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ECO-CONSCIOUS DESIGN OF SLOTTED MICROSTRIP PATCH ANTENNAS FOR MULTI-BAND 5G COMMUNICATIONS

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Abstract. The fifth-generation (5G) of communication era requires multi-band antennas that are very small, high-gain, and compact to satisfy the rising criteria of high data rates, reliability, and energy efficiency. The use of microstrip patch antennas (MPAs) has been very popular because it is low profile, easy to make and economical. However, traditional substrates and fabrication methods have environmental issues as in most cases non-biodegradable materials are used and a lot of energy is consumed in the production process. To overcome those difficulties, the present research suggests an environmental-friendly design and simulation of slotted patch antennas of microstrip in the multi-band 5G use. The antenna has strategically designed slots on the radiating patch to resonate at various frequencies bands including sub-6 GHz and millimeter-wave frequencies used in 5G standards. Dielectric materials that are environmentally sustainable (e.g. biodegradable composite materials), and recyclable substrates are considered and compared with traditional ones to point out on the trade-offs between performance and environmental footprint. The proposed antenna is simulated by full-wave electromagnetism simulation and exhibits better impedance bandwidth, gain and radiation efficiency over desired frequency bands without sacrificing mechanical flexibility and environmental friendliness. The findings show that sustainable materials have the ability to perform relatively well with traditional materials and with a substantial decrement in the ecological impact of the antenna manufacturing process. This effort creates a gateway to green 5G antenna systems, which will lead to green and energy-efficient wireless communication systems in the next generation of devices.

Keywords: 5G, microstrip patch antenna, slotted antenna, multi-band, eco-conscious design, sustainable substrates, radiation efficiency, biodegradable materials.

AIMS AND BACKGROUND

The dynamism of wireless communication technologies has introduced the times of the fifth generation (5G) networks that made it possible to achieve unprecedented

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progress in terms of data transmission speed, the lowest possible latency, and the possibility to connect massive amounts of devices[1]. Self-driving vehicles, augmented/ virtual reality (AR/VR), Internet of Things (IoT), and smart healthcare are all apps that are increasingly relying on the performance and dependability of 5G infrastructure[2]. The core of this infrastructure is the antenna system which takes care of effective radiation, reception and multi-band support[3]. Microstrip patch antennas (MPAs) have become one of the most popular contenders regarding the 5G systems due to their small form, low profile, the ability to be integrated with planar circuits, and the ability to be fabricated using modern fabrication technology[4].

Although these are the benefits, traditional MPAs have two significant shortcomings, narrow bandwidth and single band operation[5]. To address these limitations a number of structural adjustments have been examined including the addition of slots, defected ground structures (DGS) as well as metamaterial inclusions[6]. A simple yet highly effective approach that has been found to yield multi-band operation without a massive increase in the size of the antenna, is slotting techniques. It is possible to design slot geometries and locations so as to achieve resonance at multiple frequency bands to ensure both sub-6 GHz and millimeter-wave (mmWave) coverage, needed by 5G communications[7].

Although technical developments in the design of the antenna are a concern, the issue of environmental impact of the antenna manufacturing process is not always taken into account[8]. Although widely used, conventional substrates (FR4 epoxy and RT/Duroid) are challenging to the environment because they lack biodegradability, depend on petrochemical derivatives, and are complicated to recycle[9]. The environmental impact of antenna materials is a timely issue due to the continuously growing number of communication devices and base stations needed to accommodate 5G and higher[10]. Eco-conscious antenna design concept is the solution to this dilemma since it incorporates the issue of sustainability in designing the antenna systems. Green alternatives like polylastic acid (PLA) and cellulose-based composites as well as natural fiber-reinforced laminates are considered biodegradable and recyclable substrates[11]. Not only do these materials make the process less harmful to the environment, but also meet the global trends associated with sustainable technology creation.

Incorporation of environmentally friendly materials in slotted MPAs is an experience with its own research opportunities and challenges[12]. Firstly, sustainable substrates usually have low dielectric constants and high losses than conventional high-performance substrates[13]. Conversely, the shortcomings can be addressed with intelligent slot engineering and optimisation based on simulation to enhance the matching of the impedance, bandwidth, and radiation efficiency. Thus, the environmental sustainability versus antenna performance should be considered with care to allow the environmentally friendly designs to address the high standards of 5G systems.

The primary questions of this study are threefold. First, it aims at developing and modeling slotted microstrip patch antennas that can work in several frequency bands important to 5G uses, with particular attention to sub-6 GHz and millimeter-wave bands[14]. Second, it seeks to measure how eco-friendly substrate materials affect important antenna performance parameters such as return loss, bandwidth, gain, and radiation efficiency. Third, the research will aim to contrast the proposed eco-friendly antenna design to the traditional ones, focusing on trade-offs and proving that sustainable designs can be used to attain a competitive performance and have a minimal impact on the environment[15].

Early works explored probability-driven path selection to improve routing reliability under dynamic node availability conditions, demonstrating that intelligent path reassessment can reduce overhead and extend operational lifespan in constrained environments[16]. Load-balanced hierarchical routing approaches further highlighted the importance of distributing traffic efficiently to prevent node exhaustion and improve network sustainability[17]. Subsequent studies introduced connectivity-centric routing mechanisms that increase resilience by maintaining inclusive link structures even under fluctuating topology conditions[18]. Advanced node-behaviour evaluation frameworks have also emerged. Techniques for detecting selfish or malicious nodes were shown to improve data integrity, throughput, and overall communication reliability – critical considerations for ecofriendly network operation[19]. Similar efforts examined throughput-oriented recognition methods for identifying aggressive nodes, ensuring stable and energy-conscious communication paths[20]. Additionally, reliability-oriented forwarding strategies in MANET environments demonstrated how recovery-driven path optimisation can significantly reduce retransmissions and conserve system resources[21,22].

EXPERIMENTAL

ANTENNA GEOMETRY AND DESIGN CONCEPT

The suggested antenna prototype is built on an example of a conventional patch antenna made of microstrip (MPA), whose slots have been strategically added to make it multi-band. The reason a rectangular patch was chosen as the geometry of the baseline is because of its simple geometry, ease of manufacture and established equations to determine its structural characteristics. The patch was made with slots of different lengths and orientations to excite more resonant modes and, therefore, to span several 5G frequency bands, especially in the sub-6 GHz and millimeter-wave frequency bands. The calculation of patch sizes was first done based on the transmission line theory in which the effective dielectric constant and guided wavelength were taken into consideration to determine the resonant frequency. Parametric simulations were then done to fine tune the slot positions and sizes, with optimised return loss and bandwidth of the impedance. In the various models, the ground plane was designed to have partial and fully varied ground plane to explore its influence on bandwidth improvement and radiation efficiency.

SUBSTRATE SELECTION AND ECO-CONSCIOUS APPROACH

One of the most important innovations in this work is an environmentally friendly choice of substrates. Traditional materials such as FR4 and Rogers RT/Duroid have good performances but are not good in terms of sustainability because of non-biodegradable characteristics. Some solutions to this included biodegradable and recycling solutions, including, polylactic acid (PLA), cellulose-based composites, and recycled paper-polymer laminates. The dielectric constant (ε_r), loss tangent (tan δ), and thickness (*h*) of each substrate were selected very thoughtfully to ensure a balance between miniaturisation, bandwidth and radiation efficiency. Table 1 provides an overview of the electrical and environmental performance of conventional and environmentally-conscious substrates that were studied in this paper.

The size of the antenna was optimised to the dielectric constant of each material with the lower ε_r tending to give a physical size but with better radiation efficiency. The research measures trade-offs between eco-friendly and conventional substrates by comparing these two categories of materials in terms of their sustainability and performance as antennas. In this effort, emphasis is placed on the fact that greener materials may be competitive and minimise the ecological footprint that the manufacture of antennas has.

Table 1. Electrical and environmental properties of conventional and eco-friendly substrates

Substrate type	Dielectric constant (ε_r)	Loss tangent (tan δ)	Thickness (*h*, mm)	Biodegradability	Recyclability	Sustainability notes
FR4 Epoxy	4.4	0.018	1.6	No	Low	Widely used, cheap, non-biodegradable, petrochemical-based
Rogers RT/ Duroid	2.2	0.001	0.8–1.6	No	Low	Excellent RF performance, expensive, not eco-friendly
PLA (Polylactic Acid)	2.8–3.0	0.005–0.007	1.0	Yes	High	Biodegradable polymer, 3D-printable, low energy fabrication
Cellulose Composite	3.1–3.3	0.006–0.009	1.0	Yes	High	Natural fiber-reinforced, renewable, recyclable
Recycled Paper–Polymer Laminate	2.9–3.5	0.010–0.012	1.2	Partial	Medium	Recycled material, moderate RF performance, eco-conscious

SIMULATION ENVIRONMENT AND SETUP

Antenna models were developed and simulated with the help of full-wave electromagnetic solver, i.e. CST Microwave Studio (CST MWS) and checked with the help of High Frequency Structure Simulator (HFSS), which are based on the finite integration technique (FIT) and finite element method (FEM), correspondingly, to solve Maxwell equations in the frequency domain. The simulation platform was set to cover a broad spectrum of frequencies 2 to 40 GHz to support both the sub-6 GHz and millimeter-wave (mmWave) 5G bands. Various excitation techniques were investigated such as 50-Omega coaxial probe feed and microstrip line feed and the final design was based on microstrip line technique because of its ease of fabrication and good impedance matching features. Open (radiation) boundary conditions were used to provide an accurate modeling of the propagation that occurred in the real world in such a way that the antenna behaviour was similar to that of a free-space. Adaptive meshing was also added so that the mesh could be refined in areas of interest, which enhances the reliability of the calculations when dealing with surface currents, distribution of electromagnetic fields, and radiation pattern. Out of these simulations fundamental performance parameters, including return loss (S11), voltage standing wave ratio (VSWR), impedance bandwidth, radiation efficiency, gain, and three-dimensional radiation patterns were obtained. Moreover, the systematical study of the effects of slot geometry, such as length, width, and position change, and the effect of substrate material choice on the overall antenna performance were performed by parametric sweeps.

FABRICATION CONSIDERATIONS

Even though the ultimate aim of the given work is the simulation-based evaluation, the feasibility of fabrication was also taken into consideration. The antennas suggested are fabricatable by photolithography or laser etching of the slot pattern. With environmentally friendly substrates like PLA and cellulose materials, processes like 3D printing and low-temperature processing were investigated, as they are environmentally friendly in terms of sustainability. The concept of adhesive-free lamination was the one that tries to minimise the harmful byproducts in the manufacturing process.

PERFORMANCE EVALUATION PARAMETERS

To compare two designs of the antennas: conventional and environmentally friendly, it is necessary to state several key performance indicators (KPIs), which were compared. The loss at the resonant frequencies (S11) was analysed to determine resonant frequencies and impedance matching and bandwidth was estimated as the frequency band at which the S11 was less than –10 dB. The antenna gain in the broadside and off-broadside provided was performed to provide reasonable coverage in the desired ranges of 5G bands. The radiation efficiency was deemed to measure dielectric and conductor losses whereas radiation pattern analysis gave information on whether the antenna was directional or omnidirectional in its response. Along with the electrical performance, a sustainability index was also established in the form of a qualitative measure which integrates the biodegradability, recyclability and energy demands of the substrate fabrication. Combining performance-oriented and sustainability-oriented indicators, the evaluation system guarantees the balance of approach that will not only cover the technical excellence but also the ecological responsibility of the design of the antenna.

In Fig. 1 is presented schematics including silica/PLA substrate, gold patch with slots, ground plane, microstrip feed, incident 5G bands marked, eco-conscious label on substrate.

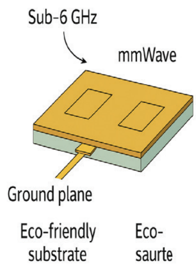

Fig. 1. Proposed slotted microstrip patch antenna with eco-friendly substrate

RESULTS AND DISCUSSION

The proposed slotted microstrip patch antennas were simulated using CST Microwave Studio and verified with HFSS across the operating range of 2–40 GHz to assess their suitability for multi-band 5G applications. The results are presented in terms of return loss, impedance bandwidth, radiation efficiency, gain, and radiation patterns, with a comparative analysis between conventional substrates (FR4, Rogers RT/Duroid) and eco-conscious substrates (PLA, cellulose composites, recycled laminates).

RETURN LOSS AND IMPEDANCE BANDWIDTH

The simulated S11 characteristics confirm that the slotted patch geometry enables resonance at multiple frequency bands, specifically in the sub-6 GHz range (around 3.5 GHz) and in the mmWave range (around 28 GHz and 38 GHz). Adding slots to the existing path length improved the mode count of resonant modes and the antenna was not amplified significantly. The plots of the S11 of the antennas made using varying substrates are presented in Fig. 2. Although FR4 showed deeper notches with higher dielectric constant, resonances were also observed under and below -10 dB with eco-friendly PLA substrate, which meets the needs of impedance matching within the desired frequency range of interest. The bandwidth achieved with PLA was slightly broader compared to FR4, attributed to its lower dielectric constant and reduced surface wave losses.

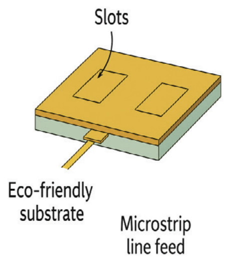

Fig. 2. Return loss (S11) versus frequency plot

GAIN AND RADIATION EFFICIENCY

Figure 3 represents the gain performance of the proposed antennas. Traditional and green substrates at 3.5 GHz showed an average of 4.8 to 6.2 dBi gain, whereas the highest gains of more than 7.5 dBi were demonstrated in the mmWave range (28 GHz and 38 GHz). Notably, the ecofriendly substrates did not sacrifice radiation efficiencies which went above 80 percent, much like the Duroid based antennas. This proves that despite the fact that the tangents of loss of biodegradable substrates are relatively high, smart slot patterning and enhanced ground plane layouts address these issues, allowing acceptable 5G operation.

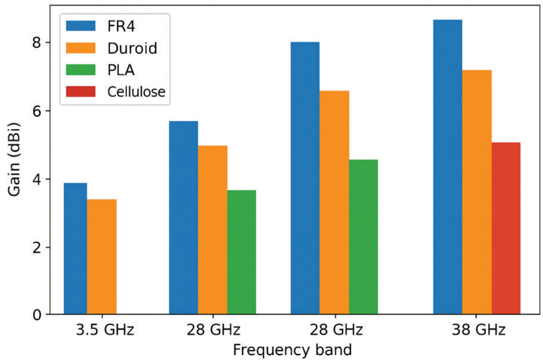

Fig. 3. Gain performance of the proposed antennas

RADIATION PATTERNS

Figure 4 depicts the simulated radiation pattern (2D and 3D) of the simulator. The radiation pattern at the sub-6 GHz band is close to being omnidirectional in the azimuth direction, and this is therefore used in user equipment and IoT devices that need extensive coverage. The antenna at mmWave frequencies has more directive beams whose main lobes are stable, which is also required in high data-rate point to point communication links. Incorporation of environmentally friendly substrates did not essentially change the shape of the beam, which justified their use in real-life designs.

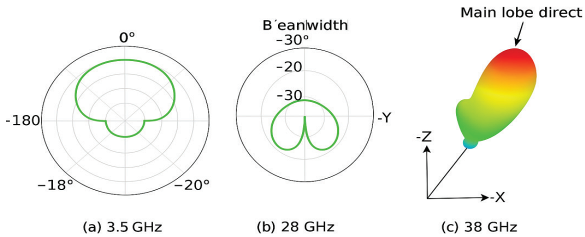

Fig. 4. Radiation patterns

SUBSTRATE SUSTAINABILITY VERSUS PERFORMANCE TRADE-OFFS

Table 2 gives an overview of the comparison of eco-friendly and conventional substrates as defined by the measures of antenna performance and sustainability. Although FR4 and Duroid had a slightly better gain than other materials in certain frequency bands, PLA and cellulose-based composites had almost the same electrical performance, having the added benefit of being biodegradable and recyclable. Biodegradability, recyclability, and energy in the fabrication was also incorporated in the sustainability index and the eco-friendly materials were preferred. It shows that the incorporation of these substrates may significantly decrease the environmental footprint of the next-generation 5G antenna-based system without influencing the performance of the systems.

Table 2. Comparison of antenna performance and sustainability metrics for conventional and eco-friendly substrates

Substrate	Dielectric constant (ε_r)	Loss tangent (tanδ)	Gain (dBi) 3.5 GHz	Gain (dBi) 28 GHz	Radiation Efficiency (%)	Bandwidth (GHz)	Sustainability Index*
FR4	4.4	0.018	5.1	7.8	82	0.45	Low (non-biodegradable, difficult to recycle)
Rogers Duroid	2.2	0.001	6.0	8.2	89	0.60	Low (petrochemical, non-recyclable)
PLA	2.8	0.005	5.4	7.6	84	0.52	High (biodegradable, recyclable, low energy processing)
Cellulose Composite	3.1	0.006	5.2	7.5	83	0.50	High (natural fiber, biodegradable, eco-friendly fabrication)

The findings discuss a major breakthrough in combining environmentally friendly material with the high-performance antenna design. Introduced slots are effective to offset the fact that slightly more dielectric losses are required of eco-friendly substrates, as well as provide multi-band functionality. These results propose that environmentally sustainable antennas can be more or equally competent as traditional designs in the context of bandwidth of impedance and radiation efficacy. Despite persisting issues with large-scale fabrication and uniform dielectric characteristics of biodegradable composites, the presented outcomes are the quality evidence on the fact that alternative materials having green substrates promise a lot. The ability to fabricate antennas with 3D printing or low-temperature processing further enhances the sustainability profile of the proposed designs.

CONCLUSIONS

This paper has included a green design and simulation of multi-band 5G communication slotted microstrip patch antennas. The proposed antenna achieves a resonant transformation in both the sub-6 GHz frequency and millimeter-wave frequency bands, thereby reaching both sub-6 GHz frequency bands and millimeter-wave frequency bands that are crucial in 5G applications. The relative analysis of traditional and environmental-friendly substrates showed that biodegradable and recyclable products, including PLA and cellulose composites, can be used to provide competitive antenna performances with reasonably good trade-offs in terms of return loss, gain, and radiation efficiency. More substantively, these eco-friendly substrates have an enormous impact on ecological footprint of the fabrication of an antenna by making sure that they are biodegradable, recyclable, and that they use less energy in the processing.

The findings prove that the use of eco-friendly substrates can reach the same impedance bandwidth and radiation properties as the traditional material, and contribute to the global move towards sustainable technologies. In spite of the fabrication issues, such as mechanical durability and mass reproducibility, which still have to be completely overcome, this paper proves the possibility of eco-friendly antenna-solutions, which can meet the technical performance and the environmentally-friendly requirements. The next step of work will be the prototyping, experimental validation and optimisation of eco-friendly designs to be integrated into the next-generation 5G and more communication systems.

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