FDTD Study of the Mutual Coupling between Microstrip Antennas for Diversity Wireless Systems

#Lamia M. Khashan[1]**, Hala A. Elsadek**[2]**, and Essam A. Hashish**[3]
[1]Department of Electronics & Communications, Faculty of Engineering, Misr International University (MIU), Cairo, EGYPT, lamia.khashan@miuegypt.edu.eg
[2]Microstrip Department, Electronics Research Institute, ElTahrir st., Dokki, Giza, EGYPT.
[3]Department of Electronics & Communications, Faculty of Engineering, Cairo University, Giza, EGYPT.

Abstract

The FDTD becomes a powerful tool for analyzing electromagnetic problems with high level of accuracy. Diversity transmission/reception is performed by using independent antenna elements for the Tx/Rx channels to form a multi-element antenna arrays (MEA). This requires an accurate study of the mutual coupling between antenna elements.

In this paper, an FDTD model for microstrip patch antenna element as well as for antenna array with mutual coupling effects is established. An investigation for the mutual coupling between different antenna classifications/arrangements is studied. Multiple subarray element arrangements are used to compare the coupling for E-plane, H-plane and Orthogonal-plane arrangements. The effect of changing the dielectric constant as well as the substrate thickness on mutual coupling level is studied. Different feed techniques are used to investigate the feed effect on the coupling level. The mutual coupling for different field polarization directions is also studied. Finally, an array designer aid tool is concluded to help in building a diversity reception microstrip multi-element array antenna.

Key-words: FDTD, PML, diversity reception, mutual coupling.

1. INTRODUCTION

Microstrip patch antennas have been widely used in mobile and satellite communication systems due to their great advantages as low cost, low profile, lightweight and easy fabrication. The major advantages are realized in applications that require moderate size array. In array design, it would be appropriate to decrease the inter-element spacing as possible, which in return increases the mutual coupling. Thus, investigation has to be done for the optimization of element spacing and mutual coupling [1].

Many theoretical models have been presented for evaluating the mutual coupling between patch antennas with a planar ground plane. The main existing models based on the method of moments (MoM), cavity model, and transmission-line model [1-3]. In this paper, a mathematical model based on Finite Difference Time Domain (FDTD) is established to investigate the mutual coupling in different microstrip antenna array configurations. The FDTD technique is a time stepping procedure, where the region being modeled is represented by two interleaved grids of discrete points. One grid contains the points at which the magnetic field is evaluated and the second grid contains the points at which the electric field is evaluated [4, 5].

Multipath fading, delay spread, and co-channel interference are factors that limit the performance of wireless communication systems. One well known method of reducing the effects of fading is by the use of diversity techniques. Diversity can be achieved in Multi-Element Array (MEA) if the mutual coupling level S_{12} between them is -15dB [3].

In this research paper, an FDTD diversity reception analysis model for independent microstrip antennas arranged in MEA is established. Different elements arrangements, polarization directions, feeding techniques are investigated to create an array design aid tool.

A Gaussian pulse is applied at the feed points and the problem space is truncated with perfectly matched layer (PML).

2. DIVERSITY CRITERIA

Diversity is the mean of generating two or more uncorrelated or less-correlated signals at the reception. Antenna diversity can be further characterized as space diversity (obtaining signals from two orthogonal polarizations) and angle diversity (obtaining signals from two or more spatial angles) [6-8].

In both transmitting and receiving, the diversity antennas must meet the following requirements:

1- No interaction between individual antenna elements.
2- Independent signal paths from transmitter to receiving antenna elements.
3- Multiple elements within the array structure.

3. MUTUAL COUPLING STUDY

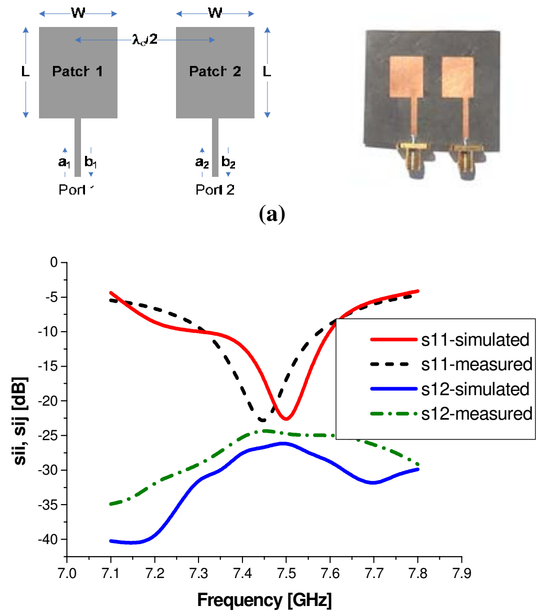
The FDTD model investigated in this paper utilizes the circuit analogy of multiple inputs/multiple outputs network. Fig.1 plots an FDTD model to calculate the mutual coupling between two microstrip line-fed patch antennas, the impedance matrix can be defined as [9].

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \qquad (1)$$

in reflection coefficients representation, the above equation can be rewritten as

$$\begin{bmatrix} V_{1r} \\ V_{2r} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} V_{1i} \\ V_{2i} \end{bmatrix} \qquad (2)$$

where V_{1r} represents the normalized reflected wave at port 1. V_{1i} represents the normalized incident wave at port 1. Note that from circuit analogy, if port 1 is excited, port 2 is terminated by 50Ω matching impedance. In two-elements problem as element 1 is excited, the reflected wave will represent the summation of self scattering S_{11} and the mutual scattering S_{21}. Subtracting this case from the single element case we obtain the S_{12}. Fig.2 illustrates these results for 2-element configuration with $\lambda_o/2$ separation where λ_o is the free space wavelength. Note that for similar array elements $S_{11}=S_{22}$ and $S_{12}=S_{21}$.



(a)

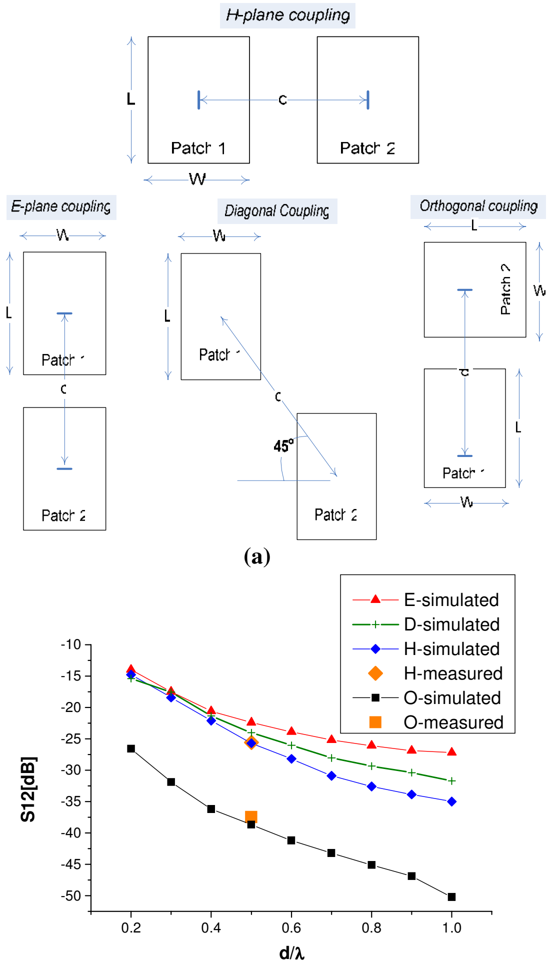
(b)

Fig. 1: (a) FDTD model to calculate the mutual coupling of 2-element line fed array, (b) FDTD simulated return loss & mutual coupling at 7.5GHz

There are many disadvantages of a large mutual coupling level as the reduction in element efficiency, reduction in antenna gain and also reduction in the average received power of the diversity antenna [3]. Therefore, the study of mutual coupling in MEA antennas are of great importance. In the following subsections, there will be a comprehensive study for such parameters.

A. Mutual coupling study for different MSA orientations

The mutual coupling is parametrically investigated including both the E-plane, H-plane, diagonal plane and orthogonal plane coupling as shown in Fig.2. The single element is rectangular microstrip patch antenna resonates at 7.5GHz on a duriod substrate with dielectric constant ε_r=2.2 and substrate thickness 0.787mm.



(a)

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Fig. 2: (a) E, H, diagonal and orthogonal line fed microstrip 2-element array, (b) FDTD simulated mutual coupling vs. inter-element spacing for E, H, diagonal and orthogonal coupling at 7.5GHz

From Fig.2.b, it is noticed that for small inter-element spacing the E and H-plane coupling introduce almost equal values. As the separation increases, the *E*-plane coupling becomes stronger than the *H*-plane. This could be attributed to the surface waves propagating along the *E*-plane direction. Hence for large inter-element distances, the mutual coupling is dominant by surface waves. The diagonal coupling is a vector sum of the *E*-plane and *H*-plane couplings depending on the diagonal angle of the arrangement. From the curve, the diversity reception / transmission occurs when $S_{12} \leq -15$dB for the element spacing $d \geq 0.23\lambda$ in the *E*-plane arrangement while $d \geq 0.29\lambda$ in H-plane. At all separations, the O-plane coupling is the lowest coupling level; it represents a lower coupling level by about 15-20dB. The *O*-plane represents the diversity reception in all array elements separations.

B. Mutual coupling study for different resonating frequencies (patch sizes)

In this subsection, the *E*-plane and *H*-plane coupling for 2-element array are studied at 1.56GHz [9], 5.2GHz and 7.5GHz, respectively.

From Fig.3, it is noted that for all frequencies of study until certain point of intersection the *H*-plane coupling is stronger. For values larger than this point, the *H*-plane coupling becomes the weaker. This is due to the surface wave effects. It is also noted that the point of intersection between *E*-plane and *H*-plane coupling is changed. As the frequency increases, the patch size decreases, so, the point of intersection occurs at smaller inter-distance. For example, at f_r=1.56GHz, the point of intersection occurs at d=0.65λ while at f_r=7.5GHz this point occurs at d=0.46λ. For certain separation point (for example d=0.5λ) the coupling level is stronger in lower frequency while it decreases as the frequency increases. This could be attributed to the fringing fields since in lower frequencies, the patch size is larger so the fringing fields introduces stronger mutual coupling.

C. Effect of different feed types on the coupling level

In this sub-section, we study the effect of feeding type on the mutual coupling level. Two element array is constructed at f_r=7.5GHz with substrate parameters ε_r=2.2 and h=0.787mm. Six feed types are studied for H-plane coupling orientation as shown in fig.4.a.

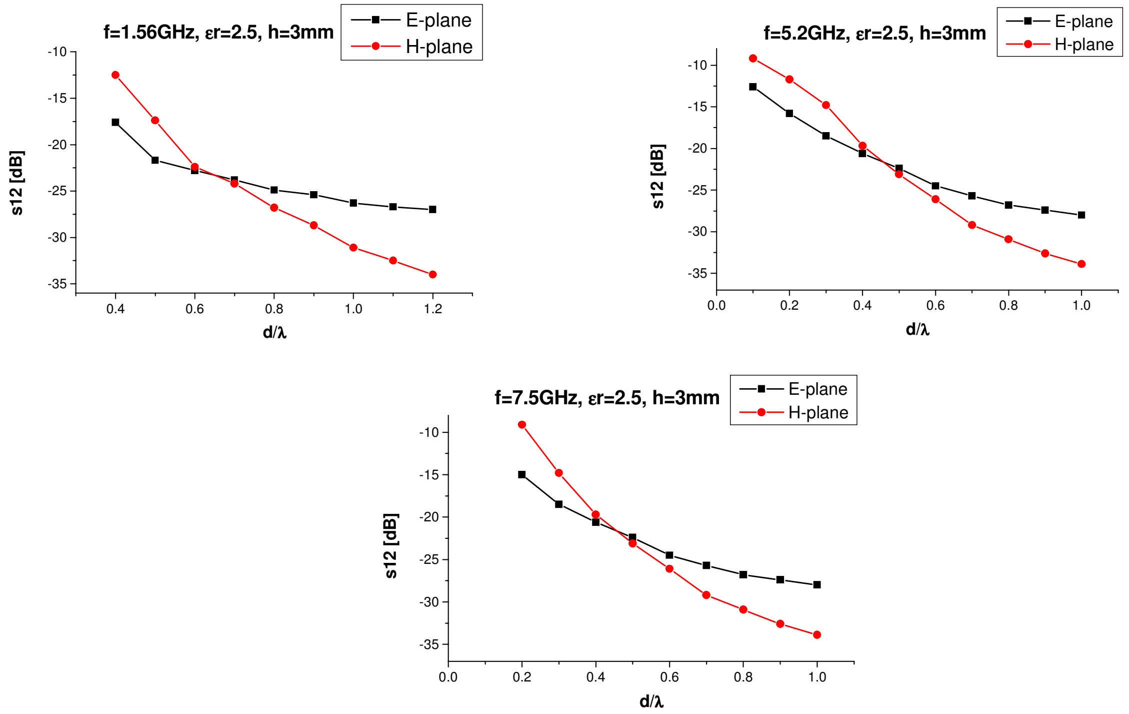
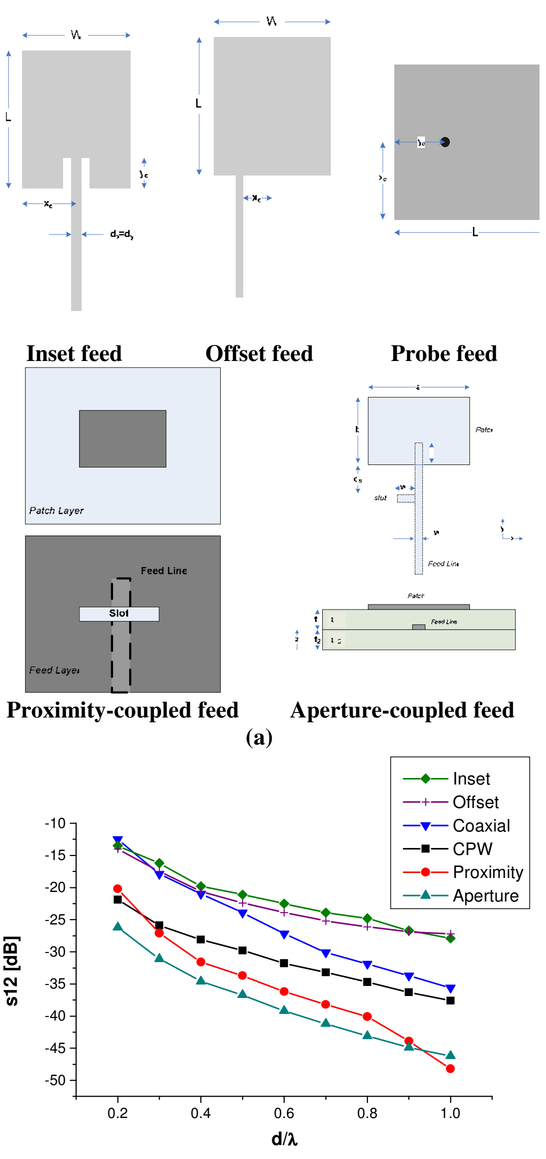


Fig. 3: Inter-element spacing vs. mutual coupling for rectangular patch antenna with substrate of ε_r=2.2 and h=0.787mm at (a) 1.56GHz [9], (b) 5.2GHz, and (c) 7.5GHz



(b)

Fig. 4: The relation between the mutual coupling level and the inter-element separation for different antenna feed techniques: (a) feeding techniques, (b) return loss of different feeding types.

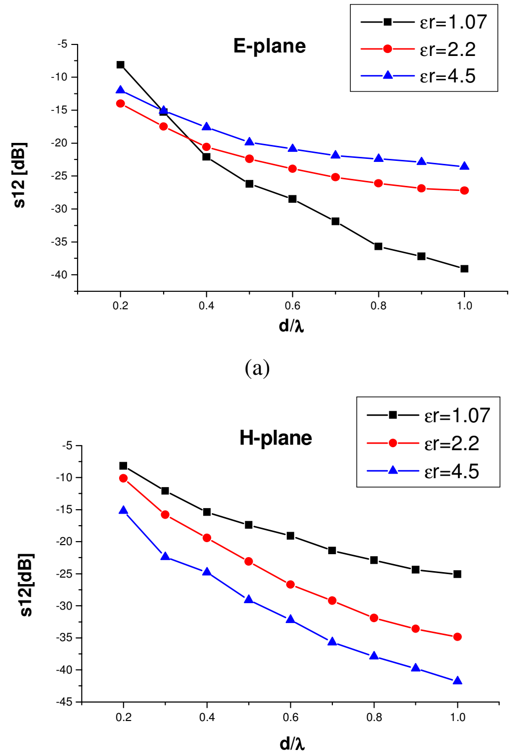
The lowest coupling level is for aperture fed antennas followed by the proximity coupling. The other four feeds present stronger coupling levels. The coaxial probe feed is the lowest one while the strongest coupling among all feed types is for the inset feed.

As for aperture coupling and multi-layer proximity feed, the feed lines are in different substrate layers hence their interchanging effect is very small or it can be neglected in some cases. On the other hand for microstrip line feed, the line is on the same layer of the patch so it introduce more coupling effect. Finally, the CPW-fed array provides an intermediate value between the proximity coupled antenna and probe-fed antenna. At small inter-element spacing (d=0.26λ), the coupling level for the CPW feed equals that for the proximity feed. As the inter-element spacing increases, the coupling level approaches that for the probe-fed array.

D. Mutual coupling study for different substrate parameters

(a) Substrate dielectric constant ε_r:

Three cases are selected at f_r=7.5GHz with ε_r=1.07 (foam), ε_r=2.2 (duriod) and ε_r=4.5 (FR4), the substrate thickness is kept the same h=0.787mm.



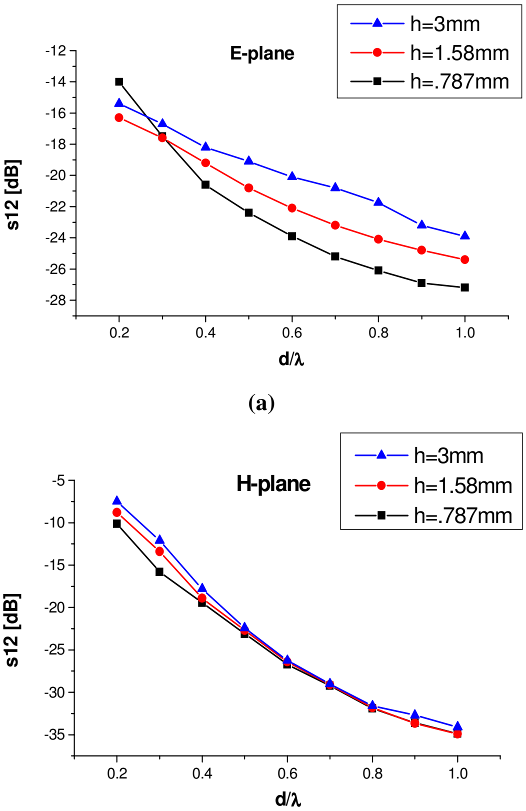
(b)

Fig. 5: Mutual coupling level versus inter-element distance for different substrate constants at (a) E-plane coupled microstrip antennas and (b) H-plane coupled antenna elements.

Figure 5.a illustrates the results at H-plane coupling on right side and E-plane coupling on the left side. It is noticed that as ε_r decreases, the mutual coupling level becomes stronger for all inter-element distances at H-plane. The H-plane coupling is due to near field or higher order waves at small distances while it is due to far field or space waves at large inter-distances [3]. As ε_r decreases, the patch size becomes larger; hence the fringing fields increase and consequently the mutual coupling level increases.

(b) Substrate height h:

Three cases are selected at f_r=7.5GHz with ε_r=2.2 and h=0.787mm, 1.5mm and 3mm, respectively. Fig.6 illustrates the results in H-plane configuration in right side while in E-plane configuration in left side. From the curves, it is noticed that increasing the substrate thickness, increases the coupling level in both coupling orientations. This effect is clear in E-plane coupling than H-coupling. This could be attributed to the fact that thick substrate excites more surface waves



(a)

(b)

Fig. 6: Mutual coupling level versus inter-element distance for different substrate thickness at (a) E-plane (b) H-plane.

E. Effect of polarization direction on mutual coupling

Three cases are selected at f_r=7.5GHz, ε_r=2.2 and h=0.787mm, the first is circularly polarized, the second is linearly polarized and the third is orthogonally polarized. From Fig.7, it is observed that S_{12} is reduced by about -20dB for O-plane or different sense of linear polarizations between adjacent array elements. This also was noted in Fig.3(b). Circular polarized elements have less mutual coupling level by about 3-5dB.

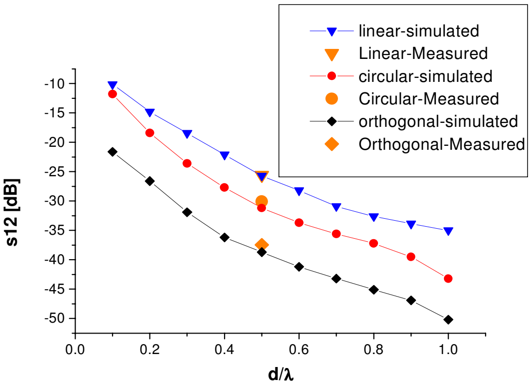


Fig. 7: Effect of polarization direction on mutual coupling level

4. CONCLUSION

In this paper, FDTD model is created to investigate a complete study for mutual coupling between adjacent array elements verses the inter-element separation change. This is to achieve diversity reception criterion for wireless communication systems. The orthogonal plane arrangements represent the lowest coupling level. It reduces the S_{12} by about 20dB. Reducing the operating frequency, increases the coupling level due to the increase on the patch size. Aperture and proximity coupling feed gives the weakest coupling levels among different feed types. Increasing the substrate thickness increases the coupling level due to surface wave effects. Increasing dielectric constant increases the coupling level in E-plane arrangement. Circular polarized elements have lower mutual coupling by about 5dB in average. This study could be a convenient aid tool for a diversity or wireless communication systems designer.

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