Chapter

New Radiation Pattern-Reconfigurable 60-GHz Antenna for 5G Communications

Yasir I.A. Al-Yasir, Hasanain A.H. Al-Behadili,
Baha A. Sawadi, Naser Ojaroudi Parchin,
Ahmed M. Abdulkhaleq, Abdulkareem S. Abdullah
and Raed A. Abd-Alhameed

Abstract

Reconfigurable beam steering using circular disc microstrip patch antenna with a ring slot is proposed. The overall dimension of the antenna is 5.4 × 5.4 mm^2 printed on 0.504 mm thick, RT5870 substrate with relative permittivity 2.3 and loss tangent 0.0012. The designed antenna operates at the expected 60 GHz 5G frequency band with a central coaxial probe feed. Two NMOS switches are utilized to generate three different beam patterns. Activating each switch individually results in a 70° shift in the main beam direction with constant frequency characteristics. The power gain is 3.9–4.8 dB in the three states of switch configurations. Simulated results in terms of return loss, peak gains and radiation pattern are presented and show good performance at the expected 60 GHz band for 5G applications.

Keywords: beam steering, 5G antennas, microstrip antennas, NMOS, reconfigurable antennas

1. Introduction

Ideally, reconfigurable antennas must be able to change their operating frequency, polarization and radiation pattern independently to provide varying operating requirements [1]. Moreover, the progress of these antennas faces significant challenges to both antenna modelling and system designer. However, these challenges will come not only from the antenna design only but also from the surrounding technologies that enable reconfigurability [2–5].

Nowadays, there exist extensive research areas covering reconfigurable antennas usually that concerned on the design and the technological perspectives. Radiation pattern and polarization-reconfigurable antennas are also very attractive topics because they can provide various characteristics which lead to a better signal to noise ratio (SNR) as well as higher quality of service (QoS) of the whole systems.

Recently, theoretical and measurement results of 5G communications operating at mmWave were studied and discussed [6, 7]. In [7], the researchers presented and designed the unprecedented hardware challenges and essential design considerations concerned with the antenna system methodology for future communications. The designed antenna provides a good and useful isotropic radiated power with minimum loses for practical use in 5G cellular communications.

In modern wireless communications systems, antennas may be required to have several angles of the main beams, and one of the methods to achieve this property is using multiple elements of a single antenna in array forms to make pattern diversity [6]. Pattern diversity of an array can be accomplished by setting the so-called array factor [7]. However, mutual coupling between antenna elements in array antennas has a significant effect on wireless radio links, causing undesirable effects on system performance. Thus, one of the efficient methods to overcoming these drawbacks is using radiation pattern-reconfigurable antennas. These antennas can diverse the main lobe direction or null direction at specific angles. In addition, it provides a wider coverage area with less interference and noise signals by controlling the main beam locations.

Generally, PIN diodes [8–10] and RF-MEMS [10, 11] are used as switching elements in order to alter the antenna radiation patterns. In [9], pattern and frequency reconfigurable annular slot antenna were presented. Matching stubs are used to achieve a planar antenna operating with three different frequencies, 5.2, 6.4 and 5.8 GHz. PIN diodes are used as switches to activate or deactivate the stubs, creating a reconfigurable matching network. In [12], the author explained the integration of the radio frequency microelectromechanical system (RF MEMS) switches with radiation pattern-reconfigurable antennas. In another design [13], a radiation pattern switchable parasitic array antenna at 60 GHz band was proposed. NMOS transistor switches are used to alter the main beam direction of the antenna with a constant frequency. Beam scanning angle of this antenna can deviate at $\pm 56^{\circ}$.

However, the radiation pattern-reconfigurable antenna must be able to alter its radiation pattern without a significant change in other characteristics such as operating frequency, impedance bandwidths, and polarizations, which can be considered as the first challenge facing the designers of the radiation pattern-reconfigurable antenna [1]. There are another two challenges for the simulation tool necessary to modelling the reconfigurable antennas [14]:

1. Modelling the switch requires a new design technology considering all the switch characteristics. Where the practical switches may have different properties and factors to be considered to get more agreement between the simulation and measurement performance.

2. The same antenna with multiple operating configurations, all of them might affect the performance of the others, must be designed and optimized simultaneously. Thus, a single structure has to be modelled to perform all different state of operations, and this involves a professional simulation technology.

The main difference between the present article, and that of other researchers dealing with reconfigurable planar antennas, is that a new design technique is used to simulate, modelling and optimize the structures, leading to a reconfigurable radiation pattern with constant impedance bandwidth and polarization characteristics at mmWave spectrum.

The work presented here introduces a new pattern-reconfigurable planar circular disk microstrip antenna capable of controlling the main beam direction using two NMOS switches. The design investigations initiate from a conventional disk antenna with a ring slot. The operational configurations are achieved through independently controllable switches, in which, each one of them is implemented as an

NMOS switch. The designed antenna alters the radiation pattern according to three switch combinations, which can alternate the main beam into three different radiation angles. The proposed antenna is printed on the top of a 0.504 mm thickness of Roger RT5870 substrate with relative permittivity 2.3 and loss tangent 0.0012 of size 5.4 × 5.4 mm^2. The radiation pattern of the designed antenna alters about 70° in yz-plane at 60 GHz frequency. CST studio simulation software [15] is used to optimize antenna and simulate the design, with hybrid co-simulation between CST MWS and CST DS used to implement the designed antenna taking into account the SPICE model for the NMOS switch and the effect of the biasing circuit.

2. Radiation pattern-reconfigurable antenna application

The range of wireless communication technologies that have emerged in the last two decades is immense. Nowadays, the tendency is to study new methods of integration and interoperability between devices. The electronics for wireless devices are being designed in the perspective of shrinking and group multiple functions in one single integrated circuit; also, the software and firmware on the processing units are being developed to be faster and less energy consuming. Besides streamlining the electronics and processing techniques, one can do improvements in the radio interface, namely in the antennas [16].

There are already different solutions to address the interoperability capabilities of the antennas. From multi-band antennas to wideband and ultra-wideband antennas, many approaches have been presented in the past years. However, this type of antennas has some disadvantages. Multi-band antennas are not versatile, they are difficult to design and not always present a good performance for all the bands, besides, and most of them are not very small, which can arouse size concerns. Ultra-wideband antennas can cover very large frequency bandwidths with seeming performance, however, this performance is not good for any particular band, which leads to low moderate gains and they are quite large as well [17].

Another way to achieve versatility is with the application of reconfigurable antennas, which allow reducing the number of antennas present in a given device, ensuring the interoperability between systems. However, this can also be integrated with more complex systems such as MIMO (multiple-input multiple-output) and/or cognitive radio systems, also known as SDR (Software Defined Radio) [18, 19]. The concept of antenna selection in MIMO systems may be explored in terms of reconfigurable antenna elements as shown in **Figure 1**. The complexity in terms of feed chains is less for the reconfigurable setup with a reduced number of antenna elements. The different configurations of the reconfigurable antennas give the antenna array a more possible option than with a conventional two-element array.

Reconfigurability allows an antenna to adapt in real time different parameters like the resonant frequency, the polarization or even the radiation pattern to some extent. These are extremely useful features for mobile devices when considering the expansion of the different communication systems in the near future. Given the versatility and advantages these antennas can provide for new wireless devices, these have been subject of much attention in the investigation field in the past few years and there are already many different solutions presented to acquire different reconfigurability to different systems. Reconfigurable antennas are designed to be implemented on various platforms which cover various wireless services that are spanned over a wide frequency range. In particular, reconfigurable antennas are proposed for higher efficiencies in various implementations that involve cognition and continuous adaptation to the environment such as in cognitive radio and MIMO systems.

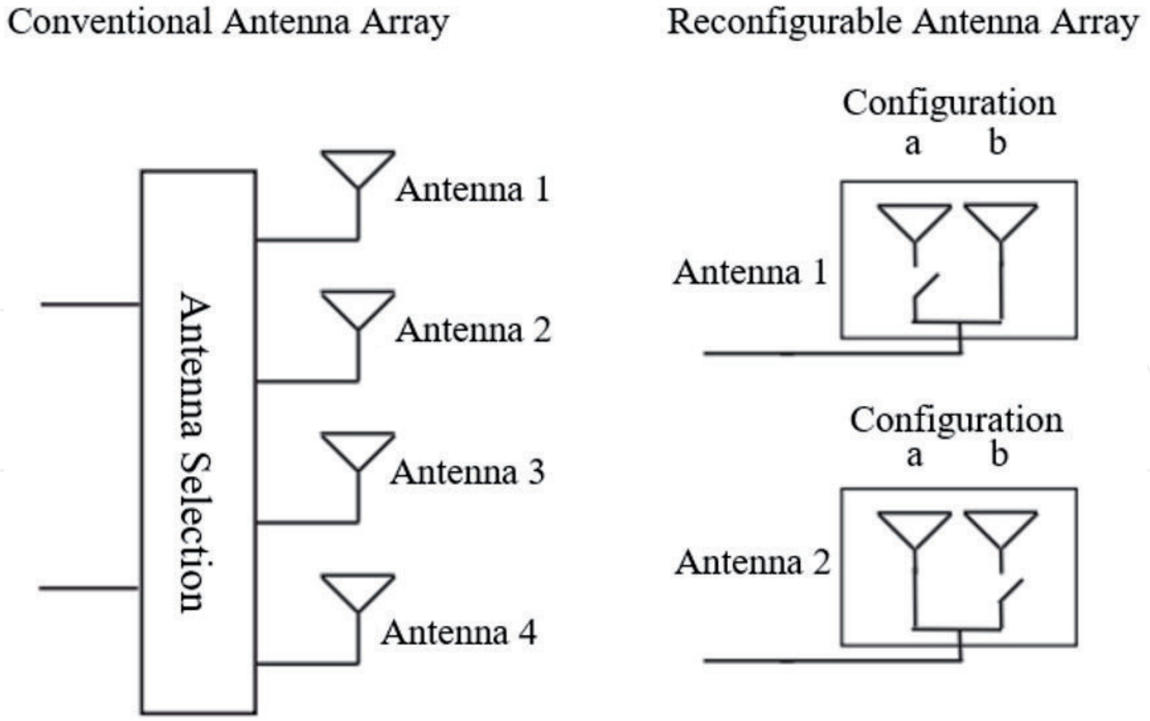

Figure 1.
Block diagram representing a MIMO antenna array with conventional antenna elements (left) and reconfigurable antenna elements (right).

A MIMO system employs multiple antennas at both the transmitter and the receiver frontends. The advantage of using such configurations is that different information can be sent simultaneously, thereby increasing the communication spectral efficiency in a multipath environment. According to the varying channel conditions and user's need, a MIMO system can adjust the modulation level, coding rate, and the transmission signalling schemes. Radiation pattern/polarization reconfigurable antennas add an additional degree of freedom in a MIMO environment and thus improve the system performance. The use of this type of antennas increases the capacity significantly by allowing the selection between different pattern diversity and polarization configurations. Reconfigurable antennas can also be used in modern space applications. In such cases, it is required to be able to reconfigure the antenna radiation pattern to serve a new coverage zone, limit fading in rainy areas, and maintain high data rate at as many frequency bands as possible [20].

Most of the advanced wireless communications' applications (cognitive radio, MIMO, Space communications) require highly efficient software controlled dynamic antennas. These antennas that can be reconfigured using software and based on users' requests have to be highly reliable as well as able to achieve the required functions. Therefore, an antenna designer proposing a new reconfigurable antenna design for an advanced application has to present a design that has minimal losses in its structure and operation. The antenna has to exhibit software accessibility as well as be able to be controlled using programmable controllers. Most importantly, a designer must ensure that the proposed antenna is able to operate under unforeseen circumstances continuously; thus, a reliability study is required from reconfigurable antenna designers.

3. Radiation pattern-reconfigurable antenna design

The first step is to design the antenna without the inclusion of reconfiguring property. This achieved by designing a circular patch antenna, by adopting

Rogers RT5870 as the dielectric substrate with h = 0.504 mm, $\varepsilon_r = 2.3$, tangent loss = 0.0012, and $L_{sub} = W_{sub} = 5.4$ mm. The antenna is designed and optimized to operate at a particular frequency of 60 GHz. This frequency is chosen because it is suitable and widely used in 5G applications. Other than the rectangular patch, the configuration used in this paper is the circular patch or disk, as shown in **Figure 2**, where R represents the actual disk radius. Based on the cavity model formulation [9], a design procedure is outlined which leads to practical designs of circular microstrip antennas for the dominant TM_{110}^{z} mode.

The procedure is as follows:

The actual radius of the patch (R) at the resonant frequency f_0 can be calculated as [9]:

$$f_0 = \frac{1.8412 \times C}{2\pi R\sqrt{\varepsilon_r}} \tag{1}$$

where C is the speed of light in free-space?

The resonant frequency of Eq. (1) does not take into account the fringing effect. Therefore, for the circular patch, a correction is introduced by using an effective radius R_e, to replace the actual radius R as:

$$R_e = R\left\{1 + \frac{2h}{\pi\varepsilon_r h}\left[ln\left(\frac{\pi R}{2h}\right) + 1.7726\right]\right\}^{1/2} \tag{2}$$

Thus, the resonant frequency of Eq. (1) should be modified by using Eq. (2) and expressed as:

$$f_0 = \frac{1.8412 \times C}{2\pi R_e\sqrt{\varepsilon_r}} \tag{3}$$

Then, a first-order approximation to the solution of Eq. (2) for R is given by:

$$R = \frac{F}{\left\{1 + \frac{2h}{\pi\varepsilon_r F}\left[ln\left(\frac{\pi F}{2h}\right) + 1.7726\right]\right\}^{1/2}} \tag{4}$$

where,

$$F = \frac{8.791 \times 10^9}{f_0\sqrt{\varepsilon_r}} \tag{5}$$

Figure 3 shows the schematic diagram of the proposed antenna. An annular slot ring circular disk planer antenna is designed. The feeding network used here

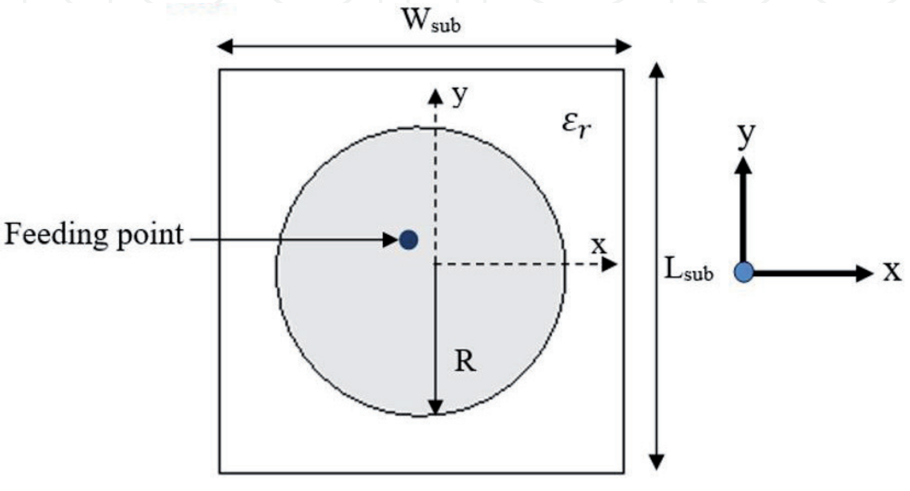

Figure 2.
Circular patch antenna.

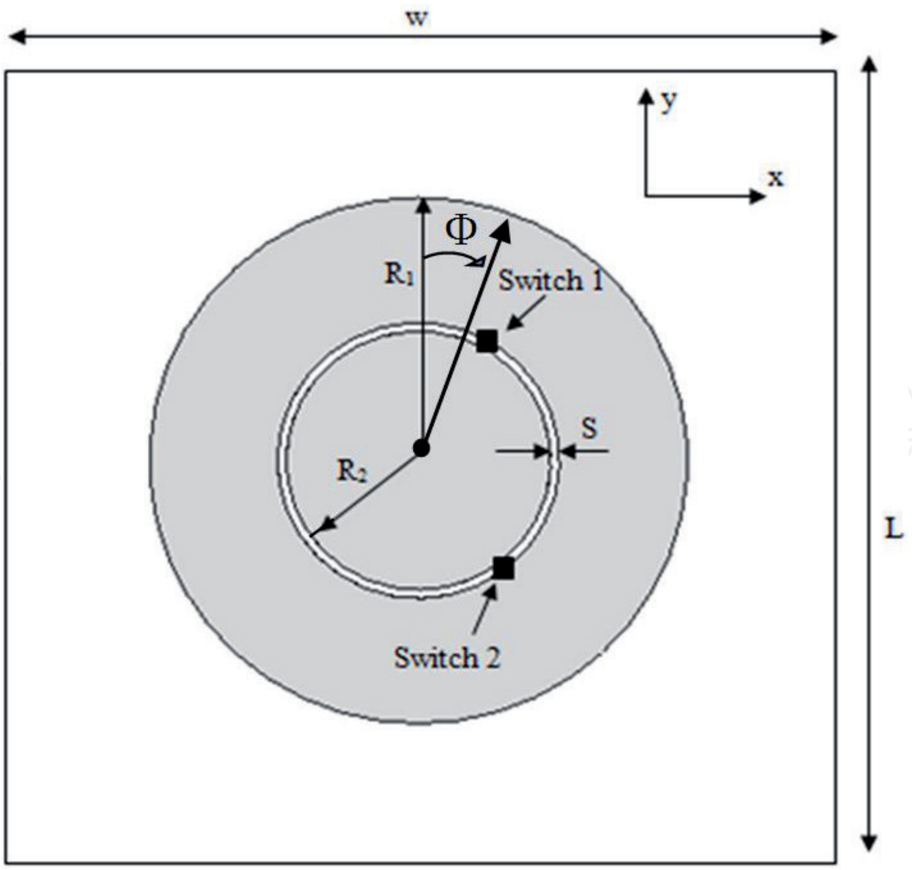

Figure 3.
The geometry structure of the proposed antenna.

W (mm)	L (mm)	S (mm)	R_1 (mm)	R_2 (mm)
5.4	5.4	0.06	1.85	0.91

Table 1.
Detailed dimensions of designed antenna shown in ***Figure 3****.*

is a coaxial probe with a radius equal to 0.07 mm. The circular disk has an outer radius R_1 = 1.85 mm and the inner radius R_2 = 0.91 mm. Detailed dimensions of the proposed antenna are shown in **Table 1**. The dimensions of this antenna are optimized to operate at the resonance frequency 60 GHz to cover 2 GHz bandwidth with a return loss less than 10 dB.

4. Parametric study and a hybrid EM-circuit co-simulation

In this section, the influences of various positions of the switches on both the response and radiation pattern of the designed antennas are discussed. Firstly, the switches are modelled as a metal tab that is represented by the ideal state of the switches. The metal tab is rotated along the slot ring of the antenna by an angle φ (φ = 00, 300, 1500, 1800). In addition, both the return loss and radiation pattern are observed. **Figure 4** shows the simulated reflection coefficient as a function of frequency for various sweep angles of φ. As the position of the switch is shifted, the resonance frequency of the antenna changes slightly around 60 GHz. In fact, this frequency shifting can be neglected since the resonance bandwidth around 60 GHz is kept unaffected. On the other hand, the effect of the parameter sweep on the radiation pattern in the yz-plane is studied and presented in **Figure 5**. It is clear that the reconfigurable property is achieved at two important and symmetrical angles (φ = 30 and 150°) along yz-plane.

Secondly, two NMOS transistor are used as switches to replacing the metal tab, in which, switch 1 is located at a position shifted by (φ = 30°) from the y-axis, whenever the switch 2 is shifted by (φ = 150°) from the y-axis. It should be noted that by using the computer simulation technology (CST), the NMOS transistor switches are modelled with a lumped element network with R_{on} = 10.2 Ω, C_{on} = 47.1 pF, R_{off} = 13.3 MΩ, C_{off} = 39 pF as shown in **Figure 6**. The figure shows the equivalent circuit for the switches in the ON and OFF states.

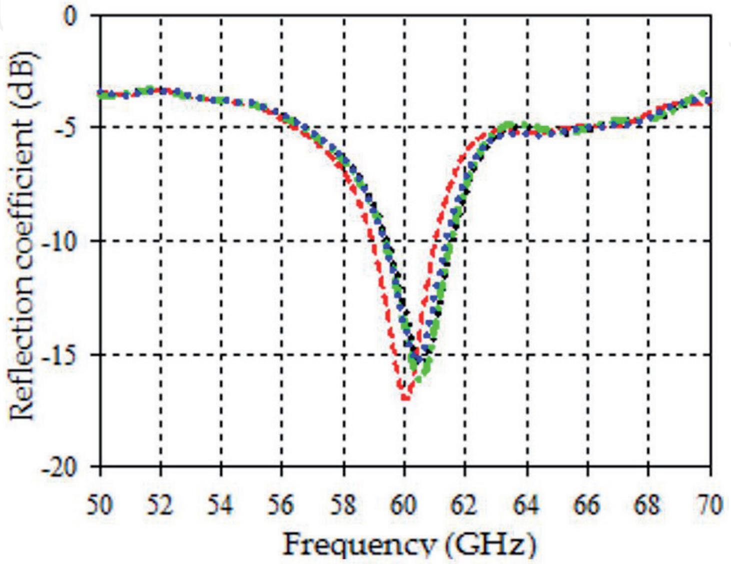

Figure 4.
The frequency response of the input reflection coefficient for different angles of φ using the metal tab as a switch (φ = 0: dotted line, φ =30: solid line, φ = 150: dashed line and φ = 180: dotted/dashed line).

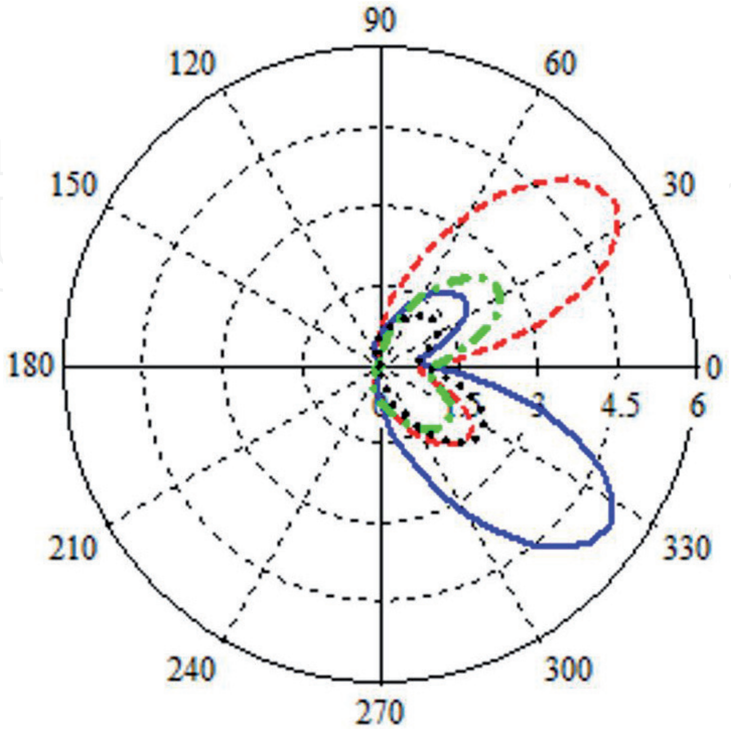

Figure 5.
Radiation pattern at yz-plane for different angles of φ using the metal tab as a switch (φ = 0: dotted line, φ =30: solid line, φ = 150: dashed line and φ = 180: dotted/dashed line).

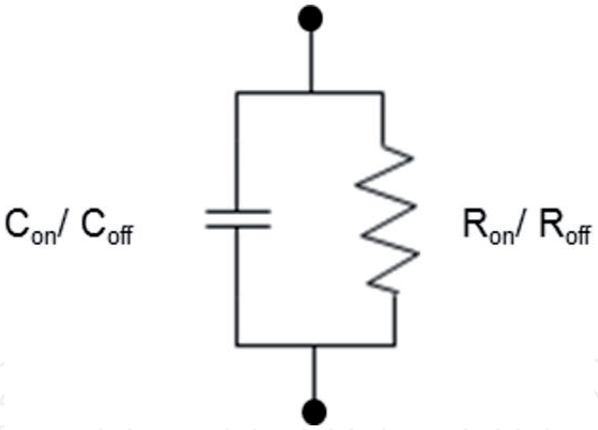

Figure 6.
Simplified electrical model of the NMOS transistor switch in ON and OFF states.

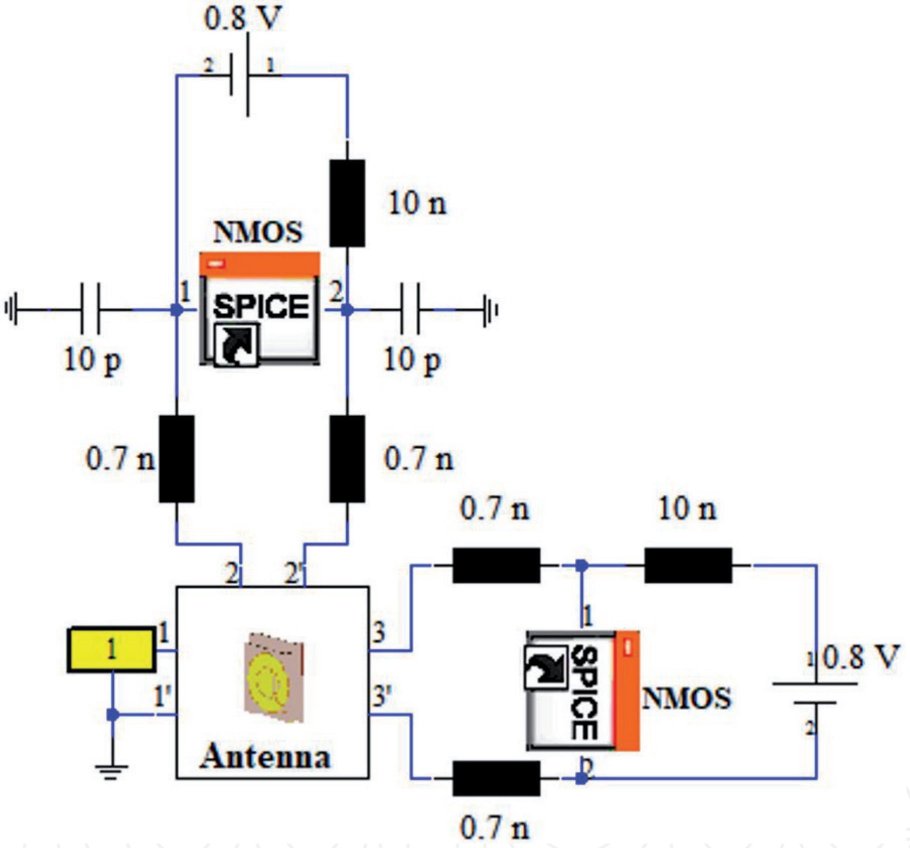

Figure 7.
A hybrid EM-circuit co-simulation of the antenna.

Finally, the co-simulation between CST MWS and CST DS for the designed radiation pattern-reconfigurable antenna are modelled and achieved, as shown in **Figure 7**. The simulation takes into account the spice model for the NMOS switches. The manufacturer-specified parasitic inductance and capacitance of the packaging are included as well.

5. Simulation results

The simulation results achieved by the CST microwave studio software. The performances of the proposed antenna, in terms of return losses, radiation patterns, efficiencies and gains, with different states of switches have been studied as follows:

5.1 Impedance bandwidth for S11 < −10 dB

Figure 8 shows the simulated results for the designed antenna. It is clear that (SW1 ON, SW2 OFF) state has −18 dB reflection coefficients at resonance frequency 60 GHz with impedance bandwidth of 3.4%. In (SW1 OFF, SW2 ON) state, the reflection coefficient is −16 dB at 61 GHz resonance frequency, with corresponding impedance bandwidth of 3.3%. Whenever, in (SW1 ON, SW2 ON) state, S_{11} is equal to −30 dB at 60.8 GHz resonance frequency, with impedance bandwidth 5.7%. The main difficulty of the designing of radiation pattern-reconfigurable antenna is that this type of reconfigurability must be accomplished without significant changes in the impedance or frequency characteristics. The achieved results overcome this difficulty by maintaining a single resonance frequency for all states of configurations.

5.2 Radiation patterns and directivities

Figures 9–11 show the simulated radiation patterns at 60 GHz in the yz-plane (E-plane). When the proposed antenna operates at (SW1 ON, SW2 OFF) state, the beam's maximal direction in the yz-plane is 35°. At (SW1 OFF, SW2 ON) state, the beam's maximal direction in the yz-plane is -35°. At (SW1 ON, SW2 ON) state, the beam's maximal direction in the yz-plane in $(35, -35^{\circ})$. ("+" indicates that the radiation pattern tilts toward the positive y-axis and "-" indicates that the radiation pattern tilts toward the negative y-axis).

As a result, the radiation patterns of the proposed antenna operating at different switching states can divers by 70° shifted along yz-plane (E-Plane). Due to the symmetry characteristics on both the antenna structure and switches positions, the single main beam direction can be altered symmetrically around the z-axis in the yz-plane as shown in **Figures 9–11**. **Figures 12–14** show the 3D simulation results for beam directivities, which correspond to the three configurations of the switches in both ON and OFF states.

5.3 Antenna gains and efficiencies

Simulation results for the realized gains of the proposed antenna as a function of frequency are shown in **Figure 15**. Simulated maximum realized gain at (SW1 ON, SW2

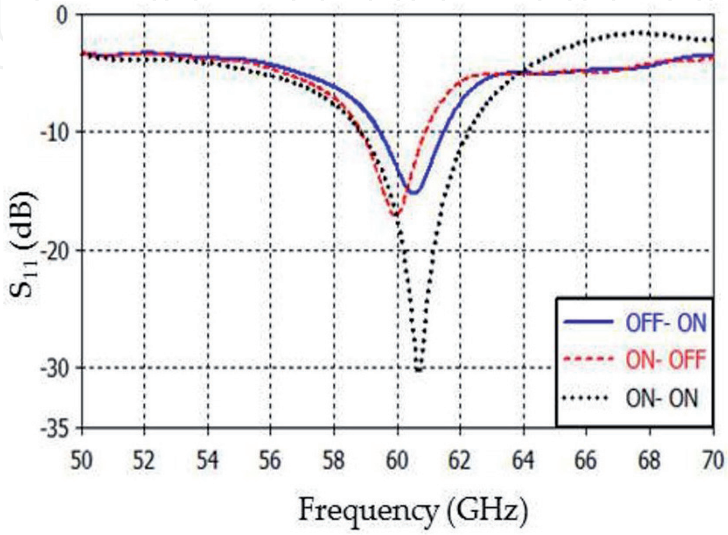

Figure 8.
Simulation results for the proposed antenna for different states of switching.

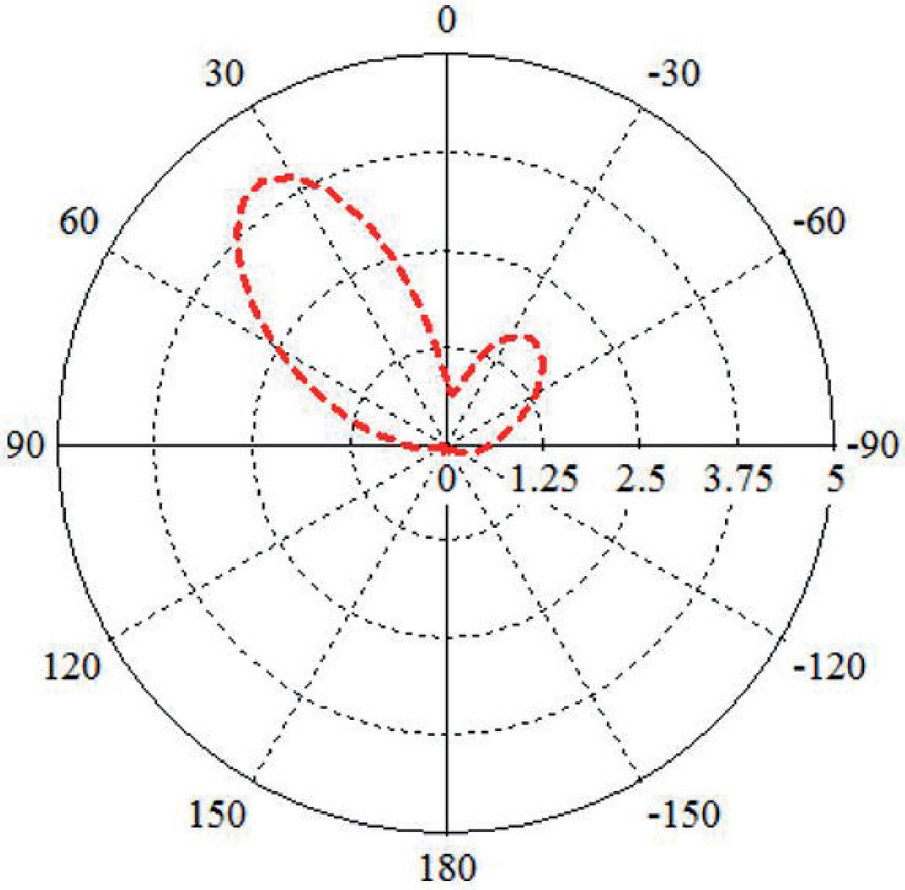

Figure 9.
Radiation pattern at yz-plane in the ON-OFF state.

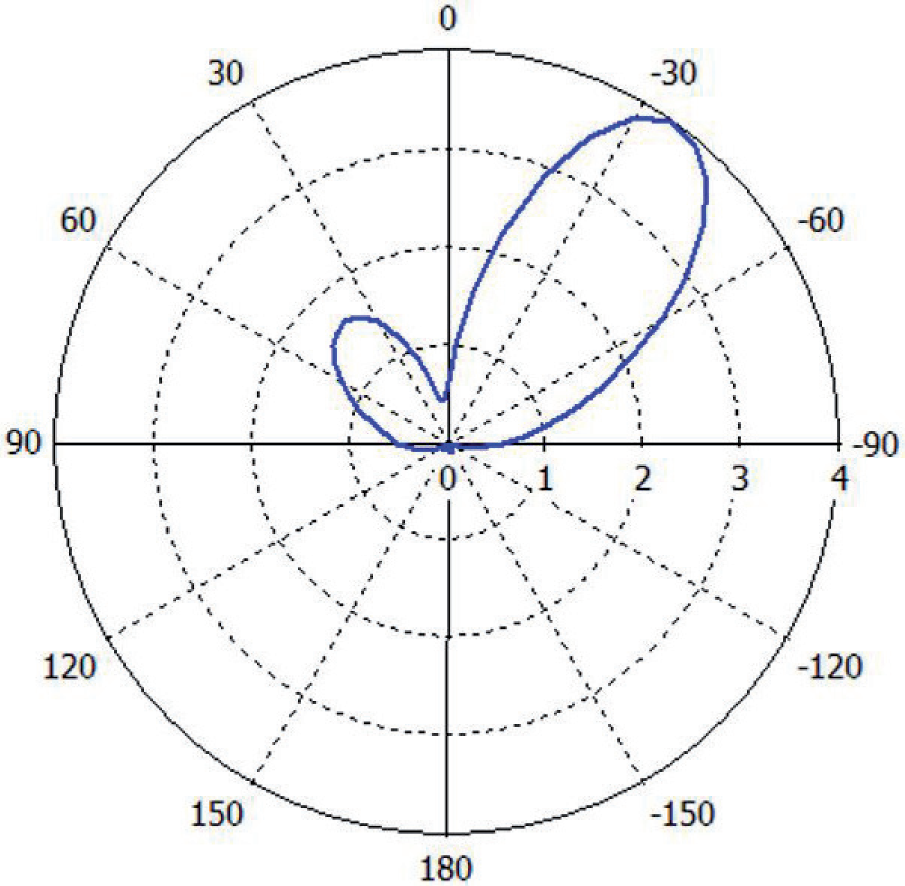

Figure 10.
The radiation pattern at yz-plane in the OFF-ON state.

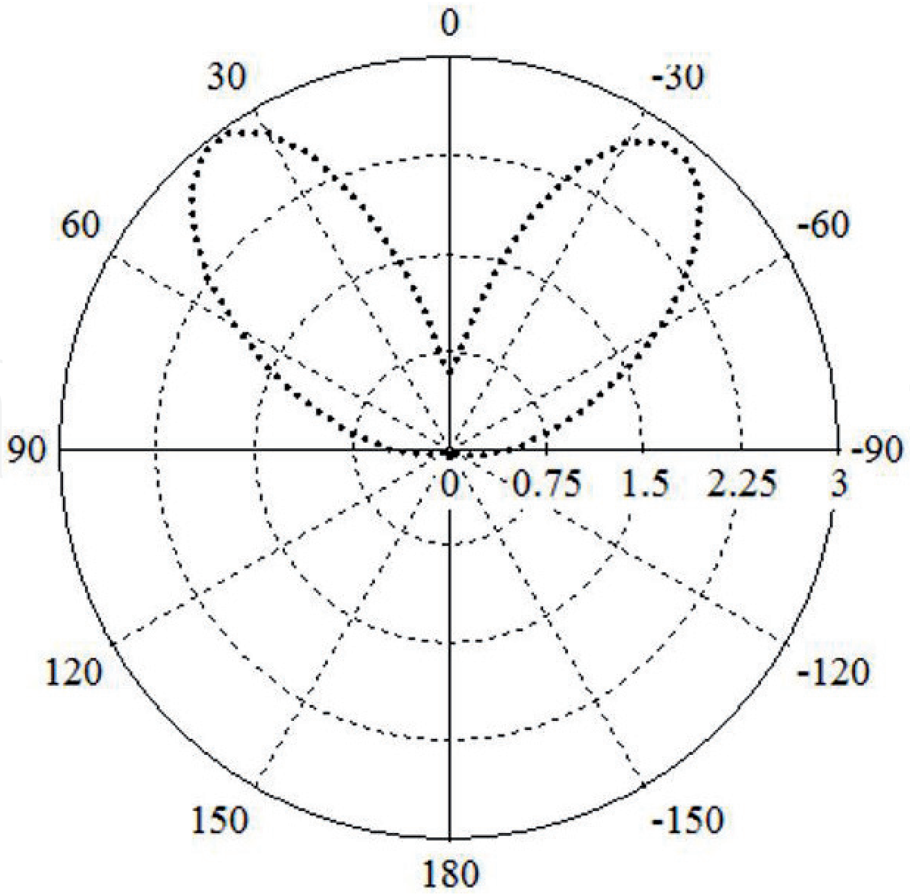

Figure 11.
Radiation pattern at yz-plane in the ON-ON state.

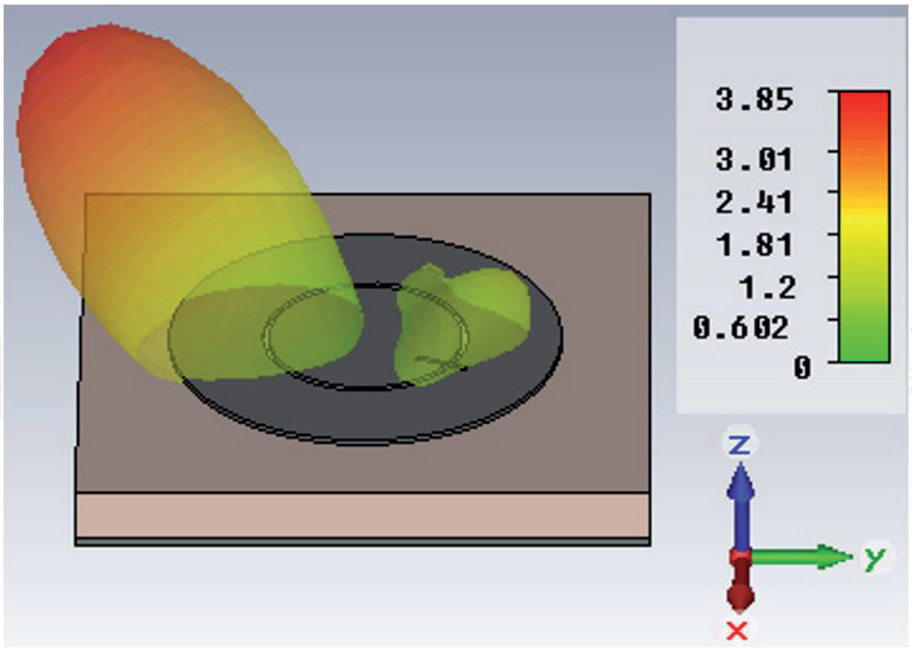

Figure 12.
3D radiation pattern in the ON-OFF state.

OFF) is 4.5 dB. At (SW1 OFF, SW2 ON) state, the maximum gain is 4.8 dB. In addition, at (SW1 ON, SW2 ON) state, the maximum gain and directivity are 3.9 dB. Total efficiency for the designed antenna is studied and plotted as a function of frequency in the useful bandwidth of 60 GHz at different state of each switch as shown in **Figure 16**. It is clear that the achieved efficiencies are better than 95% at all the states of switches.

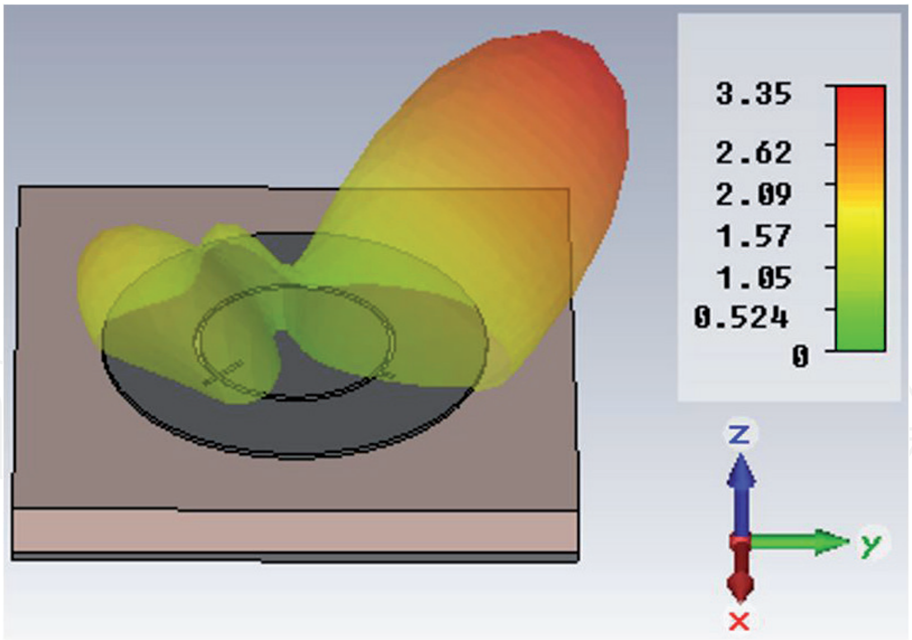

Figure 13.
3D radiation pattern in the OFF-ON state.

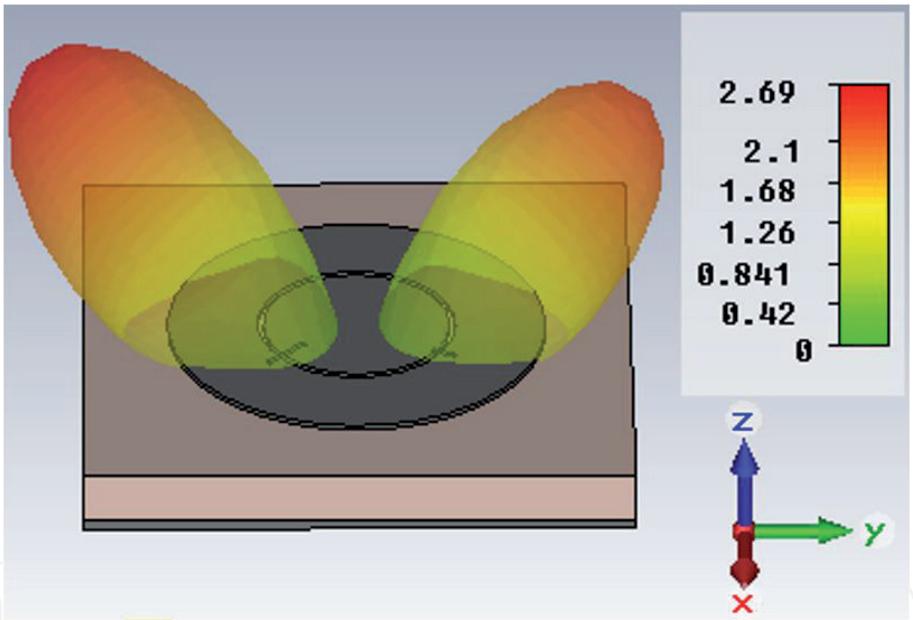

Figure 14.
3D radiation pattern in the ON-ON state.

6. Conclusion

A new design for pattern-reconfigurable circular disk antenna loaded with an annular slot ring has been presented for 60 GHz mmWave applications. The antenna is reconfigurable between three different radiation patterns by employing two NMOS switches. The achieved results show that the proposed antenna can redirect the main beam at −35 and 35° in the yz- plane with the maximum achieved gains are 4.5, 4.8 and 3.9 dB, and impedance bandwidths about 3.4, 3.3 and 5.7% in the (SW1 ON, SW2 OFF), (SW1 OFF, SW2 ON) and (SW1 ON, SW2 ON) states, respectively, at the resonance frequency 60 GHz. Antenna's efficiency better than 95% was achieved in the three states of switching configurations. The antenna beam pattern characteristics, efficiencies, peak gains and impedance bandwidths are

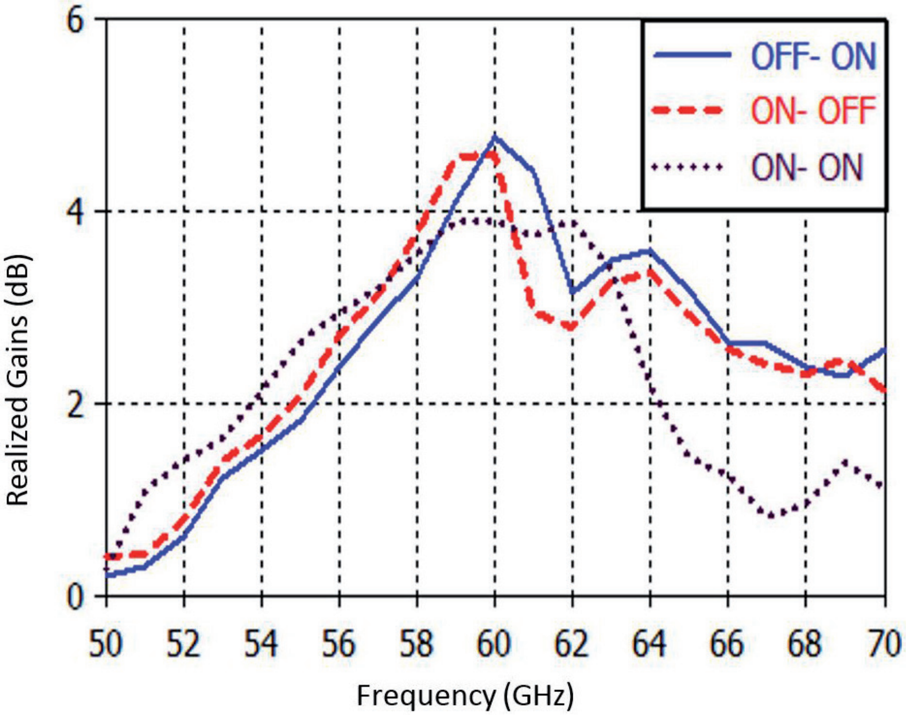

Figure 15.
Realized gain in different states of switches for the proposed antenna.

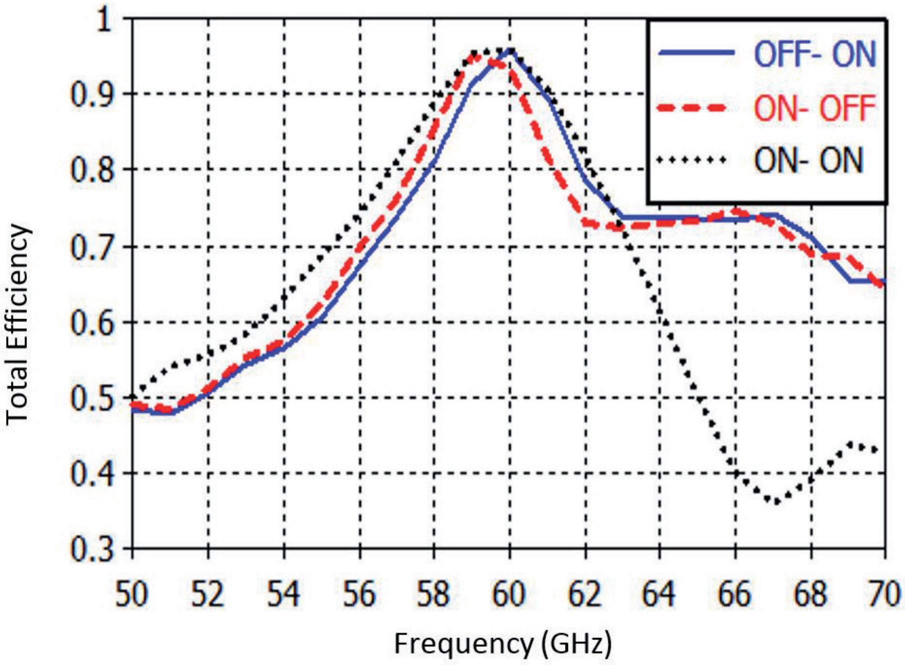

Figure 16.
Total efficiency in different states of switches for the proposed antenna.

suitable for 5G applications. Also, due to the simple construction and beam pattern diversity, the designed antenna can find different applications in MIMO systems.

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Author details

Yasir I.A. Al-Yasir[1]*, Hasanain A.H. Al-Behadili[2], Baha A. Sawadi[3],
Naser Ojaroudi Parchin[1], Ahmed M. Abdulkhaleq[1], Abdulkareem S. Abdullah[4]
and Raed A. Abd-Alhameed[1]

1 Faculty of Engineering and Informatics, University of Bradford, Bradford, UK

2 Department of Electrical Engineering, Faculty of Engineering, University of Misan, Misan, Iraq

3 Department of Communication Engineering, Iraq University College, Basra, Iraq

4 Department of Electrical Engineering, College of Engineering, University of Basra, Basra, Iraq

*Address all correspondence to: y.i.a.al-yasir@bradford.ac.uk

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