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A Quad-Element Frequency-Agile Pattern and Polarization Diverse Antenna Array for MIMO Applications

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ABSTRACT

This paper presents the design of a simple frequency reconfigurable antenna. The proposed antenna comprises of a rectangular patch antenna with a rectangular slot. The regions with dense current are identified and those regions are utilized to reconfigure the frequency. The antenna performance is made agile by using three p-i-n diodes. The electrical length of the slot is varied by using the p-i-n diodes to reconfigure the application bands. The antenna resonates at 1.8 GHz, 2.4 GHz, 3.5 GHz and 5.8 GHz and finds application in GSM, Bluetooth, WiMAX and WLAN systems. The designed antenna is distributed in the horizontal plane to construct the MIMO antenna. The placement of antennas offers complementary radiation pattern resulting in patter diversity. The evaluated Cross polarization discrimination values are greater than 20 dB. This feature augments the antenna as a polarization diversity antenna. The MIMO performance metrics such as Envelope Correlation Coefficient (ECC), Diversity Gain (DG) and Mean Effective Gain (MEG) under isotropic, indoor and outdoor conditions are evaluated and presented.

Keywords: Antenna Array, Frequency Reconfigurable Antenna, MIMO, Pattern Diversity, Polarization Diversity

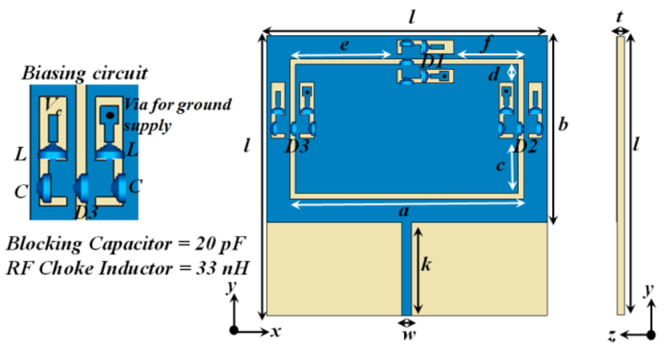
I. INTRODUCTION

Emerging applications require transmission and reception at high data rates. Multiple Input Multiple Output antennas fulfil such needs of communication systems by combating the destructive nature of scattering, reflection, fading and multipath propagation. Mutual coupling/Correlation between the adjacent antennas is a crucial factor to be considered as it has influence on the quality of the signal to be received and channel capacity. Increasing the isolation between the unit cells of the MIMO antenna is a mandatory requirement for the signals to be uncorrelated. A MIMO antenna having more number of unit cell radiators is more robust to the time varying channels. Locating many radiators closely in a MIMO antenna with high isolation is a difficult problem. The unit cells have to be closely placed to reduce the area occupied by the antenna and to offer a compact solution. Whereas closely packed antennas result in enhanced coupling factor.

A MIMO antenna with frequency agile characteristics is suitable candidature for time varying multipath channels. A complex environment with more obstructions and intrusions requires several transceivers operating in varying application bands at each instant. So placing more number of radiators in a MIMO antenna enhances data transmission rate and coverage area. Wireless communication applications requires antennas which cater for varying applications at each instant and with less construction complexity. Reconfigurable antennas can serve such requirements. Reconfigurable antennas integrate several radios in a single platform. Many radios are put in a single dais without employing more number of antenna components. The operation of multiple antennas can be done by a single reconfigurable antenna [1-3]. Multiple applications can be used without incrementing the area of the antenna. The antenna's performance can be made agile by using actuators like PIN Diodes, varactors, and MEMS. A MIMO antenna with polarization and pattern diversity characteristics will make the antenna more resilient to adverse channel conditions, enhances the channel capacity and coverage.

Several frequency reconfigurable antennas are reported in the literature. In [4], stepper motor is used to obtain frequency agile characteristics. U shaped slot and L shaped stub employed with MEMS is discussed in [5]. Filtering elements are designed at feed line of the antenna to tune different frequencies [6]. In some literatures, MIMO and frequency reconfiguration techniques are combined. To enhance the isolation, complex techniques are reported. MEMS switches [7], Neutralisation technique [8], EBG [9]-[10], resistive sheets [11], stacking of substrates [12] are done to reduce the mutual coupling.

In this paper, a rectangular frequency reconfigurable antenna is designed. The size of the antenna is 30 mm × 30 mm. The designed antenna operates at 1.8 GHz / 2.4 GHz / 3.5 GHz / 5.8 GHz. P-i-n diodes are utilized to make the antenna's response dynamic. The proposed antenna is then used to construct a 2 × 2 antenna array. Due to the orthogonal placement of the antenna, the obtained radiation pattern is complementary. The computed XPD values are above 20 dB. So the antenna is a pattern and polarization diversity antenna. The agile antenna can serve Global Positioning System, Bluetooth, WiMAX and WLAN applications. The proposed agile antenna array is a suitable solution for varying environments. The isolation between the radiators in the array antenna is greater than 30 dB without using any decoupling structures. The high isolation is due to the orthogonal placement of unit cell radiators. The inter-elemental spacing between the adjacent radiators is $0.125\lambda_g$. This ensures that high quality information is received. Section II presents the design of frequency reconfigurable antenna. Section III presents the construction of MIMO antenna. Section IV presents the results and discussions. Section V presents the conclusion.



(a)

(b)

Figure 1. Proposed frequency reconfigurable antenna. (a) Front view, (b) Side view. l = 30 mm, t = 1.6 mm, w = 2 mm, k = 10 mm, a = 20 mm, b = 15 mm, c = 7.5 mm, d = 2.3 mm, e = 13 mm, f = 5 mm

II. ANTENNA DESIGN

The design of frequency reconfigurable antenna is presented in this section. The antenna consists of a low profile rectangular patch antenna with a full ground plane. Inside the patch, a rectangular slot is etched. The electrical length of the slot is dynamically altered using the actuators. By identifying the high current accumulated region, activating/deactivating the p-i-n diodes and altering the electrical length, the required band is resonated.

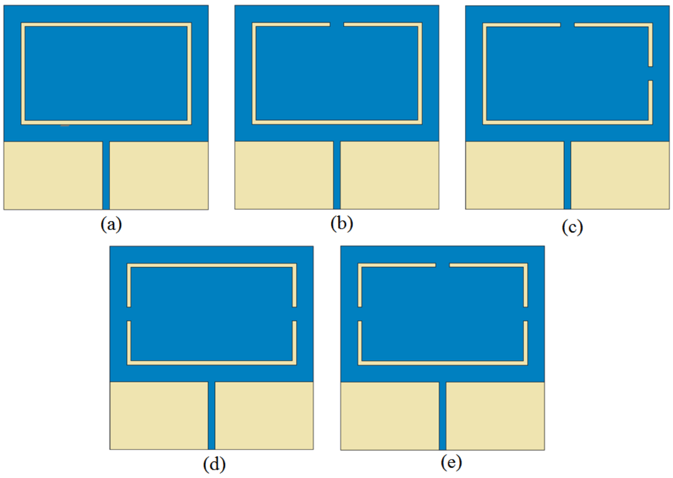


Figure 2. Different stages during the design of the proposed antenna. (a) Antenna 1 , (b) Antenna 2, (c) Antenna 3, (d) Antenna 4, (e) Antenna 5

The proposed antenna is shown in Figure 1. The proposed antenna is designed on a 1.6 mm thick FR4 substrate of loss tangent 0.025 and permittivity 4.3. The volume of the antenna is 30 × 30 × 1.6 mm³. The performance of the antenna is made agile using 3 p-i-n diodes and the antenna has 5 operating states. The evolution of the antenna is delineated in Fig 2 and the corresponding response at each stage is shown in Fig.3

A. Frequency Reconfiguration

The frequency reconfiguration is obtained by exciting the electrical length of the different application bands in different states using p-i-n diodes. In figure 2(a), the perimeter of the rectangular slot is 70 mm (wavelength corresponding to 1.8 GHz). This slot is excited to resonate at 1. 8 GHz (GSM). This is State 1. In State 2, figure 2(b), the electrical length of the slot is made as 68 mm (wavelength corresponding to 2.4 GHz) by activating the p-i-n diode 1. Hence the Bluetooth band is excited. Then, in State 3, p-in diodes 1 and 2 are activated to adjust the electrical length of the slot as 55.5 mm (wavelength corresponding to 3. 5 GHz). So, in State 3, WiMAX band is resonated. Similarly, in State 4, to excite the WLAN band, the electrical length is made as 35 mm by activating p-i-n diodes 2 and 3. Then, in State 5, all the application bands are resonated by turning ON all the p-i-n diodes.

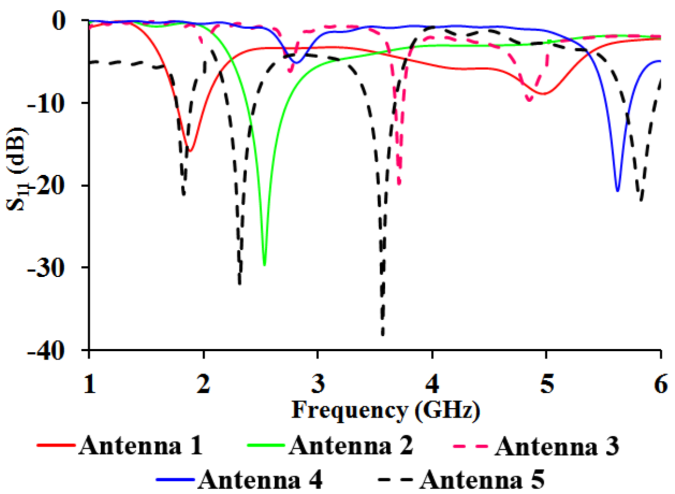


Figure 3. Reflection Coefficient Characteristics of Different Stages of Antenna during the Design of the Proposed Antenna

The different operating states of the antenna are given in Table I. The simulated reflection co-efficient characteristics are shown in Fig. 4. The results show that the antenna operates in different application bands by activating and deactivating the necessary actuators.

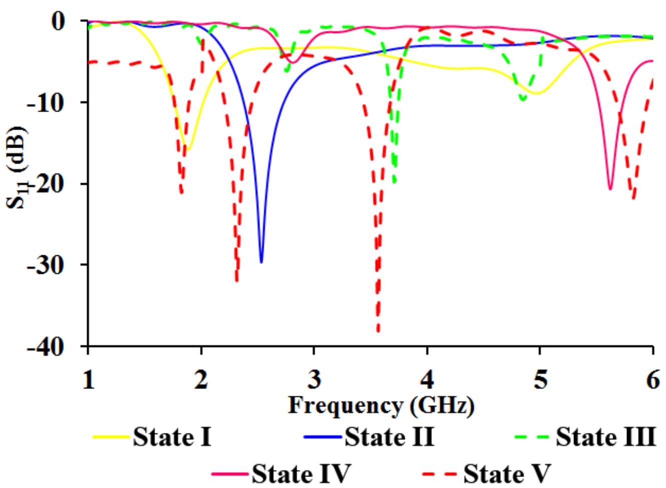


Figure 4. Reflection Coefficient Characteristics of the Proposed Antenna At Various Operating States.

TABLE I

OPERATING STATES OF THE ANTENNA

STATE	PIN DIODES			FREQUENCY (GHz)
	D1	D2	D3	
I	OFF	OF	OFF	1.8
II	ON	OFF	OFF	2.4
III	ON	ON	OFF	3.5
IV	OFF	ON	ON	5.8
V	ON	ON	ON	1.8, 2.4, 3.5, 5.8

III. IMPLEMENTATION OF QUAD ELEMENT ANTENNA ARRAY FOR MIMO TERMINALS

A planar 4-port frequency reconfigurable antenna array is implemented by orthogonally placing all the four radiators on FR4 plane of thickness 1.6 mm. The size of the FR4 plane is 70 mm × 70 mm. The edge to edge spacing between the adjacent radiators is 0.125λ_g. λ_g is the guided wavelength corresponding to the lowest resonating frequency. Since four agile antennas are deployed in this antenna array, the antennas becomes more robust to the ever changing environment. The antenna array is shown in Fig 5. The isolation between the radiators is above 30 dB by placing the radiators orthogonally. The antenna does not seek the help of decoupling structures to enhance the isolation. The probability of receiving good quality signal is high because at least one agile radiator will receive signal with high SNR. This type of arrangement is resulted in a construction of polarization and pattern diversity antenna. The two properties can be related with the following features. The orthogonal arrangement lead to radiation patterns of different orientations. Polarization purity is maintained in the constructed antenna.

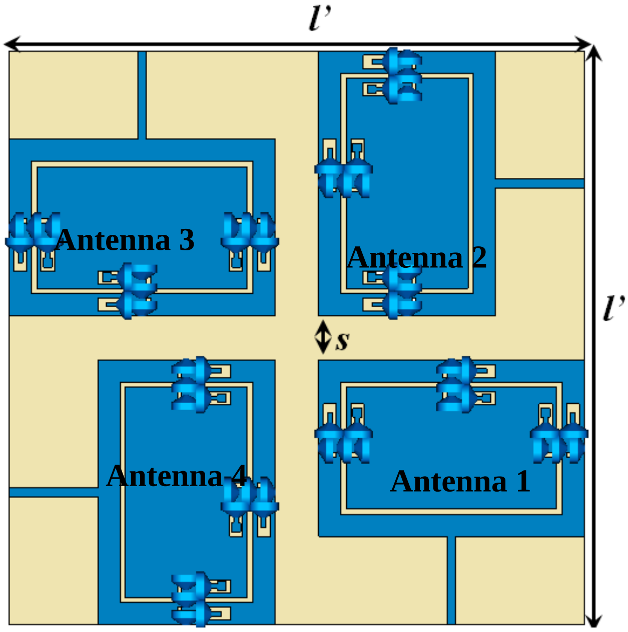


Figure 5. Proposed quad element frequency reconfigurable antenna array. (a) Front view, (b) Side view. l' = 70 mm, s = 0.125λ_g.

IV. RESULTS AND DISCUSSION

All simulations were done using CST Microwave Studio 2015. The impedance, radiation characteristics and MIMO characteristics are evaluated. BAR series p-i-n diode are utilized to reconfigure the antenna. When the p-i-n diode is turned ON (forward bias), the series resistance is 2.1 Ω and series inductance is 1.8 nH. Whereas the p-i-n diode is turned OFF (reverse bias), the reverse resistance is 300 kΩ and shunt capacitance is 0.2 pF. The biasing network isolates the RF signal and DC signal. The biasing network is comprehensively designed using RF choke inductor (33 nH) and DC blocking capacitor (20 pF). At this particular value of L and C, the radiator's and bias network's characteristic impedance match. The basing lines must be of a smaller size such that the antenna's characteristics are not disturbed. The length and the thickness of the bias lines is 1 mm and 0.25 mm respectively.

A. Impedance Characteristics

The simulated S_{11} characteristics of the unit cell radiator is shown in Fig. 4. The simulated S_{11} characteristics of the antenna array is shown in Fig. 6. The bandwidth at 1.8 GHz, 2.4 GHz, 3.5 GHz and 5.8 GHz is 2.1 %, 2.2 %, 2.4 % and 3.52 % respectively.

B. Mutual Coupling Characteristics

The coupling characteristics is most important metric while designing an antenna array. Fig. 7 depicts the mutual coupling characteristics of the proposed antenna array. The inner-elemental spacing between the antennas is 0.125λ_g. The coupling is obtained below -30 dB at the operating bands. Antenna 1 is the reference antenna. This reduced coupling level is because of the orthogonal placement of the antennas.

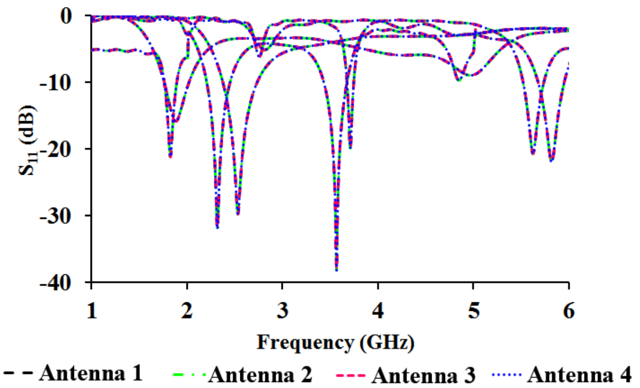


Figure 6. Reflection coefficient characteristics of the proposed antenna array

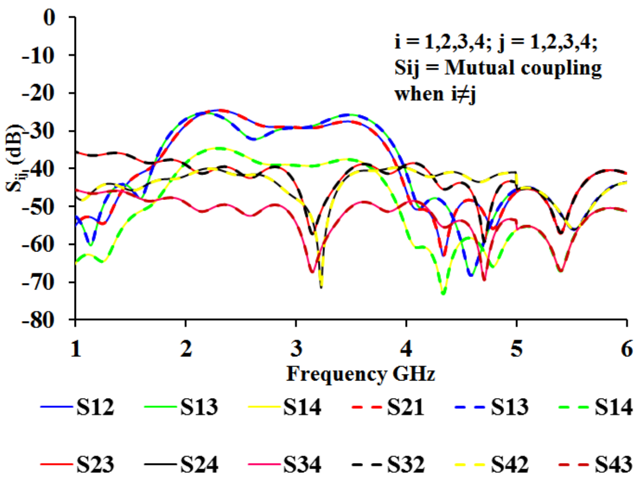


Figure 7. Mutual coupling characteristics of the proposed MIMO antenna

C. Radiation Characteristics

Table II tabulates the performance of the proposed antenna array. The radiation pattern, both xz and xy planes, are shown in Fig. 8. The simulated peak gain and percentage efficiency at State I, II, III, IV and V are 3.2 dBi & 93 %, 3.6 dBi & 80 %, 4.4 dBi & 78 %, and 5 dBi & 74 % respectively. The gain and efficiency characteristics are shown in Fig. 9. Table III tabulates the cross-polarization discrimination values. All the values are above 20 dB. This ensures the polarization discrimination between the adjacent radiators.

D. MIMO Characteristics

Envelope Correlation Coefficient (ECC) quantifies the correlation between the radiations of the antennas. ECC is given by the following far-field equation [16],

TABLE II
PERFORMANCE OF THE QUAD ELEMENT ANTENNA ARRAY

Parameter/Frequency		1.8 GHz	2.4 GHz	3.5 GHz	5.8 GHz
% BW	STATE I	2.1%	-	-	-
	STATE II	-	2.2%	-	-
	STATE III	-	-	2.4%	-
	STATE IV	-	-	-	3.52%
	STATE V	2.1%	2.2%	2.4%	3.52%
Gain (dBi)	STATE I	3.2	-	-	-
	STATE II	-	3.6	-	-
	STATE III	-	-	4.4	-
	STATE IV	-	-	-	5
	STATE V	3.2	3.6	4.4	5
Efficiency (%)	STATE I	93	-	-	-
	STATE II	-	80	-	-
	STATE III	-	-	78	-
	STATE IV	-	-	-	74
	STATE V	93	80	78	74

TABLE III

CROSS POLARIZATION DISCRIMINATION VALUES AT XZ AND XY PLANE

Frequency (GHz)	XPD(dB) (xz-plane)	XPD(dB) (xy-plane)
1.8	22	27
2.4	20	30
3.5	21	29
5.8	23	30

$$\rho_e = \frac{|\iint [\vec{F_1}(\theta,\phi).\vec{F_2}(\theta,\phi)]\, d\Omega\,|^2}{\iint |\vec{F_1}(\theta,\phi)|^2\, d\Omega \iint \vec{F_2}(\theta,\phi)|^2 d\Omega} \quad (1)$$

ECC between the antennas is below 0.15. This ensures less correlation is between the unit cell radiators and the antenna array is the potential choice for MIMO applications.

Similarly, Apparent Diversity Gain (ADG) and Effective Diversity Gain (EDG) are also evaluated. ADG (G_{app}) signifies the increment in the gain after adopting diversity technique. EDG (G_{eff}) takes radiation losses into account [17].

$$G_{eff} = \eta_{total} \times G_{app} = \eta_{total} \times 10 \times \sqrt{1-|\rho_e|^2} \quad (2)$$

The ADG and EDG of the proposed antenna array is greater than 9.98 dB and 7.50 dB respectively.

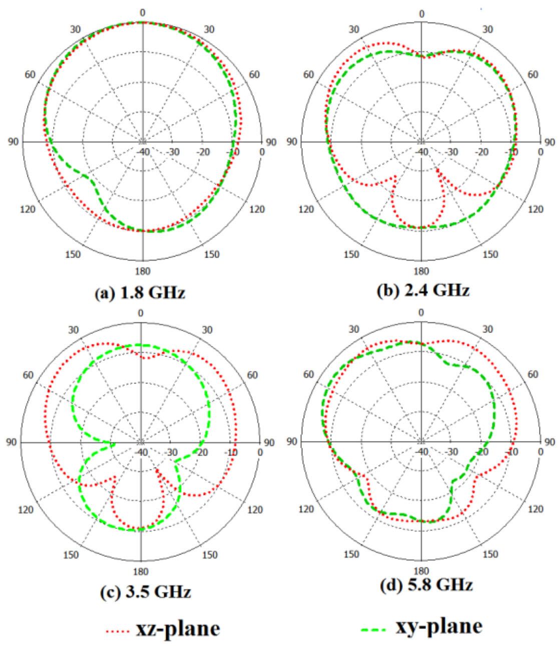


Figure 8. Simulated Radiation Pattern at Various Operating Frequencies

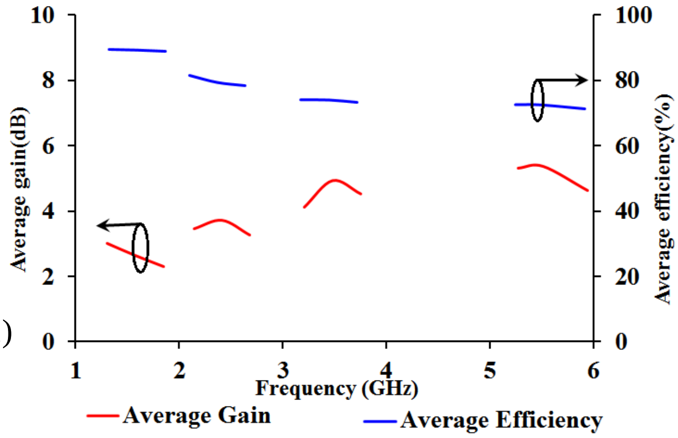


Figure 9. Simulated Average gain and Average efficiency

Mean Effective Gain (MEG) is another critical parameter to evaluate the diversity performance. The MEG difference of an array should be less than 3 dB to possess good MIMO characteristics. The estimated MEG difference between all the radiators is less than 1.3 db.

The results are evaluated in isotropic*, outdoor* (XPR = 1 dB), and indoor* (XPR = 5 dB) scenarios. For outdoor and indoor scenarios, Gaussian power distribution for both vertical and horizontal components with mean 10° and variance 15° is assumed. In the abovementioned scenarios, the designed antenna array's performance level was good.

TABLE IV

MIMO PERFORMANCE BETWEEN ANTENNA 1 AND ANTENNA 2

Frequency (GHz)	ECC by far-field*	Isolation S_{21} (dB)	ADG* (dB)	EDG* (dB)
1.8	<0.06	>30	<10	>9.60
2.4	<0.07	>30	<9.99	>8.88
3.5	<0.12	>30	<10	>9.60
5.8	<0.15	>30	<9.98	>8.86

TABLE V

MIMO PERFORMANCE BETWEEN ANTENNA 1 AND ANTENNA 3

Frequency (GHz)	ECC by far-field*	Isolation S_{21} (dB)	ADG* (dB)	EDG* (dB)
1.8	<0.14	>30	<10	>9.38
2.4	<0.07	>30	<10	>8.86
3.5	<0.11	>30	<9.99	>8.40
5.8	<0.07	>30	<10	>7.88

TABLE VI

MIMO PERFORMANCE BETWEEN ANTENNA 1 AND ANTENNA 4

Frequency (GHz)	ECC by far-field*	Isolation S_{21} (dB)	ADG* (dB)	EDG* (dB)
1.8	.<0.13	>30	<9.99	>8.15
2.4	<0.14	>30	<9.98	>7.90
3.5	<0.14	>30	<9.98	>7.54
5.8	<0.15	>30	<9.98	>7.50

Next cumulative distribution function (CDF) [18] is calculated to validate the MIMO performance of the quad element antenna under Rayleigh channel conditions [18]. It is assumed that the receiver is exploiting Maximum Ratio Combining (MRC). The equation of MRC is (3)

$$P_{MRC}(\gamma \le x) = 1 - \sum_{i=1}^{N} \left(\frac{\lambda_i^{N-1} e^{-\frac{x}{\lambda_i}}}{\prod_{j\ne k}^{N} \lambda_i - \lambda_j} \right) \quad (3)$$

where N is the number of unit cell radiators and λ is the value of eigen vectors acquired from the signal covariance matrix Λ_{MRC} derived using ρ_e and the equation of MEG is (4).

$$\Lambda_{MRC} = \rho_e \sqrt{MEG_i MEG_j} \quad (4)$$

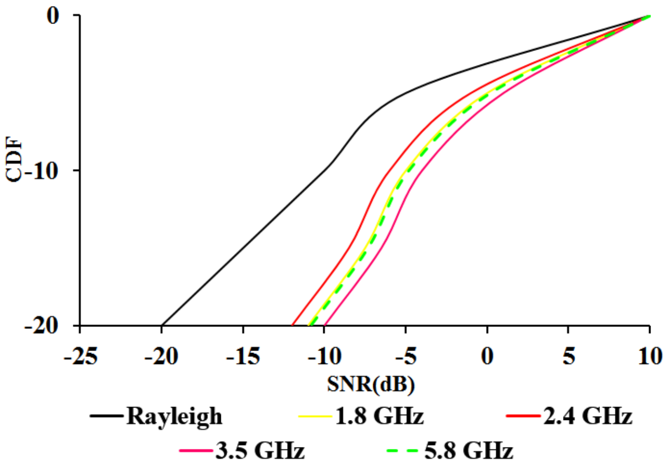


Figure 10. Cumulative Distribution Function (CDF) for the eight port antenna (a) Tri-band mode (b) UWB mode

Fig. 10 delineates the simulated curves of the CDF of the proposed quad element antenna array. With respect to the two element Rayleigh channel state, the diversity gain of the quad element antenna array in all the five states is significantly improved.

TABLE VI

COMPARISON WITH EXISTING STATE OF ART

Work	Antenna size (mm)	Reconfiguration	Actuators	Features		
				Frequency bands(GHz)	Gain (dBi)	η (%)
[13]	120×65	Frequency	MEMS	1.09	2.69	75-96
[14]	150×150	Frequency	PIN Diodes	2.50-2.80/ 2.40-2.96/ 1.71-1.88	3-5	55-92
[15]	80×40	Frequency	PIN Diodes	2.4/ 3.5	0.8-5	75.23-92.9
This work	70×70	Frequency	PIN Diodes	1.8/ 2.4/ 3.5/ 5.8	3.2-5	74-93

The features of the proposed antenna are the following:

1. The proposed antenna reconfigures frequency by simply, when compared to [4]-[5], utilizing PIN Diodes;
2. A low profile rectangular patch antenna is utilized for frequency reconfiguration;
3. The designed antenna reconfigures all the widely used wireless communication bands;

4. The MIMO antenna is constructed in a small area of 70 mm × 70 mm and comprises of four unit cell radiators;
5. The isolation between the radiators is above 30 dB and this isolation is achieved without using any decoupling structures;
6. The proposed MIMO antenna is constructed by placing all the four unit cells orthogonally. This helped to achieve coupling less than -30 dB with an inter-elemental spacing of $0.125\lambda_g$;
7. The proposed frequency agile MIMO antenna with pattern and polarization diversity makes the antenna more resistive to hostile environments.

V. CONCLUSION

A simple frequency reconfigurable antenna reconfiguring all the widely used communication bands is designed. The antenna makes use of low profile rectangular patch antenna. The antenna operates at 1.8 GHz, 2.4 GHz, 3.5 GHz and 5.8 GHz and finds application in GSM, Bluetooth, WiMAX and WLAN systems. The antenna's performance is made agile is using 3 p-i-n diodes. The antenna operates in 5 states. Then an array antenna is constructed by orthogonally placing four unit cells with an inter-elemental spacing of $0.125\lambda_g$. The orthogonal orientation resulted in pattern and polarization diversity antenna. The isolation between the radiators is greater than 3dB. The evaluated MIMO performance metrics such as Envelope Correlation Coefficient (ECC), Diversity Gain (DG) and Mean Effective Gain (MEG) under isotropic, indoor and outdoor conditions ensure that the proposed antenna is suitable candidature for dense MIMO applications.

REFERENCES

[1] P.-Y. Qin, Y. Guo, Y. Cai, E. Dutkiewicz, and C.-H. Liang, "A reconfigurable antenna with frequency and polarization agility," IEEE Antennas Wireless Propag. Lett., vol. 10, pp. 1373–1376, 2011.

[2] C. G. Christodoulou, Y. Tawk, S. A. Lane, and S. R. Erwin, "Reconfigurable antennas for wireless and space applications," Proc. IEEE, vol. 100, no. 7, pp. 2250–2261, Jul. 2012.

[3] Y. J. Cheng, "Substrate integrated waveguide frequency-agile slot antenna and its multibeam application," Prog. Electromagn. Res., vol. 130, pp. 153–168, Aug. 2012.

[4] Tawk, Y.; Costantine, J.; Avery, K.; Christodoulou, C.G., "Implementation of a Cognitive Radio Front-End Using Rotatable Controlled Reconfigurable Antennas," in *Antennas and Propagation, IEEE Transactions on* , vol.59, no.5, pp.1773-1778, May 2011

[5] Nikolaou, S.; Kingsley, N.D.; Ponchak, G.E.; Papapolymerou, J.; Tentzeris, M.M., "UWB Elliptical Monopoles With a Reconfigurable Band Notch Using MEMS Switches Actuated Without Bias Lines," in*Antennas and Propagation, IEEE Transactions on* , vol.57, no.8, pp.2242-2251, Aug. 2009

[6] Tawk, Y.; Costantine, J.; Avery, K.; Christodoulou, C.G., "Integrated wide-Narrowband Antenna for Muti-Standard Radio," in *Antennas and Propagation, IEEE Transactions on* , vol.59, no.7, pp.1773-1778, July 2011

[7] A. Grau, J. Romeu, M. J. Lee, S. Blanch, L. Jofre and F. De Flaviis, "A Dual-Linearly-Polarized MEMS-Reconfigurable Antenna for Narrowband MIMO Communication Systems," in *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 1, pp. 4-17, Jan. 2010. 22

[8] Q. Luo, J. R. Pereira and H. M. Salgado, "Reconfigurable dual-band C-shaped monopole antenna array with high isolation," in *Electronics Letters*, vol. 46, no. 13, pp. 888-889, June 24 2010. 23

[9] Fan Yang and Y. Rahmat-Samii, "Microstrip antennas integrated with electromagnetic band-gap (EBG) structures: a low mutual coupling design for array applications," in *IEEE*

Transactions on Antennas and Propagation, vol. 51, no. 10, pp. 2936-2946, Oct. 2003. 24

[10] B. Liang, B. Sanz-Izquierdo, E. A. Parker and J. C. Batchelor, "A Frequency and Polarization Reconfigurable Circularly Polarized Antenna Using Active EBG Structure for Satellite Navigation," in *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 1, pp. 33-40, Jan. 2015. 25

[11] E. Yetisir, C. C. Chen and J. L. Volakis, "Low-Profile UWB 2-Port Antenna With High Isolation," in *IEEE Antennas and Wireless Propagation Letters*, vol. 13, no. , pp. 55-58, 2014. 26

[12] M. N. Osman, M. K. Abdul Rahim, M. R. Hamid, M. F. M. Yusoff and H. A. Majid, "Compact Dual-Port Polarization-Reconfigurable Antenna With High Isolations for MIMO Application," in *IEEE Antennas and Wireless Propagation Letters*, vol. 15, no. , pp. 456-459, 2016. 27

[13] R. Hussain and M. S. Sharawi, "Integrated reconfigurable multiple-input–multiple-output antenna system with an ultra-wideband sensing antenna for cognitive radio platforms," in IET Microwaves, Antennas & Propagation, vol. 9, no. 9, pp. 940-947, 6 18 2015.

[14] A. N. Kulkarni and S. K. Sharma, "Frequency Reconfigurable Microstrip Loop Antenna Covering LTE Bands With MIMO Implementation and Wideband Microstrip Slot Antenna all for Portable Wireless DTV Media Player," in IEEE Transactions on Antennas and Propagation, vol. 61, no. 2, pp. 964-968, Feb. 2013.

[15] Jin, Z.-J.; Lim, J.-H.; Yun, T.-Y., "Frequency reconfigurable multiple-input multiple-output antenna with high isolation," in Microwaves, Antennas & Propagation, IET , vol.6, no.10, pp.1095-1101, July 17 2012

[16] M. Schwartz, W. R. Bennett, and S. Stein, *Communication System and Techniques*. New York, NY, USA:McGraw-Hill, 1965, pp.470-474.

[17] H. S. Singh, B. R. Meruva, G. K. Pandey, P. K. Bharti, and M. K. Meshram, "Low mutual coupling between MIMO antennas by using two folded shorting strips," Prog.Electromagn. Res. B. vol. 53. pp. 205-221, Jul. 2013.

[18] G. N. Alsath *et al.*, "An Integrated Tri-band/UWB Polarization Diversity Antenna for Vehicular Networks," in *IEEE Transactions on Vehicular Technology*.