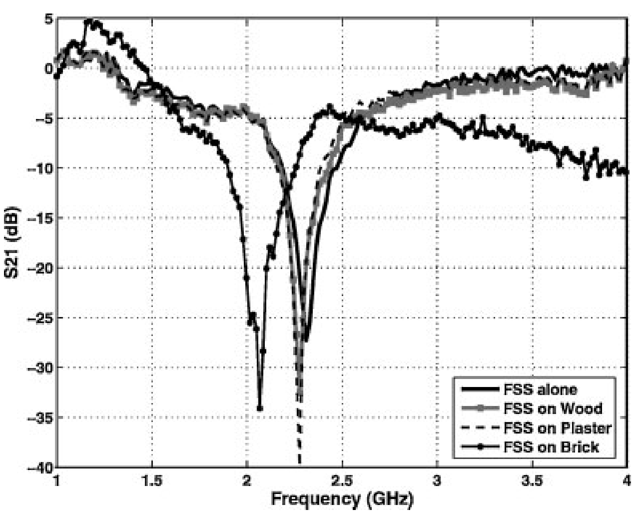

Figure 5. Interaction of the cross-dipole FSS with various building materials attached to it.

Table 1. Varying the distance between the FSS and the plaster board.

Case	Measurement		Simulations	
	Frequency GHz	Magnitude dB	Frequency GHz	Magnitude dB
FSS only	2.312	−27.28	2.317	−29.88
FSS attached	2.277	−39.64	2.234	−47.68
10 mm	2.312	−32.12	2.329	−40.2
30 mm	2.348	−32.19	2.341	−42.37
50 mm	2.33	−25.3	2.329	−41.72
70 mm	2.312	−29.08	2.329	−26.48
100 mm	2.33	−31.4	2.353	−38.68
125 mm	2.312	−26.71	2.327	−25.24

3. IMPACT OF FSS IN INDOOR PROPAGATION

In order to study the effect of deploying 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 [17, 18], 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 a transmitter and a receiver. Typical ray tracing algorithms include the shooting and bouncing ray (SBR) and the image method.

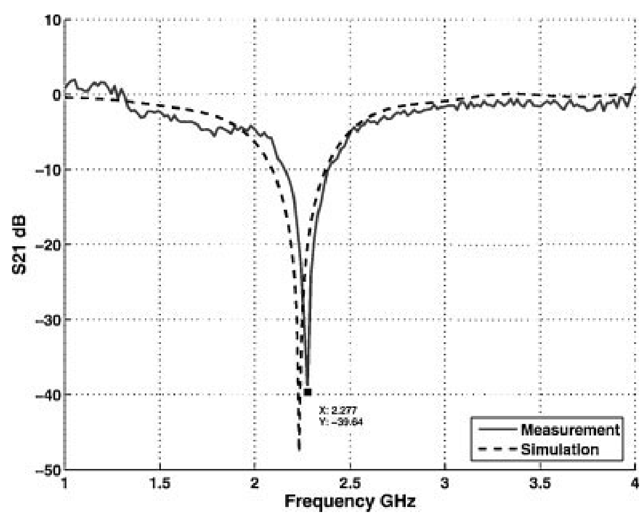

Figure 6. FSS attached to the plaster wall.

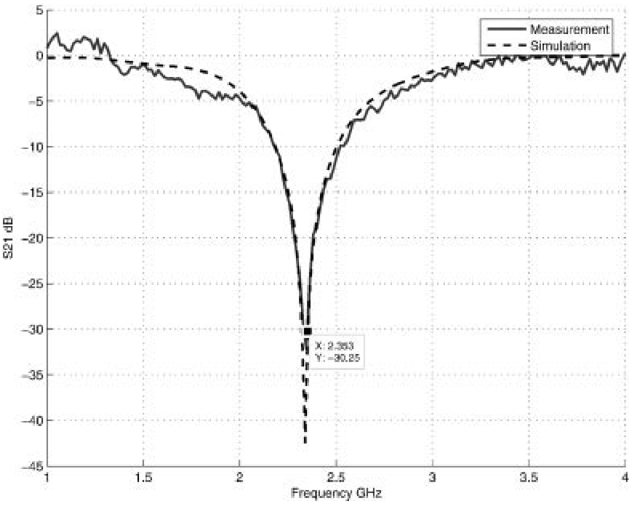

Figure 7. FSS placed 10 mm away from plaster wall.

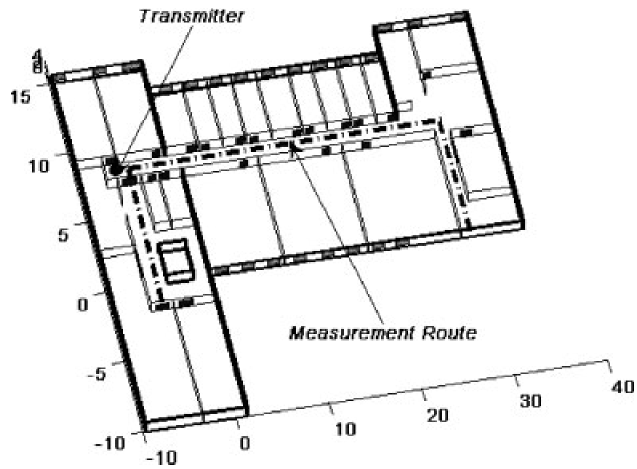

Figure 9. Measurement route.

During this work, a Ray Tracing algorithm was first implemented in MATLAB, based on the image method. In this case, 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 [17, 18]. 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-shape facet, which geometrically and morphologically describes the interface.

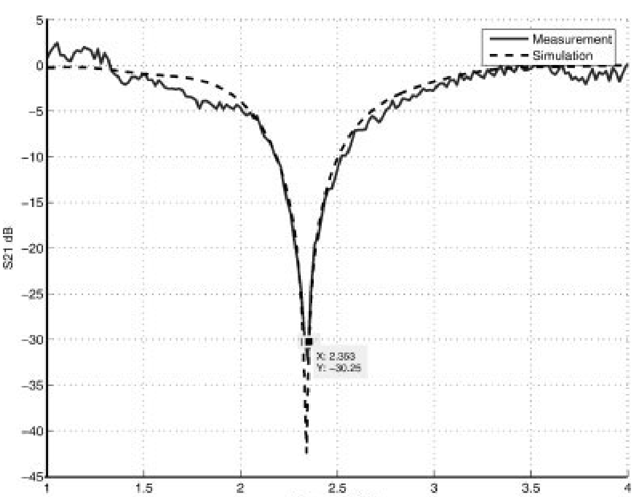

Figure 8. FSS placed 30 mm away from plaster wall.

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 9. 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 utilising a shooting and bouncing ray (SBR) algorithm. The electrical parameters of the scenario's interfaces, used in both simulators, are tabulated in Table 2. Typical constitutive parameters for different materials can be found in [2].

Figure 9 shows the measurement route consisting of 51 (both LOS and NLOS) averaged measurement points. Measurements were carried out with 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 2.4 GHz. Dipole antennas were used for transmitting and receiving. Figure 10 shows the comparison of the theoretical predictions and the measurement set.

Table 2. Electrical parameters used for CCSR interfaces.

Interface Type	Material	Electrical ε_r 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	8×10^{-3}	0.10

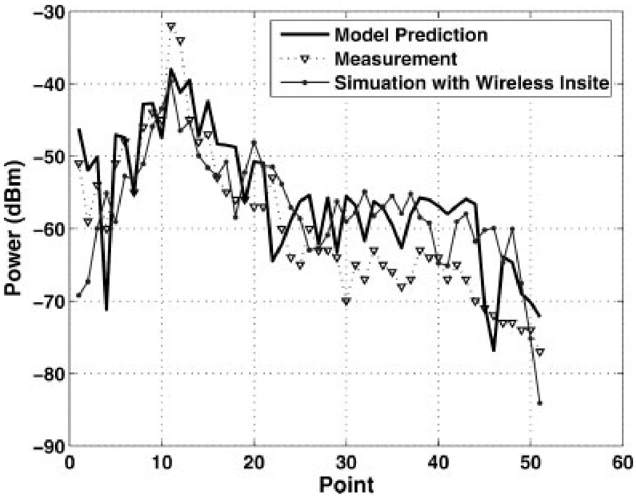

Figure 10. Comparison between measurements and modelling.

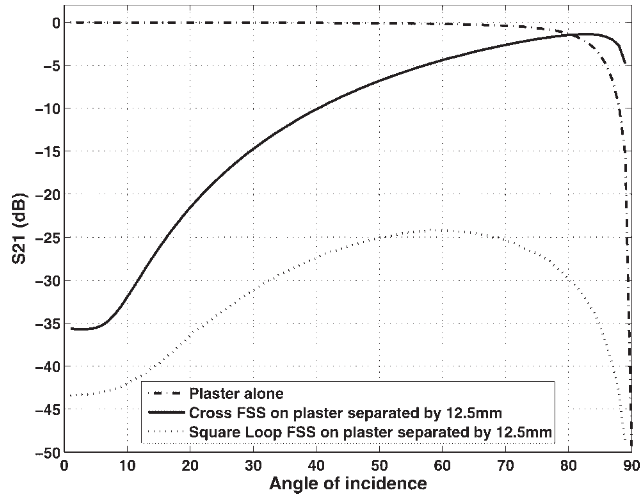

Figure 12. Comparison between the cross-dipole FSS and the square-loop FSS.

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

After the basic algorithm was verified, a simpler environment was developed (Figure 11). The facets in the simulated environment were also described in such a way in order to incorporate the theoretical and measured behaviour of the FSS, under different angles of incidence, as suggested by the CFDTD method. The simulated FSS was a square-loop design assumed to be constructed on FR4. The reason that square-loop FSS was selected instead of the cross-dipole FSS presented in Section 2 was that the square-loop design theoretically has better angular sensitivity than the cross-dipole design [9]. This is shown in Figure 12. It was also found through simulations that when the FSS is separated by 12.5 mm from the plaster wall then its frequency response does not change. This is illustrated in Figure 13.

Firstly the effect of deploying the FSS, on the four external walls was examined. These FSS were designed

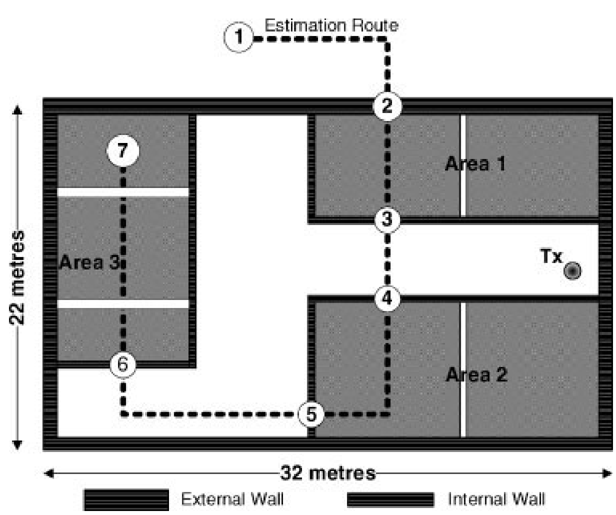

Figure 11. Scenario under investigation.

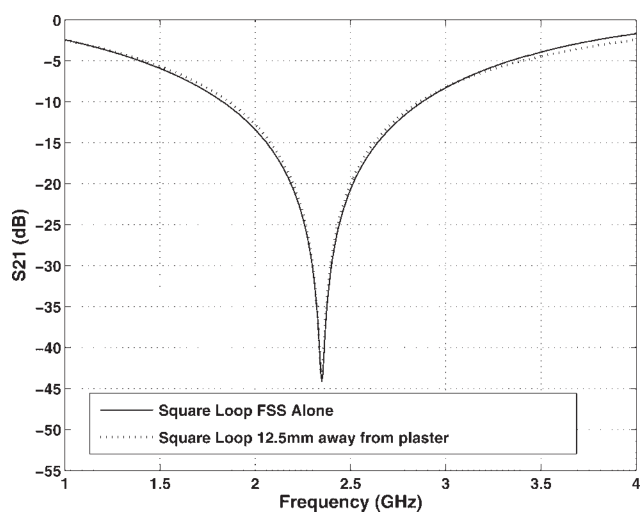

Figure 13. Comparison of the transmission loss between the case where the square loop is alone and the case where it is placed 12.5 mm in front of plaster. Both cases simulated at normal incidence.

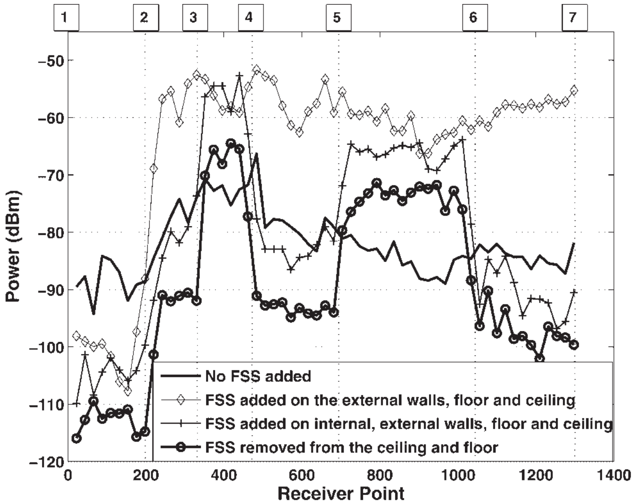

Figure 14. Comparison of different cases at 2.4 GHz. The numbers at the top of the figure correspond to the points along the estimation route as shown in Figure 11.

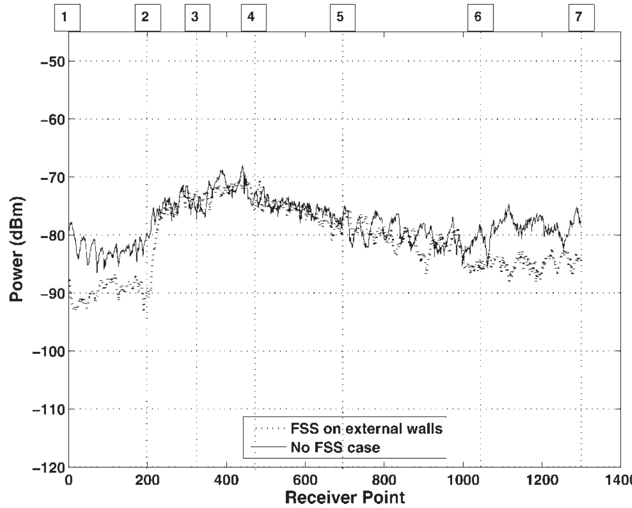

Figure 15. Comparison of different cases at 5.2 GHz.

at a tuning frequency of 2.4 GHz. Results obtained along the estimation route, are shown in Figure 14. The spacing between the receiver locations along the estimation root is 0.05 m. The results shown in Figure 14 have been averaged in order to remove the fast fading. It is obvious 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 10 dB and effectively reduces the interference to any other wireless systems operating at the same frequency outside the external walls. The power inside the building is increased by 20–25 dB depending on the position of the receiver.

The next step of the investigation was to find a way to channel the signal along the corridor, where at the same time restrict it from areas 1, 2 and 3 as shown in Figure 11. In this scenario, FSS was deployed on the internals walls as well. Results presented in Figure 14 suggest that there is a significant increase of the field strength along the corridor, compared to the non-FSS case (around 20 dB). However, there is very little change of the field strength inside areas 1, 2, 3, compared to the non-FSS case. This happens because the high attenuation suffered by the rays while crossing the internal walls is compensated by the stronger reflection (and effectively less attenuation) from the floor and/or ceiling. This is also the reason for the small reduction of the field strength ($\sim$10 dB) outside the building in the first case where FSS is added on the external walls, the ceiling and the floor. In order to verify this, the ceiling and floor FSS were then removed. The results show that there is approximately 10–15 dB increase along the corridor where at the same time there is a 10 dB field reduction inside areas 1, 2 and 3. The presence of FSS on the internal walls significantly reduces the amplitude of rays transmitted into areas 1, 2 and 3. At the same time 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, channelling the signal into other areas of interest.

To highlight the effect of a deployed FSS, tuned at 2.4 GHz, on a different frequency, a radio transmission at 5.2 GHz was assumed. The transmission and reflection coefficients were obtained through the CFDTD method. Figure 15 suggests that the FSS has very little effect on the radio propagation characteristics at this frequency since the FSS is not tuned at 5.2 GHz. This effectively means that a carefully designed and deployed FSS will not have any effect on a system operating on another frequency. A specific example could be the confinement of WLAN signals within a building without obstructing the transmission of cellular signals through such a frequency-selective building.

4. CONCLUSION

In this paper the basic isolation and passive amplification capabilities of FSS were demonstrated through the use of a specially modified ray tracing algorithm. Simulations and measurements have been carried out to verify the angular sensitivity of the reflection and transmission characteristics of the FSS and the change in the frequency response when the distance between the FSS and the building material is varied. Based on a modified Ray Tracing algorithm, 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. The results suggest that FSS can be used in indoor wireless environments in order to increase or restrict coverage.

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Marios Raspopoulos was born in Nicosia, Cyprus, on July 10, 1978. He received a diploma in electrical engineering from Higher Technical Institute in Cyprus in 2001 and an M.Eng. degree in electronics and mobile communication from the University of Surrey, UK in June 2003. In September 2004, he was awarded an M.Sc. in communications networks and software again from the University of Surrey and then continued his research work into a Ph.D. level at the Centre for Communication Systems Research (CCSR) at the University of Surrey. His research deals with techniques for improving radio propagation mainly in indoor wireless environments. His work involves deterministic modelling using ray tracing, 3D electromagnetic simulations and design of frequency selective surfaces. His other interests include antenna design and UWB communications.

Farhan A Chaudhry is currently studying for his Ph.D. in radio wave propagation at the University of Surrey within the Mobile Communications Research Group. Prior to this, in 2002 he obtained an M.Sc. in satellite communications engineering degree also from the University of Surrey. His first degree in electronics engineering was obtained in 2000 from the University of Engineering and Technology Lahore. His main research interests include development of passive techniques to enhance signal coverage, frequency selective surfaces, ray tracing algorithms, 3D electromagnetic problems, HAPS and satellite systems.

Stavros Stavrou was born in Nicosia, Cyprus, on March 10, 1972. He received a diploma in electrical engineering from Higher Technical Institute in Cyprus in 1992. In 1996, he was awarded the B.Eng. degree in communications and computer engineering from the University of Essex (UK) and in 2001 the Ph.D. in electronic and electrical engineering from the University of Surrey (UK). His Ph.D. work concentrated on radiowave propagation and RF/antenna issues for mobile communications. From 1997 to 2000, he was a research fellow with the Centre for Communication Systems Research (CCSR), University of Surrey, UK. During this period he worked on several national and international research projects. In 2000, he was appointed as a lecturer, at CCSR, at the University of Surrey. His main research interests include, radiowave propagation for different wireless systems, radio measurements for system planning, MIMO systems and radio frequency and antenna design. Dr. Stavrou has authored and co authored a number of papers in the above areas.