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Article

Design and Optimization of a Wearable Microstrip Patch Antenna for 28 GHz 5G Applications

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Abstract: This article focuses on optimizing the design of a wearable microstrip antenna tailored for 5G applications, specifically operating at 28 GHz. A comprehensive review of the relevant literature was conducted to explore various types of wearable antennas and their corresponding design methodologies. Based on these insights, an optimized antenna was developed to surpass the performance of the baseline design. The enhancement process involved systematic modifications to key design parameters, including antenna dimensions, patch geometry, slot configurations, and frequency tuning, to achieve superior operational efficiency. To evaluate and compare performance metrics, critical parameters such as gain, bandwidth, and S-parameters were analyzed. The optimized antenna exhibited a significant improvement in S-parameter values, increasing from -14 dB to -22.888 dB, while maintaining a comparable bandwidth. Additionally, the antenna demonstrated high radiation and total efficiencies of 74.53% and 74.15%, respectively, confirming its suitability for practical wearable applications. The article highlights new research opportunities in the development of wearable antennas for 5G-enabled applications, including Internet of Things (IoT) integration, health monitoring systems, and next-generation communication networks. Overall, the proposed design contributes to advancing wearable antenna technology, enhancing the performance and reliability of 5G communication systems.

Keywords: Wearable Microstrip Antenna, 5G mmWave Communication, Antenna Optimization, Radiation Efficiency.

1. Introduction

In recent years, wearable technology has garnered significant attention, driven by the growing popularity of smartwatches, fitness trackers, and other body-worn devices. As these technologies become increasingly prevalent, there is a rising demand for antennas that offer high efficiency, reliability, and optimal performance [1,2]. A wearable antenna is a compact, lightweight antenna designed to be seamlessly integrated into clothing or accessories, enabling wireless communication directly on the body. When incorporated into wearable devices or garments, such an antenna facilitates uninterrupted connectivity across various wireless communication standards [3,4].

Wearable antennas operate across a broad spectrum of frequencies, including Bluetooth, Wi-Fi, and cellular bands, depending on the application [5]. These antennas can be classified into several types, such as textile antennas, flexible antennas, and antenna arrays. Textile antennas are fabricated by embedding conductive materials, such as metallic threads or conductive polymers, into fabric, making them not only lightweight and flexible but also comfortable for prolonged wear. These antennas can be optimized to function across multiple frequency bands, including Wi-Fi and cellular networks [6,7]. Flexible antennas, on the other hand, are manufactured using thin-film substrates and other pliable materials, allowing them to conform to various surfaces while maintaining their structural integrity.

They are commonly employed in wearable devices such as smartwatches and fitness trackers, where their adaptability enables efficient operation across a range of wireless frequencies [8,9]. Additionally, antenna arrays consist of multiple antennas working in unison to enhance overall system performance. These arrays are particularly beneficial for wearable applications requiring improved signal strength and directional capabilities, making them ideal for integration into advanced wearable technologies such as smartwatches and fitness monitoring devices [10-14].

Antenna arrays can be engineered to function across a wide range of frequencies, making them highly versatile for various applications. Wearable antennas, in particular, have the potential to transform multiple industries, including healthcare, fitness, and entertainment.

- Healthcare: Wearable antennas play a crucial role in medical devices by facilitating seamless wireless communication between healthcare equipment and medical professionals. For instance, they are integral to remote patient monitoring systems, enabling real-time transmission of vital health parameters such as heart rate and blood pressure. Additionally, wearable antennas are used in medical implants, ensuring reliable data exchange between the implant and healthcare providers for continuous patient monitoring.
- Fitness: The integration of wearable antennas in fitness equipment enhances wireless communication between the device and a user’s smartphone or smartwatch. Fitness trackers utilize these antennas to transmit biometric data, including heart rate and step count, providing users with real-time feedback on their physical activity. Moreover, wearable antennas are embedded in smart clothing to monitor posture, movement, and overall performance, offering valuable insights for athletes and fitness enthusiasts.
- Entertainment: Wearable antennas also contribute significantly to the entertainment industry by enabling seamless connectivity between smart devices and entertainment systems. For example, virtual reality (VR) headsets rely on these antennas for high-speed data transmission between computers and head-mounted displays, ensuring a seamless and immersive multimedia experience with minimal latency.

The rapid advancement of 5G-enabled wearables has led to an increasing demand for antennas capable of delivering high data rates with ultra-low latency. Due to their compact size and high-frequency performance, millimeter-wave (mmWave) wearable antennas are particularly well-suited for these applications. Recent research has focused extensively on the development of mmWave wearable antennas optimized for 5G, addressing the challenges of high-frequency operation, miniaturization, and body-conformability [15,16].

Several design methodologies can be employed for mmWave wearable antennas, including slot antennas, printed monopole antennas, and microstrip patch antennas. The choice of antenna type depends on factors such as operating frequency, physical dimensions, and conformability to the human body. Microstrip patch antennas are widely used in wearable technology due to their low-profile design and inherent flexibility. They can be fabricated in various geometric shapes, including triangular, circular, and rectangular patches, while the use of advanced substrate materials such as liquid crystal polymer (LCP) enhances their flexibility and mechanical durability [16,17].

Another popular option for mmWave wearable antennas is printed monopole antennas, which offer a simple structure and low-profile design. These antennas can be implemented in different configurations, including loop antennas, inverted-F antennas, and meandering monopoles, depending on the specific application requirements [17,18]. Slot antennas, which are designed by etching a slot into a conductive surface, are also a viable choice for wearable devices due to their wide bandwidth and high gain characteristics, making them well-suited for high-frequency 5G applications.

The performance of mmWave wearable antennas is evaluated using several key metrics, including radiation pattern, gain, and bandwidth. The radiation pattern determines the antenna’s directional characteristics, while gain measures the antenna’s ability to radiate power effectively in a specific direction. Bandwidth, on the other hand, defines the frequency range over which the antenna can operate efficiently [19,20].

This research aims to develop an optimized wearable microstrip antenna operating at the mmWave band for 5G applications, specifically at 28 GHz. The primary challenge is to refine the reference design to achieve enhanced gain and bandwidth while maintaining compact dimensions suitable for wearable integration. The optimization process involves modifications to the antenna dimensions, patch structure, and slot configurations, along with fine-tuning key design parameters [18-20]. To validate the effectiveness of the proposed design, the results are systematically compared with the baseline design, ensuring significant performance improvements at the target frequency.

In the practical phase of the article, the proposed wearable antenna design is based on following [20-22], with enhancements focused on achieving optimal performance at 28 GHz. The optimization process incorporates adjustments to the antenna's geometry, material properties, and resonance frequency, ensuring that the final design meets the stringent requirements of 5G wearable applications. The final results are analyzed in terms of gain, bandwidth, and S-parameters, with a comparative evaluation against the base design to verify the effectiveness of the optimization.

2. Microstrip Design

A. Methods

This article builds upon the designs presented in [19-23], with modifications aimed at enhancing performance metrics such as gain, bandwidth, and efficiency. The antenna dimensions were systematically adjusted to achieve optimal results, and additional structural enhancements were incorporated into the physical design to improve overall performance. The CST Studio Suite (Computer Simulation Technology GmbH) was employed for both design and simulation. The antenna model was developed within the software environment, and performance parameters were iteratively refined through dimensional adjustments. Simulations were conducted to assess the impact of these modifications, ensuring that the final design meets the stringent requirements of wearable 5G applications. The results obtained were analyzed and compared with existing studies in the literature to validate the efficacy of the proposed design.

B. Design

The proposed wearable microstrip antenna is designed to operate at 28 GHz, targeting 5G communication applications. Polycarbonate was selected as the substrate material due to its suitability for wearable applications, offering a balance of mechanical flexibility and low dielectric loss. The substrate is characterized by a relative permittivity (εr) of 2.57, a loss tangent of 0.0069, and a thickness of 0.5 mm, making it an ideal candidate for conformal integration into body-worn systems. The antenna design and geometry are illustrated in Figure 1 and described in Table 1.

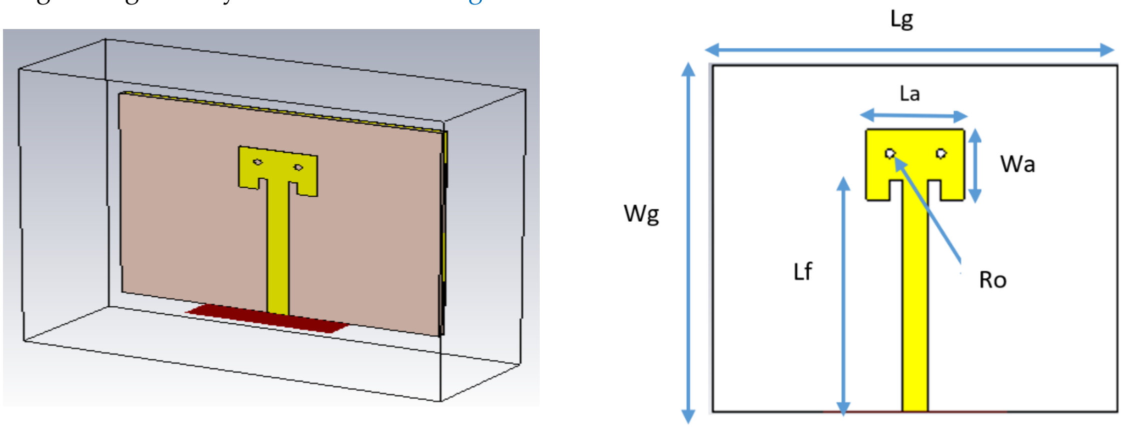


Figure 1. Wearable antenna design and parameters.

Table 1. Dimensions of Antenna (mm).

Wg	Lg	Wa	La	Wi	Li	Wf	Lf	H	Ro
15	17	3	4.25	0.831	0.45	1.444	10	0.5	0.2

The optimization process involved refining the patch dimensions to enhance the radiation characteristics. To further improve the gain, circular slots were incorporated into the patch, effectively modifying the current distribution and optimizing radiation efficiency. The proposed design was modeled and simulated in CST Studio, where various performance parameters were evaluated to ensure its effectiveness for 5G mmWave wearable applications. To address these issues, wireless control systems have emerged as a viable alternative, offering enhanced flexibility, ease of deployment, and improved operational efficiency.

3. Results and Discussion

A. Return Loss and Gain

In antenna performance evaluation, return loss quantifies the proportion of reflected signal relative to the transmitted signal, measured in decibels (dB). A well-designed antenna exhibits return losses below -10 dB, indicating efficient impedance matching and minimal signal reflection at the target frequency. The proposed wearable microstrip antenna demonstrates an S-parameter (return loss) of -22.888 dB at 28 GHz, as shown in Figure 2, signifying excellent impedance matching and reduced power reflection. Additionally, bandwidth is often analyzed using Voltage Standing Wave Ratio (VSWR) characteristics, which further confirm the antenna's ability to efficiently transmit signals within the desired frequency range.

Antenna gain is a fundamental performance metric that accounts for both directivity and electrical efficiency, measuring the antenna's ability to concentrate radiated power in a specific direction. The proposed antenna achieves a gain of 8.32 dBi at 28 GHz, which represents a significant enhancement compared to previously reported designs in the literature. This improvement suggests better energy concentration and higher radiation efficiency, making it well-suited for 5G mmWave wearable applications. The three-dimensional gain plot of the designed antenna is illustrated in Figure 3.

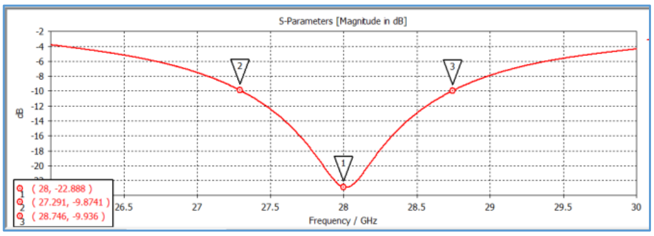


Figure 2. S-parameters/Return Losses.

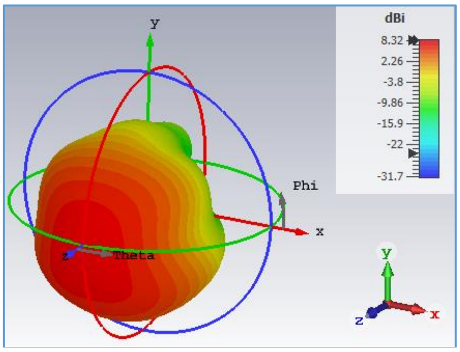
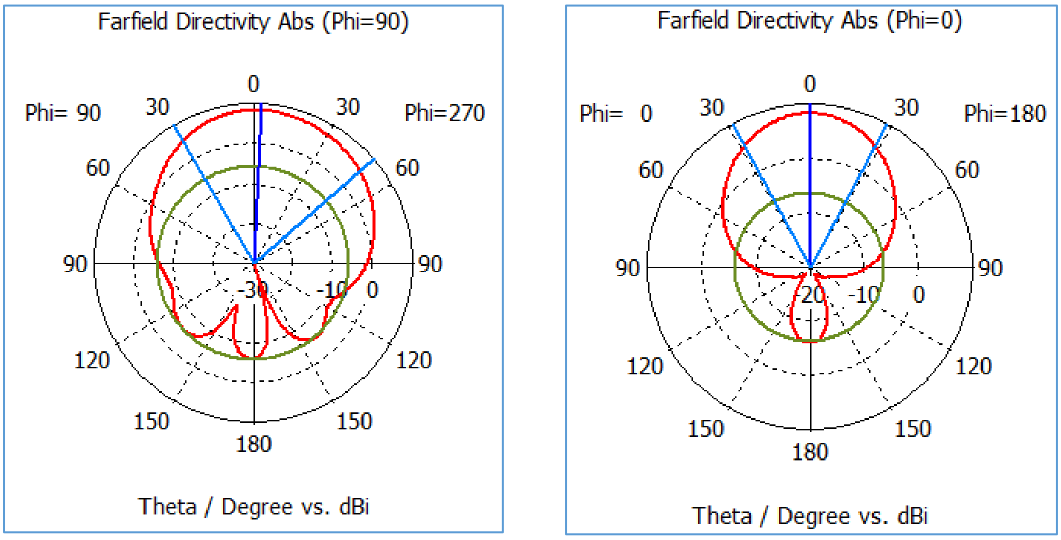


Figure 3. 3D Gain Plot of the Designed Antenna.

B. Radiation Pattern and VSWR

The radiation pattern, also known as the antenna pattern, is a graphical representation of the antenna's radiated energy distribution in space. It provides insight into how the antenna emits or receives electromagnetic waves in different directions. The radiation pattern is typically analyzed in both the E-plane and H-plane, which correspond to the electric field and magnetic field distributions, respectively. The radiation pattern plots for the designed antenna are illustrated in Figure 4(a) and Figure 4(b), representing the E-plane and H-plane radiation characteristics, respectively. These plots confirm that the proposed antenna exhibits stable and directive radiation characteristics, making it an excellent candidate for 5G wearable communication systems.



(a) (b)

Figure 4. (a) E-plane Radiation Pattern, (b) H-plane Radiation Pattern.

The Voltage Standing Wave Ratio (VSWR) is a critical parameter used to assess the impedance matching of an antenna. A VSWR value below 2 signifies minimal signal reflection and efficient power transfer between the antenna and the transmission line, ensuring optimal performance. For the proposed wearable microstrip antenna operating at 28 GHz, the VSWR value remains below 2, indicating an excellent impedance match and confirming that the antenna can effectively radiate the transmitted power without significant losses. The VSWR plot of the designed antenna is illustrated in Figure 5, demonstrating its ability to operate efficiently within the intended frequency range.

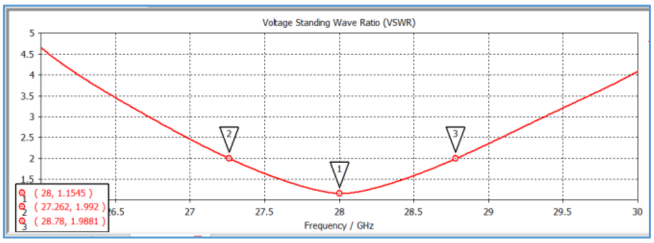


Figure 5. VSWR Plot of the Designed Antenna.

C. Summary and Comparison

The performance of the optimized wearable microstrip antenna is compared to the unoptimized design presented by following studies [21-23], as summarized in Table 2. The optimization primarily focused on enhancing the operating frequency, return loss (S-parameter), and radiation efficiency, while maintaining a similar bandwidth. The optimized antenna successfully operates at 28 GHz, achieving an improved S-parameter of -22.888 dB, compared to -14 dB in the reference design. This enhancement indicates superior impedance matching and reduced signal reflection. Additionally, the gain and VSWR remain comparable to the baseline design, with the optimized frequency ensuring more efficient signal transmission. Furthermore, the radiation and total efficiencies of the optimized antenna are measured at 74.53% and 74.15%, respectively, demonstrating its effectiveness for 5G wearable applications. These results confirm that the proposed design outperforms the reference antenna in key performance metrics while maintaining reliability for practical implementation.

Table 2. Summary results and comparison with old antenna model.

Parameter	Design Outputs	
	Other studies [21-23]	*Optimized Design*
Operating Frequency	28.36 GHz	28 GHz
Bandwidth	27.6 – 29.09 GHz	27.291-28.746 GHz
S-Parameter/Return Losses	-14 dB (at 28 GHz)	-22.888 dB (at 28 GHz)
Gain	8.86 (at 28.36 GHz)	8.32 dBi (at 28 GHz)
VSWR	1.1	1.1

The comparison between the optimized wearable microstrip antenna and the reference design by following studies [21-23] demonstrates significant improvements in key performance metrics, particularly in return loss and frequency accuracy. The optimized design precisely aligns the operating frequency at 28 GHz, ensuring better compatibility with 5G mmWave communication systems. While the bandwidth of the optimized antenna is slightly reduced (27.291 – 28.746 GHz) compared to the reference model (27.6 – 29.09 GHz), this trade-off is justified by the substantial enhancement in S-parameter performance, where the return loss improves from -14 dB to -22.888 dB. This indicates superior impedance matching and reduced signal reflection, ensuring more efficient power transmission. Additionally, the VSWR remains stable at 1.1, confirming excellent impedance characteristics and minimal energy loss.

Although the gain of the optimized design (8.32 dBi at 28 GHz) is slightly lower than that of the reference model (8.86 dBi at 28.36 GHz), the trade-off is acceptable given the improvement in return loss and impedance matching. The minor reduction in gain is compensated by the stability and efficiency of the antenna at the target frequency, making it a more reliable option for wearable 5G applications. The overall enhancements in design contribute to improved performance, efficiency, and integration capabilities, ensuring the antenna is well-suited for applications in IoT, health monitoring, and next-generation communication systems. These findings reinforce the effectiveness of the optimization approach, making the proposed antenna a strong candidate for wearable 5G mmWave communication networks.

4.Conclusion

This article presents an optimized design for a wearable microstrip antenna operating in the mmWave band at 28 GHz for 5G applications. A comprehensive review of wearable antenna technologies and design methodologies was conducted to establish a robust foundation for optimization. Based on these insights, the proposed antenna was developed and fine-tuned to surpass the performance of the baseline design. The optimization process involved modifications to antenna dimensions, patch geometry, slot configurations, and other key design parameters to enhance overall performance. The results were evaluated based on gain, bandwidth, and S-parameters, and a comparative analysis was conducted against existing research to validate the improvements. Key findings indicate that the optimized antenna achieves an S-parameter of -22.888 dB, a significant improvement over the -14 dB recorded in the reference design. Additionally, the radiation and total efficiencies were measured at 74.53% and 74.15%, respectively, confirming the antenna's efficiency for wearable 5G applications. The gain and VSWR remain consistent with the previous design while ensuring optimal operation at 28 GHz. The results of this article contribute to the ongoing advancement of 5G wearable antenna technology, paving the way for further innovations in IoT, health monitoring, and next-generation communication systems. The proposed design serves as a foundation for future research aimed at enhancing wearable antennas for high-frequency applications, ensuring improved connectivity, efficiency, and reliability in 5G-enabled wireless networks.

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