Frequency Reconfigurable Antenna Array for MM-Wave 5G Mobile Handsets

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Abstract. This study proposes a compact design of frequency-reconfigurable antenna array for fifth generation (5G) cellular networks. Eight compact discrete-fed slot antennas are placed on the top portion of a mobile phone printed-circuit-board (PCB) to form a beam-steerable array. The frequency response of the antenna can be reconfigured to operate at either 28 GHz or 38 GHz, two of the candidate frequency bands for millimeter-wave (MM-Wave) 5G communications. The reconfigurability function of the proposed design can be achieved by implementing and biasing a pair of diodes across each T-shaped slot antenna element. Rogers RT 5880 with thickness of 0.508 mm and properties of $\varepsilon = 2.2$ and $\delta = 0.0009$ has been used as the antenna substrate. The antenna element is very compact in size with a good end-fire radiation pattern in the frequency bands of interest. The proposed beam-steerable array provides very good 3D coverage. The simulation results show that the proposed design provides some good characteristics fitting the need of the 5G cellular communications.

Keywords: 5G antenna · Cellular communications · Future networks Reconfigurable antenna · Slot antenna

1 Introduction

The evolution from the current generation of cellular communications to the future generation (5G) is mainly driven by the growing need for higher data rate communications in different applications [1, 2]. Different from the design of antennas for the fourth generation (4G) cellular networks, antenna designs for the future wireless systems at higher frequencies (beyond 10 GHz) would face more challenges and needs more requirements [3, 4]. One example of the requirements for the 5G antennas is the reconfigurability function, where the same antenna is used for different modes such as diversity or cognitive radio (CR) communications. Many antenna designs with reconfigurability function are available for radar or space applications [5–7]. However, those designs cannot be directly adopted for mobile communications, which has

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different requirements. To address this need, this paper presents a frequency-reconfigurable antenna array that can operate at both 28 and 38 GHz (promising 5G candidate bands) for cellular communications.

The proposed array contains eight slot antenna elements placed on the top of a mobile-phone PCB. The array is compact in size and provides good beam steering characteristics suitable for future mobile terminals. The overall size of the antenna is 60×120 mm^2. Simulations have been done using CST software [8] to validate the feasibility of the proposed frequency reconfigurable-phased array antenna for MM-Wave 5G handset applications. This paper is structured as follows: The configuration of the proposed reconfigurable 5G mobile phone antenna is described in Sect. 2. Section 3 discusses the S-parameters and radiation performances of both the single element and the final design. The final section presents the conclusions of this study.

2 The Proposed Design Configuration

The configuration of the proposed frequency-reconfigurable 5G handset antenna is shown in Fig. 1. As illustrated, eight low-profile T-shaped slot antenna elements are employed on the top portion of the mobile phone PCB. Another set of the proposed beam steerable array could be used at the other side of the PCB to cover the other 3D half-space. It can be seen that the proposed 5G array is compact in size with dimensions 39.8×3.25 mm^2. Furthermore, there is enough space in the proposed mobile phone antenna to include 3G and 4G MIMO antennas. The antenna is designed on a Rogers RT5880 substrate with thickness (h), dielectric constant (ε_r), and loss tangent (δ) of 0.508 mm, 2.2, and 0.0009, respectively.

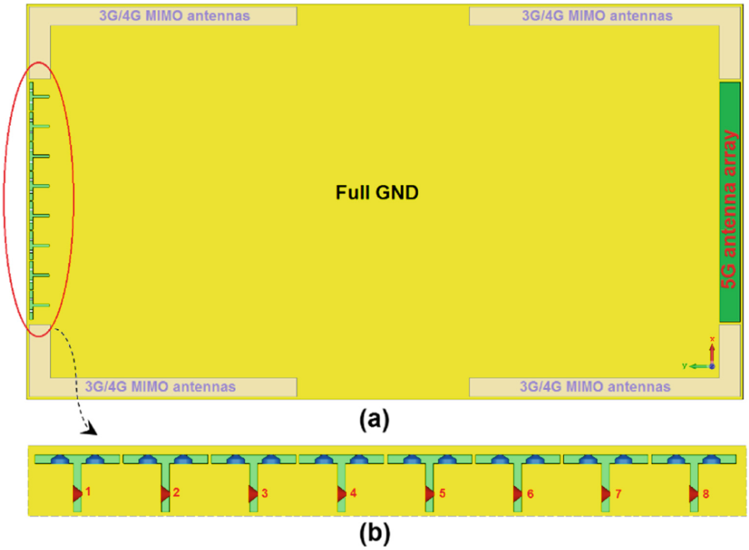

Fig. 1. (a) Configuration of the proposed reconfigurable 5G antenna and (b) its array schematic.

3 Results

3.1 Single Element Reconfigurable 5G Antenna

The configuration of the single element frequency-reconfigurable antenna is illustrated in Fig. 2(a). The antenna element is compact, with size of 3.25 × 4.8 mm^2. The optimal dimensions of the designed antenna are as follows: W = 4.8 mm, L = 2.75 mm, W_1 = 0.45 mm, L_1 = 0.5 mm, W_2 = 0.4 mm, L_2 = 1 mm, and x = 0.675 mm. As illustrated in Fig. 2(a), a pair of active elements (diode switches) across the T-shaped slot can be used to effectively change the dimension of the radiator. As a result, a reconfigurable dual band operation can be achieved. Figure 2(b) depicts the model of the diode. The parameters of an AlGaAs beam-lead PIN Diode (MA4AGBL912) including R = 4–4.9 Ω, C = 26–30 fF, L = 0.5 H (suitable for use up to 40 GHz) have been employed in the simulation of the active element [9]. S_{11} results of the antenna for different switching conditions are shown in Fig. 2(c). It can be seen that the −10 dB impedance bandwidth of the antenna is switchable to operate in frequency bands of 28 GHz and 38 GHz.

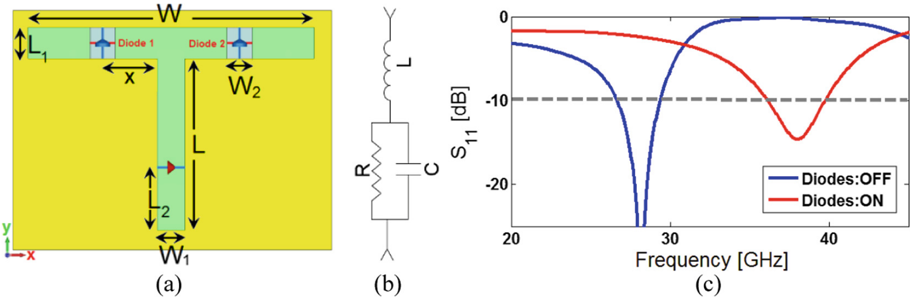

Fig. 2. (a) Single element antenna schematic, (b) diode model, and (c) S_{11} results.

The current distributions for the presented antenna at its resonance frequencies (28 GHz and 38 GHz) are illustrated in Fig. 3. It can be observed that the current flows are more dominant around the edge of the main T-shaped slot at 28 GHz. At 38 GHz, most of the current flows are around the smaller T-shape (created by the ON condition of the diodes), which explains the resonant frequency shifting of the antenna [10].

Figures 4(a), (b), and (c) illustrate the S_{11} characteristics of the proposed design for different values of *W* (slot size), *x* (placement of the diodes), and L_2 (feeding point). As shown, the antenna operation frequency varies with each of these different parameters. Based on the obtained results, it can be seen that the antenna operation frequency can be easily tuned to a desired frequency.

The 3D radiation patterns of the antenna and its fundamental properties in terms of total efficiency and directivity are investigated in Fig. 5(a) and (b). As can be seen, the antenna has desirable radiation performance and sufficient end-fire mode at 28 and 38 GHz. Based on the obtained results from Fig. 5(c) the total efficiency of the proposed reconfigurable antenna is more than −0.1 dB with good maximum gain values in the bands of interest.

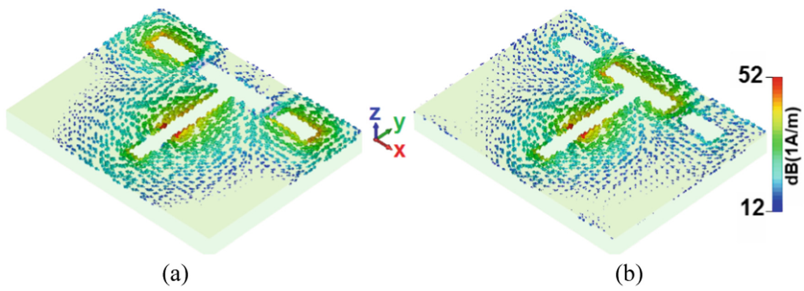

Fig. 3. Current distribution of the proposed antenna at, (a) 28 GHz and (b) 38 GHz.

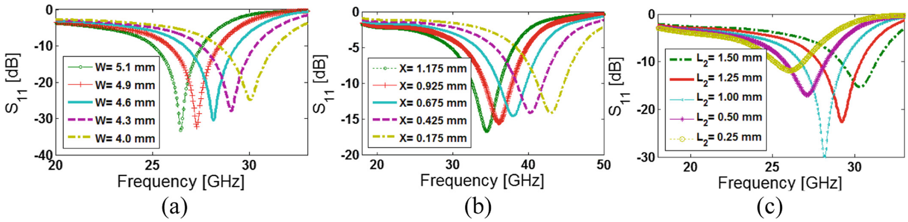

Fig. 4. S_{11} characteristics of the antenna for different values of (a) W, (b) x, and (c) L_2.

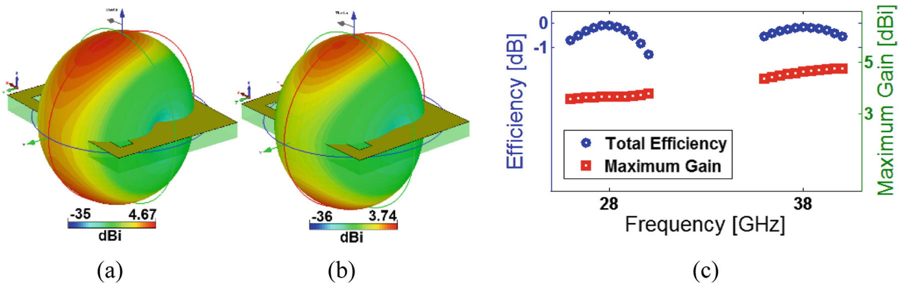

Fig. 5. (a) Radiation pattern at 28 GHz and (b) at 38 GHz, (c) fundamental properties.

3.2 Radiation Properties of the Proposed Design

The proposed array antenna is designed using eight T-shaped reconfigurable antennas. Figure 6(a) illustrates the configuration of the linear array. The array is compact, with size $W_a \times L_a = 39.8 \times 3.25\ mm^2$. The antenna element are arranged with a separation of d = 5 mm. It should be notice that in order to achieve the higher scanning angles, the distance between adjacent sources is less than λ/2 of 28 GHz. Figures 6(b) and (c) show the S parameters (S_{11} to S_{81}) of the array for different conditions of the employed active elements (ON/OFF conditions) at 28 and 38 GHz. It can be seen that the array has good impedance matching with more than 2 GHz bandwidth at 28 GHz, and 4 GHz at 38 GHz. Furthermore, as illustrated, mutual coupling characteristics of less than −13 dB are obtained for the bands of interest.

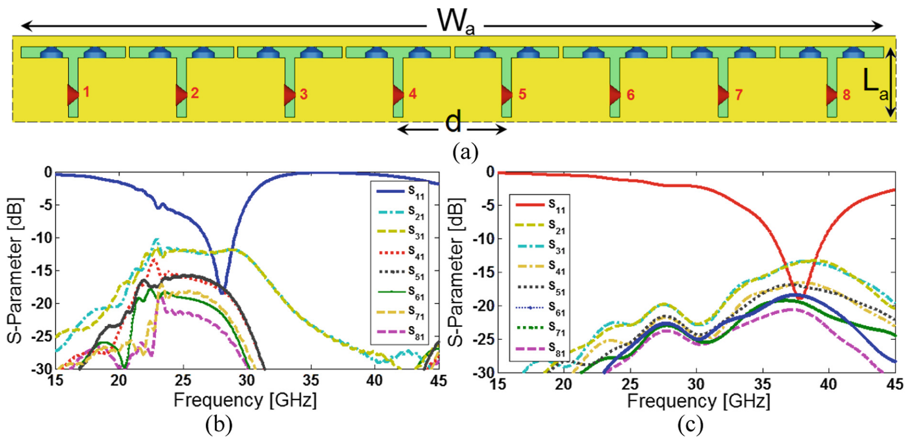

Fig. 6. (a) Array Configuration, (a) S-parameters at 28 GHz (diodes: OFF) and (c) S-parameters at 38 GHz (diodes: ON).

The 3D directional radiation beams of the proposed antenna at 28 GHz for 0°, 30°, 60°, and 80° scanning angle are illustrated in Fig. 7, showing that the proposed reconfigurable antenna array provides wide-angle scanning characteristics with a symmetrical end-fire mode. It has also sufficient values of realized gain [11].

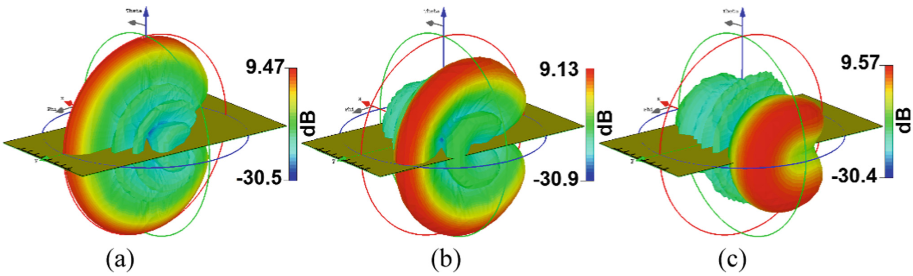

Fig. 7. 3D directional radiation beams for 28 GHz at (a) 0°, (b) 30°, and (c) 60°.

The analysis and performance of the antenna beams are obtained using CST software. The shape and direction of the array beams are determined by relative phases amplitudes applied to each radiating element as below:

$$\varphi = 2\pi(d/\lambda)\sin\theta \tag{1}$$

Where d is the distance between elements, λ is the wavelength of the desired frequency, and θ is the scanning angle. In order to see the radiation beams at different scanning angles, the phase shift between adjacent sources must be calculated according to Eq. (1). The next step is applying the calculated Phased-Shifting with same values of amplitude = 1 for each element. In order to understand the phenomenon behind this process, the phases shifting for different angles are listed in Table 1. The calculated φ for 0°, 30°, and 60° are about 0, 85, and 145, respectively.

Table 1. Required phase shifting for different scanning angles

φ	Port 1	Port 2	Port 3	Port 4	Port 5	Port 6	Port 7	Port 8
0	0	0	0 × 2	0 × 3	0 × 4	0 × 5	0 × 6	0 × 7
30	0	85	85 × 2	85 × 3	85 × 4	85 × 5	85 × 6	85 × 7
60	0	145	145 × 2	145 × 3	145 × 4	145 × 5	145 × 6	145 × 7

2D radiation patterns of the proposed antenna array with realized gain values over wide scanning angles are illustrated in Fig. 8. As can be seen, the antenna provide a very good beam steering with acceptable realized gain values for minus/plus scanning angles.

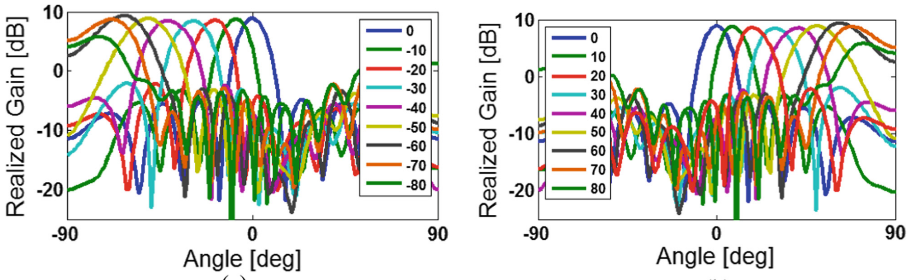

Fig. 8. Beam-steering characteristics of the design for (a) minus and (b) plus scanning angles.

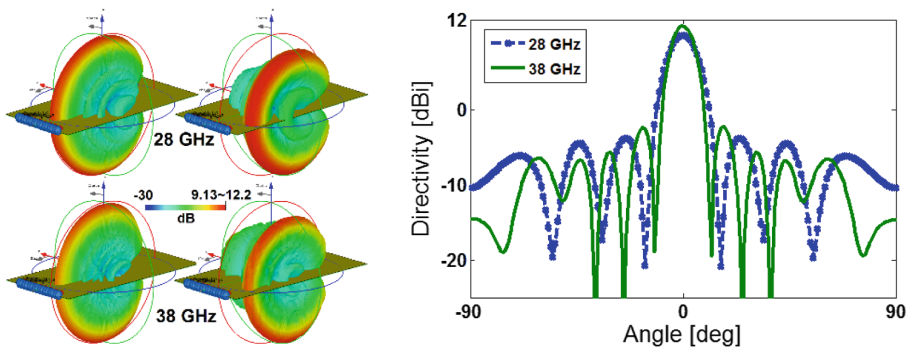

Fig. 9. (a) Beam-steering characteristics of the antenna at different frequencies and (b) directivities of the proposed antenna at 0°.

Figure 9 represents the 3D radiation beams of the proposed reconfigurable array (with directivity values) at 28 and 38 GHz: the antenna has good radiation behaviour in both of the 5G candidate bands. As mentioned above, the employed array has very similar performance with sufficient gain values at different frequencies. The simulated 2D directivity characteristics of the proposed frequency reconfigurable antenna at 0° are illustrated in Fig. 9(b). As can be seen, for the proposed design at 28/38 GHz, more than 10 dBi directivities with low side lobes have been obtained.

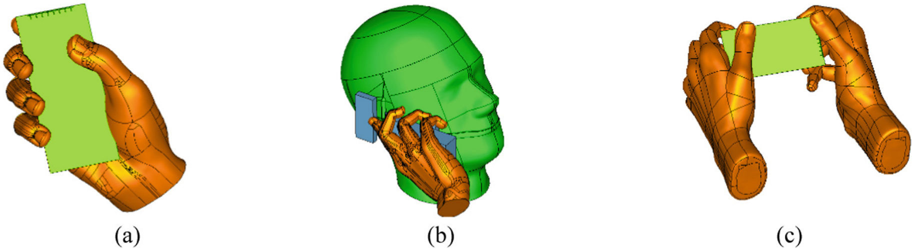

Fig. 10. (a) Data-mode, (b) talk-mode, and (c) double-hand.

4 Conclusion

The motivation of this paper is to design a new frequency reconfigurable antenna for 5G cellular communications. The antenna element is composed of a T-shaped slot radiator with a pair of active elements for switching. The operation frequency of the proposed antenna can be switched to work at 28 and 38 GHz. Using eight elements of the antenna, performance of a mobile-phone antenna array has been investigated and good results are obtained.

The employed array antenna has a compact size and is suitable for handset applications. Due to the importance of the user effect on the antenna performance and also the specific absorption rate (SAR) effects of the antenna on the human body [12] (as illustrated in Fig. 10), investigation on these parameters could be a suitable topic for further work.

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