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REVIEW ON FLEXIBLE ANTENNAS FOR WEARABLE AND IOT DEVICES IN 5G COMMUNICATION

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Abstract

The rapid evolution of fifth-generation (5G) wireless communication and the Internet of Things (IoT) has accelerated the development of flexible antenna technologies capable of supporting lightweight, compact, and wearable electronic systems. Unlike conventional rigid antennas, flexible antennas can conform to curved surfaces while maintaining satisfactory electromagnetic performance under mechanical deformation. These characteristics make them suitable for applications in healthcare monitoring, wireless body area networks (WBANs), smart textiles, consumer electronics, industrial IoT, and next-generation communication systems. This paper presents a concise review of recent developments in flexible antenna technology, focusing on substrate materials, conductive elements, antenna design approaches, fabrication techniques, and performance evaluation. Furthermore, major application domains, including wearable healthcare devices, IoT systems, and 5G communication, are discussed together with current technical challenges such as body-loading effects, mechanical reliability, and fabrication complexity. Finally, emerging research



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directions involving advanced materials, additive manufacturing, artificial intelligence-assisted antenna optimization, and sixth-generation (6G) wireless systems are highlighted. This review provides researchers and engineers with an overview of current progress while identifying opportunities for future development of flexible antenna technologies.

Keywords— Flexible antenna, Wearable antenna, Internet of Things, 5G communication, Flexible electronics, Microstrip antenna.

I. INTRODUCTION

Wireless communication technologies have undergone rapid transformation with the emergence of wearable electronics, smart healthcare devices, and Internet of Things (IoT) applications. Conventional rigid antennas are often unsuitable for these systems because they cannot easily conform to curved or deformable surfaces and may experience performance degradation when integrated into flexible electronic platforms. Flexible antennas address these limitations by combining lightweight construction, mechanical flexibility, and reliable electromagnetic performance, enabling seamless integration into wearable devices, smart textiles, biomedical sensors, and compact consumer electronics. Recent advances in flexible substrate materials such as polyimide (PI), polyethylene terephthalate (PET), polydimethylsiloxane (PDMS), and textile fabrics, together with conductive materials including silver nanoparticle inks, graphene, conductive polymers, and liquid metals, have significantly enhanced antenna flexibility without compromising communication efficiency. In parallel, manufacturing technologies such as inkjet printing, screen printing, embroidery, aerosol jet printing, and additive manufacturing have enabled economical



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fabrication of compact and conformal antennas suitable for large-scale production.

Flexible antennas are now widely employed in Wireless Body Area Networks (WBANs), Radio Frequency Identification (RFID), industrial IoT, wearable healthcare monitoring, autonomous transportation, and fifth-generation (5G) communication systems. These applications require antennas capable of maintaining stable impedance characteristics, adequate bandwidth, acceptable gain, and low Specific Absorption Rate (SAR) even under repeated bending and close proximity to the human body.

Despite considerable progress, several challenges remain, including long-term mechanical reliability, environmental durability, fabrication scalability, and maintaining consistent performance under deformation. In addition, the evolution toward sixth-generation (6G) communication introduces new requirements such as terahertz operation, intelligent communication, and multifunctional wearable platforms.

This paper presents a concise review of flexible antenna technologies by summarizing recent advances in materials, antenna design, fabrication methods, performance characteristics, and practical applications. The paper also discusses current research challenges and future opportunities that are expected to shape next-generation flexible wireless communication systems.

The major contributions of this review are as follows:

- A concise overview of materials, antenna configurations, and fabrication techniques used in flexible antenna design.
- A discussion of performance parameters relevant to wearable and IoT communication systems.



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- An overview of emerging applications in healthcare, smart textiles, WBANs, IoT, and 5G communication.
- Identification of current research challenges and promising future research directions for flexible antenna technology.

II. FLEXIBLE ANTENNA TECHNOLOGIES

Flexible antenna technology integrates advanced materials, compact antenna geometries, and modern fabrication processes to achieve reliable wireless communication under mechanical deformation. Compared with conventional rigid antennas, flexible antennas maintain stable electrical performance while being bent, folded, or attached to irregular surfaces. This capability has made them suitable for wearable electronics, biomedical monitoring, Internet of Things (IoT) devices, and compact wireless communication systems.

A. Flexible Materials

Material selection strongly influences antenna performance, flexibility, durability, and manufacturing cost. An ideal flexible substrate should possess a low dielectric constant, low dielectric loss, high mechanical strength, and good thermal stability.

Polymer-based substrates such as **Polyimide (PI)**, **Polyethylene Terephthalate (PET)**, **Polydimethylsiloxane (PDMS)**, and **Polyethylene Naphthalate (PEN)** are widely adopted because they provide excellent flexibility while maintaining stable electrical characteristics. Textile materials including cotton, felt, denim, silk, and polyester are also extensively used in wearable antennas due to their comfort and ease of integration into garments.

For conductive elements, conventional copper remains popular because of its high electrical conductivity. However, printed electronics increasingly employ



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silver nanoparticle inks, conductive polymers, graphene, carbon nanotubes, MXene materials, and liquid metals to improve flexibility while reducing structural weight. These materials enable antennas to maintain acceptable conductivity under repeated bending and stretching.

TABLE I. COMPARISON OF COMMON FLEXIBLE SUBSTRATE MATERIALS

| Material | Relative Permittivity | Advantages | Typical Applications |
|----------------|-----------------------|---|----------------------|
| PI | 3.4–3.6 | High thermal stability, excellent flexibility | Wearable 5G antennas |
| PET | 2.9–3.2 | Low cost, lightweight | IoT and RFID devices |
| PDMS | 2.6–2.8 | Highly stretchable, biocompatible | Biomedical sensors |
| Textile Fabric | 1.2–1.8 | Comfortable and washable | Smart clothing |

B. Antenna Design Approaches

Microstrip patch antennas remain the preferred configuration for flexible communication systems because of their low profile, simple fabrication, and compatibility with printed electronics. Depending on the application, antennas may be designed for single-band, dual-band, multiband, or broadband operation. Performance enhancement techniques include slot loading, defected ground structures (DGS), electromagnetic bandgap (EBG) surfaces, artificial magnetic conductors (AMC), and multiple-input multiple-output (MIMO) configurations. These methods improve impedance bandwidth, radiation efficiency, isolation,



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and gain while simultaneously reducing Specific Absorption Rate (SAR) for wearable applications.

Recent investigations have also explored fractal geometries, metamaterial-inspired structures, and substrate integrated waveguide (SIW) technologies to achieve compact dimensions and improved electromagnetic performance. Such approaches are particularly attractive for emerging 5G and future 6G communication systems that require miniaturized and high-efficiency antennas.

C. Fabrication Techniques

The choice of fabrication method directly affects antenna accuracy, production cost, and mechanical reliability. Printed electronics have significantly simplified the manufacturing of flexible antennas by enabling direct deposition of conductive materials onto flexible substrates.

Among the available techniques, **inkjet printing** is widely used because it provides maskless fabrication with minimal material waste. **Screen printing** offers higher production speed and is suitable for large-scale manufacturing. **Embroidery** enables conductive threads to be integrated directly into textile fabrics, making it attractive for wearable smart clothing.

Advanced manufacturing technologies such as **laser micromachining**, **aerosol jet printing**, **three-dimensional (3D) printing**, and **roll-to-roll processing** provide improved fabrication precision and support the realization of compact, lightweight, and high-frequency antenna structures. These techniques are increasingly adopted in research and industrial production due to their compatibility with flexible electronics and additive manufacturing.

Overall, the combination of advanced materials, optimized antenna geometries, and scalable fabrication technologies has significantly improved the performance



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and manufacturability of flexible antennas, supporting their widespread adoption in wearable and IoT communication systems.

III. PERFORMANCE ANALYSIS AND APPLICATIONS

The performance of a flexible antenna is evaluated through both electromagnetic and mechanical characteristics to ensure reliable operation in wearable and Internet of Things (IoT) environments. Since these antennas are frequently subjected to bending, stretching, and twisting, their electrical performance must remain stable under various operating conditions. Key performance indicators include reflection coefficient, voltage standing wave ratio (VSWR), gain, radiation efficiency, bandwidth, and Specific Absorption Rate (SAR).

A. Performance Analysis

The reflection coefficient (**S₁₁**) is one of the primary parameters used to assess impedance matching between the antenna and the transmission line. A value below **-10 dB** is generally considered acceptable for efficient power transmission. The **VSWR** should ideally remain below **2**, indicating minimal signal reflection and effective impedance matching.

Radiation characteristics, including antenna gain and efficiency, directly influence communication range and signal quality. Flexible antennas typically exhibit gains ranging from **2 dBi to 8 dBi**, depending on their geometry, substrate material, and operating frequency. Maintaining stable radiation performance during repeated bending is particularly important for wearable devices.

For antennas operating near the human body, **Specific Absorption Rate (SAR)** is an important safety parameter. SAR measures the amount of electromagnetic energy absorbed by biological tissues. To satisfy international safety standards, wearable antennas often incorporate **Artificial Magnetic Conductors (AMC)**,



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Electromagnetic Bandgap (EBG) structures, or optimized ground planes to reduce backward radiation toward the user.

TABLE II. TYPICAL PERFORMANCE PARAMETERS OF FLEXIBLE ANTENNAS

| Parameter | Typical Value | Importance |
|------------------------------|------------------------|---|
| Reflection Coefficient (S11) | < -10 dB | Good impedance matching |
| VSWR | < 2 | Efficient power transfer |
| Gain | 2-8 dBi | Improved communication range |
| Radiation Efficiency | >70% | Reduced conductor and dielectric losses |
| SAR | Within IEEE/FCC limits | Human safety |
| Bending Radius | 5-50 mm | Mechanical flexibility |

B. Applications

Flexible antennas have become key enabling components in wearable electronics and modern wireless communication systems because of their compact size, lightweight construction, and conformal characteristics.

1) Wearable Healthcare

Flexible antennas are widely integrated into wearable medical devices for continuous monitoring of physiological parameters such as heart rate, body temperature, respiration, and blood oxygen level. These antennas support real-time transmission of health data to smartphones or cloud-based healthcare platforms, enabling remote patient monitoring and telemedicine applications.



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2) Wireless Body Area Networks (WBANs)

In WBANs, multiple wearable sensors communicate wirelessly to monitor human health and physical activity. Flexible antennas provide stable communication links while maintaining user comfort and minimizing electromagnetic exposure. Their low-profile structure allows seamless integration into wearable accessories and medical patches.

3) Internet of Things (IoT)

IoT devices require compact, energy-efficient, and reliable antennas capable of operating across multiple wireless standards. Flexible antennas are employed in smart homes, environmental monitoring systems, industrial automation, agriculture, and asset tracking due to their ease of integration into compact electronic devices.

4) Smart Textiles

The integration of conductive fabrics and embroidered antennas has enabled the development of smart clothing capable of wireless communication and sensing. These systems are increasingly used in sports performance monitoring, military communication, emergency response, and occupational safety. Washable conductive materials and improved textile manufacturing techniques continue to enhance the durability and practicality of wearable antennas.

5) 5G Communication Systems

Flexible antennas play an essential role in fifth-generation (5G) communication by supporting compact mobile terminals, wearable electronics, and high-speed wireless connectivity. Modern antenna designs employ multiband and broadband configurations to accommodate various communication standards while



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maintaining stable performance under mechanical deformation. Emerging research is extending these concepts toward **6G communication**, where intelligent beamforming, terahertz operation, and integrated sensing will require highly efficient and adaptive flexible antenna technologies.

Overall, recent advances in materials, antenna design, and fabrication have significantly expanded the application range of flexible antennas. Their ability to provide reliable wireless communication while conforming to complex surfaces makes them promising candidates for future healthcare systems, IoT networks, and next-generation wireless communication platforms.

IV. CHALLENGES AND FUTURE RESEARCH

Despite significant progress in flexible antenna technology, several challenges continue to limit its widespread deployment in wearable and Internet of Things (IoT) applications. One of the primary concerns is maintaining consistent electromagnetic performance under repeated bending, stretching, and twisting. Mechanical deformation can alter the antenna geometry, resulting in impedance mismatch, resonant frequency shifts, and reduced radiation efficiency. Consequently, improving long-term mechanical reliability remains an important research objective.

Material selection also presents a significant challenge. Although polymer substrates and conductive textiles provide excellent flexibility, they often exhibit lower electrical conductivity and higher dielectric losses than conventional rigid materials. Furthermore, environmental factors such as moisture, temperature variation, and repeated washing can affect the electrical characteristics of textile-based antennas. The development of durable conductive nanocomposites and environmentally stable flexible materials is therefore essential.



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Wearable antennas operate in close proximity to the human body, making electromagnetic interaction another critical issue. Human tissues influence antenna impedance, radiation pattern, and efficiency while increasing electromagnetic energy absorption. Advanced electromagnetic structures such as Artificial Magnetic Conductors (AMC), Electromagnetic Bandgap (EBG) surfaces, and optimized ground planes have demonstrated considerable potential for reducing body-loading effects and improving user safety.

Future research is expected to focus on multifunctional antenna systems capable of integrating communication, sensing, localization, and wireless power transfer within a single flexible platform. Artificial intelligence and machine learning techniques are increasingly being explored for antenna optimization, adaptive beamforming, and automated design. In addition, additive manufacturing, printable electronics, biodegradable substrates, and energy-harvesting technologies are anticipated to play an important role in the development of sustainable and self-powered wireless devices. These innovations are expected to support emerging sixth-generation (6G) communication systems, smart healthcare, intelligent transportation, and large-scale IoT networks.

V. CONCLUSION

Flexible antenna technology has become a key enabling solution for modern wireless communication systems due to its lightweight structure, conformal geometry, and compatibility with wearable electronic devices. This paper has presented a concise review of flexible antenna materials, design methodologies, fabrication techniques, performance evaluation, and major application areas. Recent advances in conductive materials, printed electronics, compact antenna structures, and low-cost manufacturing have significantly enhanced the performance and practical implementation of flexible antennas in wearable



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healthcare, Wireless Body Area Networks (WBANs), Internet of Things (IoT) devices, smart textiles, and fifth-generation (5G) communication systems.

Although substantial progress has been achieved, challenges associated with mechanical reliability, human-body interaction, environmental durability, and large-scale manufacturing remain active research topics. Future developments involving advanced nanomaterials, artificial intelligence-assisted antenna optimization, additive manufacturing, and energy-harvesting technologies are expected to further improve antenna performance while supporting the requirements of future 6G communication systems. Ongoing research in these areas will facilitate the development of compact, reliable, and intelligent flexible antennas for next-generation wireless applications.

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