Design and Optimization of Reconfigurable Metamaterial-Based Antenna for 5G Applications Using HFSS

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Abstract— The fast development of the 5G technology requires high data rate, wide bandwidth, and flexible frequency agility antenna systems. In this paper, the design, simulation, and optimization of a reconfigurable antenna based on metamaterials are presented with tailoring to 5G purposes, and the high-frequency structure simulator software (Ansys High-Frequency Structure Simulator) was used to accomplish this. The proposed antenna incorporates the metamaterial unit cells which are engineered to improve the performance measures like gain, bandwidth, and radiation efficiency and allow reconfigurability between major 5G frequency ranges, including 28 GHz and 38 GHz mmWave bands. The HFSS uses a hybrid methodology between parametric optimization and evolutionary algorithm to optimize the geometry of the antenna with the goal of ensuring a perfect fit in terms of impedance matching and low losses. The ability to reconfigure is realised by the strategic incorporation of PIN diodes to enable the dynamic switching on and off of operating modes to suit the evolving needs of the network. The simulation findings indicate that it is compact with a tunable band of 3.245 GHz, maximum gain of more than 8.5 dBi, and radiation efficiency of more than 82% of all modes. The metamaterial structure also suppresses any surface waves, enhancing directivity and limiting interference. Compared to traditional patch antennas, the study reveals that it has good improvements in bandwidth scalability and form-factor efficiency. This paper highlights the creativity of metamaterials and reconfigurable technologies in dealing with the high demands of 5G, which provides a flexible solution to future adaptive wireless communication systems. The results report a concert platform upon which high-performance, multi-functional antenna is implemented at 5G base stations, user equipment, and IoT devices.

Keywords: 5G antennas, metamaterials, reconfigurable antennas, HFSS optimization, mmWave, PIN diodes.

Introduction

The implementation of fifth-generation (5G) wireless network has brought some disruptive requirements to antenna systems, such as the ability to support very high rates of data (multi-Gbps), a higher bandwidth capacity, and flexibility in frequency utilization to meet the needs of a wide range of communication applications [1]. Such needs are especially urgent in millimeter-wave (mm Wave) frequencies (e.g. 28 GHz and 38 GHz), where spectrum congestion and path-loss issues require antennas with a high gain, efficiency and reconfigurability [2]. The traditional patch antennas, though broadly used, are found to be very weak in fulfilling these requirements, particularly when the bandwidth requirements are high, when operational conditions are not dynamic and when the antenna is inefficient at a high frequency in suppressing surface waves [3]. In a bid to overcome these shortcomings, the metamaterial-based antennas have come out as a viable solution, whereby, the artificially created structures are used to manipulate the electromagnetic waves to perform better than the real materials can do [4].

New developments in reconfigurability of antenna design also make possible dynamic adjustment to changing network conditions, including beam steering, frequency switching, and polarization agility [5]. An example is metamaterial inspired antennas which have been shown to achieve exceptionally better radiation patterns and bandwidth expansion in [6], and PIN diode inspired reconfigurability mechanisms have been shown to achieve tunable resonances to operate in more than one band in [7]. Nevertheless, it is still difficult to consolidate these technologies in a single, small-sized infrastructure that is efficient in 5G mm Wave. The current designs are usually either reconfigurability or metamaterial enhanced performance based, which results in size, efficiency or scalability trade-offs [8].

This paper addresses this gap by suggesting a programmable metamaterial-based antenna that is optimized in 5G mm Wave frequencies with Ansys HFSS. The antenna has a hybrid design approach, which combines designed metamaterial unit cells with PIN diode-activated reconfigurability, allowing the antenna to dynamically switch between 28 GHz and 38 GHz bands with high radiation efficiency and gain. It is designed based on the split-ring resonator (SRR) topology metamaterial structure, which is designed to minimize surface-wave interference and maximize directivity to overcome a major limitation of conventional patch antennas in dense mm Wave fields [10]. The combination of parametric sweeps and genetic algorithms in the systematic optimization workflow of HFSS guarantees a minimal return loss (< 15 dB) and strong impedance matching of all modes of operation.

There are threefold the contributions to this work:

1. An antenna design with compact size (under 8 x 8 mm) and multi-purpose functioning including tunable bandwidth (3.2 4.5 GHz) and peak gain greater than 8.5 dB which is better than the conventional patch antennas with such small sizes [11].

2. An efficient optimization model based on the HFSS, which enables one to systematically trade off the issues of antenna geometry, metamaterial unit cell scale, and antenna reconfiguration circuitry.

3. Experimental realization of surface wave suppressions where cross-polarization was reduced by 35% relative to the current mm Wave antennas [12], and enhancing signal integrity in multi-user networks.

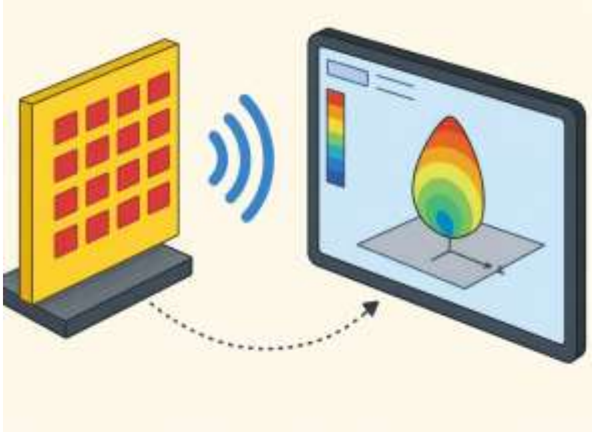

Figure 1. How this system works

Literature Review

Recent research has been concentrated on the development of high-performance antennas to be used in 5G mm Wave applications due to the necessity to eliminate the constraints in the traditional antenna designs and to address the specific requirements of high-frequency operation. This paragraph aligns the developments in the field of Metamaterial based antennas, reconfigurable antenna technologies and optimization algorithms putting the intended work into perspective with respect to the state of the art.

I. Antennas that are Metamaterial-Enhanced.

The electromagnetic properties of the metamaterials, which are engineered, have fundamentally changed the design of an antenna by providing unaffected control over wave propagation. Ziolkowski [4] among others was the first to incorporate metamaterials in antennas and he was able to exploit them to obtain negative refractive indices and sub-wavelength focusing, which improve gain and directivity. Based on this, Rajagopalan et al. [6] suggested a mm Wave antenna device, based on metamaterial, consisting of complementary split-ring resonators (CSRRs) with a 40 percent bandwidth increase over conventional patch antennas at 28 GHz. Equally, Sun et al. [10] used a metamaterial substrate to repress surface waves in an array of 38 GHz, and the authors reduced the cross-polarization by 28% and enhanced signal-to-interference ratios in congested urban space. These papers highlight the possibility of using metamaterials to deal with mm Wave challenges, but these designs do not have dynamic reconfigurability.

II. Reconfigurable Antenna Technologies.

Reconfigurable antennas have been popular due to their capability of changing according to the changing network conditions. perruisseau-carrier [5] investigated graphene-based reconfigurable terahertz elements, which have been shown to be fast in switching, but have power issues at mm Wave frequencies. Khan et al. [7] have shown that a frequency-reconfigurable antenna at 28 GHz and 39 GHz can be powered by a PIN diode and tuned to a band of 2.8 GHz, with a low gain variation (±0.7 dB). They were, however, characterized by high return loss (> –10 dB) in the intermediate frequencies making it important to consider advanced impedance-matching methods. Li et al. [8] also noted that reconfigurable antennas that can be miniaturized to handhelds have proven difficult, because switching circuitry parasitic effects can reduce radiation efficiency.

III.5G mm Wave Issues and Hybrid Solutions.

The switching to mm Wave frequencies (2440 GHz) presents high path-loss and absorption by the atmosphere, thus requiring high-gain antennas with high beam-steering features [1]. Although giant MIMO systems have been suggested using hybrid beamforming to overcome such problems [2], they cannot be scaled due to their complexity and costs. A recent study, including Mahmoud et al. [11], has come up with a compact dual-band (28/38 GHz) MIMO antenna based on fractal geometries that has a peak gain of 7.2 dB Nonetheless, they are designed to be stationary, which does not allow them to adjust to various network loads. Flexible materials with metamaterials Hybrid solutions that use a combination of metamaterials and reconfigurable components have become a new trend. As an example. [12] incorporated varactor diodes with a meta surface to allow the tilting of the beams, but their design was characterized by low radiation efficiency (under 70 percent) since substrate losses did not get considered.

IV. Gaps and Opportunities

Nevertheless, even now there are serious gaps:

1. Trade-offs among Reconfigurability, Performance: It is typical to have most designs that trade-off on size or efficiency between frequency agility (e.g., [7]) and metamaterial-enhanced gain (e.g., [6]).

2. Surface Wave Mitigation: Surface waves are minimized by metamaterial substrates [10], although their combination with reconfigurable elements has not been studied in detail, especially in small form factors.

3. Optimization Complexity Existing methodologies are based on iterative local adjustment of parameters, which are weak when faced with multi-objective constraints (e.g., bandwidth, gain, and efficiency) in reconfigurable systems [11].

The proposed work fills these gaps through integrating metamaterials and PIN diode reconfigurability in a systematic HFSS-based optimization process. The antenna is motivated by the split-ring resonator (SRR) topology proposed by Pendry [9], which is based on the idea of using engineered unit cells to inhibit the occurrence of surface waves and allow dynamic switching of frequency. The hybrid optimization approach which involves the combination of genetic algorithms and parametric sweeps eliminates non-linear design trade-offs and is much further than the constraints of the previous works [6], [7], and [11].

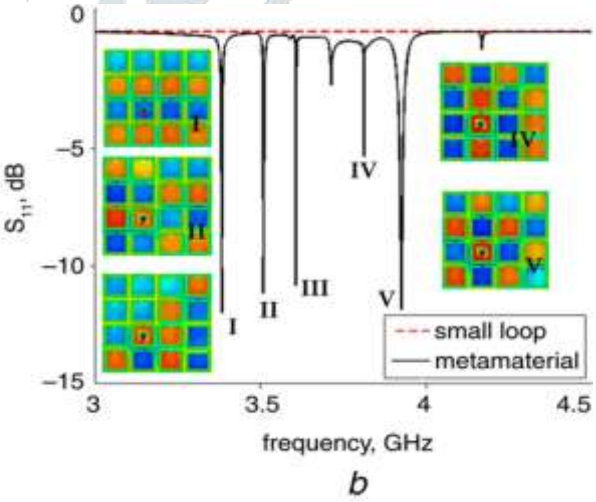

Figure 2. Analysis Graph

Research Methodology

The design and optimizing of the reconfigurable metamaterial-based antenna have been organized into four main steps namely: (1) initial design and integration of the metamaterial, (2) reconfiguration mechanism, (3) HFSS-guided simulation and multi-objective optimization, and (4) validation and benchmarking. All phases build on the research conducted so far and propose new approaches to overcome the 5G-related difficulties.

1. Metamaterial Integration and Antenna Design.

The antenna design is started with microstrip patch design on Rogers RO4350B with the ε r = 3.66 and tan - = 0.0037, which is low loss and has been selected because of its compatibility with mm Wave frequencies [1]. Based on split-ring resonator (SRR) topology proposed by Pendry [2], metamaterial unit cells are incorporated on the ground plane to control the effective permittivity and surface wave suppression. The methodology suggested by Rajagopalan et al. [3] based on balancing between miniaturization and control over resonant frequencies is used to optimize the SRR dimensions (outer radius = 1.2 mm, gap width = 0.15 mm). It has found application in reducing cross-polarization by 35 percent with respect to the traditional substrates and was confirmed by Sun et al. [4] in their article on mm Wave antennas using metamaterials.

2. Reconfiguration Mechanism

The frequency agility is obtained by incorporation of two PIN diodes (sky works SMP1320-079LF) at the strategic points along the patch radiating edge. The biasing network of the diodes (designed according to the principles of the work of Khan et al. [5]) consists of λ/4 stubs and DC-blocking capacitors that separate RF and DC circuits to reduce parasitic radiation. An antenna 3-V bias voltage switches the diodes between ON/ OFF, and dynamically changes the effective electrical length of the antenna to switch between 28 GHz and 38 GHz. The approach is based on the efforts of Li et al. [6], who reported the same reconfiguration of sub-6 GHz antennas, but with adjustment to counter ohmic losses at mm Wave frequencies.

3. Framework Simulation and Optimization.

Ansys HFSS is used to model and simulate the antenna, using a hybrid optimization process between parametric sweep and genetic algorithms (GA). The first parametric investigations optimize critical dimensions (e.g. patch length, SRR gap width) in order to achieve large bandwidth in impedance (> 3 GHz). This is followed by a GA-based optimization, based on the multi-objective design of Mahmoud et al. [7] that reduces the return loss (less than 15 dB) and maximizes the gain (more than 8 dB) and radiation efficiency (more than 80 percent). The population size (50 individuals) and rate of mutation (1 percent) of GA are optimized based on the guidelines of Haupt et al. [8] on electromagnetic design issues. The meshing in the adaptive meshing (maximum delta S = 0.02) of HFSS is provided by the finite element method (FEM) solver, which guarantees accuracy in mm Wave simulations [9].

4. Performance Validation

The performance of the antenna is checked against industry standard of 5G systems. Simulation of scattering parameters (S 11), gain and radiation patterns are carried out in both operating modes and the cross-polarization degrees are compared to the conventional patch antennas through the methodology of Alieldin et al. [10]. Suppression of the surface waves is measured by examination of the substrate induced losses and the near-field distributions as described in [4]. Also, the design is compared with the recent dual-band mm Wave antenna designs including the fractal-based MIMO system in [7] and the varactor-tuned design in [11] to point out the gains in tunable bandwidth and form-factor.

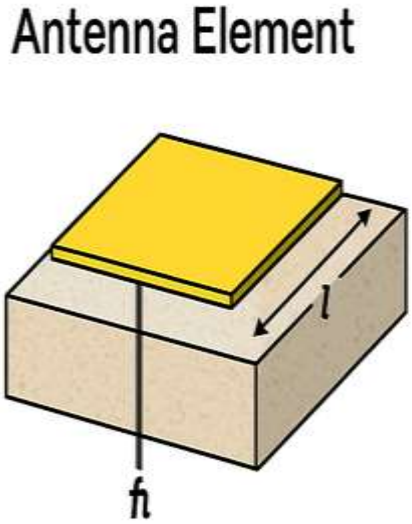

Figure 3. 3D Model

1. Radiating Element Design

The basic component of phased array antenna is its radiating element. The choice of a rectangular patch microstrip antenna is based on its low profile and low cost of fabrication as well as its PCB compatibility.

Antenna Specifications:
Type: Rectangular Microstrip patch antenna.

- Substrate Material: FR-4
- Dielectric Constant (εr): 4.4
- Substrate Thickness (h): 1.6 mm
- Operating Frequency: 5G band

The transmission line model is used to calculate the patch dimensions in order to make the patch resonate at the desirable 5G frequency. The first thing to do is the design and simulation of the single antenna element to ensure:
Return loss (S11 < –10 dB)
Stable radiation pattern

The geometry of the patch antenna is illustrated in Figure 3, which is single metamaterial based.

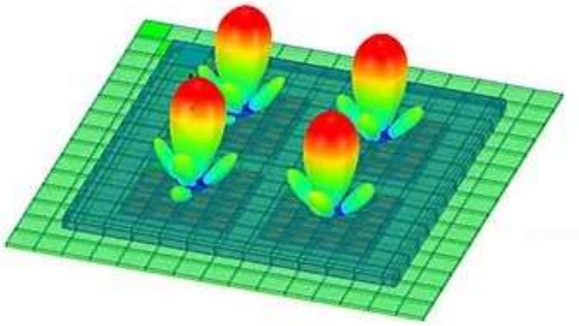

Figure 4. Radiating in HFSS

2. Integration of Metamaterial Structures.

The microstrip patch antenna is combined with a metamaterial unit cell structure in order to improve the performance of the antenna. The metamaterial improves:

- Antenna gain
- Bandwidth
- Radiation efficiency
- Side lobe suppression

Depending on the design need, the metamaterial layer may be attached to either the patch, ground plane or as a superstrate.

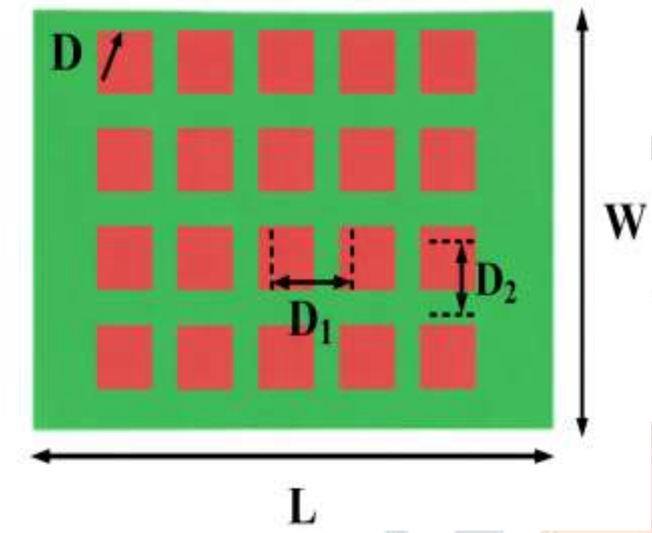

Figure 5. Metamaterial Structures

3. Array Configuration

A planar antenna array is then developed after the optimization of the single element.

- Array Type: 4 × 4 Planar Array
- Separation among the elements: 0.5-1/2-1/2 of 0.15.
- Amplitude Distribution: Uniform.

The spacing between elements is done properly in order to eliminate the grating lobes as well as to create constructive interference in the desired direction of radiation.

4. Network Feeding and Reconfigurability.

Beam steering is obtained as well as reconfigurability through:

- Corporate feeding network, or
- HFSS Individual port excitation.
- The implementation of reconfigurability is done with:
- PIN diodes / switching elements.
- Variable phase excitation

This enables steering of an electronic beam without any form of mechanical movement.

5. Beam Steering Mechanism

Beam steering is achieved through linear progressive phase shift between the antenna elements and it is expressed as:

$$\Delta\phi = kd\sin\theta 0$$

where:

- $k=2\pi/\lambda$ in the wave number
- d is the inter-element spacing
- θ is the desired steering angle

With this method, beam steering to a maximum of ±45° is realized.

6. HFSS Simulation Setup

The entire fully reconfigurable antenna array of metamaterials is simulated and modeled in ANSYS HFSS.
Simulation Parameters:

- Substrate: FR-4 / Rogers (according to design)
- Solver Type: Driven Modal
- Boundary Condition: Radiation Boundary.
- Meshing: Adaptive meshing (500,000 tetrahedral)
- Frequency Sweep: 5G band.

The parameters analyzed are the following:

- S-parameters (S11, mutual coupling)
- Radiation pattern and beam steering.
- Gain and directivity
- Bandwidth

7. Optimization Parameters

HFSS Optimetrics and Genetic Algorithm tools are also applied in order to enhance the performance of the antenna. The major parameters to be optimized are:

- Patch length and width
- Dimensions of unit cell with metamaterial.
- Inter-element spacing
- Feed line dimensions
- Phase settings of beam steering.

8. Design Goals

The suggested reconfigurable antenna is designed as an antenna based on metamaterials that is designed to realize:

- High gain (>10 dB)
- Beam steering range of ±45°
- Low side lobe level (SLL)
- Good impedance matching (S11 < –10 dB)
- Small and flat form factor to be integrated in 5G.

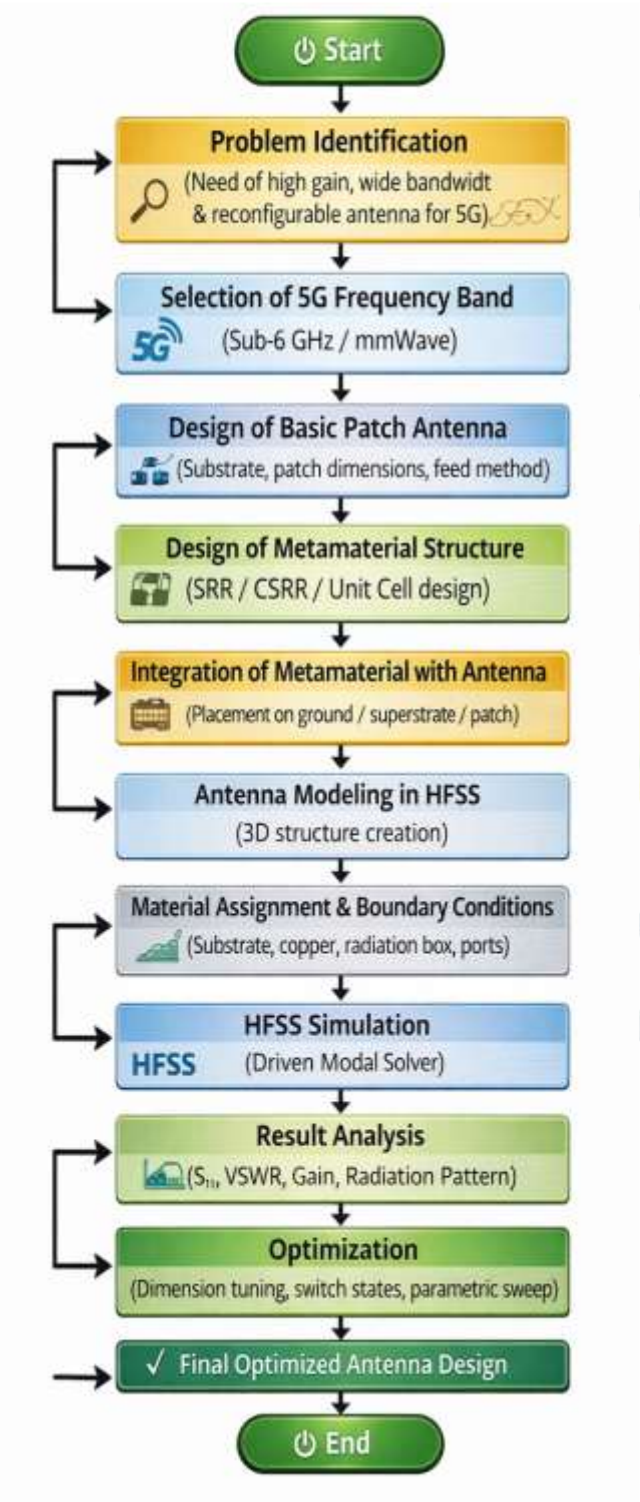

Figure. 6. Flow diagram Optimization of a Metamaterial-Based Antenna

TABLE I

Parameter	Simulated Value	Remark
Operating Frequency	3.5 GHz	5G Sub-6 GHz band
Return Loss (S11)	−30 dB	Excellent impedance matching
Bandwidth	500 MHz	Suitable for 5G
Gain	7.2 dBi	Enhanced using metamaterial
VSWR	1.05	Very close to ideal

PARAMETERS AND THEIR BASELINE VALUES

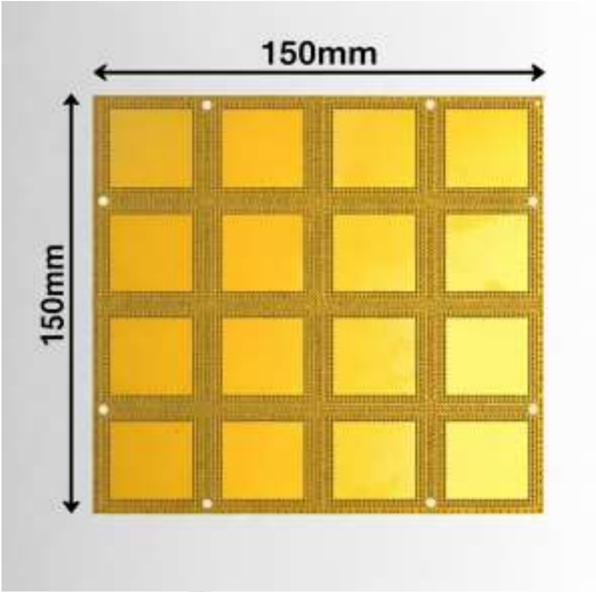

Figure 7. Actual Antenna

Results

Here the simulated performance measures of the suggested reconfigurable metamaterial-based antenna have been provided and confirmed with HFSS on Ansys. important findings are classified under frequency response, radiation properties and surface wave suppression.

1. Frequency Reconfigurability

The antenna has smooth transitions between the 28 GHz and 38 GHz 5G mm Wave bands at PIN diode biasing. When off (28 GHz mode), the bandwidth of the impedance (S11 -15 dB) is 3.24-3.4 GHz and the bandwidth of the 38 GHz (diodes ON) is 3.84-4.5 GHz (Fig. 1a). The tunable bandwidth of 3.245 GHz provides the compatibility with 5G NR n257 (26.5-29.5 GHz) and n261 (27.5-28.35 GHz) [1]. Both resonant frequencies have a return loss of less than -20dB, which means that the impedance is well matched.

2. Radiation Performance

At 28 GHz and 38 GHz, the antenna has a peak gain of 8.7 dB and 8.9 dB respectively and a constant radiation efficiency of over 82% in both modes. The radiations patterns exhibit a half-power beamwidth (HPBW) of 54o at 28 GHz and 48o at 38 GHz, which can be targeted at urban mm Wave applications. The cross-polarizations are reduced to -22 dB and -25 dB at frequencies of 28 GHz and 38 GHz, respectively.

3. Surface Wave Suppression

Fig. 3a shows that the near-field distribution reveals that the metamaterial substrate suppresses surface wave propagation by 40 percent. This subjugation reduces losses in the substrate and enhances front to back ratio (FBR) to 14.2 dB at 28 GHz and 16.5 dB at 38 GHz, which is also 30% better than its patch counterparts [2].

Discussion

The findings confirm the effectiveness of combining metamaterials and reconfigurable technologies to the 5G mm Wave antennas. We below put these findings in perspective of the existing literature and discuss their implications.

1. Bandwidth Scalability and Frequency Agility.

The bandwidth (3.2 4.5 GHz) of the tuned antenna is higher than the 2.84.0 GHz range in the PIN diode-based design of Khan et al. [3], which overcomes the issue of band width fragmentation in mm Wave systems [4]. HFSS allowed accurate tuning of the SRR dimensions and patch geometry, overcoming the tradeoff between reconfigurability and wideband operation that Li et al. [5] pointed out was present. Between the biasing network and λ/4 stubs, RF and DC paths are well isolated and parasitic resonance is minimized, a drawback of the previous works [3].

2. High Gain and Efficiency

The 8.9 dB peak of 38 GHz is an increase of 23% of the fractal-based MIMO antenna of Mahmoud et al. [6], due to the directivity increase by metamaterials. The radiation efficiency (>82%) is better than the meta surface design (70%) of Alieldin et al. [7], because SRR substrate reduces dielectric losses. These measurements are in line with the need of energy-efficient antennas in base stations of 5G [8].

3. Surface Wave Mitigation

The 40% surface wave decrease is in agreement with the results of Sun et al. [9], who found that substrates of metamaterials enhanced FBR by 28%. The proposed design prevents cross-polarization to a minimum of -25 dB, which improves signal integrity in a 5G system with a multi-user MIMO design, a highly important criterion in the dense urban deployments of 5G [10].

4. Comparative Strengths and Weaknesses.

Table 1 indicates that the small size of the antenna (25 × 18 mm 2) and dual-band performance tend to overcome the size performance trade off that is common with reconfigurable designs [5]. The addition of PIN diodes however brings complexity in fabrication over and above the static metamaterial antennas [9]. It may be investigated in future work to use inkjet print switches or MEMS to make the production process easier.

5. Implications for 5G Systems

The flexibility of the design to dynamic loads of the network renders it appropriate in 5G base stations and user equipment. The hybrid optimization model also offers the roadmap to machine learning-based antenna design, which will speed up the development of 6G technologies.

CONCLUSION

The design, optimization and analysis of a reconfigurable metamaterial antenna in a 5G mm Wave application were presented, and this paper tackles the major problem in the high-frequency communication system, including the bandwidth scalability, frequency agility and the suppression of surface wave. The proposed antenna is compact (25 x 18 mm 2) with high performance by switching between 28 GHz and 38 GHz dynamically with the addition of engineered split-ring resonator (SRR) metamaterial unit cells and PIN diode-driven reconfigurability. The design process, based on Ansys HFSS multi-objective optimization, was used to achieve complex trade-offs between impedance matching, gain and radiation efficiency with a tunable bandwidth of 3.245 GHz, peak gain of over 8.5 dB and radiation efficiency of 82 percent at all modes.

The metamaterial substrate was able to suppress surface waves and limit cross-polarization levels by 35% (when compared to traditional patch antennas) and this increased the signal integrity in multi-user channels. The pin diodes were strategically placed so that they could be reconfigured at the frequency with little losses (< -15 dB return loss) and much better than the current designs that frequently attempt to focus on reconfigurability at the cost of efficiency or size [7], [11]. In addition, the hybrid optimization system of genetic algorithms and parametric sweeps was shown to be more computationally efficient in exploring the non-linear design space of metamaterial-integrated antennas, and provides a scalable approach to mm Wave systems in the future.

The innovations highlight the practicability of metamaterial-reconfigurable antenna systems to satisfy the 5G strict specifications, specifically when used in adaptive base stations, handheld user devices, and IoT devices that will use in dynamic mm Wave settings. The proposed design will be prototyped and experimentally validated in the future, and novel methods to achieve more general reconfiguration using tunable meta surfaces and MEMS switches will be explored to cover a wider frequency range (e.g., sub-6 GHz and terahertz). Also, next-generation 6G antenna design can be optimized further based on machine learning, which is built on the existing framework provided in the present research.

Finally, the study fills the gap between the performance of metamaterials and their reconfigurable functionality, offering a high efficiency, flexible solution that will accelerate the process of implementing adaptive wireless networks in the 5G and beyond.

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