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Novel Reconfigurable Fractal Antenna Design for Modern Communication Systems

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ABSTRACT

In this paper, a design of a reconfigurable antenna structure with a miniaturized size is proposed for sub-6GHz bands 5G communications systems. The antenna shows five main frequencies at: 3.35GHz, 4.6GHz, 4.7GHz, 4.8GHz and 5.1GHz. The antenna is found to show a maximum gain of 3dBi at 3.35GHz to suit the applications of short and moderate communication systems. For this the authors applied a study of channel performance in terms of BER at the considered frequency bands of interest. Finally, an excellent performance is achieved with acceptable frequent reconfiguration quality.

1. Introduction

With the rapid advancements in wireless communication technologies, it is increasingly important for communication systems to possess the ability to dynamically modify the frequency and radiation properties of antennas. Reconfigurable antennas offer significant advantages for modern communication systems, especially in 5G applications. These antennas are lightweight, compact, and cost-effective [1]. The flexibility of reconfiguration in antenna performance, whether in terms of frequency, polarization, or radiation patterns, plays a crucial role in enhancing the antenna's capabilities, reducing the need for complex antenna arrays [3].

In recent years, the evolution of wireless communication networks has been accelerated by the demand for 5G applications, which aim to support a large number of devices with minimal latency [4]. Microstrip patch antennas have become a preferred choice in communication systems due to

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their compact size, low weight, and ease of integration with printed circuits [5, 6]. The microstrip reconfigurable antenna design proposed in [1] targeted frequency bands of 2.4 GHz and 28 GHz, using a FR-4 substrate with a relative permittivity of 4.4. The antenna, with dimensions of 30×26.5×1.6 mm^3, provided limited bandwidth and gain.

Another advancement, as described in [2], focused on an antenna capable of switching between ON and OFF modes to save energy and reduce power consumption. This design helps to optimize the antenna's performance based on the operational requirements. In [3], a reconfigurable antenna was developed using RF-MEMS shunt switches to control three rectangular patches, achieving a resonant frequency of 3 GHz. Further exploration in [4] introduced an omnidirectional antenna for mobile devices, operating at 10.15 GHz with a gain of 4.46 dBi. The design employed slotted patches to optimize its suitability for portable devices.

In [5], controlling the even- and odd-order modes was used to enhance the impedance bandwidth and generate conical broadside radiation beams. The introduction of two arrays of shorting pins allowed the resonant frequencies of TM01, TM11, and TM02 modes to move closer together, thereby improving the performance of the antenna. Another notable contribution in [6] presented a multiband frequency antenna design achieved by etching rectangular and circular slots on the surface of the patches. This approach enabled efficient frequency selection for different applications. Finally, the antenna design in [7] incorporated two PIN diodes to control right- and left-hand circular polarizations, further improving the antenna's versatility in various communication scenarios.

The recent advancements in wireless communication technologies have created a demand for antennas that are capable of dynamically adjusting their frequency and radiation properties. This ability is essential for meeting the challenges of modern communication systems, particularly in 5G applications, where antennas must support high data rates, low latency, and the ability to handle a large number of devices simultaneously [1]. Reconfigurable antennas offer numerous advantages in such applications, including their lightweight, compact size, and cost-effectiveness [2]. The capability to reconfigure antennas in terms of frequency, polarization, and radiation pattern significantly enhances their versatility, eliminating the need for large and complex antenna arrays [3].

Despite the progress made in reconfigurable antenna designs, there remains a challenge in fully realizing high-performance antennas that can operate efficiently across a wide range of frequencies while maintaining optimal gain and radiation patterns. This paper addresses these limitations by proposing a novel antenna design that improves gain performance and radiation efficiency through advanced reconfigurability techniques.

The key knowledge contribution of this paper lies in the development of a reconfigurable antenna that achieves enhanced performance across a broader frequency range with improved radiation patterns. The research gap identified in existing literature is the lack of efficient reconfigurable antennas that maintain high gain and directional control across both low and high frequencies in 5G communication systems. The objective of this paper is to present a design that not only addresses this gap but also introduces a new approach to antenna reconfiguration, incorporating dynamic frequency switching, polarization control, and radiation pattern adjustments. The novelty of this work lies in the integration of these features into a compact, low-cost design that is adaptable to a wide range of applications, including MIMO systems and 5G networks.

Recent advancements in wireless communication technologies have placed a strong emphasis on the need for antennas capable of dynamic reconfiguration. The ability to modify the frequency, polarization, and radiation properties of an antenna without physically altering its structure offers significant benefits in modern communication systems. This reconfigurability allows antennas to be optimized for various operating conditions, improving overall system performance, particularly in

demanding applications such as 5G, where flexibility, low latency, and efficient resource utilization are critical [1].

Reconfigurable antennas provide a valuable solution to the ever-growing demand for small, lightweight, and low-cost components in wireless communication. By enabling adjustments in frequency, radiation pattern, and polarization, these antennas can dynamically adapt to different communication environments, making them a more efficient and cost-effective alternative to traditional antenna arrays [2]. The design of such antennas often involves advanced techniques such as switches (e.g., MEMS, PIN diodes) and metamaterials to achieve the desired performance characteristics.

For instance, the work presented in [1] proposes a microstrip reconfigurable antenna capable of operating in two frequency bands: 2.4 GHz and 28 GHz. This design utilizes a FR-4 substrate (with a relative permittivity of 4.4) and dimensions of 30×26.5×1.6 mm^3. While the antenna provided a narrow bandwidth and moderate gain, it served as a proof of concept for frequency reconfiguration. In contrast, the antenna described in [2] introduces a switching mechanism that allows the antenna to toggle between ON and OFF states to optimize power consumption. This capability is particularly useful in low-power devices, where energy efficiency is paramount.

Further developments in reconfigurable antenna technology are found in [3], where an RF-MEMS shunt switch is used to control three rectangular patches, resulting in a resonant frequency at 3 GHz. This design allows for precise control over the antenna's frequency characteristics and provides improved flexibility for varying communication environments. In another study [4], an omnidirectional antenna operating at 10.15 GHz with a gain of 4.46 dBi is presented. This design uses slotted patches to optimize its performance for portable mobile devices, catering to the need for compact, efficient, and omnidirectional antennas in mobile communication systems.

The work in [5] demonstrates how controlling even- and odd-order modes can enhance impedance bandwidth and generate conical broadside radiation patterns. By incorporating two arrays of shorting pins, the antenna's resonant frequencies for the TM01, TM11, and TM02 modes are tuned to achieve optimal performance across a broader bandwidth. Additionally, the antenna in [6] employs etched rectangular and circular slots on the surface of the patches to achieve multiband frequency operation, enabling the antenna to serve a wide range of communication applications. Finally, [7] proposes an antenna with two PIN diodes that control the right- and left-hand circular polarizations, enhancing its versatility in handling diverse communication signals.

These studies illustrate the ongoing efforts to enhance antenna reconfigurability, but challenges remain in achieving high gain, wideband performance, and efficient radiation patterns while maintaining compact designs. The limitations of current reconfigurable antennas underscore the need for further research into more effective solutions that combine high performance with versatility.

2. Methodology

The design of a reconfigurable microstrip antenna for the 5G systems can be divided into some key points that following several steps [21-41]:

i. Frequency Range: 5G operates in multiple frequency bands, including both sub-6 GHz and millimeter-wave (mmWave) frequencies [8].
ii. Beam Steering: For 5G communication, beam steering is essential to maintain a stable and strong connection. Reconfigurability allows the antenna to dynamically adjust its beam direction, enabling better coverage and higher data rates [9].

iii. Reconfigurability Techniques: There are several ways to achieve reconfigurability in a microstrip antenna, such as using varactor diodes, PIN diodes, or MEMS (Micro-Electro-Mechanical Systems) switches. These components allow for tuning the resonance frequency or modifying the radiation pattern as required for different 5G scenarios [10].
iv. Radiation Pattern: To support beamforming and improve system performance, the antenna should have a directional radiation pattern with high gain in the desired direction and low gain in other directions [11].
v. Antenna Size and Form Factor: In 5G systems, where multiple antennas are often used (MIMO - Multiple Input Multiple Output), it is crucial to design compact antennas with a low-profile form factor. This allows for integration into various devices like smartphones, tablets, and other wireless devices [12].
vi. Efficiency and Bandwidth: Ensure that the antenna has high radiation efficiency and sufficient bandwidth to cover the 5G frequency bands with minimal signal loss [13].
vii. Cross-Polarization and Diversity: Consider designing the antenna to have low cross-polarization to minimize interference and support diversity, improving the reliability of the communication link [14].
viii. Material Selection: The choice of substrate material for the microstrip antenna is vital to achieve the desired performance. Dielectric constant, loss tangent, and thickness are important parameters to consider [15].
ix. Simulation and Prototyping: Use electromagnetic simulation tools like CST, HFSS, or ADS to model and optimize the antenna's performance. After simulation, build prototypes and conduct real-world measurements to validate the design [16].
x. Regulatory Compliance: Ensure that the designed antenna complies with relevant regulatory requirements and standards for wireless communication devices [17].
xi. Keep in mind that the design process might require several iterations to achieve the desired performance characteristics. Additionally, it is essential to consider the specific use case and application requirements of the 5G system to tailor the antenna design accordingly.

2.1 Proposed Antenna Design and Configuration

The proposed microstrip antenna, see Figure 1, is configured to improve bandwidth outcome due to change in substrate height and dielectric constancy [18]. The dimensions of the proposed microstrip antenna are calculated by using the well-known microstrip patch antenna formulas using this equation from Eq. (1), Eq. (2), Eq. (3), Eq. (4), Eq. (5), Eq. (6), Eq. (7) [19]. The proposed antenna structure is clarified in Figure 1.

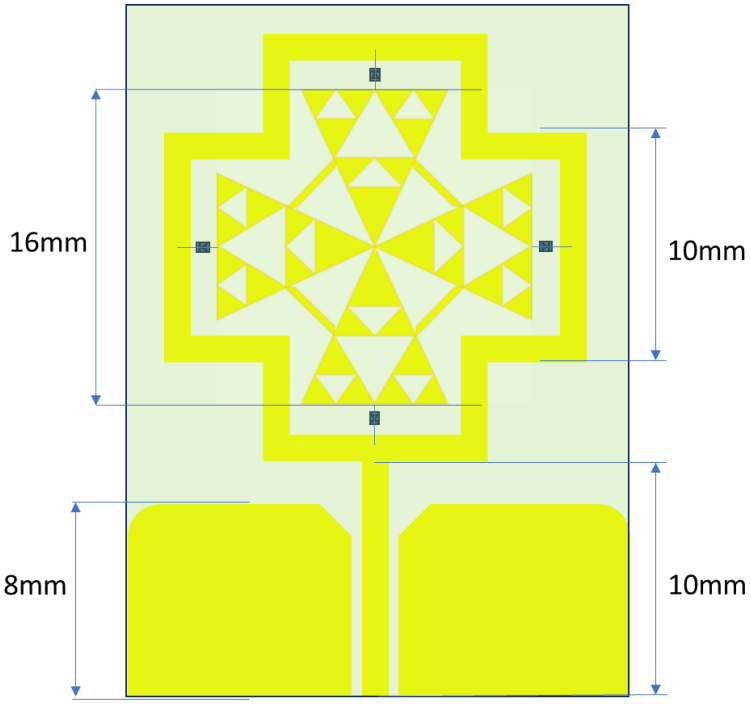

Fig. 1. Proposed antenna design

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

Sub. $\epsilon_r = 2.2, c = 2 \times \frac{10^8 m}{sec}, f_r = \quad GHz$

The effective dielectric constant ϵ_{reff}:

$$\epsilon_{reff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}\left(1 + 12\frac{h}{w_p}\right)^{-\frac{1}{2}} \tag{2}$$

Effective length due to fringing effects:

$$\Delta L = 0.412h\frac{(\epsilon_r+0.3)(\frac{w_p}{h}+0.264)}{(\epsilon_{reff}-0.268)(\frac{w_p}{h}+0.8)}h \tag{3}$$

The effective length of the patch L_{eff}:

$$L_{eff} = \frac{c}{2f_0\sqrt{\epsilon_{reff}}} \tag{4}$$

The actual length of the patch:

$$L_p = L_{eff} - 2\Delta L \tag{5}$$

To determine the ground plane dimensions length (L_g) and width of the ground plane (w_g)

$$L_g = 6h + l_p \tag{6}$$

$$w_g = 6h + w_p \tag{7}$$

2.2 Operation Process and Theory

Adaptive modulation is a shows potential technique to raise the data rate that can be consistently transmitted over fading channels. For this cause, some form of adaptive modulation is projected. The adaptive modulation system is based on the variation in the transmitted power or symbol rate transmission or BER or coding rate/schemes, or any amalgamation of these parameters [20]. The disadvantages of the adaptive modulation need an exact channel estimate at the transmission, added hardware complexity to execute adaptive transmission, and buffering/delay of the input data because the transmission rate vary with channel conditions [10]. Figure 2 shows the main units of (AM) system. The AM is based on SNR measurement and depending on the value of SNR selected the type of modulation.

When the authors connected between the outer stub using two diodes the response in terms of S11 and gain spectra are change according as seem in Figure 2 the obtain result are summarized in Table 1. It is found from provides a moderate variation in the second frequency band with a significant change in the antenna gain at 4.9GHz that is widely use in 5G system. This is achieved to switching the pin diode states that are listed in Table 1.

In this matter, the current density on the patch surface can be controlled by directing the current motion through pin diode [11]. Therefore, the antenna gain is significantly to nominate such antenna to be an excellent can dilate to application of direct adaptive modulation antenna system [12]. In which a transmitter acquired adaptive coding with gain control [13].

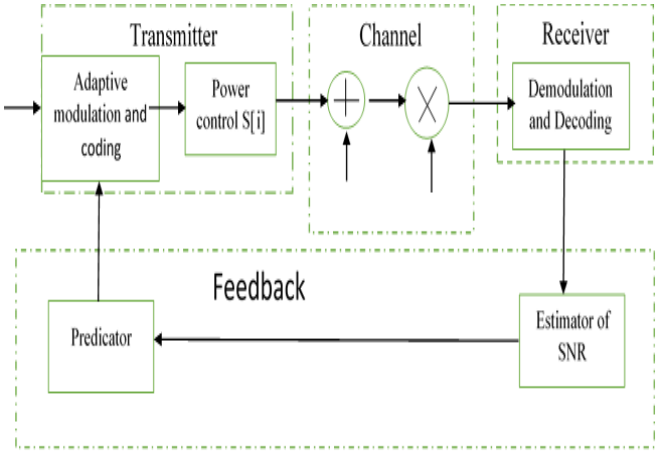

Fig. 2. Typical adaptive modulation system

Table 1
Reconfigurable-Pin diode switches

Case	F1	F2	Gain
00	3.35	5.1	3,2.8
01	-------	4.7	1.3
10	-------	4.8	0.5
11	-------	4.6	1.7

3. Results

This section displayed the simulation results of proposed antenna design in terms of S-parameters and Gain spectra. Five frequency bands (3.35GHz, 4.6GHz, 4.7GHz, 4.8GHz and 5.1GHz) are selected; because they have good results in S11 and gain spectra. The simulation is done by CST microwave studio software.

3.1 Return Losses

S11 is represents the return losses or back losses. S11 spectra show matching impedance less than -10. From Figure 3, we observed an excellent S11 impedance matching at 3.35GHz, 4.6GHz, 4.7GHz, 4.8GHz, and 5.1GHz as operating frequencies in different pin diode states.

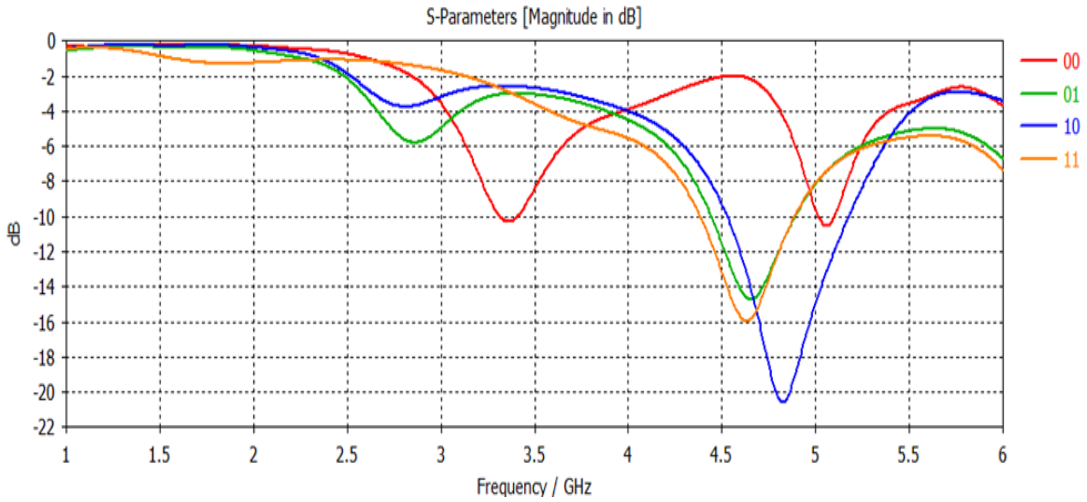

Fig. 3. S11 spectra of the proposal antenna design with pin diode switching variation

3.2 Gain Spectra

The antenna gain of the four considered cases results is shown in Figure 4. The antenna gain is found to be 3dBi and 2.8dBi at 3.35GHz and 5.1GHz, respectively, for case 1. For case 2, the antenna gain is found to be 1.3dBi at 4.7GHz. The antenna-based case 3 shows 0.5dBi at 4.8GHz. For case 4, the gain shows 1.7dBi at 4.6GHz.

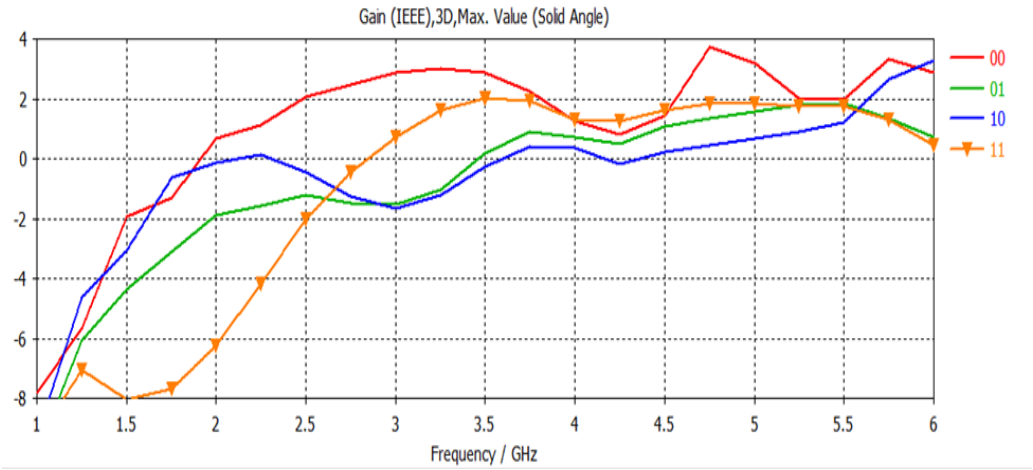

Fig. 4. Antenna gain spectra

3.3 Channel Performance

Following the antenna performance simulation, we implemented a propagation model that took received power, field strength, path loss, and attenuation effects into account. To show how that affected the Bit Error Rate (BER), we employed a digital modulation schema based on Quadrature-Amplitude-Modulation (QAM) with an effective coverage. The number of allowed mistakes at the

prepared tolerates is the definition of the considered BER in this scenario. Usually, in this kind of situation, the value falls between 0.1 and 10^{-6}. Measured in dB, the Signal-to-Noise-Ratio (SNR) has a significant impact on this ratio. The data in Figure 5 show that while a low SNR would result in an increase in BER, a high SNR would produce a low BER. It goes without saying that higher gain frequency bands offer a lower likelihood of errors due to noise effects than lower gain ones.

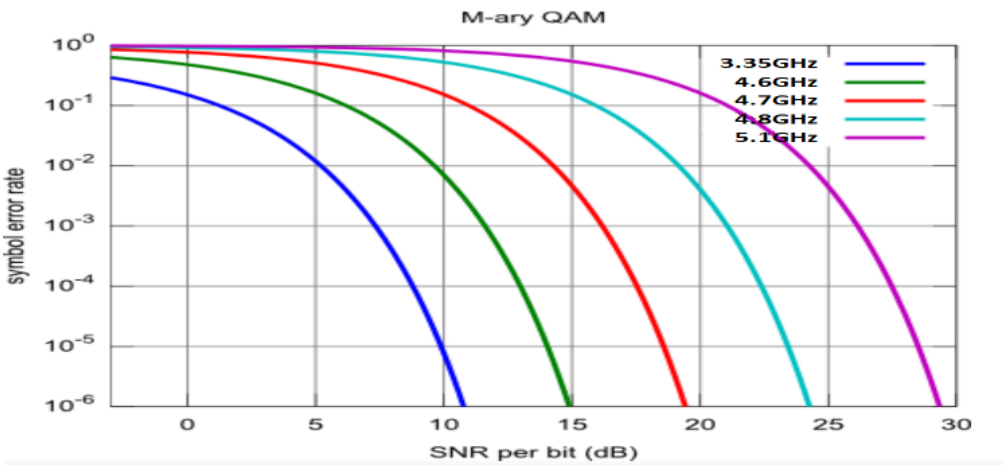

Fig. 5. BER calculations at different frequency bands

Creating a comprehensive comparison in Table 2 for reconfigurable microstrip antenna designs specifically for 5G systems. A simplified example comparison table that highlights some key features and parameters that are often considered in evaluating reconfigurable microstrip antennas for 5G systems.

Table 2
A comparison study of reconfigurable microstrip antenna design

Antenna Design	Antenna A	Antenna B	Antenna C	Antenna D
Frequency Bands Covered	Sub-6 GHz, mmWave	Sub-6 GHz	Sub-6 GHz, mmWave	Sub-6 GHz, mmWave
Reconfiguration Mechanism	PIN Diode Switches	MEMS Switches	Liquid Crystal	RF-MEMS
Beamforming Capability	Yes	No	Yes	Yes
Polarization Control	Yes	Yes	No	Yes
Bandwidth	Wide	Narrow	Ultra-Wide	Wide
Gain	High	Low	High	High
Energy Efficiency	High	High	Moderate	High
Size/ Miniaturization	Moderate	Compact	Small	Moderate
References	[21,22]	[23,24]	[25,26]	[27,28]

4. Conclusions

In this paper, a design of a reconfigurable antenna is proposed for 5G applications. The antenna shows excellent matching of S11 less than -10dB at five frequency bands of 3.35GHz, 4.6GHz, 4.7GHz, 4.8GHz, and 5.1GHz. It is found the proposed antenna shows an excellent response to the pin diodes switching variation. The proposed antenna is miniaturized to occupy an area of 25×20mm^2. The

channel performance in terms of BER is calculated at the frequency band of inters. It is found that the proposed antenna realizes in general an acceptable BER for all considered frequency bands.

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