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FREQUENCY-SELECTIVE WALLPAPER FOR REDUCING INTERFERENCE WHILE INCREASING MIMO CAPACITY IN INDOOR ENVIRONMENTS

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Abstract

The design and features of frequency-selective wallpaper created for attachment onto regular walls in order to filter out signals operating at 5 GHz while at the same time allowing the desired radio communication services to propagate through such walls are presented. An analysis of the characteristics of the radio channel evaluated in a typical indoor environment, when considering either regular walls or walls with the designed wallpaper, is performed through a ray-launching programme for both single input single output (SISO) and multiple input multiple output (MIMO) systems. In this way, parameters such as the signal to interference ratio, power delay profile, and channel capacity are obtained and compared for the two mentioned scenarios (with and without wallpapers).

1 Introduction

The growth of wireless communication systems over the last decade has led to the necessity of minimizing interferences between coexisting systems, as well as solving capacity problems arising from the conflicts between the availability of spectrum and the number of users. Some strategies aimed at tackling the mentioned issues have included advanced signal processing techniques or antenna design technology. However, such solutions are often complex and/or expensive. Another strategy for indoor scenarios would be to modify the physical wave propagation environment by covering the walls with frequency-selective (F-S) wallpapers so that undesired interferences are blocked (reflected) while desired radio communication services are able to propagate through the walls. In this sense, the signal to interference ratio (SIR) can be improved [6,7].

Due to the fact that F-S wallpapers confine the signals of the system operating at the blocked frequency within the room, the characteristics of the radio channel can be improved when considering high performance systems such as MIMO, which typically gain in a rich scattering environment and where the capacity of the radio channel is afforded by the number of uncorrelated channels and their individual strengths [8]. This paper analyzes the ability of the designed F-S wallpaper to improve the SIR while achieving better radio channel characteristics in MIMO systems. This furthers previous works such as [6,7,3] in which only SISO systems are considered within rooms consisting of either F-S walls or F-S windows.

2 Wallpaper design

2.1 Frequency-Selective Surfaces

Frequency-selective surfaces (FSSs) play a key role in many antenna systems for fixed modern and mobile communications services. FSSs are essentially array structures that consist of a plurality of thin conducting elements, often printed on a dielectric substrate for support. They behave as passive electromagnetic filters. Frequently these arrays take the form of periodic apertures in a conducting plane. If the FSS is made of an array of conductors, incident waves are reflected by the surface at certain frequencies (reflection band or stop band), while the surface is transparent to these waves at other frequencies (transmission band or pass-band). In the case of conducting arrays, the resonance is due to high induced element currents. The surface then acts as a metallic sheet at resonance. If an array of apertures is to be used, the FSS is mostly reflective and exhibits a pass-band at resonance which results from strong fields in the apertures [5].

2.2 Wallpaper with Low Transmission at 5 GHz

The design of the wallpaper was made with the software PB-FDTD, which is based on the unit cell analysis technique and whose underlying numerical technique is the finite-difference time-domain (FDTD) method. The program utilizes the

periodic boundary conditions which reduce the computational volume to that of a single unit cell.

The purpose of the wallpaper's design was to block/confine 5 GHz signals (e.g. IEEE 802.11a systems) while at the same time allowing wireless services at other frequencies (e. g. cellular mobile communication signals) to pass through. To do so, the FSS geometry shown in Fig. 1 was considered.

A periodic pattern of perfectly electric conducting (PEC) metallic hexagons can be observed where a is the periodicity along the x and y axis, respectively, h_i is the height, w is the width, and t is the distance between metallic hexagons. The dimensions of the FSS were determined by a parameter study that assigned the following values: w=0.4 mm, t=1.3 mm, and a=11.1 mm.

In order to evaluate the performance of the wallpaper, a structure consisting of the FSS attached onto a gypsum wall was considered in the simulations, as can be observed in Fig. 2. The wall was assumed to have a thickness of T=51.5 mm and a relative permittivity and conductivity of ε_r=5 and σ=0.0084 Am^{-2}, respectively.

The transmission coefficient of the resulting F-S wall is given in dB in Fig. 3 as a function of frequency for different angles of incidence, as well as both *hard* (vertical) and *soft* (horizontal) polarizations. The angles of incidence (θ) expressed in the plot are related to the broadside direction, as depicted in Fig. 2. For comparison, the case where only the gypsum wall is considered (no wallpaper is attached onto it), assuming broadside incidence, is also shown in the plot.

It can be noted that an additional transmission attenuation of 20 dB appears at 5 GHz for both polarizations compared to the unmodified wall, as desired. The resonant frequency varies by a mere 0.4 GHz for angles of incidence in the range from broadside up to 69.6º.

3 Ray-launching Approach

In order to obtain the results presented in this work, a ray-launching programme based on ray optics and the uniform theory of diffraction (UTD) was used to perform the simulations. Ray launching techniques shoot rays at a number of discrete angles from a transmitter and these rays interact with objects present in the environment as they propagate. In this way, the launched rays are reflected, transmitted, diffracted, and scattered throughout the environment. Rays that arbitrarily pass close to a receiver location are used to predict the actual propagation paths and therefore, the total field reaching the receiver can be evaluated as the coherent summation of all contributions impinging on it.

The ray-launching tool used in this work can be applied for the analysis of both SISO and MIMO systems. For results related to the MIMO system, it has been assumed that the number of transmitting antennas (N_t) and the number of receiving antennas (N_r) are equal, which means $N = N_t = N_r$. In order to obtain the channel transfer matrix ($G_{N\times N}$), $N\times N$ simulations are performed for each receiver position. In each simulation, the

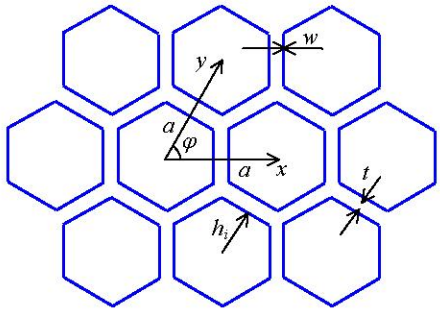

Figure 1: Hexagonal geometry of the FSS.

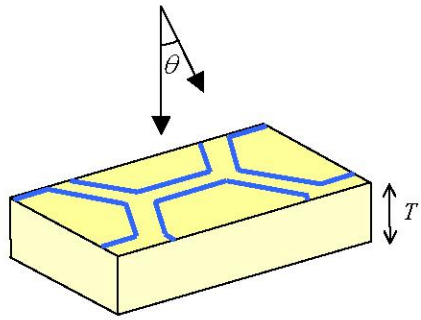

Figure 2: Scheme of the wallpaper attached onto the gypsum wall.

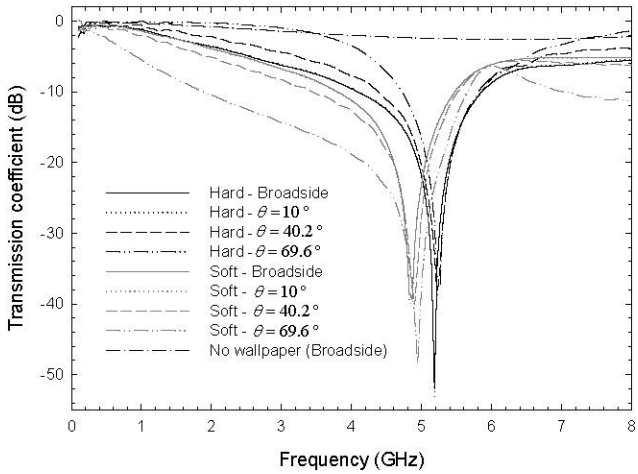

Figure 3: Transmission coefficient for the structure considered in Fig. 2.

coefficient $G(n,m)$ is calculated as the coherent sum of all rays at the receiver in the antenna m when only the antenna n is transmitting.

The contributions that have been taken into account are: direct (E_1), multiple reflected (E_2), multiple transmitted (E_3), multiple diffracted (E_4), multiple reflected/diffracted (E_5), multiple transmitted/diffracted (E_6), and multiple transmitted/reflected (E_7) rays. Therefore, the matrix G for a given receiver position is obtained as:

$$G(n,m) = \sum_{c=1}^{7} E_c(n,m) \quad (1)$$

where the direct, reflected, transmitted, diffracted, reflected/diffracted, transmitted/diffracted, and transmitted/reflected components are calculated as:

$$E_1(n,m) = \frac{E_o}{r} e^{-jkr} \quad (2)$$

$$E_2(n,m) = \sum_i R_i \frac{E_o}{r_i} e^{-jkr_i} \quad (3)$$

$$E_3(n,m) = \sum_i T_i \frac{E_o}{r_i} e^{-jkr_i} \quad (4)$$

$$E_4(n,m) = \sum_i \frac{E_o}{s_i'} e^{-jks_i'} D_i \sqrt{\frac{s_i'}{s_i(s_i + s_i')}} e^{-jks_i} \quad (5)$$

$$E_5(n,m) = \sum_i \frac{E_o}{s_i'} e^{-jks_i'} D_i R_i \sqrt{\frac{s_i'}{s_i(s_i + s'_i)}} e^{-jks_i} \quad (6)$$

$$E_6(n,m) = \sum_i \frac{E_o}{s_i'} e^{-jks_i'} D_i T_i \sqrt{\frac{s_i'}{s_i(s_i + s'_i)}} e^{-jks_i} \quad (7)$$

$$E_7(n,m) = \sum_i T_i R_i \frac{E_o}{r_i} e^{-jkr_i} \quad (8)$$

where E_o is the emitted field strength, k is the wave number, r and r_i are the propagation path lengths between the source n and the receiver m, s' is the path length from the source to the diffracting wedge, s is the path length from the diffracting wedge to the receiver, D_i is the diffraction coefficient for finitely conducting wedges given in [4], and T_i and R_i are the transmission and reflection coefficients, respectively. In this case, T_i and R_i depend on the polarization of the incident wave, angle of incidence, permittivity, and conductivity.

For the analysis, it has been assumed that the transmitter has no knowledge of the channel and that it distributes power equally among all transmitters [1].

4 Results

4.1 SISO Case

An analysis of the use of the designed wallpapers in an indoor environment was carried out using the mentioned ray-launching software, firstly for a SISO system, considering the two-room floor plan (top view) depicted in Fig. 4, where distances are expressed in meters.

As can be seen, the floor consists of two 5×5 m^2 square rooms with two apertures each, bearing a width of 1.6 m (acting as windows) and assumed to be infinitely high for the simulations. Transmitter *Tx1* is located inside Room 2 so that it gives coverage to that area. *Tx2* is located in Room 1 and therefore, its signal becomes an interference when entering Room 2.

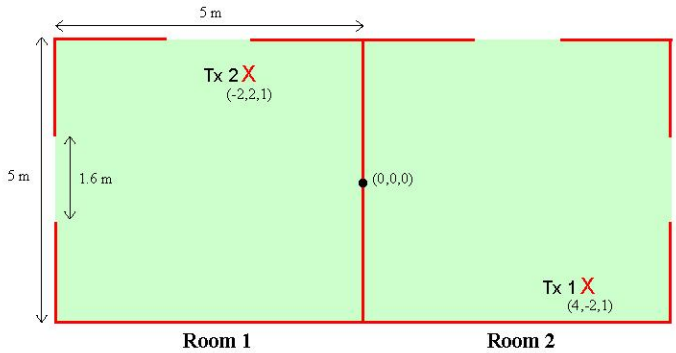

Figure 4: Geometry of the two rooms and the transmitter locations (top view).

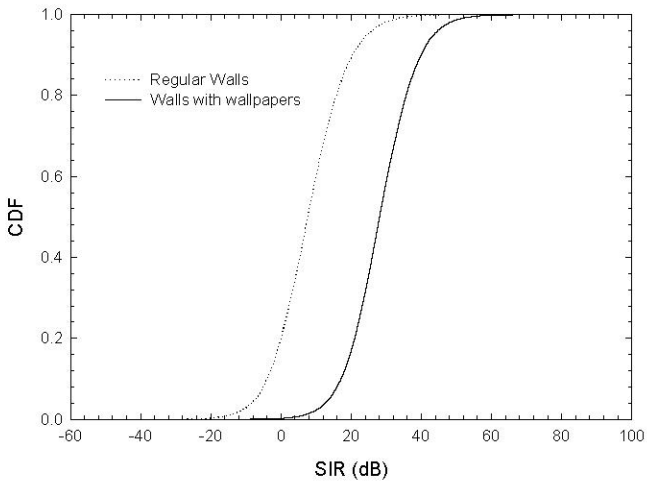

Figure 5: CDF of the SIR in Room 2.

In Fig. 5, the cumulative distribution function (CDF) of the signal to interference ratio (SIR) over every point in Room 2 is depicted, considering the two cases where regular gypsum walls are considered and wallpaper-gypsum walls are assumed. The simulations were performed assuming omnidirectional antennas, a frequency of 5 GHz, *soft* (horizontal) polarization and both *Tx1* and *Tx2* bearing a height of 1 m (which is the third coordinate that can be seen in the position of both transmitters).

It can be observed how an improvement of about 20 dB in SIR is achieved by using the F-S walls. This is in agreement with expected values, according to Fig. 3.

In order to evaluate the power delay profile (PDP) between a transmitter and a receiver in Room 2 for both regular gypsum and F-S wall cases, the scheme shown in Fig. 6 was considered, where transmitter *Tx1* and receiver *Rx1* are located.

In this case, the mentioned PDP can be observed in Fig. 7 for both regular gypsum and F-S wall cases. The curves reveal an average of 20 realizations undertaken at different frequencies ranging from 4.9 to 5.1 GHz with a 0.01 GHz step. Furthermore, a low-pass filtering with cut-off at 40 MHz was carried out in the frequency domain by a *Blackman* window for each realization. The simulations were performed assuming omnidirectional antennas, a frequency of 5 GHz,

hard (vertical) polarization and both *Tx1* and *Tx2* bearing a height of 1 m.

It should be noted how the PDP curve corresponding to the F-S wall case decreases more slowly when increasing the time delay. Hence, there are more different outstanding paths reaching the receiver, which means a larger r.m.s delay spread. Specifically, an r.m.s. delay spread of 22 ns can be calculated from the wallpaper case results (a coherence bandwidth of around 7 MHz), as compared to a value of 4 ns for the regular gypsum wall case (a coherence bandwidth of around 42 MHz).

4.2 MIMO Case

An analysis of the use of the designed wallpapers in an indoor environment, assuming a MIMO system operating inside of it, was also performed. In Fig. 8 the geometry considered in this case is depicted, where transmitter *Tx1* and receiver *Rx1,* which are located inside Room 2, consist of four omnidirectional antennas spaced $\lambda/2$.

In this way, the singular values of the channel transfer matrix G (square roots of the eigenvalues of G^TG and GG^T) can be observed in Fig. 9, as a function of frequency, for both regular gypsum walls and wallpapers cases.

The simulation parameters considered in this case were: omnidirectional antennas, *hard* (vertical) polarization and both transmitting and receiving antennas bearing a height of 1 m. It can be observed that, in the case where regular walls are considered, there are three main singular values, since the fourth is practically negligible. However, when considering the use of the designed wallpaper covering all of the walls, the magnitude of the four singular values increases, with an emphasis on the fourth value, so that, in this case, four outstanding subchannels are obtained instead of three. In this sense, one degree of freedom is gained, as compared to the case in which regular walls are assumed, therefore increasing the capacity of the radio channel.

The capacity of a wireless system with N_t transmitters and N_r receivers with an averaged signal to noise rate (SNR) of ρ at each receiving antenna can be obtained as [2]:

$$C = \log_2\left(\det\left(I_{N_r} + \frac{\rho}{N_t} HH^H\right)\right) \quad bits/s/Hz \quad (9)$$

where I_{Nr} is the $N_r \times N_r$ identity matrix, $(\ )^H$ is the Hermitian transposition, and H is the normalized channel transfer matrix.

The channel transfer matrix, G, is normalized in order to remove the path loss component. It reveals only the relative variations of the responses among all elements.

This means that the average signal to noise ratio is constant and independent of the position of the receiver. The above-mentioned normalization can be carried out by the Frobenius norm, which is defined by:

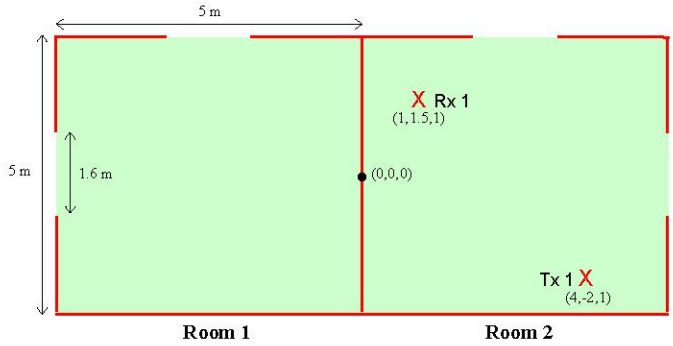

Figure 6: Geometry of the two rooms and the transmitter and receiver locations (top view).

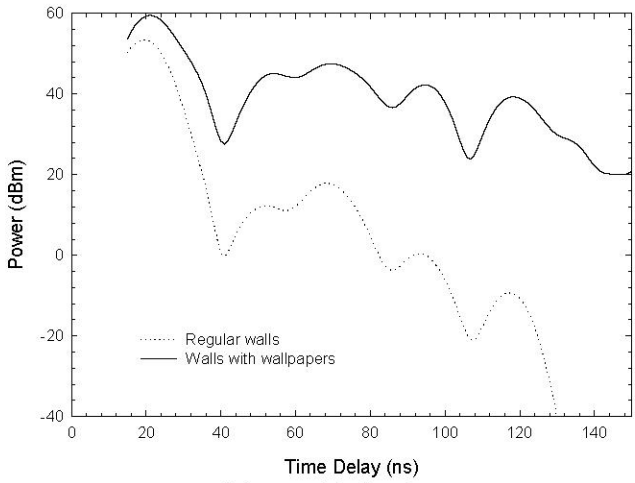

Figure 7: Power delay profile for the geometry in Fig. 6.

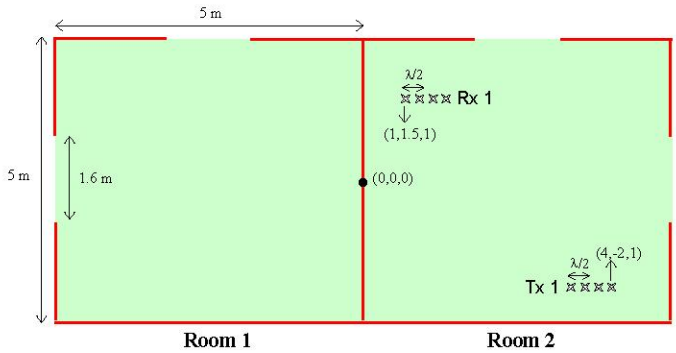

Figure 8: Geometry of the two rooms and the MIMO transmitter and receiver locations (top view).

$$H = \frac{G}{\sqrt{\dfrac{\sum_{j=1}^{N_r}\sum_{k=1}^{N_t}\left|G_{j,k}\right|^2}{N_t N_r}}} \quad (10)$$

In this way, the CDF of capacity in Room 2 in Fig. 8 was calculated for the two types of walls under study, considering the frequency variation analysis shown in Fig. 9 and a number

of different transmitter and receiver positions, as depicted in Fig. 10.

As can be observed, five different transmitter positions spaced 0.6λ from each other were assumed (from *Tx1* to *Tx5*), consisting of an array of four omnidirectional antennas spaced λ/2, and for each of them, two different linear paths were considered, in which twenty different receiver positions spaced 0.6λ (consisting of arrays of four omnidirectional antennas spaced λ/2) were evaluated. *Tx1* and *Rx1* were assumed to be located at the same positions (coordinates) as those considered in Fig. 8.

In Fig. 11, the above-mentioned CDF of capacity at Room2 can be observed for both the regular gypsum and the F-S wall cases for a SNR of 10 dB. The simulation parameters considered in this case were: omnidirectional antennas, *hard* (vertical) polarization and both transmitting and receiving antennas bearing a height of 1 m. For comparison, the CDF of the capacity for an independent and identically distributed (i.i.d) Rayleigh fading channel has also been depicted in the plot.

It can be noted how an improvement in MIMO capacity is achieved by using the designed wallpapers. Specifically, the mean value of the capacity, when considering regular walls, is 8.6 bits/s/Hz whereas for the case in which wallpapers are considered, it is 9.4 bits/s/Hz.

5 Conclusions

Frequency-selective (F-S) wallpaper created with the aim of being attached onto regular walls has been designed in order to filter out signals operating at 5 GHz while at the same time allowing the desired radio communication services located at other frequencies to pass through. The results clearly reveal that by applying the F-S wallpaper in indoor environments, not only is the interference level reduced by an additional attenuation of 20 dB, as compared to the unmodified wall, but also the characteristics of the radio channel are improved for multiantenna systems, due to the lower spatial correlation obtained.

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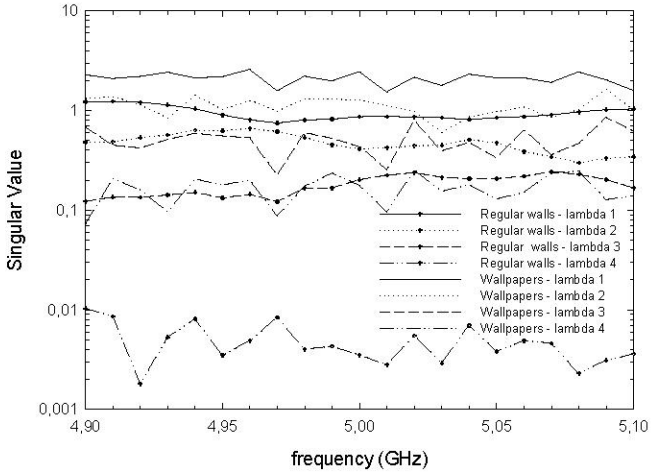

Figure 9: Singular values for the channel transfer matrix considering the geometry in Fig. 8.

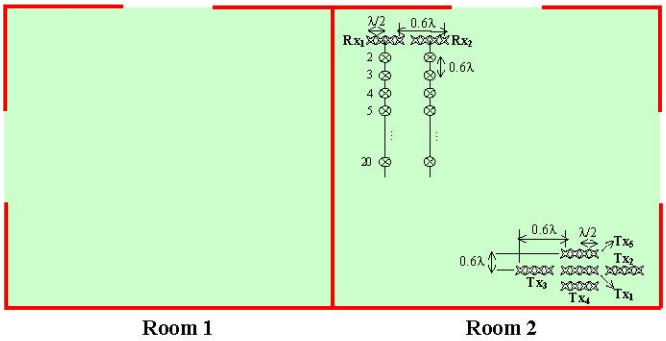

Figure 10: Geometry of the two rooms and the MIMO transmitter and receiver locations (top view).

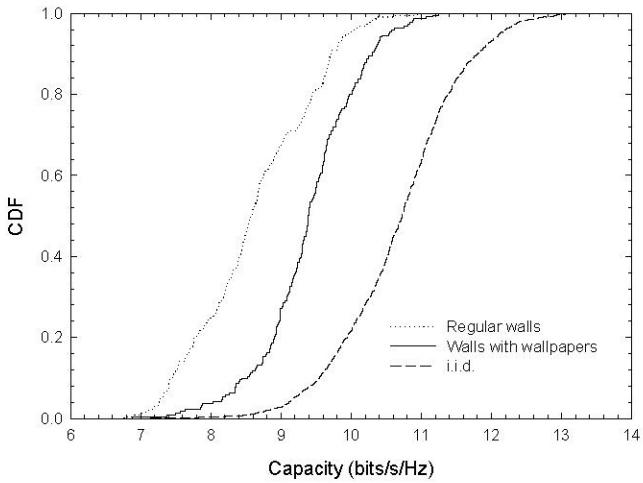

Figure 11: CDF of capacity in Room 2 for regular gypsum and frequency-selective wall cases.

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