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Enhancing the Capacity of SISO & MIMO Systems within Modified Environments Using Frequency Selective Surfaces

تحسين سعة الأنظمة المتعددة والأُحادية بواسطة تعديل البيئة باستخدام السطوح الانتقائية الترددية

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Abstract

In this paper, the design of a Double Square Loop Frequency Selective Surface (DSL FSS) is presented. The DSL FSS is designed to band-stop 2.4 GHz and 5.5 GHz and allow all other frequencies to pass into an area of interest. 'Wireless InSite' is used to simulate wave propagation in modified buildings with FSS to prove the enhancement of capacity. The simulation was carried out on Single Input Single Output (SISO) and Multiple Input Multiple Output (MIMO) systems. The effect of Frequency Selective Surfaces (FSS) on such systems' capacity was verified. The target SISO and MIMO systems are located in a floor inside Al-Ahliyya Amman University.

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الملخص

تتمثل الفكرة الأساسية لهذا البحث في تحسين مواد بناء جدران المباني لتعمل عمل مرشح مزدوج الفعالية؛ لمنع دخول ترددات معينة لمنطقة الاهتمام. وتقدم هذه الورقة تصميم حلقتين بشكل مربع للسطح الانتقائي للترددات، حيث يعمل هذا التصميم على منع الترددات، في نطاق 2.4 جيجاهيرتز ونطاق 5.5 جيجاهيرتز، من دخول منطقة الاهتمام. واستعمل برنامج ("Wireless InSite")، الذي يعمل بمبدأ دراسة مسارات انتشار الموجات الكهرومغناطيسية ومحاكاتها. وتمّ تطبيق هذه المحاكاة داخل مبنى في جامعة عمان الأهلية على النظام أحادي الهوائيات في المدخلات والمخرجات، وعلى النظام متعدد الهوائيات في المدخلات والمخرجات؛ لإثبات أثر السطح الانتقائي للترددات على تحسين السعة.

I.   Introduction

The intensive use of communication systems nowadays increases chances of interference between neighboring systems. Especially, in unlicensed bands such as the Industrial, Scientific and Medical (ISM) bands. This interference degrades systems' performance [1], in addition to affecting the transmitting systems' security [2]. Therefore, it is necessary to research new techniques that differentiate between two frequencies to allow different devices in the network to communicate more effectively.

Recent studies focus on how to block all unwanted transmissions [3]. This is done by modifying the physical environment by adding an FSS to walls. Frequency Selective Surfaces (FSSs) filter the unwanted frequency so as to eliminate interference to minimum and give a good transparency to other frequencies [4, 5].

This paper aims to shield the two frequency ranges: 2.4GHz and 5.5GHz, and give the other frequencies a maximum transparency. An FSS wallpaper is to be attached on the wall inside the area of interest to block the two mentioned frequency ranges. Researchers and scientists develop FSS using many shapes: loaded dipole, Jerusalem cross, tripole, cross dipole, dipole, and square loop [5].

This paper also presents the two analysis techniques, Equivalent Circuit Model (ECM) and Finite Integration Technique (FIT). It applies them on the DSL FSS design for this study. Previous research showed that the square loop FSS has the best response and stability when applied within the angular insensitivity, cross polarization Transverse Electric (TE) or Transverse Magnetic (TM) modes with a small band separation [6].
An example, is shown in Fig. 1. FSS in building 2 blocks the external interference from the Wi-Fi router in building 1 and reserves the strength of the internal router signal. The figure also shows that FSS does not block mobile base station signals. Attaching FSS to walls of building 2 guarantees shielding of the signal and keeping it exclusive for users in this building.

The protocols that use 2.4GHz ISM band are 802.11b/g. The 2.4GHz band suffers interference problems occasionally because of the intensive use of cordless-phones, microwave oven, and Bluetooth devices [7].

The 5.5GHz frequency range has at least 23 non overlapped channels. The protocol that uses 5GHz Unli-
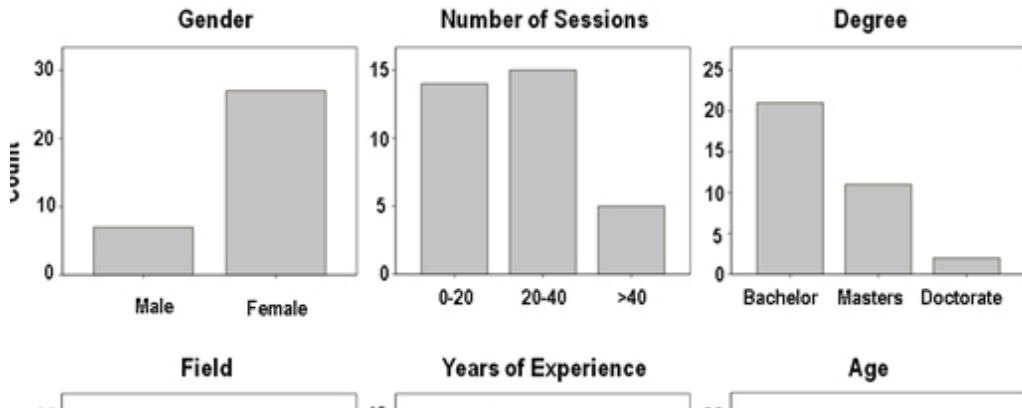
Fig. 1. Modifying the indoor environment to mitigate interference problems

censed National Information Infrastructure (U-NII) band is 802.11a. The 5.5GHz band performance is always dependent on the environment. This frequency range is used also by weather-radars and in military applications because it lies in the C Band, 4.0 to 8.0GHz [8].

Adding MIMO antennas to the 802.11 standards was a step of improvement introduced as 802.11n. 802.11n operates on both the 2.4GHz and 5GHz bands [9]. Since MIMO systems are intensively used nowadays, it is more interesting to find out how the capacity of MIMO systems can be enhanced. The tests and analysis for FSS inside modified environments with SISO and MIMO systems is presented in this study.

In order to give a clean verification, the area of interest is modeled inside 'Wireless InSite' [10] with the FSS transmission and reflection details. Also, DSL FSS will be tested on SISO and MIMO systems to check its effect on enhancing the capacity [11].

II.   Frequency Selective Surfaces

FSSs are surfaces usually used to shield and cover an area of interest from the outer frequencies. The word selective means that is it not blocking all the outer frequencies, but shield a frequency of interest, 2.4GHz and 5.5GHz. The blocked frequency depends on the shape used to design the FSS. The shape used in this paper is DSL FSS because it has the best performance in comparison with other shapes [12].
In order to assist the evaluation, the interior structure of the area of interest will be modeled inside 'Wireless InSite' with the FSS transmission and reflection response details [11]. Also, the whole system will be tested on SISO and MIMO systems to check its capacity enhancement.

A. EQUIVALENT CIRCUIT MODEL

Equivalent Circuit Model (ECM) is a simple analysis method for FSS. The quick response of this model with the variation of the element dimensions is considered the most important feature of ECM. It is perfect for modeling the DSL FSS. On the other hand, this is considered a disadvantage regarding other complicated shapes [12].

Since ECM is a scalar technique, the analysis is limited to linear polarizations and simple geometries of FSS elements. The accuracy of this method varies from a study to another although it takes the properties of dielectric substrates and the incident angles of signals into consideration, due to the assumptions use in the ECM approximation [13]. This model was first tried on frequency selective circuits by Anderson [14], as it models FSS as energy-storing components, inductive or capacitive in an equivalent circuit decided by the element shape [13].

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The parameters of the patterns were determined using ECM by MATLAB. The parameters of interest are the periodicity (P), the gap between two DSLs (g1), the gap between the two squares (g2), the width of the outer square loop (w1), the width of the inner square loop (w2), the length of one side of the outer square loop (d1), and the length of one side of the inner square loop (d2), as shown in Fig. 2.
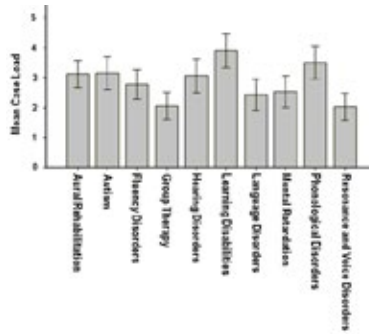
Fig. 2. The parameters of DSL FSS

It models FSS as an equivalent inductive and capacitive components representing the periodic array in a transmission line, where the circuit components are evaluated by ECM approximation of conducting strips based on Marcuvitz [15]. Since Marcuvitz's equations are only applied on oblique incident angles, it illuminates the inductive component by TE-wave incidence and the capacitive component by TM-wave incidence. On the other hand, in 1985, Lee had presented a modified version of Marcuvitz equations, presenting the two other cases of incidence which are the inductive component by TM-wave incidence and the capacitive component by TE-wave incidence [14]. Thus, the model can be used now in all cases to find the transmission properties of FSS.

The developed Marcuvitz equations for inductance are given by [16]:

1.

$$X_{TE} = F(P, w, \lambda) = \frac{p \cos \theta}{\lambda} \left[\ln \csc(\frac{\pi w}{2P}) + G(P, w, \lambda, \theta) \right]$$

2.

$$X_{TE} = \frac{P \sec \theta}{\lambda} \left[\ln \csc(\frac{\pi w}{2P}) + G(p, w, \lambda, \emptyset) \right]$$

The developed Marcuvitz equations for capacitance are given by:

3.

$$B_{TM} = 4F(p, g, \lambda) = \frac{4p \cos \emptyset}{\lambda} \left[\ln \csc(\frac{\pi g}{2P}) + G(P, g, \lambda, \emptyset) \right] \varepsilon_{eff}$$

4.

$$B_{TE} = \frac{4p \sec \theta}{\lambda} \left[\ln \csc(\frac{\pi g}{2P}) + G(P, g, \lambda, \theta) \right] \varepsilon_{eff}$$

where G is the correction term:

5.

$$G\left(p, w, \lambda, \frac{\theta}{\emptyset}\right) = \frac{0.5(1-\beta^2)^2\left[\left(1-\frac{\beta^2}{4}\right)(C_{1+}+C_{1-}) + 4\beta^2 C_{1+}C_{1-}\right]}{\left(1-\frac{\beta^2}{4}\right) + \beta^2\left(1+\frac{\beta^2}{2}-\frac{\beta^4}{8}\right)(C_{1+}+C_{1-}) + 2\beta^6 C_{1+}C_{1-}}$$

where $\beta = \sin\frac{\pi w}{2P}$, or $\beta \sin\frac{\pi w}{2P}$ for $G\left(P, g, \lambda, \frac{\theta}{\emptyset}\right)$,

6.

$$C_{1\pm}^{TE} = \frac{1}{\sqrt{\left(\frac{P\sin\theta}{\lambda} \pm 1\right)^2 - \frac{P^2}{\lambda^2}}} - 1,$$

7.

$$C_{1\pm}^{TM} = \frac{1}{\sqrt{1 - \frac{P^2\cos\emptyset}{\lambda^2}}} - 1$$

8.

$$L_{f1} = 2 * (L_1 /\!/ L_2) * \frac{d_1}{P}$$

where $L_1 = F(P, w_1, \lambda)$ and $L_2 = F(P, w_2, \lambda)$

9.

$$C_{f1} = 0.75 * C_1 * \frac{d_1}{P}$$

where $C_1 = 4F(P, g_1, \lambda)$

10.

$$L_{f2} = L_3 * \frac{d_2}{P}$$

where $L_3 = F(P, 2w_2, \lambda)$

11.

$$C_{f2} = (C_1 \text{ in series with } C_2) * \frac{d_2}{P}$$

Where $C_2=4F(P, g_2, \lambda)$, θ is the angle of incidence, λ is the wavelength of the resonant frequency, and ε_{-eff} is the effective permittivity of the dielectric substrate [14]. The capacitive value is changed due to the surrounding dielectric substrate permittivity. FSS response depends on the DSL FSS dimensions as shown in the

equations above, the dielectric substrate that FSS is places on, and the incident angles.

Since the grating lobes have a bad influence on the FSS performance, some parameters must be taken into consideration. To suppress them for a range of incident angles the following must be valid: $[p(1+\sin\theta)<\lambda]$ for TE-wave incidence and $[p(\cos\theta)<\lambda]$ for TM-wave incidence [17].

If FSS had grating lobes, the $C_1+{}^{\wedge}TE$ and $C_{(1\_}{}^{\wedge}+){}^{\wedge}TM$ will become complex, creating both jX_{-L} and $-j(1/B_e\_c)$. Therefore, it's not pure capacitance or inductance, therefore the equivalent impedance of FSS will be expressed by:

12.

$$Z_{FSS} = j\left(X_L - \frac{1}{B_c}\right)$$

and the normalize impedance will be expressed by:

13.

$$Z_n = \frac{Z_{FSS}}{Z_0} = j\left(\frac{X_L}{Z_0} - \frac{1}{B_c Z_0}\right) = j\left(\frac{X_L}{Z_0} - \frac{Y_0}{B_c}\right)$$

$$\text{where } Z_0 = 377\Omega.$$

Fig. 3 illustrates a T-network of impedances, where $Z_1 = Z_2 = 0$ and $Z_3 = Z_n$ represents the double inductor-capacitor (LC) circuits parallel to each other [13]. Based on the ABCD matrix technique. The S-matrix can be expressed by [18]:

14.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \begin{bmatrix} \frac{A+B-C-D}{\Delta} & \frac{2(AD-BC)}{\Delta} \\ \frac{2}{\Delta} & \frac{-A+B-C+D}{\Delta} \end{bmatrix}$$

$$\text{where } \Delta = A + B + C + D$$

Since and according to symmetry rules, the matrix ABCD will be express by:

15.

$$S_{21} = \frac{2}{A+B+C+D} = \frac{2}{1+0+\frac{1}{Z_3}+1} = \frac{2}{2+Y} = \tau$$

16.

$$S_{11} = 1 - |\tau|^2 = 1 - \frac{4}{4+Y^2} = \Gamma$$

$$\text{where } Y = j\left[\left(\frac{C_{f1}}{1-L_{f1}C_{f1}}\right) + \left(\frac{C_{f2}}{1-L_{f2}C_{f2}}\right)\right]$$
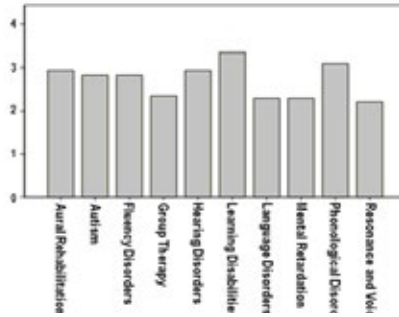
Fig. 3. Transmission line as T-network, where $Z_1 = Z_2 = 0$

This study uses MATLAB as a tool for solving ECM's theoretical formulas. The main target is to design the double square loop FSS with two resonant frequencies, $f\_r1 = 2.4$GHz and $f\_r2 = 5.5$GHz. The dimensions of the designed DSL are: P=18.5mm, g1=0.5mm, g2=1mm, w1=0.5mm, w2=1mm, d1=18mm, d2=15mm, and $\mathcal{E}\_r = 3$.

B. UNIT CELL MODELLING
The Computer Simulation Technology-Microwave Studio (CST-MWS) [19] is used to test the designed DSL FSS performance, as shown in Fig. 4. The FIT is the analysis method used in this software.
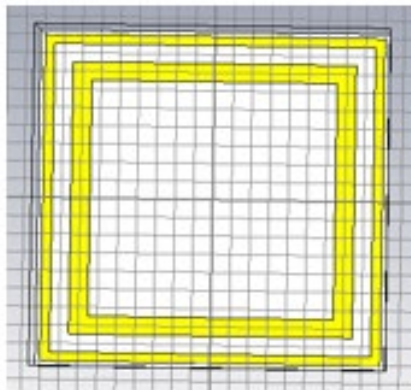
Fig. 4. The designed unit cell of DSL FSS inside CST-MWS

The transmission coefficient S_21 is presented for TE and TM modes as shown in Fig. 5 and Fig. 6, respectively. It also shows that the maximum attenuation at the resonant frequencies is -48dB. The reflection coefficient S_11 is also presented for TE and TM modes, as shown in Fig. 7 and Fig. 8, respectively. The thickness of copper is 0.07mm and printed over a 0.1mm thick dielectric and its relative permittivity value is $\mathcal{E}\_r = 3$.
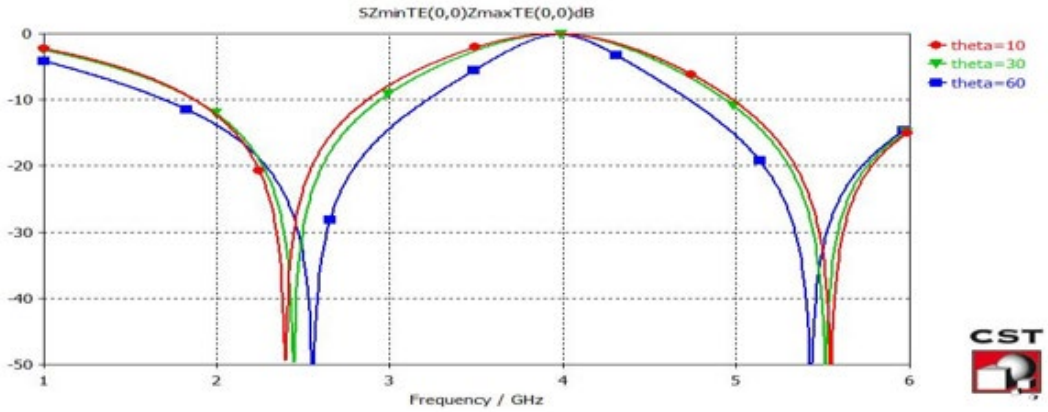
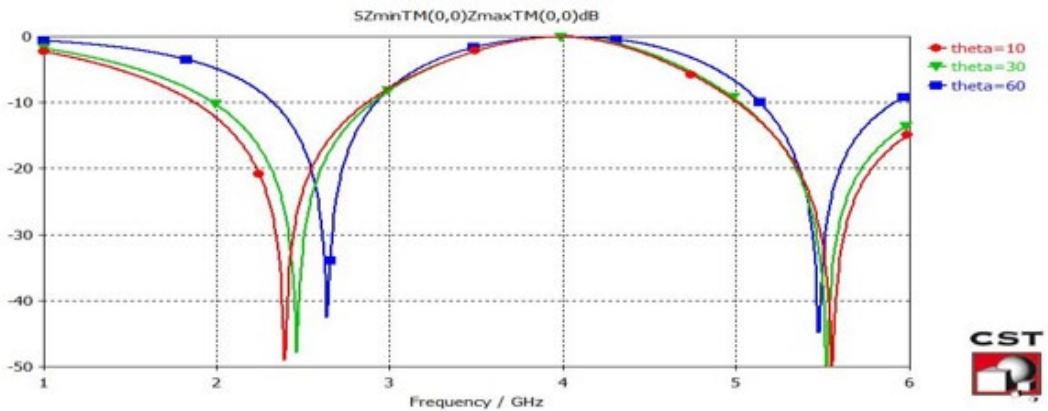**Fig. 5. The transmission response S_−21 for TE-mode of DSL FSS.**

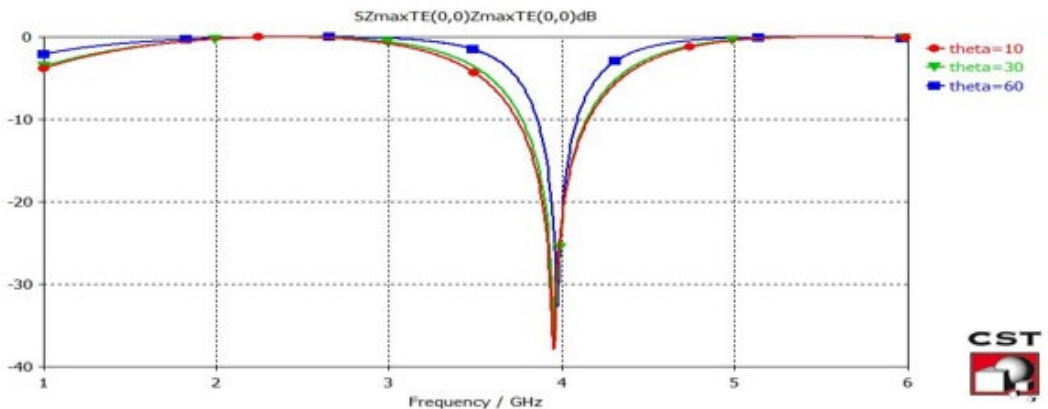**Fig. 6. The transmission response S_−21 for TM-mode of DSL FSS.**

Fig. 7. The reflection response S_−11 for TE-mode of DSL FSS.
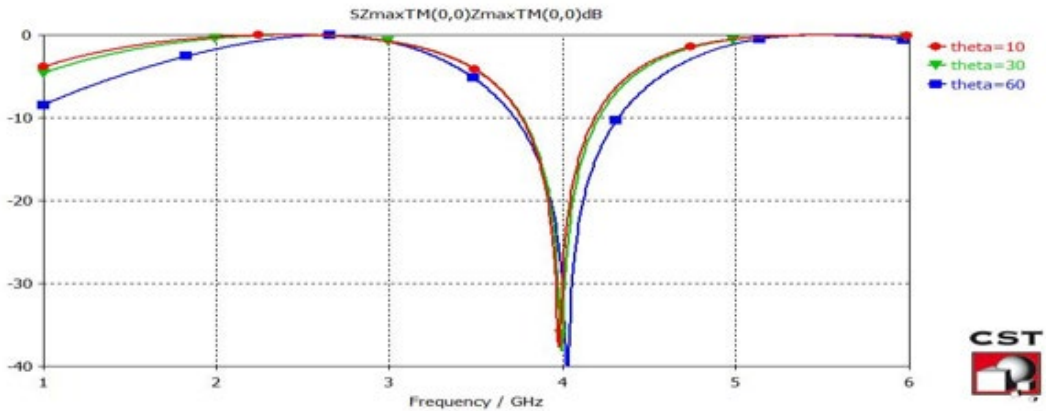
Fig. 8. The reflection response S_{-11} for TM-mode of DSL FSS.

C. TESTING FSS PROTOTYPE

The fabricated FSS samples were measured inside a half-wave chamber at Loughborough University. To measure the DSL FSS transmission response, a half-wave chamber and the following microwave measurement equipment's were used: An HP8757D scalar network analyser, an HP83650L swept frequency generator operating in the frequency range 10MHz-50GHz. The FSS window was mounted on a rotating plane screen, shown in Fig. 9, which is partially shielded from external microwave radiation. The screen has an aperture with dimensions of 30cm×60cm. The front side is fully covered with absorbers.

Wideband pyramidal horn antennas from Rohde & Schwarz (HF906) operating between 1-18GHz were employed as transmitter and receiver antennas. One antenna was mounted on a tripod and the other on the rotating bridge. Both of antennas were positioned at the height of the centre of the aperture.

To measure the transmitted power at any angle of incidence a free space calibration had to be performed, with no FSS inside window, to take into account the antenna and cable losses. The calibration data were subsequently subtracted from the measured FSS data. The transmitting antenna was located at a distance of 1m from the stand and the receiving one at 1.4m, as shown in Fig. 9.

In indoor environments, the direction of incident waves is indeterminate. Consequently, it is necessary to check the designed structure for a range of different incidence angles. Fig. 10 shows both the simulated under CST-MWS, ECM, and the measured transmission (S_{21}) results for DSL FSS. Good agreement between the measured and simulated results was observed. It also shows that the attenuation at the resonant frequencies is -40dB. The TE-wave incidence results is identical to TM-wave incident results because the DSL FSS response has the dual polarization features.

III.   Wireless Insite, SISO & MIMO

'Wireless InSite' is used to give the closest simulation to signals propagating from the transmitter (Tx) to the receiver (Rx) in the area of study. It takes values of the reflection coefficient (Γ) and the transmission coefficient (τ) for each incident angle. Most interestingly, 'Wireless InSite' gives results for the propagation without and with designed FSS. SISO and MIMO systems will be applied in 'Wireless InSite' to test the capacity in a floor in the Faculty of Engineering at Al-Ahliyya Amman University.

(a) Transmitter and FSS on screen
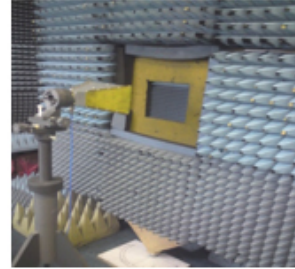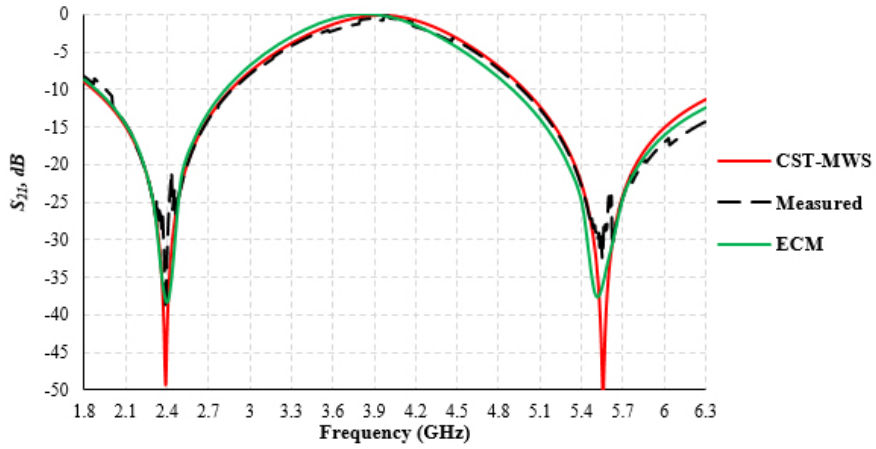

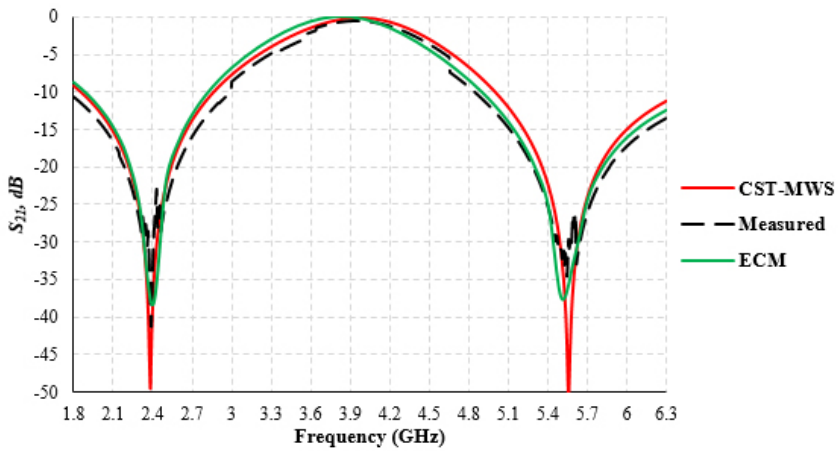(b) Rotating Bridge and Receiver Antenna
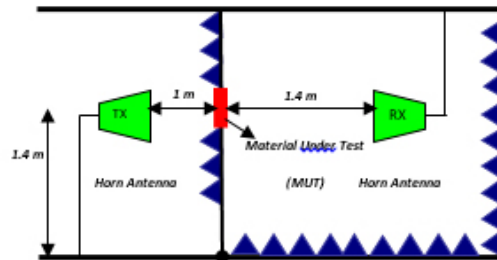
(c) Plan of Half-Wave Chamber

Fig. 9. Photo and diagram of FSS under test inside half-wave chamber.

The test will be applied to the floor with and without FSS. The more walls the area of interest has, the more obstacles it got which decreases coverage and capacity levels [20-22]. In spite of the fact that furniture and people are also effective, they are not considered in 'Wireless InSite' for this paper [23]. The comparison between the scenario with or without FSS must prove how affective is the FSS on the propagation and whether it enhances the capacity or not.

'Wireless InSite' simulates the effect of modified indoor environments for SISO and 2X2 MIMO. DSL FSSs will be attached to walls of the room of interest to band-stop 2.4GHz and 5.5GHz. DSL FSSs are placed away from the wall by $\lambda/10$ in order to eliminate the coupling effect [14]. The area of interest is 22mx12m, as shown in Fig. 11. The walls are a brick construction, the door is a wooden door, the floor and celling are concrete, and the windows are made of glass. Table 1.1 shows the specification of each material used in the this scenario.

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(a) TE-wave

(b) TM-wave

Fig. 10. The simulated and measured angular response ($\theta=0^\circ$) for DSL- FSS, with $\varepsilon r=3$ used in the CST-MWS and ECM simulations.
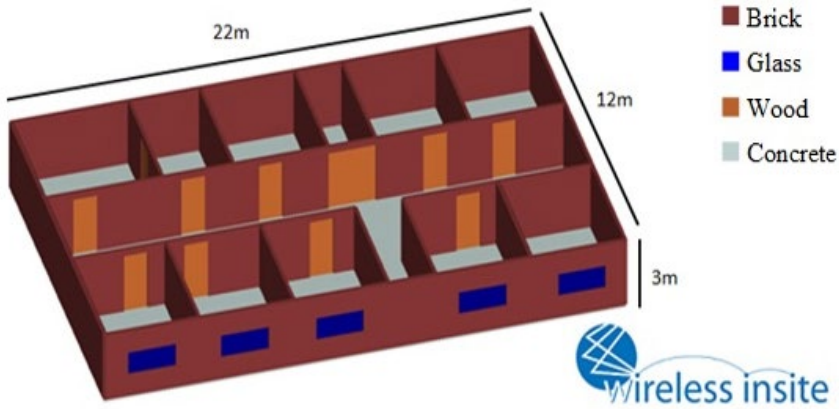
Fig. 11. 3D view for the floor of Computer Engineering Department at Al-Ahliyya Amman University.

Table 1.1. Electrical parameters used for building interfaces

Interface Type	Material	Relative Electrical Permittivity, ε_r	Conductivity, σ (S/m)	Thickness (meter)
External & Internal Walls	Brick	4.44	0.001	0.150
Floor & Ceiling	Concrete	7	0.015	0.30
Doors	Wood	5	0	0.04
Windows	Glass	2.4	0	0.003

For the conventional SISO systems studied so far the fundamental formulation of capacity proposed by Shannon is given by [23],

17.

$$C = \log_2\left(1 + \frac{S}{N}\right)$$

where C is the capacity in bps/Hz, S is the signal power in watts, and *N* is the noise power in watts.
The formulation for 2X2 MIMO model to determine the capacity is presented as follows [24],

18.

$$C = \log_2 det\left(I + \frac{\rho}{n} HH^T\right)$$

where ρ is the signal to noise ratio , C is the capacity in bits/s/Hz, det for determinant, I for 2X2 identity matrix , n for the number of antennas used which is 2 in this study, H is the channel matrix, and H^T is its conjugate-transpose matrix.
The channel matrix (H) is also evaluated using 'Wireless InSite'. Its response is determined by the sum of all rays arrived at each receiver antenna, and is computed by the following formula [25]:

19.

$$h_{ij} = \sum_{k=1}^{M} \sqrt{P_k} \cdot e^{i(2\pi/\lambda)l_k} \cdot e^{i2\pi f_0 T_k}$$

where M is the number of received rays, P_k is the received power, l_k is the length of the ray, f_o is the carrier frequency, and T_k is the time delay of the ray. All of these parameters are obtained from 'Wireless InSite'.

The 2X2 MIMO system, as shown in Fig. 12. Both the transmitter and receiver are assumed to consist of two omnidirectional antenna elements, transmitting 17dBm and spaced by λ/2. The transmitter is placed on the ceiling of one room. Receivers are spread on the floor, each with two antennas presenting the 2X2 MIMO system. Receivers are 1m away over the floor and their sensitivity is -71dBm. All angles of incidence between 0° and 60° for vertically polarized antennas. Fig. 13 shows the area of interest with DSL FSS.
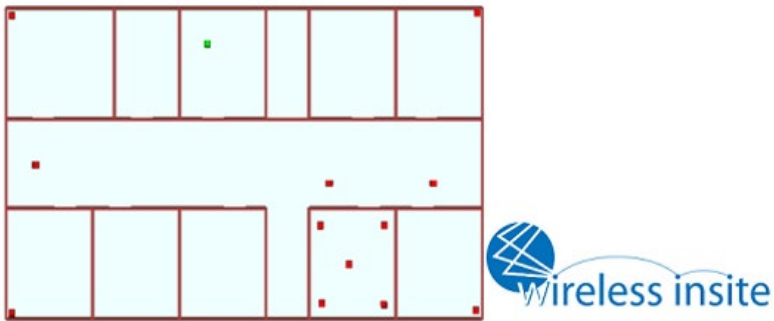

Fig. 12. 2D view for the floor of interest for evaluating SISO and 2X2 MIMO systems. Green square represents Tx and red squares represent receivers.
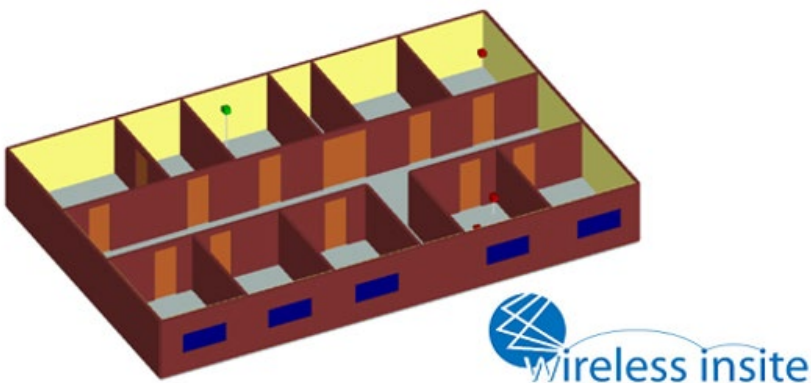

Fig. 13. 3D view for the floor of interest for evaluating SISO and 2X2 MIMO systems with DSL FSS, in yellow, in outer wall.

A comparison between SISO and MIMO systems with and without FSS will be stated. The capacity enhancement is presented by the Cumulative Distribution Functions (CDFs), as shown in Fig. 14 and Fig. 15.
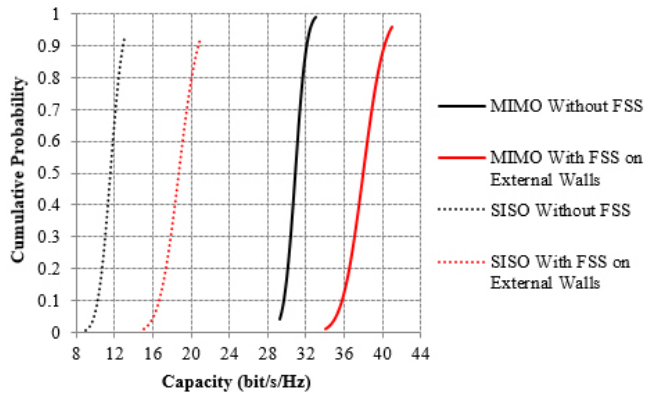
Fig. 14. A Cumulative Distribution Function (CDF) plot showing the comparison between SISO & MIMO systems with and without DSL FSS for 2.4GHz.
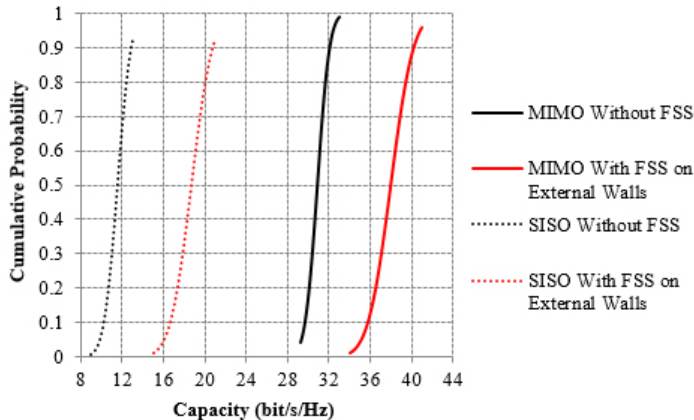

Fig. 15. A CDF plot showing the comparison between SISO & MIMO systems with and without DSL FSS for 5.5GHz.

It is clear that the capacity is increased for SISO and MIMO systems after attaching DSL FSS wallpaper on the external walls inside the floor of interest. Since the presence of DSL FSS wallpaper in an indoor environment can increase the presence of strong reflected components in every receiving location as shown in [4, 6, 11], the proposed surface are able to enhance any potential benefits in terms of capacity and diversity gain from using MIMO systems in a modified indoor environment. The idea is that the presence of various multipath components at every receiving element would make the channel more Rayleigh (lower K-factor) achieving lower correlation and hence higher capacity.

IV.   Conclusion

MIMO systems are intensively used nowadays because MIMO can service multiple devices. It also have a higher

capacity based on the DSL FSS design. The DSL FSS is designed to result in a better performance and stability. DSL FSS is able to band-stop two frequencies instead of one band as in single loop FSS. Two factors affect the performance of FSS; the band-stop response and the effective angles of incidence range which should be from 0° to 60^{0}. ECM is used to design the DSL FSS since it provides reasonable results and a quick response. CST-MWS based on FIT technique is also used which counts the number of parameters of the conductor and the dielectric which has a good agreement with the measurement results. 'Wireless InSite' is used to show how the designed DSL FSS can enhance the capacity of both SISO and MIMO systems.

Nidal Qasem received his B.Sc. degree in Electronic and Communication Engineering (Honours) from AL-Ahliyya Amman University, Amman, Jordan, in 2004. He obtained his M.Sc. degree in Electronic and Electrical Engineering from Loughborough University, Loughborough, United Kingdom, in 2006. He then pursued a PhD degree at Loughborough University. He is currently working as Asst. Professor in the department of Electronics and Communication engineering at Al-Ahliyya Amman University.

His research interests are propagation control in buildings, specifically improving the received power, FSS measurements and designs, dielectric characterizations of building materials, and wireless system performance analyses.

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