

Conducting Polymer-Based Textile Microstrip Patch Antennas: A Comprehensive Review of Materials, Fabrication Techniques, Performance Characteristics, and Sensing Applications

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Abstract - The advancement of wearable electronics and body-centric wireless communication systems has necessitated the development of flexible, lightweight, and conformal antenna structures. Conducting polymer-based textile microstrip patch antennas have emerged as promising alternatives to conventional metallic antennas due to their inherent mechanical flexibility, low weight, and compatibility with soft substrates. This review presents a comprehensive and technically detailed analysis of conducting polymer-integrated textile antennas, focusing on material properties, electromagnetic performance, fabrication techniques, and sensing capabilities. Various conducting polymers, including polyaniline (PANI), polypyrrole (PPy), polythiophene (PT), and PEDOT:PSS, are critically evaluated in terms of electrical conductivity, surface impedance, and RF performance metrics such as gain, efficiency, and bandwidth. Textile substrates such as cotton, polyester, and denim are analyzed based on dielectric properties and environmental sensitivity. The review further explores fabrication methodologies, including dip coating, inkjet printing, and screen printing, and their impact on antenna performance. Additionally, antenna-based sensing mechanisms and associated signal processing algorithms are discussed to highlight their role in wearable biosensing systems. The study provides a consolidated understanding of the trade-offs and design considerations necessary for developing efficient and reliable textile antenna systems.

Keywords - Microstrip patch antenna, Conducting polymers, Textile antennas, Flexible electronics, RF sensing, Wearable systems.

I. INTRODUCTION

The rapid proliferation of wireless technologies, particularly in the domains of wearable electronics, Internet of Things (IoT), and biomedical monitoring systems, has significantly influenced antenna design methodologies. Conventional antenna structures, typically fabricated using rigid metallic conductors on dielectric substrates such as FR-4 or Rogers laminates, are not suitable for applications requiring mechanical flexibility and conformability [1], [2]. This limitation has driven extensive research into alternative materials and fabrication techniques capable of supporting flexible and wearable antenna systems. Microstrip patch antennas (MPAs) have been widely adopted due to their low-profile structure, ease of integration with electronic circuits,

and planar geometry. However, their performance is inherently constrained by narrow bandwidth, moderate gain, and fixed structural rigidity [3]. To address these limitations, researchers have explored the integration of unconventional materials such as conducting polymers and textile substrates, enabling the realization of flexible antenna systems that can conform to non-planar surfaces and withstand mechanical deformation.

Conducting polymers represent a unique class of materials that combine electrical conductivity with mechanical flexibility. Unlike conventional metals, their conductivity can be tuned through chemical doping and structural modifications, allowing dynamic control over electromagnetic properties [4]. Materials such as PANI, PPy, PT, and PEDOT:PSS have demonstrated potential in RF and microwave applications, particularly when integrated with flexible substrates. Simultaneously, textile materials have emerged as viable dielectric substrates for wearable antennas. Fabrics such as cotton, polyester, and denim offer low dielectric constants, lightweight characteristics, and user comfort, making them suitable for body-worn applications [5]. The integration of conducting polymers onto textile substrates enables the development of fully flexible antenna systems capable of maintaining performance under bending, stretching, and environmental variations.

II. MICROSTRIP PATCH ANTENNAS: FUNDAMENTAL PRINCIPLES

Microstrip patch antennas are planar resonant structures consisting of a metallic patch printed on a dielectric substrate with a ground plane on the opposite side. The operation of MPAs is based on the formation of standing electromagnetic waves within the patch structure, where radiation occurs due to fringing fields at the edges of the patch [6]. The resonant frequency of a rectangular microstrip patch antenna is primarily determined by its physical dimensions and the effective dielectric constant of the substrate. The effective dielectric constant accounts for the fringing fields extending into the surrounding air, resulting in a slightly lower value than the actual substrate permittivity. The resonant behavior can be approximated using cavity model theory, where the

patch is treated as a resonant cavity bounded by electric and magnetic walls.

Although MPAs offer several advantages, including low profile and ease of fabrication, they suffer from inherent limitations such as narrow impedance bandwidth, typically in the range of 2–5%, and moderate gain levels between 5–8 dBi [7]. These limitations are primarily attributed to surface wave losses, dielectric losses, and limited radiation efficiency. To overcome these challenges, various techniques have been proposed, including slot loading, stacked patch configurations, and the use of parasitic elements. More recently, material-based approaches involving tunable conductors and substrates have gained attention, enabling dynamic control of antenna characteristics without significant structural modifications.

III. CONDUCTING POLYMERS IN RF AND MICROWAVE ANTENNA DESIGN

Conducting polymers are organic materials characterized by conjugated π -electron systems that enable electrical conductivity through charge delocalization. Unlike conventional metallic conductors, their electrical properties can be modulated through doping, molecular alignment, and processing conditions [8]. Among the commonly studied conducting polymers, polyaniline (PANI) is known for its relatively high conductivity and environmental stability. However, its processability and mechanical flexibility are limited compared to other polymers. Polypyrrole (PPy) offers moderate conductivity but suffers from poor mechanical robustness and environmental degradation under prolonged exposure. Polythiophene (PT) exhibits better flexibility but relatively lower conductivity. PEDOT:PSS has emerged as one of the most promising conducting polymers for RF applications due to its high conductivity, excellent processability, and compatibility with solution-based fabrication techniques. The conductivity of PEDOT:PSS can be significantly enhanced through secondary doping using solvents such as dimethyl sulfoxide (DMSO) and ethylene glycol (EG), which improve polymer chain alignment and reduce insulating barriers [9].

TABLE I. Electrical and RF Performance of Conducting Polymers

Polymer	Conductivity (S/cm)	Surface Resistance (Ω /sq)	Gain (dBi)	Efficiency (%)	Bandwidth (MHz)
PANI	10^2 – 10^3	10–50	2.5–3.2	60–70	80–120
PPy	10 – 10^2	20–80	2.0–2.8	55–65	70–110
PT	10 – 10^2	15–60	2.8–3.5	65–75	100–150
PEDOT:PSS	10^3 – 10^4	5–20	3.5–5.5	70–85	120–250

The performance of conducting polymer-based antennas is evaluated using several key electromagnetic parameters, including return loss (S_{11}), gain, radiation efficiency, and bandwidth. The conductivity of the radiating element plays a crucial role in determining these parameters, as lower conductivity leads to increased ohmic losses and reduced radiation efficiency [10]. The return loss (S_{11}) indicates the impedance matching between the antenna and the feed line, with values below –10 dB considered acceptable for most applications. Conducting polymer antennas typically achieve S_{11} values in the range of –15 dB to –25 dB, depending on material properties and fabrication quality. Gain and efficiency

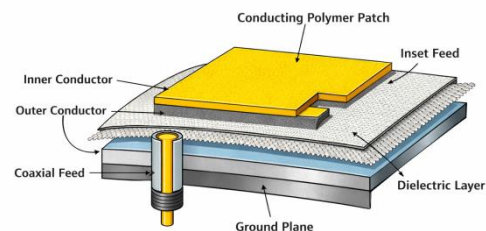
are influenced by both material conductivity and substrate characteristics. While conducting polymers exhibit lower conductivity compared to metals, their integration with low-loss textile substrates can compensate for these limitations by improving radiation characteristics.

IV. TEXTILE SUBSTRATES FOR FLEXIBLE ANTENNAS

Textile materials serve as dielectric substrates in wearable antenna systems, providing mechanical flexibility and user comfort. Among the various textile options, cotton is widely used due to its low dielectric constant, typically in the range of 1.6–1.8, and moderate loss tangent of 0.02–0.05 [11]. Polyester and denim are also commonly used, offering slightly higher dielectric constants and improved mechanical durability. The dielectric properties of textile substrates are influenced by factors such as weave structure, thickness, and moisture content.

TABLE II. Dielectric and Mechanical Properties of Textile Substrates

Material	ϵ_r	$\tan\delta$	Thickness (mm)	Gain (dBi)	Efficiency (%)
Cotton	1.6–1.8	0.02–0.05	0.5–1.0	3–5	70–85
Polyester	1.9–2.2	0.01–0.03	0.3–0.8	3.5–6	75–88
Denim	1.7–2.0	0.03–0.05	0.6–1.0	2.5–4.5	65–75



Textile-Based Microstrip Patch Antenna Structure

Fig. 1: Schematic of textile-based microstrip patch antenna structure

V. FABRICATION TECHNIQUES FOR CONDUCTING POLYMER TEXTILE ANTENNAS

The fabrication process of conducting polymer-based textile antennas is a critical determinant of their electromagnetic performance, mechanical durability, and reproducibility. Unlike conventional metallic antennas, which rely on subtractive processes such as etching, textile antennas require additive and low-temperature fabrication techniques compatible with flexible and porous substrates. The interaction between conducting polymer inks and textile fibers significantly influences coating uniformity, adhesion, and surface conductivity, thereby affecting RF characteristics such as impedance matching and radiation efficiency [12]. Dip coating is one of the most widely used fabrication techniques for textile antennas, particularly for natural fibers such as cotton. In this process, the textile substrate is immersed in a conducting polymer solution, allowing the polymer to infiltrate the porous fiber network through capillary action. The

withdrawal speed and solution viscosity govern the thickness and uniformity of the deposited film. Multiple coating cycles are often required to achieve the desired conductivity, typically in the range of 800–1200 S/cm for PEDOT:PSS-based coatings after secondary doping [13]. The primary advantage of dip coating lies in its simplicity and ability to achieve strong adhesion between the polymer and textile fibers. However, the technique suffers from limited control over pattern definition and thickness uniformity. Screen printing is another widely adopted method, particularly for large-area and scalable fabrication. In this technique, a patterned mesh is used to deposit conducting polymer paste onto the textile substrate. Screen printing allows precise control over antenna geometry, including patch dimensions and feed lines, making it suitable for reproducible antenna fabrication. The rheological properties of the ink, including viscosity and surface tension, play a crucial role in determining print quality. Despite its scalability, the resolution is limited compared to other techniques, and surface roughness of textiles can lead to non-uniform deposition [14]. Inkjet printing has emerged as a highly promising technique for high-resolution and material-efficient fabrication of flexible antennas. It enables digital patterning of conducting polymer inks with micrometer-scale precision, making it suitable for compact antenna designs. The droplet-based deposition mechanism allows fine control over film thickness and geometry. However, challenges such as nozzle clogging, ink stability, and substrate wetting behavior must be addressed to ensure consistent performance [15]. Spray coating offers a rapid and scalable approach for depositing thin conductive films over large areas. The atomization of polymer solutions allows uniform coverage, but process parameters such as spray distance, pressure, and solvent evaporation rate must be carefully controlled to avoid thickness non-uniformity and defects. Post-processing techniques, including thermal annealing and solvent treatment, significantly enhance electrical conductivity. Thermal annealing at temperatures between 80°C and 150°C promotes polymer chain alignment and removes residual solvents, reducing surface resistance. Secondary doping using solvents such as DMSO or ethylene glycol further improves conductivity by facilitating phase separation and enhancing charge transport pathways [16].

TABLE III. Quantitative Comparison of Fabrication Techniques

Technique	Typical Conductivity (S/cm)	Thickness Control (μm)	Resolution (μm)	Cost	Scalability
Dip Coating	500–1200	10–50	Low (>500)	Low	High
Screen Printing	800–1500	5–30	Medium (100–300)	Low	Very High
Inkjet Printing	600–1200	1–10	High (20–50)	Medium	Medium
Spray Coating	400–1000	5–40	Low (>300)	Low	High

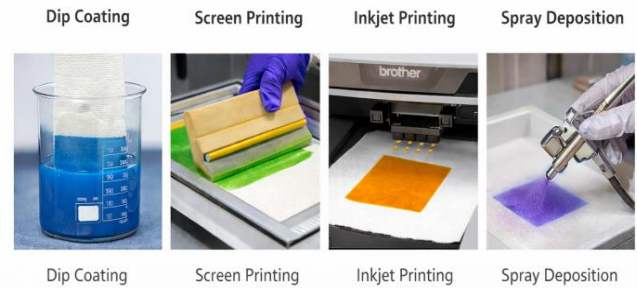


Fig. 2: Schematic illustration of fabrication techniques: dip coating, screen printing, ink-jet printing, and spray deposition.

VI. COMPARATIVE REVIEW OF CONDUCTING POLYMER-BASED TEXTILE ANTENNAS

A comprehensive review of reported literature reveals that the performance of conducting polymer-based textile antennas is strongly influenced by the interplay between material properties, substrate characteristics, and fabrication techniques. Several studies have demonstrated the feasibility of replacing metallic conductors with conducting polymers while maintaining acceptable RF performance for wearable applications [17]. Antennas fabricated using PANI on cotton substrates typically exhibit moderate gain values in the range of 2.5–3.5 dBi and radiation efficiency between 60% and 70%. While PANI offers reasonable conductivity, its environmental stability and mechanical durability under repeated bending are relatively limited [18]. In contrast, PPy-based antennas show slightly lower gain and efficiency due to higher surface resistance, although they provide better flexibility. PEDOT:PSS-based antennas have demonstrated superior performance among conducting polymers, with gain values ranging from 3.5 to 5.5 dBi and efficiency exceeding 80% in optimized designs. The improved performance is attributed to higher conductivity and better film uniformity achieved through solution processing techniques [19]. The choice of textile substrate also plays a significant role in determining antenna performance. Cotton substrates, due to their low dielectric constant, enable wider bandwidth and improved radiation efficiency. However, their moisture sensitivity can lead to variations in dielectric properties, affecting antenna stability. Polyester substrates, on the other hand, offer better environmental stability but slightly higher dielectric constants, which may reduce bandwidth [20].

TABLE IV. Comparative Analysis of Reported Textile Antennas

Polymer	Substrate	Frequency (GHz)	Gain (dBi)	Efficiency (%)	Bandwidth (MHz)	S ₁₁ (dB)
PANI	Cotton	2.45	3.1	68	110	-18
PPy	Polyester	2.4	2.6	62	95	-16
PEDOT:PSS	Cotton	2.45	4.8	82	210	-22
PEDOT:PSS	Denim	5.8	4.2	78	180	-20

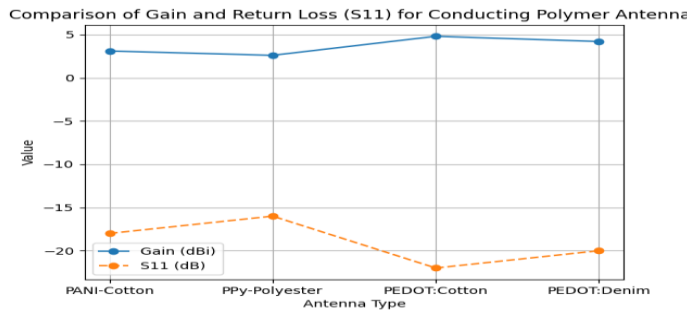


Fig. 3: Comparison of radiation patterns and return loss characteristics for different conducting polymer antennas.

VII. APPLICATION DOMAINS OF TEXTILE CONDUCTING POLYMER ANTENNAS

Conducting polymer-based textile antennas have found applications across multiple domains due to their flexibility, lightweight nature, and compatibility with wearable platforms. In wearable healthcare systems, these antennas are integrated into garments for continuous monitoring of physiological parameters such as heart rate, respiration, and body temperature. The ability to operate in close proximity to the human body while maintaining stable performance is a key requirement in such applications [21]. In body area networks (BANs), textile antennas enable seamless communication between sensors distributed across the body. The flexibility of conducting polymer-based antennas ensures consistent performance under dynamic conditions, including bending and movement. These systems typically operate in the 2.4 GHz ISM band, requiring compact and efficient antenna designs. The Internet of Things (IoT) represents another significant application area, where textile antennas are used in smart clothing and connected devices. The integration of antennas into fabrics enables unobtrusive communication, enhancing user convenience and system functionality [22]. Defense and military applications also benefit from textile antennas, particularly in wearable communication systems for soldiers. These antennas provide reliable communication while minimizing weight and maintaining flexibility. Additionally, textile antennas are being explored for RF identification (RFID) systems and energy harvesting applications, where their conformal nature and low cost offer significant advantages.

TABLE V. Application-Oriented Performance Requirements

Application	Frequency (GHz)	Gain (dBi)	Efficiency (%)	Key Requirement
Wearable Healthcare	2.4-2.5	2-5	70-85	Flexibility, low SAR
BAN Systems	2.4-5	3-6	75-88	Stability under motion
IoT Devices	2.4 / 5.8	3-7	70-90	Low cost, compact
Military	1-6	5-8	80-90	Durability
RFID	0.9-2.4	1-3	60-75	Low power



Fig. 4: Illustration of application scenarios: wearable healthcare, IoT smart textiles, and body area networks.

VIII. PERFORMANCE LIMITATIONS AND PRACTICAL CONSIDERATIONS

Despite the promising performance of conducting polymer-based textile antennas, several practical challenges must be addressed for real-world deployment. One of the primary limitations is the relatively lower electrical conductivity of conducting polymers compared to conventional metals. This results in increased ohmic losses, which can reduce radiation efficiency and gain [23]. Environmental factors such as humidity, temperature, and mechanical deformation also influence antenna performance. Textile substrates, particularly cotton, exhibit moisture absorption, leading to variations in dielectric constant and detuning of the resonant frequency. Experimental studies have reported frequency shifts of approximately 2-5% under high humidity conditions [24]. Mechanical deformation, including bending and stretching, can alter the current distribution and impedance characteristics of the antenna. While conducting polymers provide flexibility, repeated mechanical stress may lead to micro-cracks and degradation of electrical performance over time. Encapsulation techniques using polymer coatings have been proposed to enhance durability and environmental stability [25]. Another important consideration is the reproducibility of fabrication processes. Variations in coating thickness, ink composition, and substrate properties can lead to inconsistencies in antenna performance. Therefore, process optimization and standardization are essential for large-scale manufacturing.

TABLE VI. Quantitative Impact of Environmental Factors

Parameter	Condition	Frequency Shift (%)	Efficiency Change (%)
Humidity	20% → 80% RH	2-5	-5 to -10
Bending Radius	Flat → 30 mm	1-3	-3 to -7
Temperature	25°C → 60°C	1-2	-2 to -5

IX. MICROWAVE SENSING MECHANISMS USING TEXTILE PATCH ANTENNAS

Textile-based microstrip patch antennas have increasingly been explored as dual-function devices capable of both wireless communication and sensing. The sensing capability arises from the inherent dependence of antenna electromagnetic behavior on the surrounding dielectric environment. Any perturbation in the effective permittivity or conductivity near the antenna structure leads to measurable variations in key RF parameters such as resonant frequency,

return loss (S_{11}), and impedance characteristics [26]. The sensing mechanism is fundamentally governed by electromagnetic field interaction between the antenna and the surrounding medium. When the antenna is exposed to external stimuli such as humidity, mechanical strain, or biological tissues, the effective dielectric constant (ϵ_{eff}) of the system changes. This variation alters the stored electric and magnetic energy within the antenna structure, leading to a shift in resonant frequency. For example, an increase in moisture content in a cotton substrate increases ϵ_{eff} , resulting in a downward shift in resonant frequency.

In wearable biosensing applications, textile antennas are often placed in close proximity to the human body, where variations in tissue properties such as hydration level, glucose concentration, or sweat composition influence antenna performance. These interactions enable non-invasive monitoring of physiological parameters through RF measurements. The sensitivity of the antenna can be enhanced by optimizing substrate properties, antenna geometry, and conducting polymer characteristics. Conducting polymers further contribute to sensing functionality due to their tunable electrical properties. Changes in environmental conditions such as temperature, pH, or chemical exposure can modify the conductivity of the polymer layer, thereby influencing current distribution and impedance. This dual sensitivity to dielectric and conductive variations makes conducting polymer-based textile antennas highly suitable for multifunctional sensing applications.

TABLE VII. Quantitative Sensing Response of Textile Antennas

Parameter	Stimulus	Observed Shift	Sensitivity
Resonant Frequency	Humidity (20–80% RH)	50–120 MHz	~1.5 MHz/%RH
Return Loss (S_{11})	Sweat presence	3–8 dB variation	Moderate
Frequency Shift	Bending (radius 20–50 mm)	20–60 MHz	Low–Moderate
Impedance	Temperature (25–60°C)	5–10 Ω change	Moderate

computational techniques. The measured RF parameters, including S_{11} , resonant frequency, and phase response, are typically acquired using vector network analyzers or embedded RF modules. These raw measurements must be processed to identify patterns and correlate them with specific sensing conditions [27]. In basic sensing systems, threshold-based detection methods are employed, where predefined limits are used to identify the presence or absence of a stimulus. While this approach is computationally simple, it lacks robustness in noisy environments and cannot handle complex variations in sensor response.

To achieve quantitative sensing, regression-based techniques are widely used. Linear and polynomial regression models establish relationships between RF parameters and environmental variables such as humidity or strain. These models are particularly effective for applications where the response exhibits a predictable trend.

More advanced sensing systems employ machine learning algorithms to improve accuracy and adaptability. Supervised learning techniques such as Support Vector Machines (SVM), Artificial Neural Networks (ANN), and k-Nearest Neighbors (KNN) are commonly used for classification and prediction tasks. These algorithms can handle nonlinear relationships and complex patterns, making them suitable for multi-parameter sensing applications [28]. Frequency-domain analysis using Fast Fourier Transform (FFT) enables precise detection of frequency shifts, while digital filtering techniques are used to remove noise and enhance signal quality. In real-time wearable systems, lightweight algorithms are implemented on embedded processors to enable on-device analysis and wireless data transmission.

TABLE VIII. Algorithmic Techniques for Antenna-Based Sensing

Algorithm	Application	Accuracy (%)	Computational Complexity
Threshold Detection	Presence sensing	70–80	Low
Linear Regression	Humidity/strain estimation	80–88	Low
ANN	Pattern recognition	90–96	High
SVM	Classification	88–94	Medium
FFT Analysis	Frequency tracking	>95	Medium

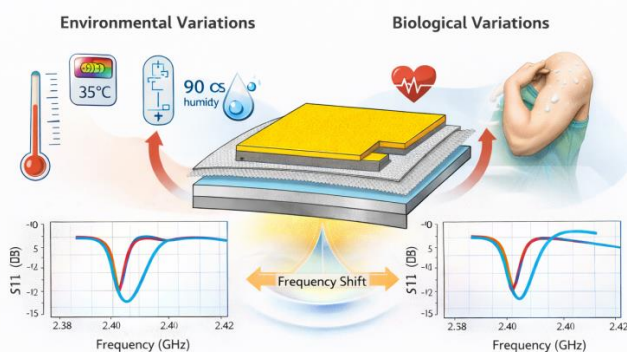


Fig. 5: Conceptual illustration of sensing mechanism showing frequency shift due to environmental and biological variations.

X. SIGNAL PROCESSING AND ALGORITHMS FOR ANTENNA-BASED SENSING

The extraction of meaningful information from antenna-based sensing systems requires robust signal processing and

XI. INTEGRATION OF SENSING AND COMMUNICATION SYSTEMS

One of the most significant advantages of conducting polymer-based textile antennas is their ability to integrate sensing and communication functionalities within a single platform. This integration reduces system complexity, minimizes power consumption, and enables compact wearable devices suitable for continuous monitoring applications [29]. In such systems, the antenna serves as both a sensing element and a communication interface. Variations in antenna parameters due to environmental or biological stimuli are directly encoded into the transmitted or reflected RF signals. This eliminates the need for separate sensing components, thereby reducing system size and cost. The integration process involves coupling the antenna with low-power wireless

communication modules such as Bluetooth Low Energy (BLE), Zigbee, or RFID systems. These communication protocols enable real-time data transmission to external devices such as smartphones or cloud-based platforms for further analysis.

From a system design perspective, challenges include maintaining impedance matching under varying sensing conditions, minimizing interference between sensing and communication functions, and ensuring reliable performance under mechanical deformation. Advances in flexible electronics and printed circuit integration have facilitated the development of fully integrated smart textile systems.

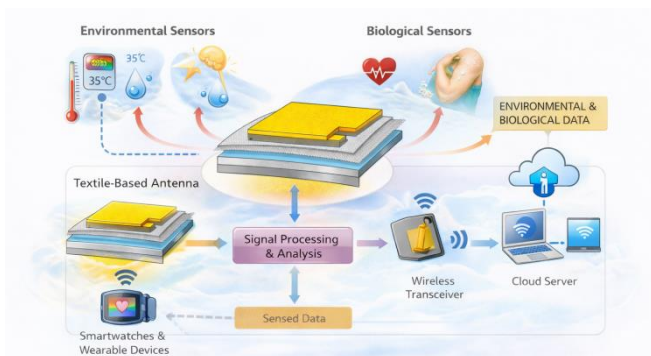


Fig. 6: Block diagram of integrated textile antenna system for sensing and wireless communication.

XII. DISCUSSION AND CONCLUSION

This review has presented a comprehensive analysis of conducting polymer-based textile microstrip patch antennas, focusing on material properties, fabrication techniques, performance characteristics, and sensing capabilities. The integration of conducting polymers with textile substrates enables the development of flexible, lightweight, and conformal antenna systems suitable for wearable and IoT applications. Among the various conducting polymers, materials such as PANI, PPy, PT, and PEDOT:PSS exhibit distinct trade-offs between conductivity, flexibility, and environmental stability. While their conductivity is lower than that of conventional metals, advances in material processing and doping techniques have significantly improved their RF performance. Textile substrates such as cotton, polyester, and denim provide favorable dielectric properties and mechanical flexibility, enabling efficient radiation and conformal integration. Fabrication techniques play a crucial role in determining antenna performance, with methods such as dip

coating, screen printing, and inkjet printing offering different levels of resolution, scalability, and cost-effectiveness. The selection of fabrication methodology must consider both electrical performance and mechanical durability. The sensing capability of textile antennas adds an additional dimension to their functionality, enabling applications in wearable healthcare, environmental monitoring, and smart textiles. The integration of signal processing and machine learning algorithms further enhances sensing accuracy and adaptability, making these systems suitable for real-time applications. Despite significant progress, challenges related to conductivity limitations, environmental sensitivity, and long-term durability remain. Addressing these challenges requires further research in material optimization, fabrication process control, and system-level integration. Overall, conducting polymer-based textile antennas represent a promising platform for next-generation flexible wireless systems, offering a balance between performance, flexibility, and multifunctionality.

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