Frequency Agile MIMO Antenna Design for 5G Dynamic Spectrum Sharing in CR Networks

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ABSTRACT: *In this work, 2-element slot-based frequency reconfigurable (FR) multiple-input-multiple-output (MIMO) antenna design antenna with a very wide-sweep is proposed for dynamic spectrum sharing (DSS) in 5G technologies. FR is achieved using varactor diode with frequency tuning range from 1655~2605 MHz. The design is a low profile with planar structure having a single element footprint of 19.5×20 mm². The two slot antenna elements of the MIMO configuration are etched out from a ground (GND) plane of dimensions of 60×120 mm². The proposed antenna is narrow-band and hence it is suitable for RF front-end in the 5G-enabled DSS in cognitive radio (CR) applications.*

Keywords: *MIMO antennas, narrow-band, frequency reconfigurable, 5G, Dynamic Spectrum Sharing, Cognitive Radio.*

1. INTRODUCTION

The exponential growth of the multimedia applications and their use in small-handheld devices has expanded the traffic loads massively. In order to meet these demands, the research is focusing on maximizing the utilization of the available spectrum in **fifth generation (5G) wireless communication standards**. One of the most important problems to be tackled in the future deployment is the lack of radio frequency spectrum [1]. An effective solution of the aforementioned problems is the cognitive radio (CR) dynamic spectrum sharing (DSS) which is an emerging concept in the wireless transmission and relies on opportunistic spectrum access and sharing techniques [2]. The front-end of such systems are required to be embedded with frequency reconfigurable (FR) antennas with continues resonating bands to cover a very-wide frequency spectrum and can be switched to any desired band as per user requirements.

FR antennas can dynamically switch the operating bands to other frequency bands to avoid spectrum congestion and address the issues of spectrum resources scarcity. Various types of FR antennas are reported in literature including monopole [3]-[5], dipole [6]-[7], bow-tie [8]-[9], patch [10]-[11], printed inverted F-Antenna (PIFA) [12] and slot [13]-

[16] antennas with different characteristics. Slot-based radiating structures are quite popular because they are easy to fabricate and have compact planar structure with ease of integration with other circuit components.

For future generation 5G applications, the implementation of MIMO antenna designs are crucially important. Such antenna systems are critically important to efficiently utilize the spectrum resources, it must provide high data rate and could be useful for DSS. Several FR MIMO antennas were presented in [17]–[20]. A slot based MIMO antenna design of 4-antenna element and with wide tuning capabilities was presented in [17], [18]. In [19], a miniaturized sub-1 GHz MIMO antenna was presented for multi-band operation. The frequency quad bands covered were from 0.665~3.89 GHz with a total board dimensions of 60×120× 0.76 mm³. Although, such antennas covered wide-band, however they have complex biasing circuit or facing poor Z_{in} over the entire band. A table of comparison is provided to compare the features of the proposed design with the most relevant antenna structures. From given Table-I, it can be seen that the proposed antenna design outperforms as compare to the other closely related works as available in literature.

Table-I: Comparison of the proposed MIMO antenna system with other related works

In this work, 2-element narrow-band FR MIMO antenna design with very wide-band tuning is proposed for DSS in 5G wireless standards. The proposed slot-based antenna covered frequency band between 1655~2605 MHz and hence it covered various sub-6 GHz 5G bands. For the proposed 2-element antenna design, single element with a footprint of 19.5×20 mm² was etched out from GND plane having dimensions of 60×120 mm². The proposed MIMO antenna is a narrow-band design suitable to be used as RF front-end 5G enabled DSS in CR applications.

2. DESIGN DETAILS

The proposed slot-based 2-element FR MIMO antenna design is shown in Figs. 1(a) and 1(b) while the antenna prototype is given in Figs. 1(c) and 1(d). The antenna was fabricated on Rogers RO4350 substrate board with ϵ_r value of 3.48. The top layer of the antenna contains the micro-strip feed line and the biasing circuitry as given in Fig. 1(a) while the ground (GND) plane having slot structures is illustrated in Fig. 1(b). Two modified-pentagonal slot structures were etched from the GND plane and were loaded reactively using varactor diode (D_v) SMV-1233 to achieve frequency tunability over a wide-band. The effective length of the slot antenna was reconfigured by varying the capacitance of varactor diode to reactively load the slot structure. The varactor diode D_v was reverse biased having series circuit of an RF chokes (L_1 and L_2) and current limiting resistors (R_1 and R_2). The dimensions of the printed circuit board (PCB) used were 60×120×0.76 mm³ with a single slot area of about 19.5×20 mm².

Fig. 1: Proposed 2-Element FR antenna (a) Top view (b) GND layer (c) Fabrication antenna top view (d) Fabrication antenna bottom layer.

3. SLOT ANTENNA OPERATION AND DESIGN PROCEDURE

3.1 Theoretical background

Frequency reconfigurable antenna with MIMO capabilities are the suitable solutions for such scenarios. In this section, the slot antenna operation, theoretical background and step by step design procedure is discussed. The fundamental resonance frequency (f_r) of the closed slot-line antenna with rectangular or modified rectangular structure slot antenna with short circuited ends can be modeled as a $\lambda/2$ transmission line [21]. The f_r of the slot antenna is given by:

$$f_r = \frac{c}{2(l_1 + l_2)} \times \sqrt{\frac{\epsilon_r + 1}{2\epsilon_r}} \quad (1)$$

In given Eq. (1), l_1 & l_2 are the average length of the internal and external slot and c is the speed of light in free space. Equation (1) can be used to determine the resonance frequency of closed slot-line antenna with rectangular or modified rectangular structure as given in [22]. The antenna was operating at sub-4 GHz bands without reactive loading. By using the varactor diodes, f_r of was brought down to sub-3 GHz bands without any additional circuit component. The varactor diodes location on the slot structure, its capacitance and input impedance (Z_{in}) of the slot line structure helped in determining the resonating bands of the slot antenna. Reactive loading of the slot antenna is a non-uniform process as certain position of varactor diode gives different effect on the resonating bands. Hence, it is critical to determine the exact placement of the varactor diode for optimal performance with good Z_{in} matching over a wide-band from 1655~2605 MHz.

3.2 Design Procedure

The design procedure of the proposed antenna design was started with a rectangular-shaped slot structure and then turned into to modified pentagonal shaped-structure to enhance the Z_{in} matching. The given slot antenna was fed with 50 Ω microstrip feed-line. The given slot was optimized for its various segment, width & length of the feedline, width of the slot, its placement, and distance between two antenna elements as well as the defected GND structure (DGS) to obtain better isolation. Several parametric analysis were carried out to obtain the optimized parameters as mentioned above. It has been observed that the performance in terms of Z_{in} matching was degraded significantly by varying the position or orientation of diode or antenna slot itself. The two antennas were placed on the opposite sides to minimize the field coupling for better MIMO performance. The final optimized antenna design is considered as best in terms of single element size, frequency sweep over a wide band and narrow-band operation for better 5G power management.

Fig. 2: Antenna design analysis (a) Parametric sweeps on antenna dimensions (b) Parametric sweeps on distance between antenna elements (c) Current density without DGS (d) Current density with DGS

Fig. 2(a) shows the parametric analysis of the electrical length of the slot antenna and the corresponding to $\text{Re}\{Z_{in}\}$ values. It has been observed that the antenna started resonating at the lower frequency bands by increasing its effective electrical length. Fig. 2(b) shows the reflection coefficient curves by increasing the distance between the slot antenna elements. It can be seen that S_{11} curves have insignificant shift by increasing the distance between adjacent antenna elements. Similarly, the current density analysis without and with the defected ground structure is presented in Figs. 2(c) and 2(d),

respectively. This helped in understanding to lower the mutual coupling between closely spaced antenna elements. A parametric sweeps were also performed to obtain the optimal position of the varactor diode placement, in order to obtain maximum effective slot loading.

4. SIMULATION AND MEASURMENT RESULTS

In this section, the simulated and measured results are discussed. This included scattering parameters (S-parameters), radiation characteristics and envelope correlation coefficient (ECC).

The simulated and measured reflection coefficient (S_{11}) curves of the given slot antenna design were computed as shown in Fig. 3. The frequency bands coverage was from 1655~2605 MHz with minimum -10 dB bandwidth (BW) of 25 MHz. The simulated and measured S_{11} are given in Fig. 3(a) and Fig. 3(b), respectively. A continuous variation in the resonating bands were obtained over the entire operational bands. The simulated results matched well with the measurements. The measured S_{11} show shows the frequency sweeps from 1655~2605 MHz with minimum -10 dB bandwidth of 27 MHz over the entire band. The simulated and measured isolation S_{12} curves are shown in Fig. 2(c) and 2(d), respectively, with worst case isolation values better than 15 dB over the entire operation bands of interest.

Fig. 3: S-parameters of curves (a) Simulated $|S_{11}|$ (b) Measured $|S_{11}|$ (c) Simulated $|S_{12}|$ (d) Measured $|S_{12}|$

For the proposed antenna design, the simulated and measured normalized 2-D pattern are given in Fig. 4(a)-4(d). Normalized gain patterns are the better representation of radiation characteristics and provide easy reference for looking at side lobe level (SLL), easy comparison of lobes etc. The total gain patterns for the given antenna elements 1 and 2 at 1.84 GHz are shown in Fig. 4(a) and Fig. 4(b), respectively. The curves are θ -cut at $\phi = 0^\circ$ and $\phi = 90^\circ$. Similarly, the normalized gain patterns at 2.56 GHz for both antenna elements are shown in Fig. 4(c) and Fig. 4(d). The tilt in the radiation patterns helped in lower field to enhance the MIMO performance metrics. The biasing circuit has very minimal effects on the gain of the antenna design. The radiating part is well isolated using the RF chokes from the voltage source.

The peak gain and efficiency ($\% \eta$) were also computed for the given slot antenna design. Both the simulated and measured values are given in Table-I. It has been observed that $\% \eta$ of the antenna is more than 76% while peak gain values were more 2.8 dBi over the given operation bands. To properly characterize the MIMO performance metrics, ECC diversity gain (DG) values were computed using far-field radiation patterns and are provided in Table-II.

Fig. 4: Simulated and measured 2-D gain pattern (a) Ant-1 at 1.86 GHz (b) Ant-2 at 1.86 GHz (c) Ant-1 at 2.56 GHz (d) Ant-2 at 2.56 GHz

Table II: ECC, Peak gain (PG) and efficiency ($\% \eta$) and Diversity Gain (DG) values of the proposed antenna

5. CONCLUSIONS

A low profile, modified pentagonal shaped FR MIMO antenna design is presented for small cell devices with DSS in 5G technologies. The proposed narrow-band MIMO antenna design with-band tunability covered frequency bands from 1655~2605 MHz. A simple varactor diode per antenna element was utilized to achieve this wide-band configuration. Two modified pentagonal slot antenna based elements were etched out from GND plan with single element dimensions of $19.5 \times 20 \text{ mm}^2$. The given antenna design is a narrow-band design suitable to be used as RF front-end in the 5G enabled DSS in cognitive radio (CR) applications.

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Ref.	Ant. Type	Ant. Size mm ² /mm ³	Bands GHz	Efficiency % η	Peak Gain dBi
[15]	slot	35~20	0.42~1.48	-	Above -0.4
[16]	loop	25~10~0.2	0.9,2.4,3.5,5.5	60,63,65,69	1.7,1.3,2.1,2
[17]	slot	31~25	1.32~1.49,1.75~5.2	min. 40, max. 81	min. 0.5, max. 4.5
[18]	slot	30~24	1.8~2.45	min. 50, max. 73	min. -2.6, max. 2.5
[19]	slot	36~24	0.665~1.1,1.13,1.45~2.005,2.42~3.89	min. 59, max. 83	min. 1.2, max. 3.95
[20]	slot	46~20~1.6	2.4~2.5,4.9~5.725	min. 55, max. 90	min. -0.5, max. 3.29
Prop. work	slot	19.5×20	1.655~2.605	min. 76, max. 90	min. 2.46, max. 4.98

Table-I: Comparison of the proposed MIMO antenna system with other related works

Simulated Results					Measured Results				
f_s (GHz)	ECC ₁₂	PG (dBi)	% η	DG _{sim}	f_m (GHz)	ECC ₁₂	PG (dBi)	% η	DG _{mea}
1.67	0.105	2.8	80	9.92	1.67	0.113	2.46	76	9.95
1.84	0.0865	3.2	85	9.998	1.86	0.0823	2.9	79	9.9947
2.10	0.0631	3.86	88	9.923	1.99	0.0775	3.4	82	9.989
2.25	0.0723	4.4	92	9.985	2.26	0.0816	3.89	86	9.9841
2.5	0.0585	5.2	94	9.92	2.56	0.0678	4.98	90	9.915

Table II: ECC, Peak gain (PG) and efficiency (% η) and Diversity Gain (DG) values of the proposed antenna

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The simulated and measured reflection coefficient (S_{11}) curves of the given slot antenna design were computed as shown in Fig. 3. The frequency bands coverage was from 1655~2605 MHz with minimum -10 dB bandwidth (BW) of 25 MHz. The simulated and measured S_{11} are given in Fig. 3(a) and Fig. 3(b), respectively. A continuous variation in the resonating bands were obtained over the entire operational bands. The simulated results matched well with the measurements. The measured S_{11} show shows the frequency sweeps from 1655~2605 MHz with minimum -10 dB bandwidth of 27 MHz over the entire band. The simulated and measured isolation S_{12} curves are shown in Fig. 2(c) and 2(d), respectively, with worst case isolation values better than 15 dB over the entire operation bands of interest.

Fig. 3: S-parameters of curves (a) Simulated $|S_{11}|$ (b) Measured $|S_{11}|$ (c) Simulated $|S_{12}|$ (d) Measured $|S_{12}|$

For the proposed antenna design, the simulated and measured normalized 2-D pattern are given in Fig. 4(a)-4(d). Normalized gain patterns are the better representation of radiation characteristics and provide easy reference for looking at side lobe level (SLL), easy comparison of lobes etc. The total gain patterns for the given antenna elements 1 and 2 at 1.84 GHz are shown in Fig. 4(a) and Fig. 4(b), respectively. The curves are θ -cut at $\phi = 0^\circ$ and $\phi = 90^\circ$. Similarly, the normalized gain patterns at 2.56 GHz for both antenna elements are shown in Fig. 4(c) and Fig. 4(d). The tilt in the radiation patterns helped in lower field to enhance the MIMO performance metrics. The biasing circuit has very minimal effects on the gain of the antenna design. The radiating part is well isolated using the RF chokes from the voltage source.

The peak gain and efficiency ($\% \eta$) were also computed for the given slot antenna design. Both the simulated and measured values are given in Table-I. It has been observed that $\% \eta$ of the antenna is more than 76% while peak gain values were more 2.8 dBi over the given operation bands. To properly characterize the MIMO performance metrics, ECC diversity gain (DG) values were computed using far-field radiation patterns and are provided in Table-II.

Fig. 4: Simulated and measured 2-D gain pattern (a) Ant-1 at 1.86 GHz (b) Ant-2 at 1.86 GHz (c) Ant-1 at 2.56 GHz (d) Ant-2 at 2.56 GHz

Table II: ECC, Peak gain (PG) and efficiency ($\% \eta$) and Diversity Gain (DG) values of the proposed antenna

5. CONCLUSIONS

A low profile, modified pentagonal shaped FR MIMO antenna design is presented for small cell devices with DSS in 5G technologies. The proposed narrow-band MIMO antenna design with-band tunability covered frequency bands from 1655~2605 MHz. A simple varactor diode per antenna element was utilized to achieve this wide-band configuration. Two modified pentagonal slot antenna based elements were etched out from GND plan with single element dimensions of $19.5 \times 20 \text{ mm}^2$. The given antenna design is a narrow-band design suitable to be used as RF front-end in the 5G enabled DSS in cognitive radio (CR) applications.

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