HIGH EFFICIENT 3.6GHz 4 – ELEMENT CPW FED MIMO ANTENNA USING U – SHAPED OPEN SPIRAL SLOTS FOR 5G MOBILE COMMUNICATIONS

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Abstract – This paper presents the investigation on different substrates that can be used in designing of microstrip monopole antenna such as FR – 4, Arlon 250 ™, Rogers RT / Duroid 5880 ™, Teflon and Rogers RO4350 to operate at 3.6GHz frequency. Main aim of this paper is to propose 4 x 4 Multiple-Input Multiple-Output (MIMO) antenna with coplanar waveguide (CPW) fed technique operating at 3.3 – 3.8GHz for advanced 5G mobile applications. With the help of orthogonal mode arrangement, isolation between MIMO antennas is better than 12dB and achieved radiation efficiency of 97 – 98%. Proposed antenna achieves 550MHz impedance bandwidth at S_{11}< -10dB over operating bandwidth from 3.33 GHz to 3.88 GHz and its peak gain value is 4.90dB. The design is suitable for fifth generation mobile communications exhibited by MIMO antenna performance parameters Envelope correlation coefficient (ECC) < 0.01, diversity gain (DG) ~ 10dB, total active reflection coefficient (TARC) <0.3, Channel capacity loss (CCL) < 0.1bits/Hz and mean effective gain (MEG) is greater than 2.5dB. According to simulation results and MIMO parameters, this proposed antenna met the future 5G applications.
Keywords –Coplanar Waveguide (CPW)-fed, U – shaped spiral slot, Multiple-Input Multiple-Output (MIMO), Isolation, Radiation efficiency, 5G mobile applications.

1. Introduction

With the advancements in the communication system there is a huge increase in the cellular communication and in mobile systems. For the growth of the mobile industry, new technologies and services were resulted. So, with the adverse development in modern wireless communication there are various development in the mobile systems has higher throughput and also increasing day by day. In past olden days wired communication means the transmission of data takes place through the wires in which the devices are connected through the cables. Therefore, there are some of the disadvantages as the installation and the reconfiguration is expensive and as there is no network connection so a device cannot shift from one location to another instantly. By considering all these conditions Wireless communication were came into exist for transmitting the data from one point to another point without requirement of wires within a limited time information is transmitted from the transmitter to the receiver. Mobile Communication was started with the 1G which is the first generation, it was an analogue system which was introduced in 1979 by NTT it uses the circuit switching. As there are some drawbacks as the analogue signals are voice type there are some interferences and noisy. Another drawback was security issue. So, to overcome all this issues 2G were came into the exist and was launched in 1991as the GSM as the 2G systems was digitized by the voice signals. In 2G the mobile services are passed in the form of messaging consumption of power through battery is less Now, coming to the disadvantages the data transmission bits are less compatible with advanced generations and complex data will be handled with difficulty. By considering all the disadvantages of 2G system there was a middle technology called as 2.5G or EDGE as it was moved on further as 3G were into invention 3G applies to the voice process of telephone and also messaging which is wireless and its development was in early of 21st century for connecting mobile phones it was available. In 3G the downloading speed was about 7.2Mbps. By using cellular technology, it works and the signals are passed from cell tower to the mobile. The drawbacks of 3G were for the infrastructure and for base stations it costs high and the consumption of the power is high. By considering that drawbacks of 3G and by adding some advancements in that system 4G were came into the existence and allows broadband network. It provides network for data, voice, signal and aims to provide uninterrupted services with high quality and 100Mbps and 1Gbps for downlink. The 4G comes into two categories as LTE and WiMAX. The disadvantages of 4G where battery consumption was high as it was 10 times faster than 3G, consumption of data was large in a shorter time, Limited use of internet and there is a traffic in the signal as there is limited number of towers. So, from all these drawbacks of 4G then the 5G were under the research so, 5G is nothing but Fifth Generation it enables the consumers to connect virtually everywhere. 5G was enables peak data rates as the 20 gigabits per second the downlink capacity was about 20Gbps and the downlink spectral efficiency was about 30 bits per second per hertz, The uplink data rate was about 10Gbps and uplink spectral efficiency was about 15 bits per second per hertz. 5G enables the consumer’s process easy by making the uploading and downloading quickly. Hence the uploading and downloading process can be done simultaneously as it is capable carry multi-mode. Its bandwidth and bit ratio are high as compared with 4G so this 5G will make the things easier. 5G is 100times faster than the 4G in speed so the data rate is high [1 – 3]. As an information from Federal communication commission (FCC) and International Telecommunication Union (ITU), sub – 6GHz band frequencies allocated for 5G are represented in table 1. The above frequency bands have been intensively reported in [4-5]. 5G has higher bandwidth and higher spectrum so a single antenna cannot be able to transfer such a higher frequency so Multiple Input Multiple Output(MIMO) came into the existence [6]. The MIMO process is categorized into three as the Preceding, Multiplexing and diversity gain. So, by considering all the features for transmitting a 5G signal MIMO can be used[7-8].

Table 1. Allocated 5G spectrum of some countries

Country	**Frequency bands**	**Country**	**Frequency bands**
America	2.49 – 2.69GHz / 3.5 - 3.7GHz	France	3.46 – 3.8GHz
Australia	3.4 - 3.7GHz	Germany	3.4 – 3.8GHz
China	3.3 - 3.6GHz / 4.8 - 5.0GHz	Italy	3.6 – 3.8GHz
England	3.4 - 3.8GHz	Japan	3.6 - 4.2GHz / 4.4 -4.9GHz

Europe	3.4 - 3.8GHz	Korea	3.4 - 3.7GHz

In this paper [9] for the purpose of 5G applications a wideband 10-port MIMO antenna was designed with a size of 155x75x0.8mm^3. It covers the bandwidth which ranges from 3.3-5.5GHz and Envelope correlation coefficient(ECC) <0.06. To increase the coupling U-Shaped slots are etched. In [10], an eight antenna MIMO array for the dual band purpose was designed for the 5G smartphone applications; in this an antenna size is 145x75x0.8mm^3. Therefore, two bands' frequencies are in the ranges of 3.4-3.6 GHz and 4.8-5 GHz and gain is -6dB. In this paper [11] a MIMO antenna for5G application was designed which are 4x4 and 8x8 with the rightly arranged orthogonal mode structure and the bandwidth is ranging from 3.4-3.6GHz and its ECCs will be less than 0.06/0.07. In [12] a 10-array antenna was designed in the 3.6GHz band with 10x10 MIMO antenna with the frequency ranging from 3.4-3.8GHz and the ECC is less than 0.1 this proposed antenna has a microstrip line-fed-open-slot with channel capacity loss (CCL) is 57.5bps/Hz. For the purpose [13] of 5G application smartphone Eight antenna array antenna which is dual band MIMO in which its frequency bands are 3.3-3.6GHz, 4.8-5.0GHz and the antenna is formed by T-ship which is the open slot. In this article [14] Eight antenna MIMO array was designed hence it is a compact building block with which it is the Two-shared aperture antennas in which its frequency is ranging from the 3.4-3.6GHz and the efficiency is 59%-73% and its ECC is less than 0.05 and also CCL is 46bps/Hz. In this paper [15] a MIMO antenna was designed for the purpose of the 5G applications which is by using stable current nulls a high isolation block is built by employing a 4 port MIMO and an eight port MIMO and its size is about 145mmx75mmx0.8mm frequency covers in the range from 3.4-3.6GHz. In this paper [16] for the smartphone applications which are multimode for future purpose 4G/5G multiple antennas the dimensions of this antenna were about 130mmx70mmx0.8mm and the frequency cover in the range of 3.4-3.6GHz. In this [17] design MIMO antenna was designed which is compact in structure and decoupled building block for designing an eight 3.5/3.8 antenna with the help of dual inverted F-loop antennas which covers in range of 3.4-3.6GHz, 5.725-5.875GHz. In this Proposal [18] a dual band 8 element MIMO was designed with a neutral line which is short for the application of 5G mobile Handset in which its frequency covers in the ranges of 3.4-3.6GHz and 4.55-4.75GHz with a less ECC of less than 0.05. In this [19] paper a dual band 8x8 MIMO was designed for the 5G smartphone applications which covers frequency from 3.4-3.6GHz and 5.1-5.9GHz with an ECC is less than 0.1 hence the array element is composed of L-shaped open slot and a monopole antenna which is U-shaped. For the future smartphone applications 3.6GHz MIMO [20] was designed with which it is compact and the low-profile antenna array with the eight-element loop. It is composed of the two symmetric and four antennas were proposed with a frequency ranging from 3.4-3.8GHz and the ECC is less than 0.08. In this design [21] a MIMO antenna was designed in the frequency range of 3.5GHz which is eight element array for the purpose of wireless application which covers the frequency from 3.4-3.6GHz the design abruptly looks like compact when inverted L-shape is surrounded by a IL-strip. A dual element and a dual band

MIMO antenna [22] were designed for the mobile terminals for enhancing isolation defected ground structure (DGS) was used and the dimensions of the design were about $50x100x1.56mm^3$ the gain obtained for low band was about -4dBi and the high band was 2.4dBi. In this paper [23] for the purpose of smartphone application of bands which are used for long term evolution eight element MIMO was designed by using a integrated metal frame and its frequency covers in the range of 2.496-2.69GHz and 3.4-3.8GHz. By using independent tuning techniques [24] in the decoupling of multimode for mobile applications for the mobile terminals for solving some 5G promising features in between antenna elements isolation is the key metric feature the dimensions of this MIMO were about $150x75x0.8mm^3$ and there is an enhancing in the isolation from about 12.7dBto the >21dB by using the decoupling structure. In this design [25] a triple band MIMO antenna was designed for purpose of 5G applications it has a better efficiency as it concentrates about 60% and also its isolation is greater than the -14dB it has a clear not that it satisfies the promising features of 5G. In this proposed antenna [26] for the 5G smartphone applications 8x8 array antenna which is dual band was designed and there is a side-edge frame was printed for reducing the mutual coupling in between two middle antenna units a neutralization line was introduced the frequency covers in the range of the 3.4-3.6GHZ and 4.8-5.1GHZ for fifth generation. The ECC is less than the 0.08 and the CCL in lower band is 37.5bps/Hz and higher band is about 38.5bps/Hz.

In this paper, initially monopole antenna has been designed using CPW-fed on various substrates such as FR – 4, Arlon 250 ™, Rogers RT / Duroid 5880 ™, Teflon and Rogers RO4350. The proposed MIMO antenna consist open U – shaped spiral slots etched on radiating element. This proposed antenna achieves 15.19% fractional bandwidth at 3.62GHz. The simulated results S – parameters, VSWR, radiation pattern, surface current distribution, MIMO antenna parameters such as ECC, DG, TARC, CCL and MEG are reported in further sections.

2. Monopole antenna design and discussion

In this single antenna design configuration is designed on Rogers RO4350 substrate material having dielectric constant of 3.66 and its loss tangent is 0.004. Figure 2 shows the coplanar waveguide (CPW) guide feed antenna, in this U – shaped spiral slots are inscribed in the patch to provide better impedance matching and wide bandwidth. The presences of spiral slot in the patch element contribute the good impedance characteristics. This design has been simulated using High Frequency Structure Simulator (HFSS) tool. Optimized geometrical parameters represented on figure 2 are obtained from standard mathematical equations of microstrip patch antenna (MPA) [27].

The dimensions of microstrip antenna are computed by using the following mathematical expressions.

a) Width of radiating patch,

$$w_p = \frac{c}{2 f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{2}$$

b) Effective dielectric constant,

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{w_p}\right]^{-1/2} \quad (3)$$

c) Extension of patch length,

$$\Delta L = 0.412h \frac{\left(\varepsilon_{eff} + 0.3\right)\left(\frac{w_p}{h} + 0.264\right)}{\left(\varepsilon_{eff} - 0.258\right)\left(\frac{w_p}{h} + 0.8\right)} \quad (4)$$

d) Length of radiating patch, $L_p = L_{eff} - 2\Delta L$ (5)

Where $L_{eff} = \frac{c}{2 f_r \sqrt{\varepsilon_{eff}}}$ (6)

Where 'c' is velocity of light = 3 x 10^8 m/s, 'f_r' is resonant frequency, GHz and 'ε_r' is dielectric constant of substrate = 3.66.

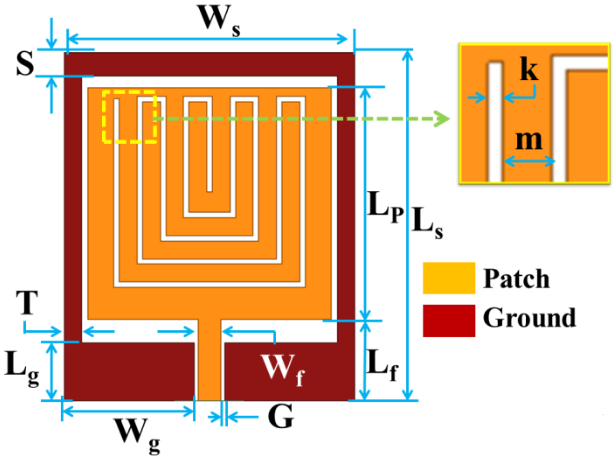


Fig 1. Geometry of proposed single element antenna design

Table 2. Geometrical parameters of designed antenna in mm

L_s	W_s	L_f	W_f	L_g	W_g
30	32	7	2	5	11.2
L_p	S	T	G	K	m
20	2	1.5	0.3	0.46	1.54

With changing the substrate material, the dielectric constants of substrate materials has been changed. Because of electrical, mechanical and thermal properties, these substrate materials are found to be exists for planar antenna configurations. In these five types of substrate materials are considered for antenna design with their respective properties. The dielectric materials used are FR – 4, Arlon 250 ™, Rogers RT / Duroid 5880 ™, Teflon and Rogers RO4350 having dielectric constants (ε_r) of 4.4, 2.5, 2.2, 2.1 and 3.66 respectively. Here the thickness (h) of substrates is 0.8mm. Performance of designed CPW fed monopole antenna using various substrate materials has been investigated interms of S – parameters and VSWR. Figure 2 shows the reflection coefficient characteristics of proposed monopole antenna with various substrates. These characteristics show the impact of dielectric constant on impedance bandwidth. While using FR – 4 material, designed antenna resonates at

3.43GHz having impedance bandwidth (BW) of 480MHz but its reflection coefficient (S_{11}) at resonant frequency (f_r) is less compared to other materials performance. Impedance bandwidth achieved from 3.46GHz to 3.72GHz at 3.665GHz center frequency. Reflection coefficient at resonant frequency is -22.63dB for Arlon AD 250 ™ substrate material. Bandwidth ratio (BR) and fractional bandwidth (FBW) obtained for designed antennas using Rogers RT / Duroid 5880 and Teflon materials are 1.08:1 and 8.23%, 1.08:1 and 7.59% respectively. Impedance bandwidth, S_{11}, BR and FBW parameters of these four substrate materials are altering. In this work, Rogers RO4350 substrate material is used to propose this antenna for 5G band mobile applications. Table 1 illustrated that FCC and ITU – T allocated 5G frequency spectrum within the limits of 3.3 – 3.8GHz. Proposed antenna designed on Rogers RO4350 substrate material is simulated using High frequency structure simulator (HFSS) simulation tool. Designed antenna has been achieved 690MHz huge bandwidth to cover 5G spectrum band from 3.29GHz to 3.98GHz with maximum reflection coefficient of -52.93dB. Figure 3 illustrates the investigation on VSWR parameter of proposed antenna design using various substrate materials. VSWR plot states that impedance matching condition at resonant frequency. VSWR values at resonant frequencies of designed antenna using FR – 4, Arlon AD 250 ™, Rogers RT/Duroid 5880, Teflon and Rogers RO4350 are 1.27, 1.59, 1.12, 1.20 and 1.00 respectively. Table 3 shows the antenna parameters such as resonating frequency, impedance bandwidth, reflection coefficient, bandwidth ratio, fractional bandwidth and voltage standing wave ratio (VSWR). From table 3, it is clear that designed antenna approximately reaches the requirement of 5G frequency spectrum interms of bandwidth and impedance matching by using Rogers RO4350 substrate material (dielectric constant = 3.66 and loss tangent = 0.004). Using this material, work has been extended to investigate performance of designed antenna interms of other parameters such as group delay, radiation pattern and 3D gain polar plots. Figure 4 illustrates the group delay characteristics of proposed monopole antenna have been designed on Rogers RO4350 material. Group delay is nothing but time taken to receive an electromagnetic (EM) signal from transmitted antenna. Group delay at resonant frequency of proposed monopole antenna is 36.8ns.

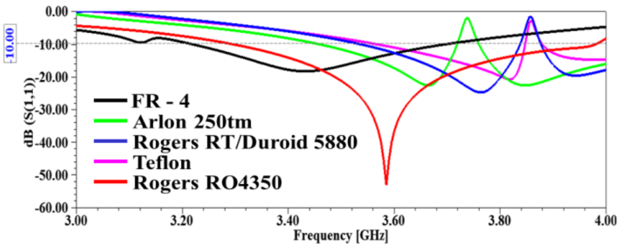


Fig 2. S_{11} characteristics of designed monopole antenna which is composed with various substrate materials

Table 3. Variation of antenna parameters with different substrate materials

Substrate	f_r, GHz	BW, MHz	f_L, GHz	f_H, GHz	S_{11}, dB	BR	FBW	VSWR
FR – 4	3.43	480	3.22	3.70	-18.30	1.15:1	13.99%	1.27
Arlon 250 ™	3.665	260	3.46	3.72	-22.63	1.07:1	7.09%	1.59

Rogers RT / Duroid 5880	3.765	310	3.53	3.84	-24.74	1.08:1	8.23%	1.12
Teflon	3.82	290	3.56	3.85	-20.75	1.08:1	7.59%	1.20
Rogers RO4350	3.585	690	3.29	3.98	-52.93	1.21:1	19.24%	1.00

(Where f_r – resonant frequency, BW – Bandwidth, f_L – lower frequency, f_H – upper frequency, S_{11} – reflection coefficient, BR – Bandwidth ratio, FBW – fractional bandwidth, VSWR – voltage standing wave ratio)

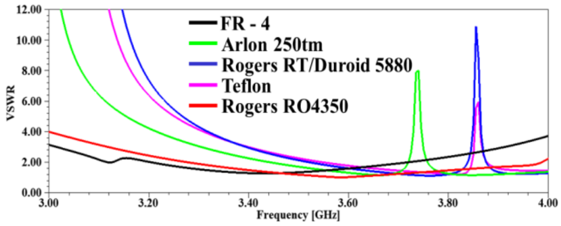


Fig 3. VSWR characteristics of designed monopole antenna which is composed with various substrate materials

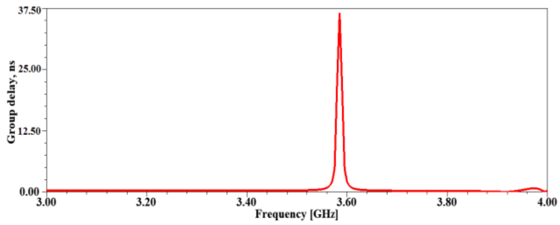
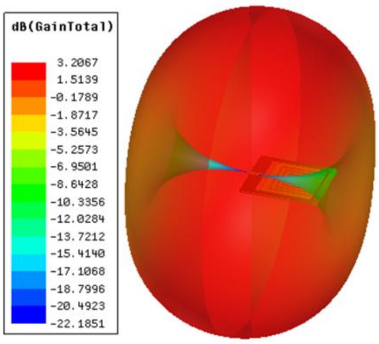
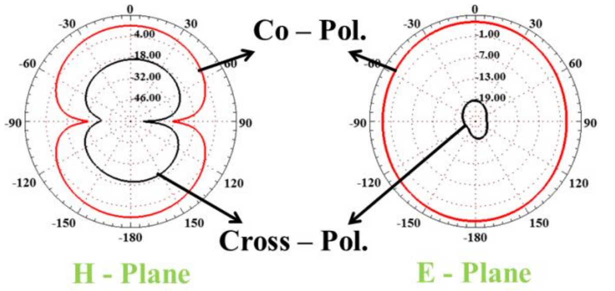


Figure 4. Group delay characteristics of designed monopole antenna on Rogers RO4350 material



(a) 3D Gain polar plot



(b) Radiation pattern

Figure 5. Far – field characteristics of proposed monopole antenna using Rogers RO4350 substrate

Gain value at resonant frequency of proposed monopole antenna is 3.20dB is shown in 3D polar plot figure 5(a). These characteristics show the radiation behavior of monopole antenna. Figure 5(b) shows the co-polarization and cross-polarization radiation pattern characteristics in 2D pattern at resonant frequency 3.585GHz of proposed monopole antenna. Co & Cross – polarization patterns in H – plane shows the bidirectional characteristics and Omni directional characteristics in E – plane as co & cross polarization patterns.

3. 4 – Element MIMO antenna design and its performance

MIMO (Multiple Input Multiple Output) antennas are used at both transmitter and receiver sections. These MIMO antennas are used to minimize the errors, optimize data speed, increases the signal to noise ratio (SNR) and improvement in channel capacity of radio transmissions. MIMO antenna plays a key role in development of long term evaluations (LTE) for wireless Microwave Access (WiMax). This LTE uses MIMO technology to increase speed upto 100Mbps and greater.

Figure 6 shows the proposed MIMO antenna design printed on Rogers RO4350 substrate material having dielectric constant of 3.66 and its loss tangent is 0.004. Overall geometrical configuration of proposed MIMO antenna with CPW feeding is L_{MIMO} x W_{MIMO}(57.5mm x 57.5mm). Optimized spacing between antenna elements (d) is 2.5mm to achieve efficient bandwidth and also improves the isolation between antenna elements.

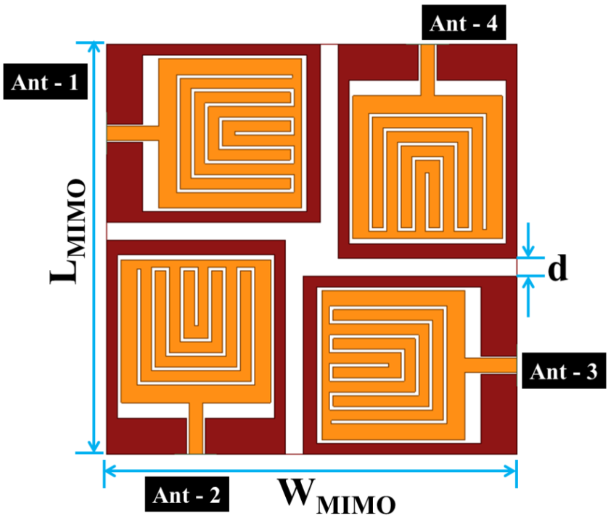


Figure 7. Geometrical configuration of proposed CPW-fed MIMO antenna

Figure 8 shows the return loss characteristics of each element in proposed MIMO antenna design. Main objective of this proposed work is this antenna should be resonate over

5G bandwidth spectrum (3.3 – 3.8GHz). Reflection coefficient (S_{11}) is nothing but it quantifies the how much of power is reflected by an element due to impedance discontinuity. Figure 8 shows the power reflection by an individual antenna element in MIMO structure due to impedance mismatching condition. Impedance bandwidth achieved by proposed MIMO antenna design is 550MHz over the operating range from 3.33GHz to 3.88GHz, which suits the 5G spectrum allocated by FCC & ITU – T specifications. This proposed MIMO antenna resonates at 3.62GHz frequency and its corresponding magnitude reflection coefficient is -35.33dB.

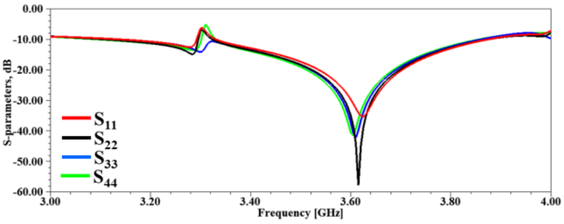
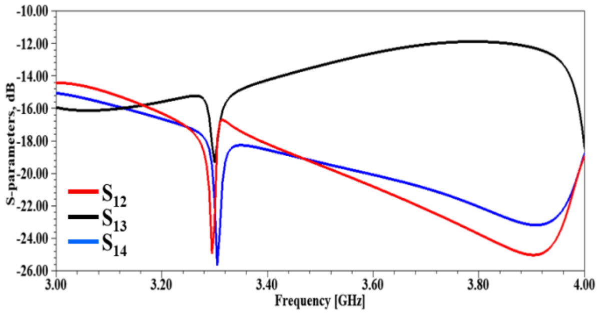
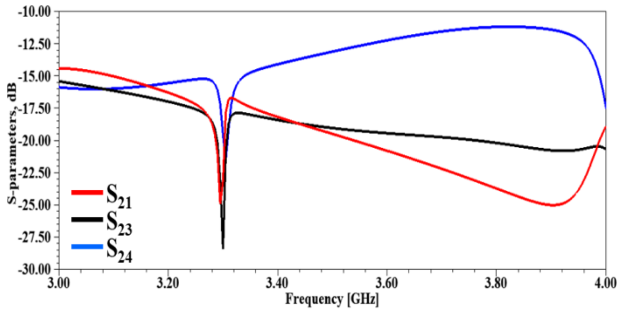


Figure 8. Reflection coefficient characteristics of proposed CPW - fed MIMO antenna

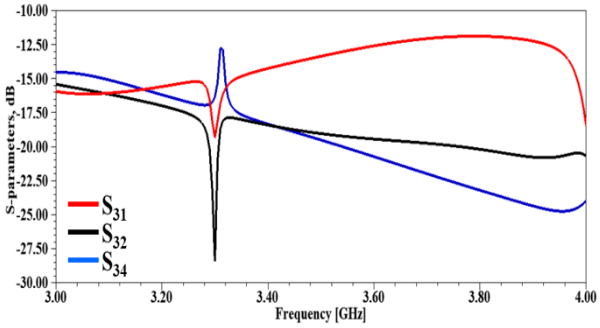
Another important aspect is investigated to measure the MIMO antennas performance is insertion loss (S_{ij}, i,j=1,2,3,4 & i≠j) characteristics. Insertion loss characteristics of MIMO antenna performance are reported in figure 9(a-d).Reflection coefficient & Insertion loss factor at resonant frequency is reported in table 4. From table 4, insertion loss or isolation between multiple antennas is very compact and these antennas obey the symmetric property ($S_{ij} = S_{ji}$, i,j = 1,2,3,4 & i≠j) at resonant frequency.



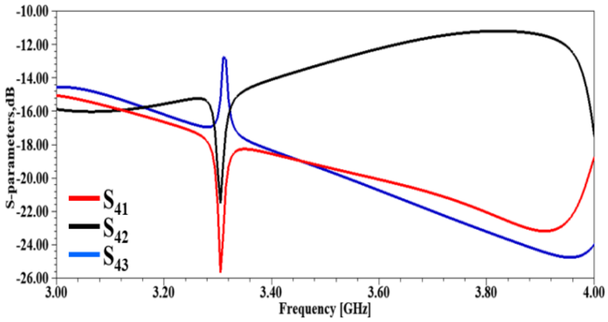
(a) Insertion loss w.r.t. antenna – 1



(b) Insertion loss w.r.t. antenna - 2



(c) Insertion loss w.r.t. antenna – 3



(d) Insertion loss w.r.t. antenna - 4

Figure 9. Insertion loss characteristics of proposed CPW - fed MIMO antenna performance

Table 4. S – parameter measurements of designed MIMO antenna at resonant frequency 3.62GHz

S – Parameters	Ant# – 1	Ant – 2	Ant – 3	Ant – 4
Ant – 1	**S_{11} = -35.33**	S_{12} = -21.08	S_{13} = -12.48	S_{14} = -20.23
Ant – 2	S_{21} = -21.08	**S_{22} = -57.81**	S_{23} = -19.51	S_{24} = -12.10
Ant – 3	S_{31} = -12.48	S_{32} = -19.51	**S_{33} = -42.28**	S_{34} = -20.99
Ant – 4	S_{41} = -20.23	S_{42} = -12.10	S_{43} = -20.99	**S_{44} = -41.60**

(# Ant - Antenna)

Another way of measuring impedance performance over impedance bandwidth region is voltage standing wave ratio (VSWR) parameter. The VSWR value at resonant frequency of proposed MIMO antenna is 1.03. Ideal value of VSWR is 1 and $1 \leq VSWR \leq \infty$ for practical considerations. Figure 10 demonstrates that this complete operating bandwidth is less than 2. Figure 11 shows the input impedance characteristics of proposed MIMO antenna and it states that impedance is perfectly matched within the bandwidth range.

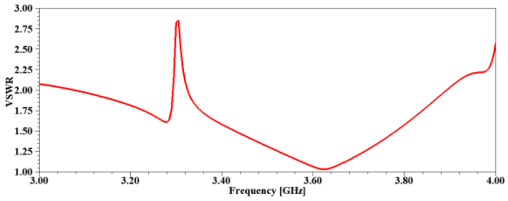


Figure 10. VSWR characteristics of proposed MIMO antenna design

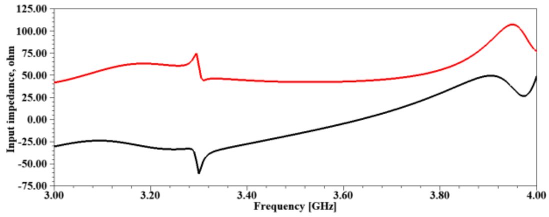
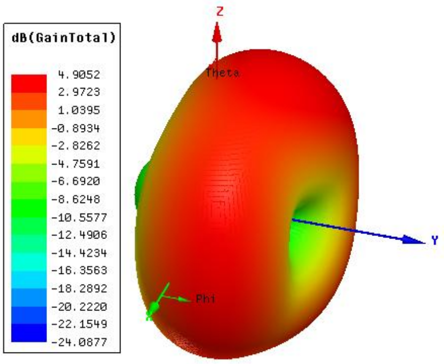
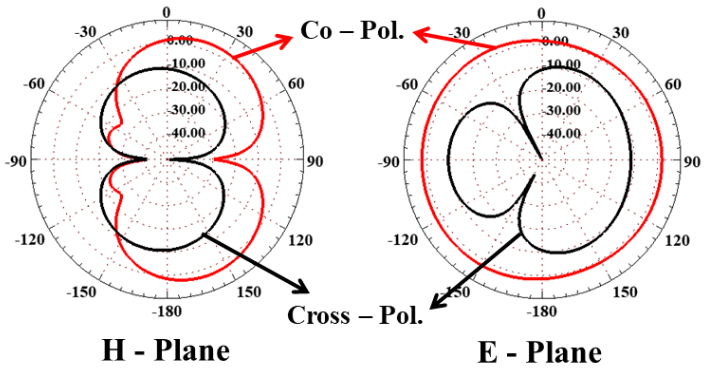


Figure 11. Input impedance characteristics of proposed CPW – fed MIMO antenna design



(a) 3D polar plot



(b) Radiation pattern

Figure 12. Far – field characteristics of proposed CPW – fed MIMO antenna design

Figure 12 shows the far field reports of proposed MIMO antenna in terms of 3D polar plot and radiation pattern. Peak gain value obtained at the resonant frequency of proposed antenna is 4.90dBi and its radiation pattern expressed in co - & cross – polarization as shown in figure 12(b).

Performance of MIMO antennas are analyzed by computing envelope correlation coefficient (ECC), diversity gain (DG), Total active reflection coefficient (TARC), Channel capacity loss (CCL) and Mean effective gain (MEG) [7, 8, 28]. ECC is an essential parameter to examine that how MIMO elements are independent on each other. The critical value of ECC is in between 0 to 1. Figure 13(a) shows the ECC characteristics of 4-element MIMO antenna, which shows that correlation between two elements is almost zero. Diversity gain defines the amount of transmitted power reduction without loss is used in MIMO antennas. Figure 13(b) exhibits the diversity gain of 4-element MIMO antenna is nearly 10dB over the operating bandwidth. TARC is defined as the square root of difference between powers available at all ports and radiated power to the available power. The critical range values of TARC are in between 0 to 1. Figure 13(c) shows the TARC characteristics of proposed 4-element MIMO antenna. Figure 13(d) shows the channel capacity loss (CCL) characteristics of 4-element MIMO antenna, which shows the CCL value over the entire bandwidth is less than 0.2 bits/Hz. Ideally CCL value should be less than 0.4 bits/Hz. CCL provides the channel losses in ECC. Mean effective gain (MEG) is the ratio of mean received power to the mean incident power of antenna. Ideally MEG value should be between -3dB to -12dB. Figure 13(e) shows the MEG between antenna-1, 2, 3 & 4. These MIMO performance parameters are analyzed interms of S – parameters and the standard mathematical expressions are illustrated here.

ECC parameter computed by using radiation pattern excited by an antenna. It can be expressed as [29]:

$$\rho = \frac{\left|\iint_{4\pi}[\vec{F_1}(\theta,\emptyset).\vec{F_2}(\theta,\emptyset)]\right|^2}{\iint_{4\pi}\left|\vec{F_1}(\theta,\emptyset)\right|^2 d\Omega \iint_{4\pi}\left|\vec{F_2}(\theta,\emptyset)\right|^2 d\Omega} \quad (7)$$

Where $F_i(\theta,\Phi)$ is the field pattern of antenna when the i^{th} port is excited and all other ports are terminated for load matching condition. This expression is somewhat difficult to understand and simplification from 3D radiation pattern measurements. So the simple expression for ECC using S-parameters and radiation efficiency is given by [30]:

$$\left|\rho_{i,j}\right|^2 = \left|\frac{|S_{ii}{}^*S_{ij} + S_{ji}{}^*S_{jj}|}{\sqrt{\left|(1-|S_{ii}|^2-|S_{ji}|^2)(1-|S_{jj}|^2-|S_{ij}|^2)\right|}}\right|^2 \quad (8)$$

Where ρ_{ij} is the correlation coefficient and S_{ij} is the S-parameters between two ports. The lower and upper boundaries for the correlation coefficient are $0 \le \rho \le 1$ [31].

Diversity Gain (DG) can be expressed as: $DG = 10 * \sqrt{1-\rho^2}$ (9)

The general expression for the TARC evaluated from two port networks is [32]:

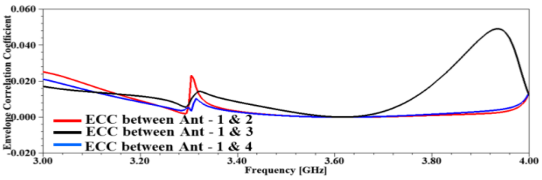
$$TARC = \sqrt{\frac{Available\ \ power - radiated\ \ power}{Available\ \ power}} = \sqrt{\frac{|S_{11}+S_{12}e^{j\theta}|^2 + |S_{21}+S_{22}e^{j\theta}|^2}{2}} \quad (10)$$

Mathematically CCL value is computed from S- parameters. The necessary equations are as follows [33]:

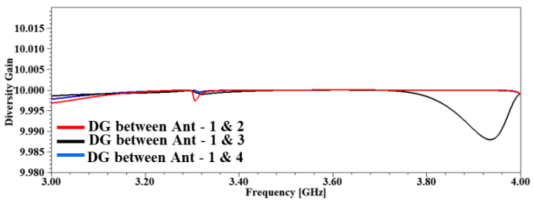
$$CCL = -\log_2\begin{vmatrix}\sigma_{ii} & \sigma_{ij}\\ \sigma_{ji} & \sigma_{jj}\end{vmatrix} \quad (11)$$

Where $\sigma_{ii} = 1 - |S_{ii}|^2 - \left|S_{jj}\right|^2$ (12)

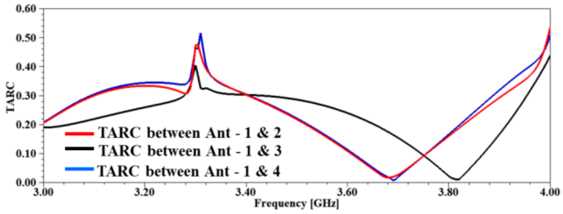
$\sigma_{ij} = -(S_{ii}{}^*S_{ij} + S_{ji}S_{jj}{}^*)$ (13)



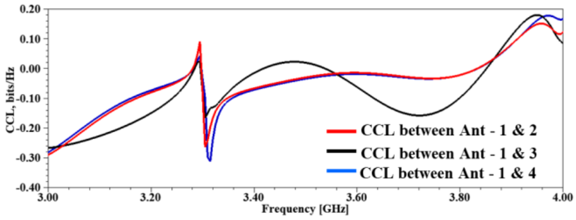
(a) Envelope correlation coefficient characteristics



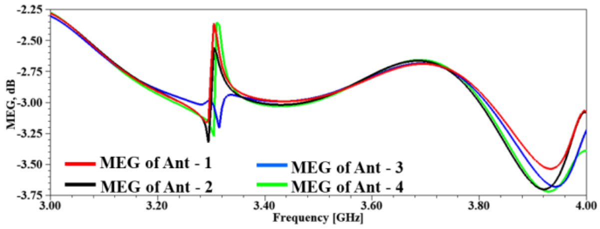
(b) Diversity gain characteristics



(c) Total active reflection coefficient characteristics



(d) Channel capacity loss characteristics



(e) Mean effective gain characteristics

Figure 13. Evolution of proposed CPW – fed 4 – element MIMO antenna performance interms of ECC, DG, TARC, CCL & MEG

Figure 14 shows the gain characteristics of proposed MIMO antenna design. Figure 15 shows the radiation efficiency characteristics of proposed antenna design. Throughout the operating bandwidth of design, this proposed antenna exhibits 98 – 99% radiation efficiency. These characteristics signifies that this proposed antenna is well opted for 5G wireless cellular communication applications. The functional behavior of designed MIMO antennas characteristics are justified in current distribution plot as shown in figure 16. As can be observed from figure 16, when antenna – 1 is excited, the surface current is more concentrated only at antenna – 1 and remaining antennas are not radiated. The surface current is strongly originated on the opposite elements resulting in mutual coupling between antenna – 1 & 3 and antenna – 2 & 4. In fact that the mutual coupling can be reduced by increasing the distance between the elements but it leads to increase the size of the structure. But compact miniaturized structure is the one of the major requirement in antenna design so that this proposed design can be optimized to 2.5mm spacing between antenna elements.

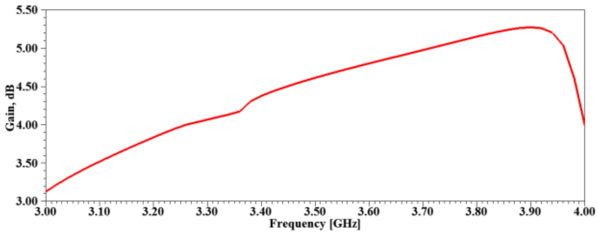


Figure 14. Gain versus frequency characteristics of proposed antenna design

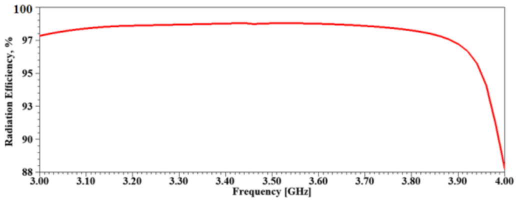


Figure 15. Radiation efficiency versus frequency characteristics of proposed antenna design

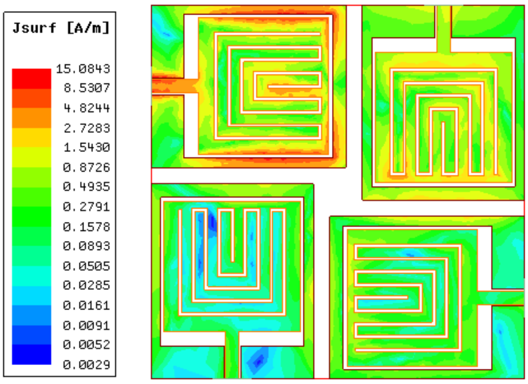


Figure 16. Surface current distribution of proposed 4 x 4 MIMO antenna

4. Comparison of proposed antenna with existed works

Table 5 shows that the advancements in the proposed 4 – element MIMO antenna design compared with the existed works reported in the literature survey interms of design techniques used for developing, used substrate material, operating band, impedance bandwidth, peak gain, envelope correlation coefficient (ECC) and radiation efficiency (η). Compared with the reported works obtained impedance bandwidth is 550MHz, which is very high and achieved maximum radiation efficiency is 98 - 99%, which shows that this proposed antenna is efficient for 5G mobile applications over the operating frequency range.

Table 5: Performance comparison of proposed 4 – element MIMO antenna with earlier designed works

Ref.	YoP	Substrate	Size (mm^2)	IBW, GHz	FBW	f_r, GHz	Isolation	η %	ECC
Proposed		Rogers RO4350	57.5 x 57.55	3.33 – 3.88	15.19	3.62	> 12dB	98 – 99	< 0.01
[34]	2018	FR – 4	150 x 75	3.4 – 3.6	5.71	3.5	> 17dB	50 – 70	< 0.08
[35]	2018	FR – 4	130 x 74	3.3 – 3.6	8.57	3.5	> 16dB	83 – 87	< 0.01
[36]	2017	FR – 4	150 x 80	3.3 – 3.8	13.88	3.6	> 11dB	42 – 65	< 0.015
[37]	2017	FR – 4	150 x 75	3.4 – 3.6	5.71	3.5	> 17.1dB	45 – 62	< 0.05
[38]	2019	FR – 4	75 x 150	3.4 – 3.8	11.11	3.6	> 15dB	-	< 0.05
[39]	2018	FR – 4	150 x 80	3.4 – 3.6	5.71	3.5	>17.5dB	-	< 0.05
[40]	2017	FR – 4	150 x 73	3.4 – 3.8	11.11	3.6	> 10dB	-	< 0.08
[41]	2018	FR – 4	145 x 75	3.3 – 3.6	8.57	3.5	> 10dB	-	< 0.15

[42]	2019	FR – 4	145 x 75	3.4 – 3.6	5.71	3.5	> 12dB	-	< 0.11
[43]	2020	Rogers RO4003C	159 x 75.1	3.4 – 3.8	11.11	3.6	> 14.7dB	-	< 0.014

5. Conclusion

In this communication, 4 x 4 MIMO system composed in orthogonal mode and which is printed on Rogers RO4350 substrate material having dielectric constant of 3.66 and its loss tangent is 0.004. The overall physical dimension of the designed antenna is 57.5mm x 57.5mm x 0.8mm. Here high isolation can be obtained by arranging elements in orthogonal mode with optimized spacing between elements. Proposed antenna achieves operating bandwidth 3.33 – 3.88GHz at -10dB impedance bandwidth. This proposed antenna obtains 15.19% fractional impedance bandwidth at resonant frequency of 3.62GHz having S_{11} = -35.33dB and S_{12}> 12dB.Besides, the radiation efficiency of simulated 4 x 4 MIMO antenna is 97 – 98% and ECC of proposed antenna is less than 0.01 across entire bandwidth. The proposed MIMO antenna is compact in size and low – profile system provides better solution for 5G mobile applications with good isolation and high radiation efficiency.

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