

## Decoupling Techniques Used for 5G with Multiple mm-wave Antennas

1<sup>st</sup> Ahmed H. Elshoshi, Department of Electric Engineering , Higher Institute of Engineering Technology , Tripoli, Libya, a.elshoshi@hiett.edu.ly

2<sup>nd</sup> Abderaof M. Elmrabet, Department of Electrical and Electronic Engineering, Faculty of Engineering, University of Zawia , Zawia, Libya, a.elmrabet@zu.edu.ly

3<sup>rd</sup> Radwan Khershif, Department of Computer Engineering, Faculty of Engineering, University of Zawia , Zawia, Libya, khershif@zu.edu.ly

4<sup>th</sup> Nadir M. Alshoushi, Department of Electric Engineering, Azzaytuna University, Tarhuna, Libya  
naderelshoshi@gmail.com

### Abstract

The deployment of multiple antenna system has become the key of the current generations for the purpose of increasing the spectrum efficiency and quality of services. In this paper, a compact 2x1 linear array antenna is designed and simulated using CST microwave studio. Firstly, a single radiating element antenna is designed with dimensions of 4.235x3.0187x 0.035 mm<sup>3</sup> fed by microstrip inset feeder, placed on a substrate made of Rogers RT5880 substrate with dielectric constant (permittivity) of 2.2 and loss tangent of 0.0009 and physical dimensions of 10.235x9.0187.x1 mm<sup>3</sup>, this design works at a resonant frequency of 28GHz , with bandwidth of 3.74 GHz, and return loss of approximately -24 dB to achieve gain of 7.3 dBi.

The design is extended to a linear array with two radiating elements placed on the top of the substrate with distance in between is 6.352 mm, and a technique of isolation is defected ground structure (DGS) in the substrate's bottom, resulting in mutual coupling S21 is about -18dBi, at the band range of interest

of 26-32 GHz. Another decoupling techniques is used, called parasitic element on the top of substrate with I –shape between the radiating elements to result in mutual coupling of roughly -38dB, 28GHz, 28.128 GHz and 28.42 GHz which provides directivities of 8.11, 8.14, 8.19 dBi respectively with an omnidirectional shapes. The envelope correlation coefficient (ECC) is evaluated and resulted in approximately zero within the operating range of the antenna with diversity gain (DG) reaches up to 10 dBi. Another decoupling technique called Electromagnetic band gap (EBG) structure is modified in this design to work as a stop band for unwanted mutual energy to control the mutual coupling to less than -28dB and provide a directivities of .28 dBi, and 8.34dBi at resonant frequencies of 28.2 GHz and 28.6 GHz respectively.

**Keywords:** Multiple antennas, mutual coupling, patch antenna, and decoupling techniques.

## I. Introduction

Wireless communications have addressed various challenges in technologies of current and upcoming generations, therefore, the integration of electronic wireless devices have been experienced with different aspects of life. Presently, the 5<sup>th</sup> generation has become the interest of global research because of speeding up the rate of transmission and therefore providing higher performance [1]. Whereas, to develop any technology in wireless communications; it is important to take into account some parameters for choosing a specific technology to evaluate the proposed system, such as, the ability to provide higher throughput for a given bandwidth, supporting better consumption of power efficiency. The system should work well in channel conditions,

which is a significant problem especially for multipath channel. Bandwidth efficiency is a crucial parameter, since system should occupy minimum radio frequency bandwidth with less circuit complexity [2,3].

Multiple Inputs – Multiple outputs technique (MIMO) is a key technology that has been developed for 4G telecommunications. It is the model that places multiple antennas at transmitter and receiver side. It is deployed to improve the performance of wireless systems and provides the diversity for meeting the requirements of 5G; thus enhancing the spectral efficiency, and reliability [4]. The objective of the 5G is to increase the transmission rate to meet 20 Gbps, ultra-low latency with 1 ms [5].

In communication systems, frequency domain is the principle for any design, in 5G, lots of frequency bands are used such as 0.45 to 6.0 GHz, 24.25 and 52.6 GHz and 28 GHz[5]. Therefore, the evolution of mobile communications for 5G demands supports the interoperability, more coverage provided, with less system complexity. At mm-wave frequencies, a 5G antenna design should be a compact in physical dimension, fulfilling the bandwidth efficiency requirements. Therefore, the gain of the 5G antennas with MIMO deployment should be evaluated as a diversity gain [3].

The challenging aspect of MIMO technology is to maintain such multiple antennas within the compact and small size in designing antenna; this will introduce a mutual coupling between neighbors' antennas which results in performance degradation due to the distance between antennas are too close. However, it is possible to reduce this issue by increasing the space between antenna

elements; whereas, this will increase the antenna size which is not practical or desirable for current wireless devices [6].

Surface current that follows on the ground plane can also generate a field correlation, which may degrade the diversity performance of MIMO system. Mutual coupling can be defined as the energy absorbed by a close antenna when one antenna is radiating [7]. The mutual coupling leads to change the input impedance, reflection coefficients, and radiation characteristics of the MIMO antennas [4].

## II. Paper objective

To resolve this problem, this paper introduces some technique to decouple the effect of mutual coupling which are as follow:

- Defected Ground Structure, this is used to decrease the mutual of correlation coefficients between antennas.
- Parasitic elements , these can be inserted on the top of the substrate with different shapes, this can improve the isolation between Antennas elements and improve the diversity just
- Electromagnetic band gap structures. It is also used to reduce the mutual coupling and acts as stop band filter to stop the elect of surface wave propagation.

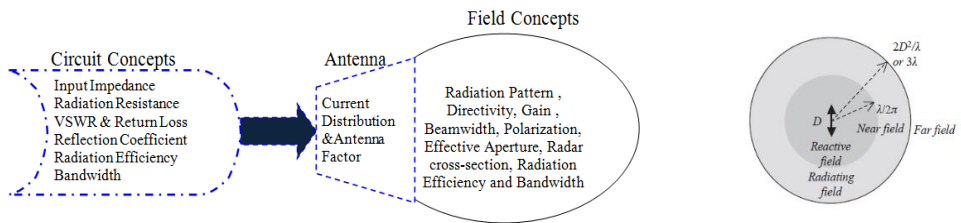
The main objective of this paper is as follows:

- 1- Design an antenna that works at 28 GHz band, which is one of the common 5G frequency spectrums. Then this structure will be modified by extending the design to two elements and measure the metrics of antenna.
- 2- Introduce the decoupling techniques to the design such as defected ground structure, parasitic element form and

electromagnetic band gap structures (EBGs) and evaluate the same metrics of the design, and then compare the results.

### III. Principles of antenna design.

The importance of designing an antenna is the mechanism of controlling the current distribution, which determines the behavior of the input impedance and radiation pattern. The evaluation of antenna is based on the measurement of polarization, resonant frequency and bandwidth, input impedance, directivity and gain [8]. These parameters are essential for assessment of antenna performance, as they are grouped in terms of field point of view and circuit point of view as presented in figure (1).



**Figure (1):** scheme antenna parameters , and radiation pattern regions

Each antenna retains specific characteristics that make it suitable for particular services. Therefore, achieving a stable radiation, good gain and good impedance matched well with the feeder part is essential for obtaining better performance and meeting conditions. However, before starting with the designing process of any antenna, there are some parameters such as, radiation pattern, return loss, impedance bandwidth, and surface current. The radiation pattern of an antenna is a graphical representation of the radiated field or power as a function of the angle at a particular distance  $r$ , which should be large enough to get independency of

the fields with distance considered as far-field. The following table shows the field regions of the antenna [8].

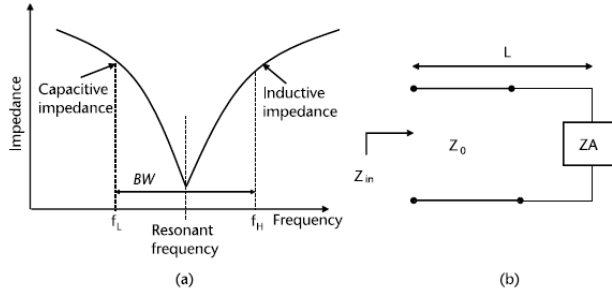
**Table (1):** field regions of radiation pattern

| Antenna Size (D)     | $D \ll \lambda$               | $D \approx \lambda$               | $D \gg \lambda$                   |
|----------------------|-------------------------------|-----------------------------------|-----------------------------------|
| Reactive Near-field  | $r < \lambda/2\pi$            | $r < \lambda/2\pi$                | $r < \lambda/2\pi$                |
| Radiating Near-field | $\lambda/2\pi < r < 3\lambda$ | $\lambda/2\pi < r < 3\lambda$     | $\lambda/2\pi < r < 2D^2/\lambda$ |
| Far Field            | $r < 3\lambda$                | $r < 3\lambda$ and $2D^2/\lambda$ | $r > 2D^2/\lambda$                |

An antenna bandwidth is also required for evaluating the antenna performance. It determines the range of frequency at which the antenna can work properly. The bandwidth is usually calculated in percentage value called bandwidth impedance, determined by dividing the band of operation by the center frequency. To increase the bandwidth of antenna, there are many techniques can be modified as increasing the substrate height, modifying a partial ground, slots in the radiating element, or choosing co-planar Waveguide (CPW) excitation. Figure (2) shows the reflection coefficient of a particular design and how to determine the bandwidth of operation. The impedance bandwidth of an antenna can be defined as the frequency band where the reflection coefficient remains less than or equal to  $-10\text{dB}$ . The impedance bandwidth can be defined as the fractional bandwidth as given by:

$$\text{Impedance Bandwidth} = \frac{f_H - f_L}{(f_H + f_L)/2} \times 100\% \quad (1)$$

Since  $f_H$  higher band of the frequency and  $f_L$  lower band, where  $f_H - f_L$  is the oprating bandwidth where the antenna is functioning.



**Figure 2** (a) Antenna impedance and bandwidth diagram, (b) antenna resistance model [8].

Impedance matching is extremely crucial. Thus the antenna is just a load to a transmission line from the circuit point; it is recognized as reflection coefficient.

$$\Gamma = \frac{Z_a - Z_0}{Z_a + Z_0} \quad (2)$$

Return loss (expressed in dB):

$$L_{RT} = -20 \log_{10}(\Gamma) = -20 \log_{10} \left( \frac{Z_a - Z_0}{Z_a + Z_0} \right) \quad (3)$$

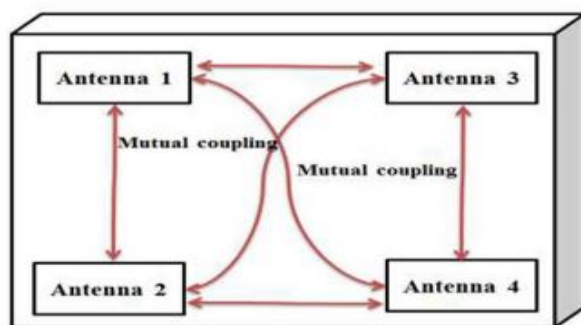
VSWR (a ratio between 1 and infinity):

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} \quad (4)$$

The commonly required specification of an antenna is  $L_{RT} < -10$  dB or  $VSWR < 2$ . These two are actually very close. Directivity is also very important parameter in antenna, which is a measure of the concentration of radiated power in a particular direction. It is defined as the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions. It is measured in the far-field, while the gain is measured as a ratio of radiated power to the input power [8].

#### IV. Mutual Coupling

Mutual coupling is a major problem of performance reduction; it can be quantified by measuring the antenna isolation. It does not only degrade the efficiency of the antenna, but also change the radiation pattern too. It is one of the limitations affected the antenna arrays. If the energy received by the antenna array is with high correlation, then antenna array will lose its function; rather it functions more as a single large antenna, which creates a beam steering much less effective [9,10]. Here is a simple schematic to explain the different paths through which the waves travel from one antenna to the other radiators as in figure 3.



**Figure 3:** Mutual Coupling phenomena

In MIMO system, although it increases the rate of data transmission, but it suffers from mutual coupling among the deployed antennas, if the antenna element spacing is less than the  $\lambda_0/2$ , half of the free space wavelength, then the antenna suffer from the surface wave and the space wave coupling effect between the antenna elements. For that reason, as the compactness increases, the chances of mutual coupling effect increase, resulting in degradation in the MIMO antenna performance due to power losses in a rich scattering environment. Therefore, an effective

isolation technique is a must in the design of a compact MIMO antenna. Besides this, pattern and spatial diversity need to be taken care of while introducing any isolation techniques; it should not disturb the antenna far-field radiation pattern and the impedance matching at large [9,10].

To justify MIMO antennas performance, some of the diversity parameters, such as envelope correlation coefficient ECC and DG (diversity gain) have to be calculated and verified. The ECC describes how one antenna is correlated with other antennas present in their region of interference. Part of interference is considered an area that is coming under  $\lambda_0/2$  distance from the concerned antenna resulting in MC among the antennas, and hence, it degrades the antenna performance. If the gap between the adjacent antennas is more than  $\lambda_0/2$ , it will not affect the nearby antennas; however, to achieve compactness; generally, two antennas are placed tightly [11]. A general equation to compute ECC is given as:

$$ECC = \frac{|\sum_{n=1}^N s_{i,n}^* s_{n,j}|^2}{\prod_{k=(i,j)} [1 - \sum_{n=1}^N s_{i,n}^* s_{n,k}]}$$

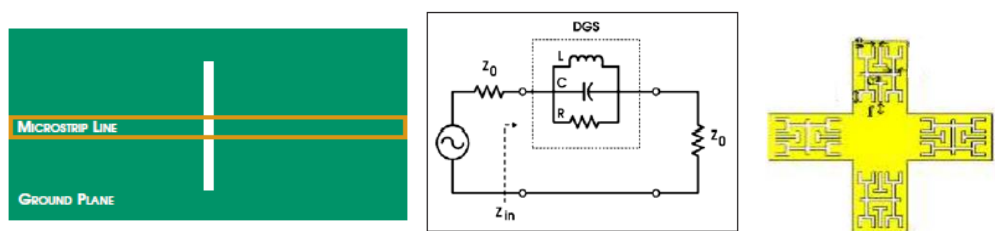
(5)

Here, i and j are antenna elements (radiators) and N is the total number of antennas taken under considerations. While, diversity gain states the amount of improvement obtained from MIMO compared to SISO (Single Input Single Output). The maximum diversity gain is 10 at the 1% probability level with maximum-ratio combining. it can be calculated as:

$$DG = 10\sqrt{1 - ECC^2}$$

(6)

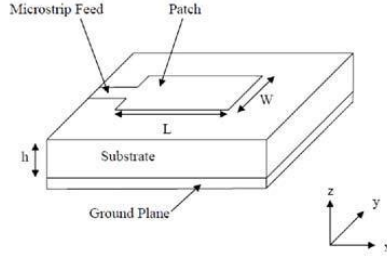
To reduce the amount of mutual coupling, various techniques can be used such as defected ground structure (DGS) [11], to cut a part of the ground plane with different shapes works as a stop band to reject the surface waves. Parasitic elements can also be used on the top of the substrate and between the neighboring antennas to null out the mutual coupling. Electromagnetic band gap structure (EBGS), prevents propagation of surface-waves. This property has been exploited to reduce mutual coupling in the antenna arrays.



**Figure 4:** Decoupling Techniques [12]

## V. Antenna Design and Simulation

The main target in this paper is to design a MIMO antenna and use decoupling techniques to evaluate the mutual coupling resulting from the design, and then evaluate its performance in terms of resonant frequencies, fractional bandwidth, gain, efficiency, current distribution radiation pattern, envelop correlation coefficient and diversity gain. Figure (5) demonstrates the geometry of patch antenna.



**Figure (5)** Microstrip patch antenna geometry

The physical dimensions of the design are calculated based on the following equations: to design any antenna, it is important to set some parameters such as desired frequency ( $f_r$ ), permittivity ( $\epsilon_r$ ) of the substrate material and thickness ( $h$ ) of substrate. Whenever, these parameters are determined, the design will follow this procedure.

1. Determine the width of the patch antenna using the following equation:

$$W = \frac{c_0}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}} \quad (7)$$

Where  $c_0$  is the velocity in free space  $c_0 = 3 \times 10^8 \text{ m/s}$

2. Determine the length of the patch based on the following equations:

$$L = \frac{\lambda}{2} = \frac{c_0 / \sqrt{\epsilon_{\text{reff}}}}{2f_r} \quad (8)$$

Where  $\lambda$  is the wavelength, and  $\epsilon_{\text{reff}}$  is the effective permittivity.

$$L + 2\Delta l = \frac{c_0 / \sqrt{\epsilon_{\text{reff}}}}{2f_r}, \text{ and } \Delta l = 0.412h \frac{(\epsilon_{\text{reff}} + 0.3) \left( \frac{W}{h} + 0.264 \right)}{(\epsilon_{\text{reff}} - 0.258) \left( \frac{W}{h} + 0. \right)}$$

Since  $\frac{w}{h}$  is the ratio of the patch width to the thickness of the substrate, thereby the final dimension of the antenna length is given as

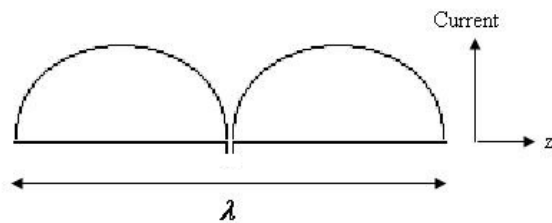
$$L = \frac{c_0}{2f_r \sqrt{\epsilon_{\text{reff}}}} - 2\Delta l \quad (9)$$

3. Based on the results achieved form 1 and 2 , it is simple to calculate the width  $W_s$  and length  $L_s$  of the antenna, that is

$$W_s = W + 6h \quad (10)$$

$$L_s = L + 6h \quad (11)$$

There are essential parameters that can fundamentally affect the performance of the antenna such as input impedance; the ability to give power to the antenna efficiently requires determining the connector position between feeders and conducting element of the antenna. This will provide current distribution control and magnetic current control, therefore resizing antenna is important to minimizing input antenna and thereby increasing directivity. For example, in full wavelength dipole antenna with in phase current distribution, the current distribution is formed as in figure (6)

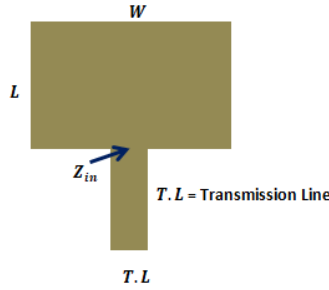


**Figure (6)** current distribution of a dipole with full wave

In this case it is noticed that the current at the input feeding point is approximately zero, this indicates that the impedance at the input will get larger and might be infinity resulting in mismatching

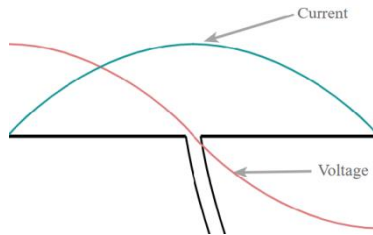
and energy reflecting, thereby reducing the antenna performance. The same procedure experienced in case of microstrip antenna, when the patch is fed at the center edge, the current is very small and the impedance is larger, so that the reflection coefficient at feeding point will increase and resulting in antenna performance degradation. The input impedance  $Z_{in}$  of the patch from its edge is calculated as :

$$Z_{in}(edge) \approx 90 \left( \frac{\epsilon_r^2}{\epsilon_r - 1} \right) \left( \frac{L}{W} \right)^2 \quad (12)$$



**Figure (7):** Microstrip Patch antenna

The solution is to find the appropriate position for feeding the patch; inset fed is the way to improve the matching process between the feeder and the conducting element of the antenna where the input impedance goes down as well as voltage and the current goes up as in the following case of dipole.



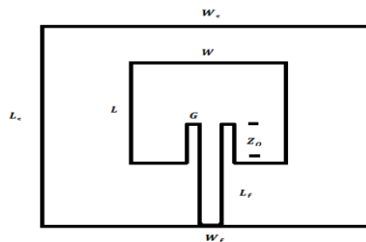
**Figure (8):** Current and voltage status in dipole with full wavelength

As seen from figure (8), that by feeding at the middle will reduce the voltage and therefor reduce the input impedance and increase the current, meaning reduce the mismatching effect. The following equation will helps to find the appropriate position for this process.

$$Z_{in}(T.L) \approx Z_{in}(edge)\cos^2\left(\frac{\pi}{L}Z_o\right) \quad (14)$$

Where  $Z_{in}(T.L)$  is input impedance for transmission line,  $Z_{in}(edge)$  is the input impedance at the patch edge and  $Z_o$  is the position of inset line measured in mm.

In this paper, the microstrip antenna is designed at mm-wave with resonant frequency of 28 GHz, which is a very common frequency used in 5G applications. The radiation element is a rectangular patch microstrip placed on the tope of Rogers RT5880 substrate with dielectric constant (permittivity) of 2.2 and loss tangent of 0.0009. The radiating element is made of copper with thickness 35 $\mu$ m, and is feed by Microstrip feed line. The thickness of substrate is adjusted to 1 mm. the antenna size of initial design is 10.235x9.0187.x1mm<sup>3</sup>, which is compatible for serving 5G application and can be called a compact antenna. The design is shown in figure 9 followed by the table that represented the physical dimensions of the antenna using the design equations.

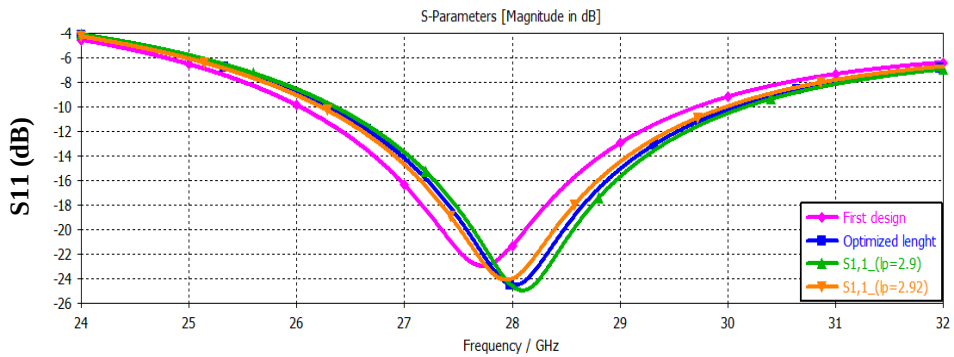


**Figure 9** Initial Design of the antenna

**Table 2 :** The initial dimensions of the antenna with full ground

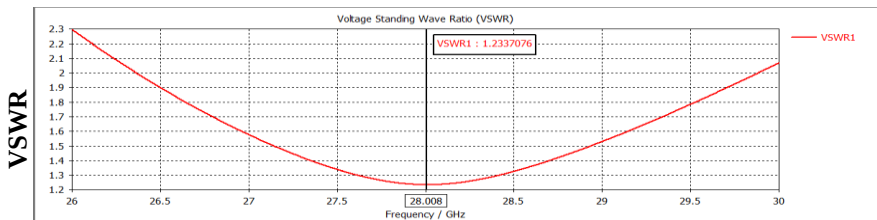
| Description               | symbol | Value in mm |
|---------------------------|--------|-------------|
| Width of patch            | $W$    | 4.235       |
| Length of Patch           | $L$    | 3.0187      |
| Width of Substrate        | $W_s$  | 10.235      |
| Length of Substrate       | $L_s$  | 9.0187      |
| Thickness of Substrate    | $H$    | 1.2         |
| Inset position            | $Z_0$  | 0.9182      |
| Cut width of patch inset  | $G$    | 0.035       |
| Thickness of copper patch | $T$    | 0.035       |
| Feeder Width              | $W_f$  | 0.626       |
| Feeder Length             | $L_f$  | 2.0133      |

By optimizing the length of the patch, it is easy to set the resonant frequency to desired frequency, as there is an opposite relationship between the length of the patch and the frequency. Figure (10) shows the return loss of the first design and optimized patch length, the initial design of patch length with dimension of 3.0187mm has a resonant frequency of 27.73 GHz with return loss of -23 dB and bandwidth of roughly 3.68 GHz to provide fractional bandwidth of 13%. In case of set the length to 2.91 mm, the frequency is obtained at 28GHz which is the desired resonant frequency of this structure. At 28 GHz, the bandwidth is about 3.74 GHz which is very suitable for wideband antennas.



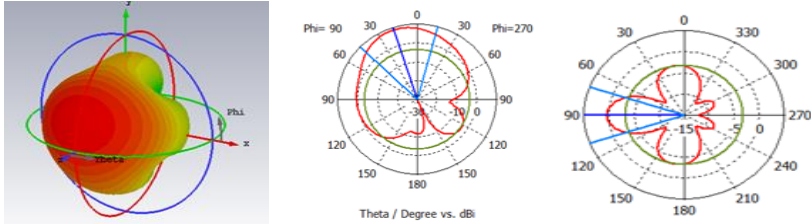
**Figure 10:** Return loss with different lengths of patch

As return loss is achieved, VSWR can be obtained which should meet the the range of 1-2 where the antenna can function properly at. In this design VSWR is about 1.23 as shown in figure 11 .

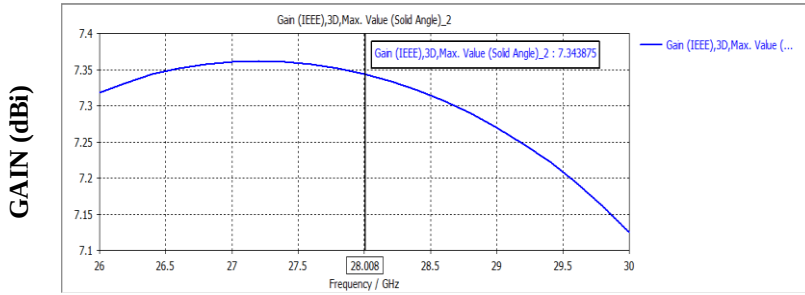


**Figure 11:** VSWR at 28 GHz

Figure (12) shows the radiation pattern in both H- field and E-field, it shows a directional radiation pattern with main lobe of around 7 dBi. While figure (13) demonstrates the gain of the antenna which has about 7.3dBi at resonant frequency 28 GHz.

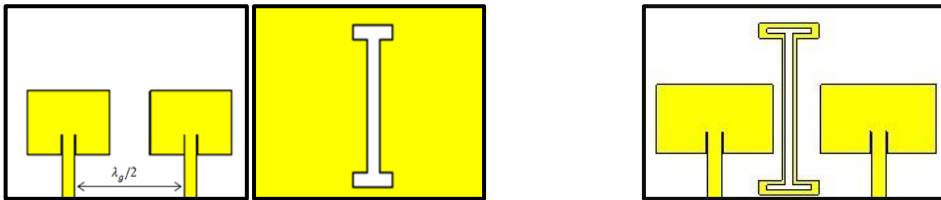


**Figure 12:** Radiation pattern of 3D and Ploz shape at 28GHz



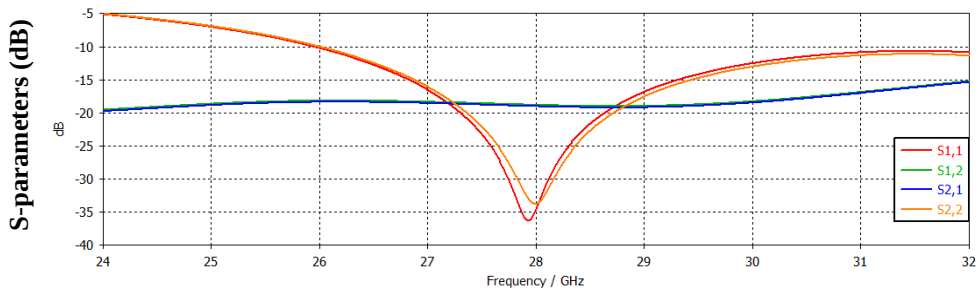
**Figure 13:** Gain of the antenna at 28 GHz

The design is extended to be an array with two elements to increase the overall gain and therefore the directivity. For normal design the distance between elements should be no less than  $\lambda/2$  to avoid the problem of mutual coupling which degrade the system performance, however, the size of the antenna array will increase, which becomes inappropriate for current devices, in this design the space between antennas is set based on the following equation  $\lambda_g = \frac{c_0/\sqrt{\epsilon_{reff}}}{2f_r}$ , which is 6.352 mm. The following design represents the array with two elements and space as set on the figure.



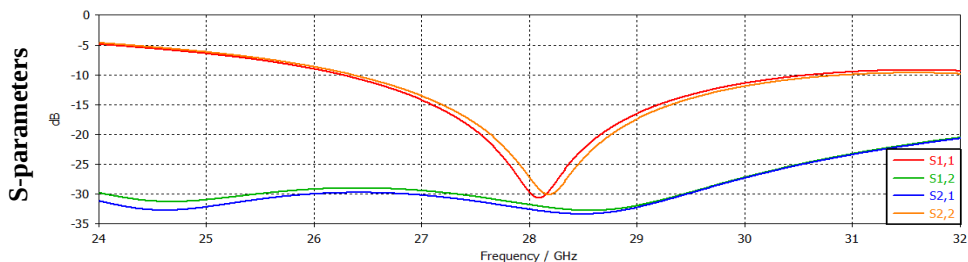
**Figure14:** Array with two elements and DGS on the ground plane, and parasitic element and EBGs on the top of substrate.

After simulating the design, figure (15) , with DGS at the bottom of the substrate (ground plane), the result of return loss shows a significant improvement with resonant frequency of about 27.9 GHz and return loss of about 36 dBi , where  $S_{21}$  is evaluated to determine the effect of mutual coupling, at about 27.9 GHz the mutual coupling is about -18dBi, which keeps around this value over the bandwidth of interest between 26-32 GHz.



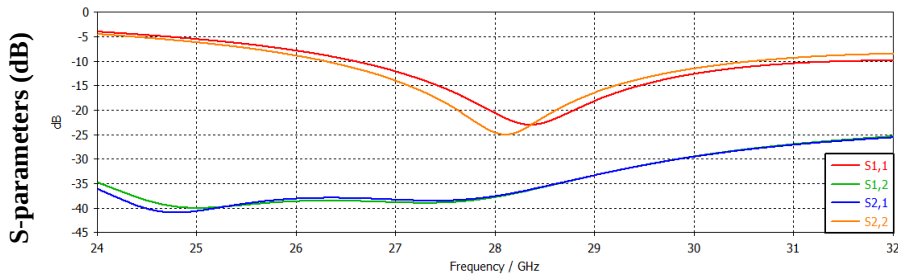
**Figure (15):** Return loss at 27.9 GHz and mutual coupling of -18dBi

Then the structure is modified to insert parasitic slab element between the radiating elements on the top of substrate with the same dimensions as that for DGS and full ground. This structure is resulted in a considerable reduction of mutual coupling to reach less than -30dB of  $S_{21}$ - parameter and resonant frequency shifted at 28.182 GHz with bandwidth of about 4GHz as shown in figure (16).



**Figure (16):** Return loss at 28.182 GHz and mutual coupling of -30 dBi

Afterward, design is modified to include both parasitic element and DGS , in this design results in a return loss of -25dBi resonating at 28.182 GHz and -23dB resonating at 28.42 GHz , with reduction on mutual coupling is roughly -38dB at resonating frequencies.



**Figure (17):** Return loss at 28.182 GHz and 28.42 GHz with mutual coupling of -38dBi

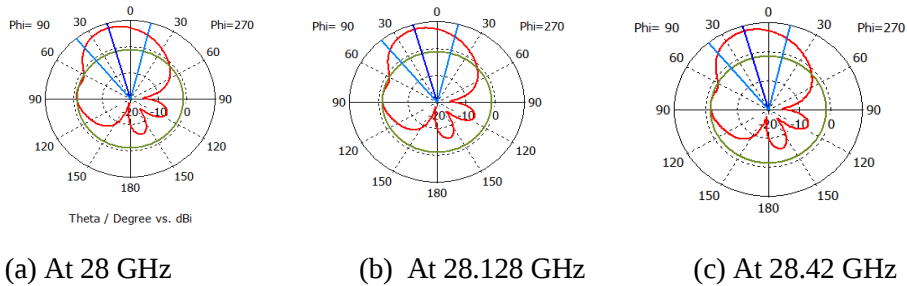
The following table summarizes the techniques of isolation and mutual coupling for all cases.

Table (3): Comparison between design with DGS and parasitic element

| No | Technique                     | BW(GHz) | Resonant freq.(GHz) | MutualCoupling |
|----|-------------------------------|---------|---------------------|----------------|
| 1  | Design with DGS               | 6       | 28, and 27.9        | -18 dB         |
| 2  | Design with parasitic element | 4       | 28.182              | -30dB          |
| 3  | Design with DGS and Parasitic | ~4      | 28.182, and 28.42   | -38dB          |

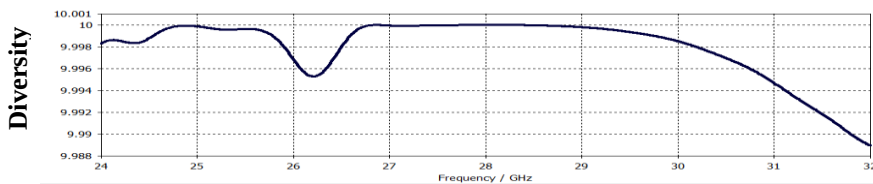
The table (3) shows that the structure with DGS and Parasitic element results in better isolation from MC over the results obtained from using each technique individually. Figure (18) shows the radiation pattern of the design at 28GHz, 28.128 GHz

and 28.42 GHz which provides directivities of 8.11, 8.14, 8.19 dBi respectively with an omnidirectional shapes.



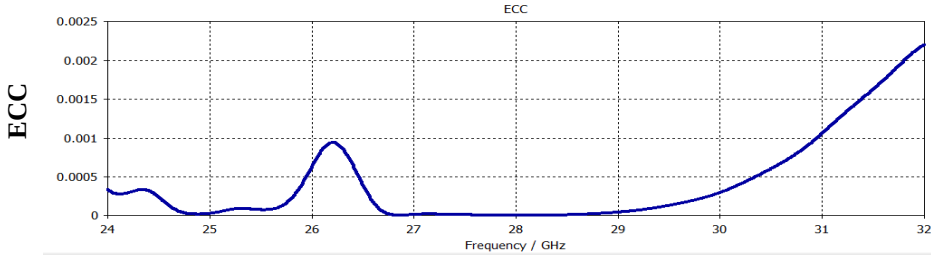
**Figure(18)** Radiation pattern at three resonant frequencies

Now, it is useful to consider the effect of envelop correlation coefficient (ECC) and diversity gain (DG) which can mathematically be calculated as demonstrated in equations (5) and (6). Principally, there should be approximately zero value for ECC to ensure the reduction effect of correlation between radiating elements which is exhibited in figure (19) with vale approximately zero over the band range of interest and high diversity gain reach up to 10 dBi at the operating bandwidth.

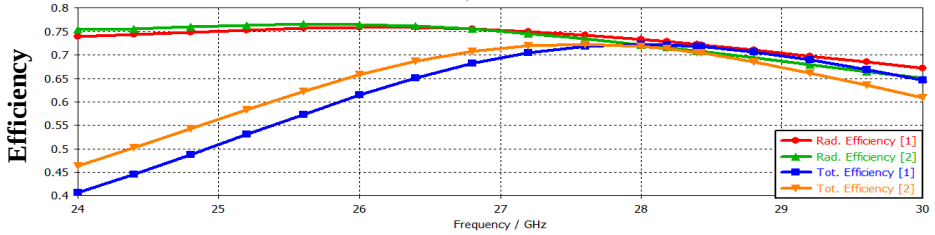


**Figure (19):** Envelop correlation coefficient of two linear elements

Figure (20) , shows the efficiency of the design with EBG Structure, reaching up to 74% at the frequency band of interest.



**Figure (20):** Diversity gain of two linear elements



**Figure (21):** Radiated and total Efficiency

## VI. Conclusion

To sum up, a compact linear array of multiple antennas with 2x1 is designed and simulated using CST microwave studio, with the use of isolation techniques that are used to enhance the performance of the antenna and reduce the effect of mutual coupling. The decoupling techniques that are used in this design are DGS , parasitic element and EBG structure. The results demonstrates that for the use of DGS in the linear two radiating elements, the mutual coupling is approximately - 18 dB to achieve gain of 7.3 dBi, while a considerable reduction noticed for using a parasitic element to reach up to – 38dB at the band range of interest of 26-32 GHz. Electromagnetic band gap (EBG) structure is also used to work as a stop band for rejecting the unwanted energy resulted from mutual coupling to provide a reduction up to -28 dBi. In this design ECC and DG are also evaluated to meet zero and 10dBi respectively. For

further investigations, it is important to increase the number of radiating elements placed on the a compact single substrate, but also it is essential to control the effect of mutual coupling to increase the overall diversity gain and control the effect of correlation among elements, therefore, different decoupling techniques can be used for further study about this issue, especially at mm-wave and higher frequencies.

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