Devices and Methods of Measurements
2024;15(4):269–286
Suhas R. Kale, Dipak P. Patil

DOI: 10.21122/2220-9506-2024-15-4-269-286

A Review of Wearable Antennas for 5G and Body-Centric Wireless Communication

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Received 25.06.2024
Accepted for publication 14.11.2024

Abstract

Wearable antennas for body-centric wireless communications have become very popular recently. Wearable antennas are body worn as a part of clothing on the human body and enable hands-free operation, which should also be comfortable. The latest 5G wireless technology has many advantages over 4G like high data transmission rate, low latency, etc. With the help of advanced and innovative technologies, wearable antennas can be developed using various materials. This paper presents a detailed review of the application of wearable antennas designed specifically for 5G and body-centric wireless communications. It also presents the selection of materials for the antennas and different fabrication techniques. The paper also looks at the bending of antennas at different radii and analyzes its impact on durability.

Keywords: wearable antenna, bending analysis, body-centric wireless communications, 5G wireless communication

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Для цитирования:
Suhas R. Kale, Dipak P. Patil.
A Review of Wearable Antennas for 5G and Body-Centric Wireless Communication.
Приборы и методы измерений.
2024. Т. 15. № 4. С. 269–286.
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Обзор носимых антенн для технологии 5G и телоцентрической беспроводной связи

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Поступила 25.06.2024
Принята к печати 14.11.2024

В последнее время большую популярность приобрели носимые антенны для так называемой телоцентрической беспроводной связи. Такие носимые антенны носятся непосредственно на теле человека как элемент одежды и обеспечивают связь без помощи рук, что предоставляет дополнительные удобства. Новейшая технология беспроводной связи 5G имеет ряд преимуществ перед 4G, таких как высокая скорость передачи данных, низкая латентность и др. Использование передовых и инновационных технологий позволяет разрабатывать носимые антенны на основе различных материалов. В настоящей статье проведён подробный анализ применения носимых антенн, разработанных специально для 5G и телоцентрической беспроводной связи. Рассмотрены вопросы выбора материала для антенн и методов их изготовления. В статье также рассматривается влияние радиуса изгиба антенн на их характеристики и надёжность.

Ключевые слова: носимая антенна, анализ изгиба, телоцентрическая беспроводная связь, беспроводная связь 5G

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1. Introduction

An antenna is an important part of wireless communication systems. Wireless communication uses antennas for transmitting and receiving. In the final phase of the transmitter, the electrical signal will be transformed into an electromagnetic signal by the use of an antenna. To achieve continuous signal reception at a distance, it is necessary to make use of a receiver antenna that is capable of capturing the needed electromagnetic signal and converting it into an electrical signal. Subsequently, the signal undergoes processing at the receiver. The popularity of wearable technologies has increased, and body-worn wireless communication devices have become even more important with 5G communications. These devices depend on the wearable antenna to provide wireless connectivity between devices and networks.

The lightweight and compact wearable antenna can be worn on the human body or attached to garments. It enhances wireless communication on the body by optimizing signal transmission and reception. The need for high-speed data transmission and the increasing number of devices connected to the Internet makes this type of communication more and more important. The integration of wearable antennas into wireless technology and body area networks has been seeing steady growth and has attracted significant interest. This is mostly due to the utilization of textile materials, which provide users with an increased degree of comfort and flexibility. Wearable electronics offer several advantages, including durability, adaptability, compactness, comfort, and energy efficiency. In modern times, advancements in technology demand the development of compact antennas that can be effectively utilized in body-worn networks.

From 2014 through 2019, the Cisco® Visual Networking Index Predicts the number of devices that can be worn will increase by five times to 578 million in 2019 [1]. As per precedence research, from 2022 to 2030, the market for wearable technologies is projected to expand at a CAGR of 13.89 %. In 2021, the worldwide market for wearable tech was estimated at $121.7 billion, and by 2030, that number is going to increase to around $392.4 billion [2]. Figure 1 shows various applications of wearable technology.

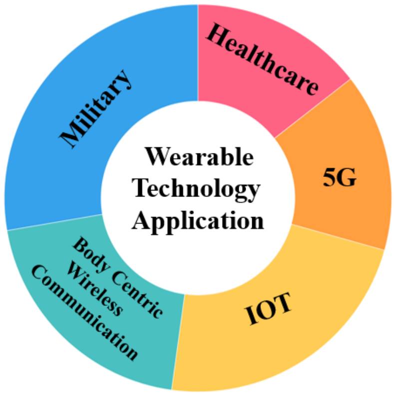


Figure 1 – Various application wearable technology [3]

This paper covers the latest wearable antenna developments for 5G and BCWC. The first section discusses wearable antennas and technology applications. BCWC is classified in Section 2. Textile antenna material classification is provided in Section 3. The stages and techniques for fabricating wearable antennas are covered in Section 4. Additionally, Section 5 covered the bending scenarios for antennas in various radiuses as well as the effect of bending on return loss. However, section 6 provides the wearable antenna for 5G MIMO and sub-6GHz applications. Section 7 discusses wearable antennas about future 6G connectivity. The last Section presents the article's overall conclusion.

2. Body centric wireless communication

BCWC helps to link devices that are either implanted in the body or worn on the human body or enables communication between individuals in close physical contact. Due to its economic and social impact on a diverse variety of applications, including healthcare monitoring, intelligent entertainment, and many others. Due to the numerous opportunities in this field, many researchers have focused their efforts in the area of health monitoring. It fits perfectly into the realm of local area networks as found in the human body. IEEE 802.15.6 is the latest international Wireless Body Area Network standard. This standard defines short-range communication, extremely low-power wireless communications within or near the human body. Figure 2 shows the three types of body-centric communications: in, on, and off. On-body communication operates within the frequency ranges of 2.360–2.400 GHz and 2.400–2.483 GHz, while in-body communication occurs within the frequency range of 402–405 MHz [4].

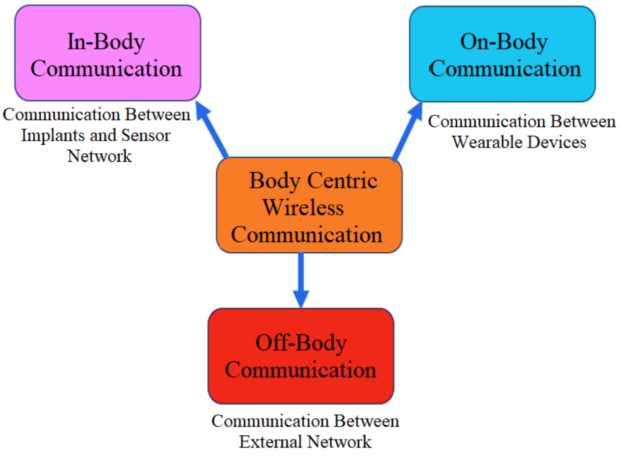


Figure 2 – Body-centric wireless communication domains [5]

Antenna and propagation research for telemedicine systems falls into two categories: external systems and communication with implanted sensors. A network of low-power wearable devices, both implanted and external, can use short-range UHF radio frequencies. However, compact devices may face limitations in data processing, power, and storage, affecting their functionality. To address these issues, incorporating a larger control device or base station into the wearable network is necessary. Body-worn communication systems have already been developed for specific occupations like paramedics, firefighters, and the military [3]

Implants for medical purposes and sensor networks can communicate with each other inside the body. Wireless communication links between wearable technologies and on-body networks enable on-body communications. Information can be transmitted between people or between individuals and a central unit through off-body communications. This communication typically occurs from a location outside the body to a device or system on the body [5].

Many antennas are placed in the body to check brain activity, cardiac activity, etc., or they can be worn on the body, called "On-Body Communication". It is possible to communicate off-body by using an external base unit as shown in Figure 3. WBAN is used for various applications like healthcare Monitoring Applications.

2.1. In-body communication

One of the components of the in-body communication system is an IMD, while the other component is an external device for monitoring health. There is the capability of IMDs to monitor the wireless transmission of physiological data from patients in real-time [7]. IMDs have been utilized for a variety of applications, including but not limited to capsule endoscopy [8], real-time glucose monitoring [9] and brain implants [10]. The characteristics of IMDs include a high gain, a low SAR, flexibility, a small size, and a high bandwidth.

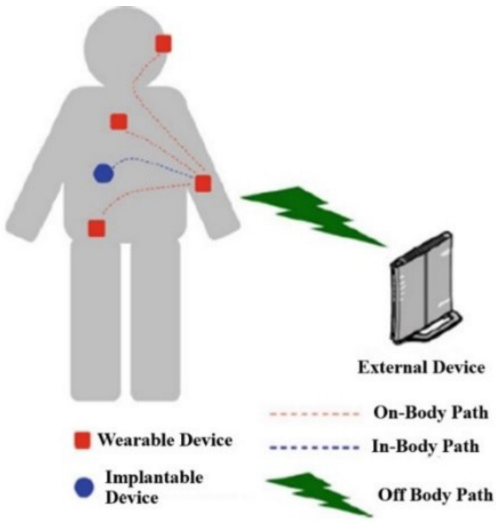


Figure 3 – Schematic of body centric wireless communication [6]

Garcia-Pardo, Concepcion, et al. propose a miniaturized ultra-wideband system to overcome the narrow bandwidth of the medical implant communications service band and achieve high data rates for body-implanted communication. Indigenous sensor networks have at least one sensor within a human. These wireless endogenous sensors are used in medical applications to capture and track critical information for treatment and health. In [11] the author has developed a wearable flexible antenna using Rogers XT8100 substrate, whose dimensions are 20 mm in width, 30 mm in height, and 50 µm in thickness of the substrate. The proposed antenna is primarily well-suited for facilitating communication within the human body, specifically in the intestinal region. Its intended application is for capsule endoscopy, a medical procedure involving the use of a small capsule to examine the gastrointestinal tract. The antenna operates throughout the ISM and UWB frequency bands, enabling effective in-body communication.

RFID is an emerging technology that has the potential to improve patient safety and hospital care.

RFID technology is used to monitor patients, staff, and equipment in hospitals, and to uniquely identify patients and their prescriptions, and can contribute to a safer healthcare environment and reduce the likelihood of medical errors. Implanted radio tags (rather than body-worn) are less likely to be misplaced, are untraceable, and are well suited for screening cooperative patients [12]. Implantable antennas need to be small, or even compact because they are implanted inside the human body. The human body also reduces the effect of antenna performance. A technique for in-body wireless communication with RFID tags inserted into a person's forearm was covered in [16]. The antenna's suggested measurements are 4 mm in width and 15.75 mm in length. A portable reader confirms a maximum reading range of 1.3 cm, and a three-layer phantom is used to test impedance characteristics. AVGs are life-saving medical devices that are essential to the survival of patients receiving hemodialysis for chronic kidney disease. Nevertheless, the use of AVGs often results in suboptimal outcomes due to several postoperative complications. These complications include restenosis, which is characterized by the accumulation of cellular material, and the formation of blood clots and infections. These complications contribute significantly to morbidity and mortality rates. The author in [17], especially for use in high-resolution monitoring applications, has developed a compact, dual-band implanted antenna. An outline of the intelligent AVG and its architecture are shown in Figure 4.

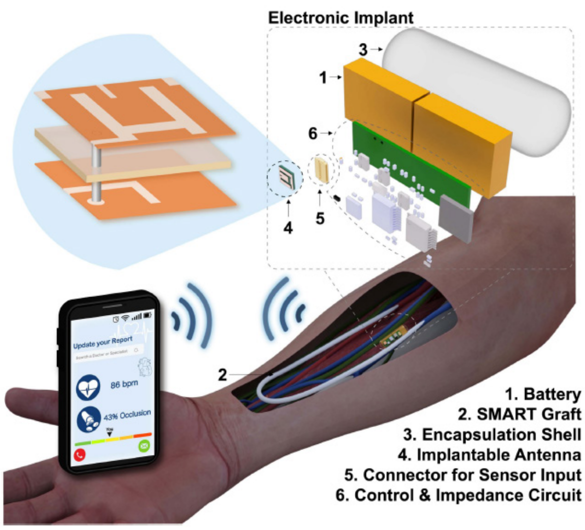


Figure 4 – Outline of the intelligent autologous vein grafts and its architecture [13]

The device functions in the 1.4 and 2.45 GHz frequency bands, which are mostly utilized for biotelemetry and wireless power transfer applications. Dimensions of the developed miniaturized antenna are $5 \times 5 \times 0.635$ mm^3. This antenna covers the 300 MHz to 1.4 GHz range and 380 MHz in the 2.45 GHz band. Additionally, it also exhibits favorable impedance matching at two resonant frequencies. The developed antenna [13] is useful for patients suffering from chronic kidney disease and undergoing hemodialysis.

The author developed an E-shaped monopole antenna for pacemaker control and heartbeat monitoring [14]. The rectangular antenna was designed as a flexible felt substrate and measures 37 mm by 30 mm. This system is mainly useful for people suffering from arrhythmias. Pacemakers are very important for that patient. After the implantation of the pacemaker, a pacemaker stimulates the heart with electrical pulses to transmit information until it returns to a regular rhythm and pumps blood. This dual-band antenna system is mounted on the chest of the patient to measure the heartbeats, and the results will be sent to the doctor. The doctor controls the pacemaker's electrical pulse value to save the patient.

Because IMDs can monitor internal physiological data in real time and treat diseases remotely, their application in telemedicine is becoming more and more significant [18]. Some examples of implantable medical devices are shown in [14], [15], and [16]. However, IMDs' battery lives are capped by their capacities [17]. IMDs can't accommodate larger batteries because of their small size. Therefore, if the batteries in an IMD need to be changed, patients go through the misery of multiple operations. The aforesaid concerns can be addressed by implementing wireless power transfer technologies in healthcare systems [18]. The comparison of various implantable antennas is reported in Table 1.

2.2. Off-body communication

In an off-body communication setup, one node of the communication system is located on a person's body, while the other is located at a considerable distance from them. Whenever a base station or numerous broadcast stations are present, this kind of communication becomes apparent. Figure 5 shows a schematic representation of a wireless communication OFF-Body antenna. A directed radiation pattern on an IoT device's antenna sends patient data to the doctor's device [26].

Table 1

Comparison of implantable antenna

Ref	Antenna type	Dimension	Frequency	Substrate	Reflection coeff (S11)	Band-width (%)	SAR (W/Kg)		Implant-able param-eter	Appli-cation
							1 g	10 g		
[19]	Meander Line	10 mx 10 mmx 0:635 mm	WMTS (1.42 GHz) and ISM Band (2.42 GHz)	Rogers RT/duroid 6010	for 1.42 GHZ, -25 for 2.4 GHz -34	3.57, 6.37	215, 565	38.7, 94.6	Skin	biote-lemetry and ISM
[20]	Fractal shaped MIMO antenna	0.13λ×0.06λ× ×0.01 λ	2.4–2.48 GHz	Rogers RT/Du-roid 6010	-30	38.75	278	38.7	brain and skin	ISM
[21]	Square ring an-tennas	9.8×9.8× ×0.889 mm^3	2.4GHz	Rogers RO6010	-25	30	NA	93.2 for the scalp 87.5 for the heart	scalp and heart	ISM
[22]	a flat zigzag structure	3×3×0.5 mm	2.4–2.48GHz	Rogers 3010	-24.9	22	32.3	10.8	heart	ISM
[23]	semi-circular slotted patch	8×9× ×0.635 mm^3	WMTS (1.42 GHz) and ISM Band (2.42 GHz)	Rogers RT/Du-roid 6010	−48 and −48	10 and 9.4	500 and 686	112 and 136	skin	biote-lemetry and ISM
[24]	slotted patch	8×6×0.5 mm^3	915 MHz and 2450 MHz	Rogers 6010	-28.5 and -22.8	9.84 and 8.57	971.56 and 807.34	118.26 102.04	scalp	ISM
[25]	MIMO	5.652×π× ×0.13 mm^3	(402–405 MHz) (433.1–438.8 MHz)	Rogers RO3010	-30	33.90 %	269.3 275.2	538.6 550.4	head and large intestine	Biote-lemetry

Respiration, also known as breathing, holds significant physiological significance within the realm of living organisms. The measurement of breathing rate serves as a crucial indicator in monitoring the development of illness, and an atypical breathing rate holds significant value as an indicator of a severe medical condition.

The author introduces a unique wearable antenna that can detect human breath without contact. The antenna uses multimaterial fiber for 2.4 GHz short-range wireless network applications. Composite metal-glass-polymer fibers provide a remarkable degree of flexibility, rendering them suitable for seamless integration into textiles without affecting the comfort or movement of the wearer. Additionally, these fibers effectively hide the antenna from potential disturbances caused by the surrounding environment [27].

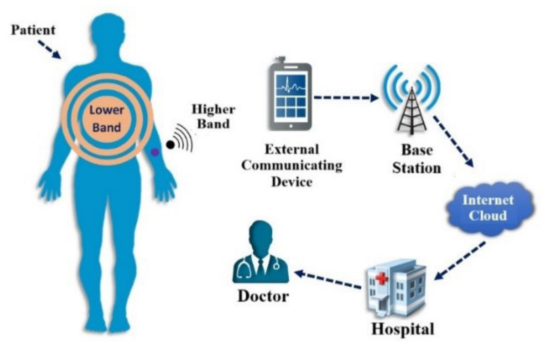


Figure 5 – Schematic representation of a wireless communication OFF-Body antenna [26]

Devices and Methods of Measurements
2024;15(4):269–286
Suhas R. Kale, Dipak P. Patil

Scarpello et al. [29] study return loss and mutual coupling stability across varying humidity, investigating bending array, body mounting, and textile layers.

Their research measures and simulates gain patterns in free space for body antennas operating in the 2.4–2.4835 GHz ISM band.

Rescue personnel vests incorporate high-gain textile antenna arrays at this frequency, highlighting a future trend where clothing not only protects but also provides real-time data on wearer and environmental conditions, enhancing safety and comfort. Furthermore, the incorporation of monitoring systems into the clothing, particularly in a discreet manner that is seamlessly integrated into the garment, serves to improve the functionality and, of utmost significance, the safety of the individual wearing it. The textile-based antenna integrates seamlessly into protective apparel like firefighter garments [30].

2.3. On-body communication

On-body communication systems are classified as body-centric if both the transmitting and receiving nodes are carried by or attached to the human body. These types of wireless communication systems provide a compelling solution for establishing connections between different electronic devices that are wearable or transported by a person. The entire network is made by using several sensors, a data processing unit, and many input/output modules. The present communication system has the potential to be used for monitoring physiological measurements and various other applications by using multiple devices carried by people in their daily lives.

Figure 6 illustrates a body-worn dual-mode antenna that was developed for the healthcare system by Lin, C. H., et al. [31] that supports both on-body and off-body communication functions.

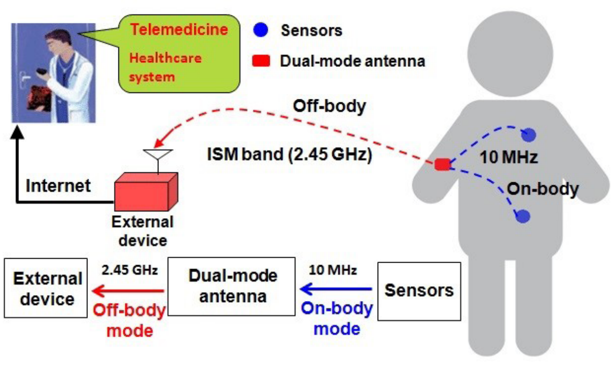


Figure 6 – On/off body communication in medical applications [31]

Lin, C. H., et al. studied the on-body electric field distribution, reflection coefficient (S11), and radiation patterns in the off-body mode.

The system has a ground (GND) electrode, feeding pin, and signal electrode. The proposed antenna is 30 mm in length 33 mm in width, and 4 mm in height. Near the 4 mm height, the signal electrode's center is the feeding pin.

In the ISM band, the folded ground structure resonates at 2.45 GHz. On-body antennas must be compact for user comfort and sensor node integration. The author introduced a dual-band, small, miniaturized antenna for on-body and off-body communication [32].

Miniaturization is achieved by etching two open-end slots on the rectangular patch. Data from body sensor nodes is received by the antenna at 2.45 GHz. It then sends this data to external monitoring equipment at 5.0 GHz in ISM bands. The antenna is 15 mm×28 mm×1.57 mm. A wide bandwidth of 250–370 MHz improves biological tissue antenna robustness. The body receives 2.45 GHz and 5.0 GHz radiation. The external control unit communicates satisfactorily at 5.0 GHz with 7.18 dB directivity. A flexible, compact multi-band wearable antenna with a basic, low-profile structure was presented by Al-Sehemi, Abdullah, et al. [32]. This antenna covers a wide range of biomedical frequency bands, operating between 0.824 to 0.975 GHz and 1.90 to 6 GHz. The bio-composite natural rubber substrate used in the antenna eliminates allergic or harmful reactions when placed on the body. The substrate can be easily processed, is inexpensive, is flexible, and is resistant to dust and water.

The field of WBAN is growing, enabling the implantation of sensors in or on the human body. These sensors communicate with a central node that stores data on a computer or in the cloud. Positioning sensors on an athlete is challenging due to constant movement. Real-time data should be accessible to coaches, athletes, and the public. To address this, the author in [33] studied the best sensor placement for optimal connectivity with the remote node. The wrist sensor showed good communication with the breast sensor, and the best Line of sight reception angles were identified for all sensor placements.

The range of on-body communications is limited to the close vicinity of the user. The transmission of biophysical signals can occur within the human body, whereby a wearable transmitter is used to relay these signals to a receiver that is also linked to the body. The survey paper [34] discussed wearable antennas used for WBAN applications with flexible substrates. The antenna's ability to be worn on the human body must be flexible for on-body application to occur. Wearable antennas are developed using various fabrics as substrates. The fabric's increased ability to absorb moisture results in a higher dielectric constant for the material. As wearable antennas made up of fabrics can become dirty after being integrated into garments, the properties of the antennas change after the fabrics are washed. Scarpello, M. L., et al. [35] have found a solution to this problem by coating them with thermoplastic polyurethane, which also protects against corrosion and water absorption. Compared to coating wearable antennas, the antennas can be made using screen printing technology with conductive ink on textile substrates. Both functions together result in better stable performance. Before coating, after washing, and after many cycles, the antenna's performance is examined.

Anbalagan, Abirami, et al. [36] developed a novel low-profile embroidered textile antenna from the cotton substrate and conductive Zari threads for real-time pulse monitoring in wearable applications. The antenna's compact design and rectangular slot improve return loss and gain. On-body study demonstrates that the antenna operates well with absorption rates below the IEC threshold for 1 g and 10 g tissue. Real-time heart rate monitoring is provided via a Particle Photon, which also uploads data through the cloud to the Particle app. This antenna can be used for on-body uses because it doesn't get affected by changes in shape. The antenna's designed dimensions are $51 \times 45 \times 0.785$ mm. Chahat, Nacer, et al [37] demonstrated a small, $25 \times 10 \times 1.6$ mm^3 size microstrip fed monopole antenna for UWB on-body applications using substrate AR350 with a dielectric constant of 3.5. For impulse radio application, time domain analysis over the voxel body model is carried out.

For on-body WBAN, Kumar, Vivek, and Bharat Gupta proposed a Swastik Slot Ultra-Wide Band (3–10.6 GHz) Antenna [38]. This health monitor antenna is worn on or around the body. Partial ground plane, slot, and feed increase antenna bandwidth. T he antenna is 27 mm×27 mm×1.6 mm. This SS-UWB patch antenna has 1.77–5.6 dB quasi-Omni directional gain and covers 4.25–12.5 GHz [8.25 GHz]. Over open space, this antenna gains 0.81–3.0 (1.8–0.85 dB). An on-body conformal MTM antenna for WBAN communication is presented by Hazarika et al. [39]. The author invented the zero-reflection-phase MTM monopole antenna. A 2×2 array of H-shaped unit cells minimizes back radiation and increases gain. In the conformal configuration's frequency ranges, the MTM reduces the maximum SAR averaged across 1 gram to 0.174 and 0.207 watts per kilogram when the body and antenna are 1 mm apart. B. Bahaa et al. introduced a wide-band spring textile (WST) antenna for wearable communications [40]. $32 \times 42 \times 3$ mm^3 felt antenna. This antenna runs from 3.14 to 5.45 GHz. The highest gain is 6 dBi at 3.5 GHz and its bandwidth is 2306 MHz Due to its wide frequency coverage, this antenna is excellent for 5G and IoT wireless applications. When near the chest, the antenna has low SAR for on-body transmission. Gupta et al. [41] study a square ring-shaped ground antenna with a truncated patch for dual-mode bio-telemetry on and off the body. Analysis and optimization of the proposed antenna design on a multilayer flat tissue phantom show its broad frequency range and low SAR values for tissue safety. The proposed antenna design resonates with WLAN, LTE, and ISM frequencies from 2.6 to 5.2 GHz. It also resists posture-induced frequency detuning. When near tissue, it exhibits 15 % peak radiation efficiency at 2.45 GHz. Low SAR values help ensure tissue safety [42]. The researcher identified a limitation in the field of on-body communication, specifically noting that the proximity of an antenna to the human body has a significant impact on its performance. The primary factors contributing to this influence include frequency shifting, degradation of radiation pattern, and loss of efficiency. The impact of bodily movement on these factors varies. Das, Gautam Kumar, et al. [43] solved the problem using metamaterial over the body-attached antenna. In multilayer phantom mode, antenna performance was examined.

3. Material classification for textile antenna

A textile antenna employs fabric or conductive material integrated into clothing, requiring flexibility, durability, and comfort. Textiles with low dielectric constants minimize surface wave losses and enhance antenna bandwidth. Critical factors such as loss tangent and dielectric properties influence antenna performance. Ten alternative fabrics – cotton, quartzel fabric, cordura/lycra [44], felt, moleskin, silk, tween, panama, jeans, and denim – were evaluated as substitutes for the original polyester substrate in the antenna design. These fabrics maintain the same dimensions in width and length as 100 % polyester but vary in thickness to accommodate different material characteristics (Table 2).

Table 2

Properties fornonconductive materials

Refs. No	Substrate material	Permittivity εr	Loss tangent tanδ
[32]	Biocomposite Natural Rubber	2.3624	0.0077
[43]	Felt	1.22	0.016
[44]	Cordura	1.90	0.0098
[44]	Lycra	1.50	0.0093
[45]	Quartz Fabric	1.95	0.0004
[46]	Jeans	1.7	0.025
[47]	Denim	1.7	0.085
[51]	Cotton	1.60	0.0400
[55]	100% polyester	1.90	0.0045
[57]	Foam	1.7	0.0025

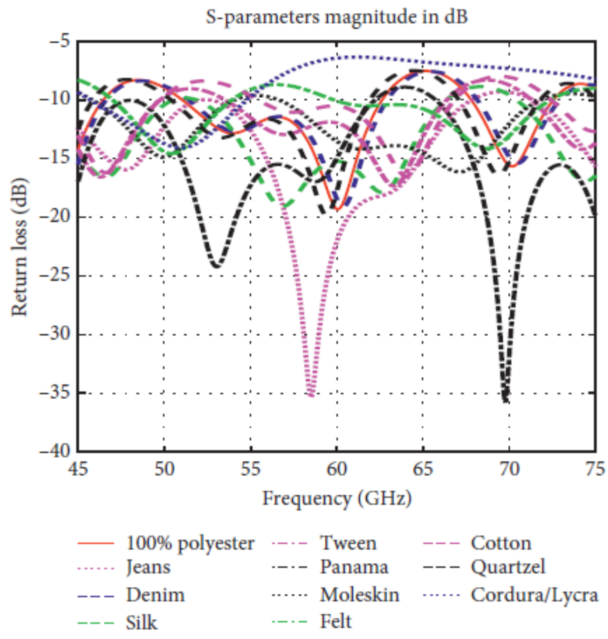


Figure 7 – Antenna performance comparison in free-space return loss for various textile substrates [48]

According to the data in Figure 7, the fabrics that closest resembled the original design in terms of bandwidth and center frequency were denim, tween, and quartzel. The gain was greater than 8 dBi across all substrates except for cordura/lycra.

The results were quite similar to those obtained with polyester fabric since denim and quartzel cloths have the same thickness and relative permittivity. The results of this free-space analysis of fabric variations are summarized in Table 3 [48].

Table 3

Antenna performance summary in free space for various fabrics (Reprinted) [48]

Substrate	Relative Permittivity	Thickness (mm)	Center Frequency (GHz)	Bandwidth (GHz)	Gain (dBi)	Radiation Efficiency (%)
100% Polyster	1.9	1.5	60.06	11.578	8.531	89.69
Jeans	1.7	1	58.5	15.094	7.841	93.19
Denim	1.87	1.5	60.36	11.505	8.653	89.91
Silk	1.75	1.16	56.82	14.439	8.298	92.33
Tween	1.69	1.37	60.3	12.818	9.138	91.88
Panamma	2.12	1.04	53.069	14.184	8.864	91.48
Felt	1.38	1.38	68.772	12.507	9.824	93.64
Moleskin	1.45	1.17	67.11	15.141	8.862	91.87
Cotton	1.63	1.5	64.05	11.357	9.686	91.58
Quartzel fabric	1.95	1.5	59.4	11.515	8.217	89.16
Cordura/Lycra	1.5	0.5	50.97	9.052	5.213	95.49

4. Fabrication methods

4.1. Fabrication steps

Fabrication steps for cloth as substrate are as follows:

a) To decide the application requirements.

b) Identifying the antenna geometry and substrate and numerical modeling of the antenna.

c) Simulation using any Electromagnetic Simulator.

d) Using a cutter, cutting plotter, or Computer Numerical Control machine to cut self-adhesive, conductive copper tape or foil will shape the antenna.

e) Sticking copper tape or foil on the substrate.

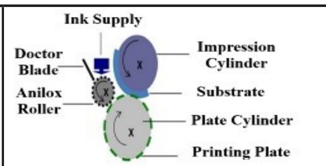
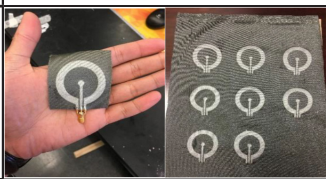
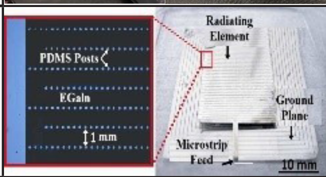
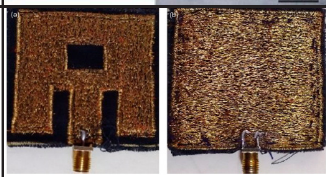
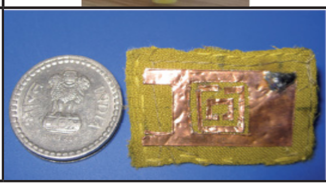
f) Connecting Subminiature version A Connector.

4.2. Fabrication methods

Fabrication is challenging in wearable antennas. The design of a compact and inexpensive antenna system poses various obstacles to achieving desirable radiation properties. These challenges include ensuring a lightweight structure that can operate across multiple frequency bands while maintaining stable performance under varied situations such as bending or rolling. An economical and straightforward approach to producing flexible electronics and RFIDs is through line patterning, a method proposed by Hohnholz and MacDiarmid in 2001 [49]. Various fabrication method's advantages and disadvantages are given in Table 4.

Table 4

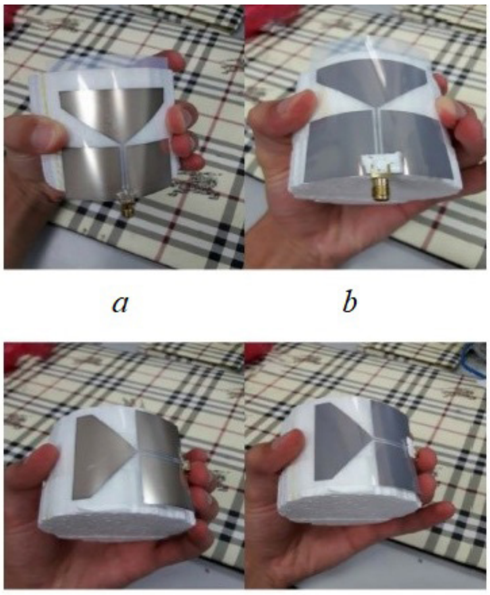
Different fabrication methods

Ref.	Type of antenna	Fabrication Method used		Advantages	Disadvantages
[52] [53] [54]	RFID Antenna	Flexography		high resolution, cost-effectiveness high conductivity ink	low ink viscosity
[55]	Coplanar Keyhole Antenna	Screen Printing		easy and cost-effective	1. less printing resolution no control on deposited ink thickness and no. of layer
[56]	Microstrip Patch Antenna	Soft Photo lithography Process		generate complex patterns precisely and at a high resolution	1. lengthy process 2. low throughput 3. dangerous chemicals used for etching
[36]	Embroidered textile microstrip Antenna	Stitching, Sewing and Embroidery		E fiber exhibits very low electrical loss and excellent mechanical strength	Stitching wrinkles the material, deforming the antenna
[57]	Inkjet-Printed flexible antenna	Inkjet Printing		cost-effective easy to use	Due to huge particle size, inkjet printer nozzle obstruction occurs
[58]	Microstrip Patch Antenna	Copper Tape		Easy method and cost-effective	Resonance frequency changes due to nonconductive glue connected between substrate and patch

5. Bending analysis of wearable antenna

The fundamental issue in wearing antennas is keeping them flat, especially when made of textiles. Human body movements bend the wearable antenna often [59].

The human body bends everywhere. Enjoy the ease of cloth antennas that can endure bending without affecting performance. Bending can affect antenna gain, bandwidth, and resonant frequency for your application [60]. The author [61] conducted a bending study on the antenna by mounting it on a cylinder (εr = 1) and adjusting positions, as depicted in the Figure 8. Vertically placed antenna on cylinder looking outward (*a*) and within (*b*). The antenna is horizontal on the cylinder in (*c*) and (*d*) with the structure pointing outward and inward.

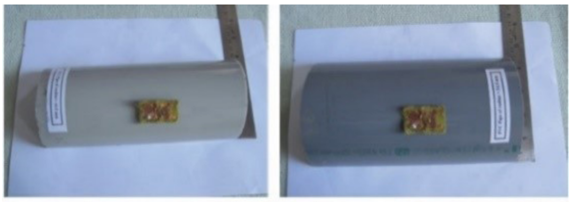


a *b* *c* *d*

Figure 8 – Bending position around vertical cylinder with diameter of: *a* – 80 mm; *b* – 60 mm; *c* – 40 mm; *d* – 20 mm [61]

PVC pipes with 54.5- and 44.5-mm internal radii resemble the shoulder, wrist, and knee. Figure 8 shows antenna bending on both PVC pipes for their examination. Antenna resonance is 5.367 GHz and the return loss is -17.97 dB when bent around a 54.5 mm pipe (Figure 9). When bent on a 44.5 mm pipe, the antenna sonance frequency shifts to 5.388 GHz and the return loss is -20.22 dB [58].

The antenna in [62] is wrapped around a hollow cylinder made of PVC tubing with a diameter of either 22 or 48 mm so that the bending feasibility may be evaluated. At several different bending diameters, we looked into the S11 properties of the flexible foam. The graph shown in Figure 10, it can be observed that bending with a small diameter results in a maximum value of S11 at 39.22 dB. However, this configuration exhibits a bandwidth of 8.47 GHz, which falls below the threshold of 10 dB, with a slight deviation in the initial frequency.



a *b*

Figure 9 – Picture of the suggested antenna curved around internal radii: (*a* – 54.5 mm; *b* – 44.5 mm) PVC pipes [58]

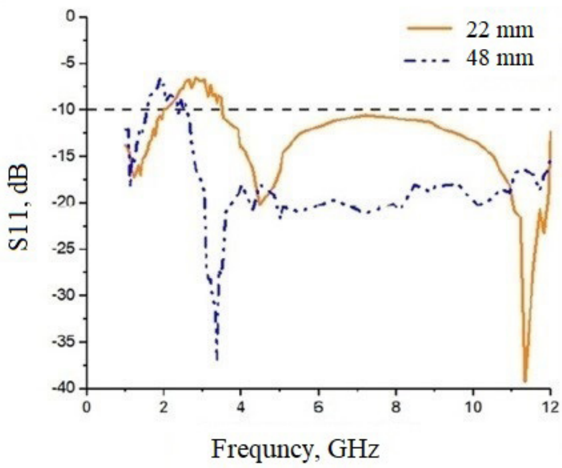


Figure 10 – Comparison of S11 for bending at diameters of 22 mm and 48 mm [62]

The deformation of a flexible antenna varies across different frequency ranges and becomes particularly significant at higher frequencies due to the antenna's reduced size. This is primarily attributed to impedance mismatching and the limited bandwidth of the antenna [63].

Muhammad Usman Ali Khan et al. [63] study the impact of bending levels on the performance of antennas fabricated from PET, Teflon, and PVC substrates. The research focuses on bending radii of 14 mm and 27 mm for flexible polymer antennas operating at frequencies ranging from 2.45 to 7.45 GHz, categorized into three frequency ranges: (i) 2.2–2.5 GHz, (ii) 2.5–5.0 GHz, and (iii) above

Devices and Methods of Measurements
2024;15(4):269–286
Suhas R. Kale, Dipak P. Patil

5 GHz. Radial curvatures were achieved using polystyrene foam cylinders to maintain consistent curvature in the flexible antenna structure as shown in Figure 11.

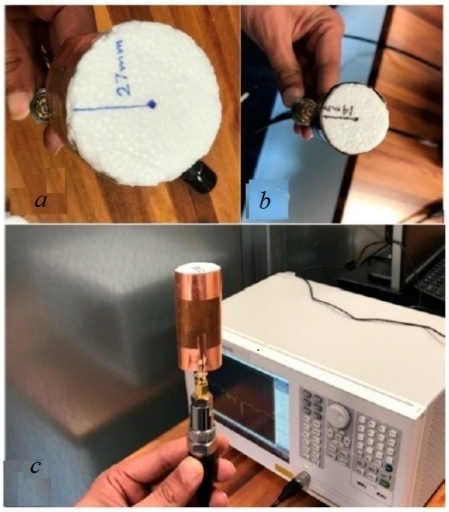


Figure 11 – Picture of a flexible antenna bend produced by cylindrical polystyrene foam (*a*) at 27 mm, (*b*) at 14 mm, and (*c*) attached to the Voltage Network Analyzer at 14 mm [63]

Table 5

Percentage frequency shift in resonant frequencies for PET, PTFE, and PVC surfaces for three operating frequencies and two bend conditions (27 and 14 mm) [50]

	Substarte		PET	PTFE	PVC
Resonant Frequency	Operating at 2.4 GHz	Flat	2.426	2.438	2.417
		27 mm	2.412	2.469	2.394
		Shift(%)	-0.58	1.25	-0.96
		14 mm	2.402	2.484	2.366
		Shift(%)	-0.99	1.85	3.42
	Operating at 4.25 GHz	Flat	4.312	4.381	4.267
		27 mm	4.442	4.392	4.294
		Shift(%)	2.92	0.25	0.62
		14 mm	4.468	4.453	4.366
		Shift(%)	3.49	1.61	2.26
	Operating at 7.45 GHz	Flat	7.387	7.443	7.507
		27 mm	7.425	7.429	7.541
		Shift(%)	0.51	-0.01	0.45
		14 mm	7.464	7.421	7.658
		Shift(%)	1.03	-0.29	1.97

Note: Negative sign with frequency shift (%) that occurs towards the lowest components of frequency

Usman Ali, et al. develop and analyze four 2.4 GHz wearable antenna models with flexible microstrip patches. Rectangular patches supported by EBG ground planes form the antennas' radiating element. These ground planes can be mushroom-shaped, slotted, or helical. Both antennas and EBG surfaces use a 3 mm wash cotton textile substrate. The proposed antennas utilize an electro-textile material known as Zelt, which serves as a conductive medium. The antennas that have been designed are subsequently examined in both on-body and off-body scenarios while considering their normal and bent states. The performance of wearable antennas must be stable despite being subjected to a wide range of deformation. The proposed antenna's bending effect is shown in Figure 12 for four possible radii 45 mm, 35 mm, 25 mm, and 15 mm in both E and H planes [64].

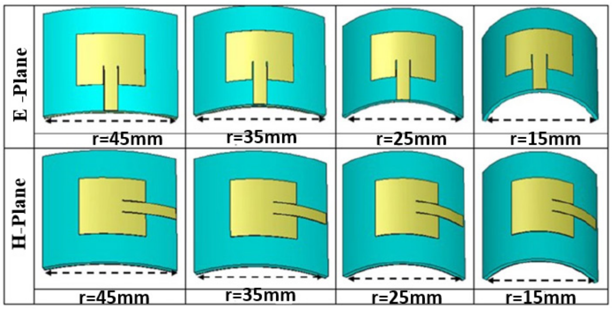


Figure 12 – Proposed antenna bending with varying E and H plane radii [64]

Under a bent situation, Antenna-1's return loss is −14 dB, compared to −24.46 dB at 2.4 GHz (Figure 13). Under bent circumstances, Antenna 2, Antenna 3, and Antenna 4 have lower return loss.

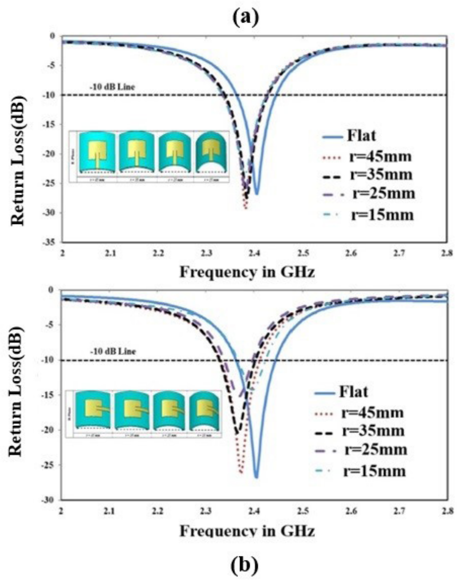


Figure 13 – Comparison of antenna return loss in the E-plane (*a*) and H-planes (*b*) at various bending radii [64]

The author in [65] developed and Analyzed A small, flexible hexagonal microstrip patch antenna with foam substrate. The bending performance of the antenna is under consideration for radii of 24 mm and 11 mm. It was noted by the author that when the bending radius is 24 mm, the highest value of S11 is recorded as 35.60 dB, accompanied by a bandwidth of 5.33 GHz. Nevertheless, the antenna's bandwidth performance at a frequency of 5.94 GHz is enhanced when the bending radius is set at 11 mm.

6. Application of wearable antenna in 5G

The 5G network facilitates a range of functions and offers increased bandwidth and fast download speeds [66]. There are a growing number of uses for wearable technology in the fields of defense, medicine, and consumer electronics. Wearable technology will also likely to work in the development of 5G networks, which will have enhanced data transfer speeds and decreased dropout rates across a wider region via a greater number of smaller micro- and pico-cell [67].

The Ericsson Mobility Report [68] projects that there will be 3.5 billion 5G subscriptions in 2026, indicating that the demand for 5G will continue to be high in the upcoming years. To facilitate the implementation of 5G technology, the Federal Communications Commission will allocate spectrum resources. The 5G frequency spectrum is comprised of four distinct groupings. To begin with, the High-Frequency Band encompasses the frequency ranges of 28, 24, 37, 39 and 47 GHz. Furthermore, within the frequency range below 6 GHz, the Mid Frequency Band encompasses the frequencies of 2.5 GHz, 3.5 GHz, and the range of 3.7–4.2 GHz. Finally, the 600, 800, and 900 MHz Low Frequency Band is below 1 GHz. Future Wi-Fi technology may use unlicensed frequencies from 5.9 to 95 GHz [60]. The 3GPP studied 5G frequencies. 3GPP Release 15 Table 3 lists 5G NR frequency bands. The first 5G bands are 700 MHz, 3.5 GHz, and 26/28 GHz. Establishing and using 5G requires these bands [66].

The integration of 5G technology into healthcare systems holds significant potential for both the public and private sectors. Unobtrusive mm-wave communications efficiently collect and transmit data from healthcare devices. The author designed and modeled a flexible graphene-based antenna. 5G antennas for wearable health devices were developed and integrated into head-mounted imaging systems. The antenna uses an 18-µm-thick graphene layer for the conductive radiation field and ground and operates at 34.5 GHz. The patch is fractally designed for portability. The antenna is made of flexible polyamide and has a 1.5 mm substrate for wearable applications [69].

6.1. 5G Sub 6GHz

In the contemporary global landscape, particularly in the aftermath of the COVID-19 pandemic, the proliferation of wireless communication devices has reached unprecedented levels. Consequently, the adoption of 5G technologies has become an imperative requirement, as it provides a data transmission speed that is 100 times faster than the existing 4G standard. The success of 5G technology depends on compact antennas. In recent years, 5G communication is expected to use microstrip patch antenna designs [70].

Desai, Arpan, et al. developed a patch antenna with a transparent flexible co-planar waveguide and polyethylene terephthalate substrate. A transparent silver tin oxide (AgHT-8) sheet wideband high-gain antenna measures 0.48 $\lambda \times 0.64\ \lambda$ at 4.28 GHz. The proposed transparent flexible antenna offers a 40 % bandwidth from 3.89 to 5.9 GHz, over 3 dBi gain, and over 80 % efficiency. Flexible and transparent, the antenna performed well in sub-6 GHz 5G and WLAN [59]. In this paper, Kumar, Anubhav, et al. develop a highly isolated two-port dual-band antenna. The antenna is reduced in size by using a beak-shaped radiator with open stubs. At higher frequencies, a T-shaped stub has been used for isolation, whereas open-ended slots successfully decrease the antenna in size, improving its impedance and isolating it by more than 20 dB. For lower frequencies, the MIMO antenna's isolation can be improved by suppressing current across radiators without increasing antenna size. The two-port antenna works on frequencies between 2500 and 3700 MHz (5G n7, n48, and n77) and 2570 and 2300 MHz (LTE 38, 40, 41, 42, and 43). Sub-6 GHz bands, including 5.15/5.85 GHz used for WLAN, 2.4/5.0 GHz used for Wi-Fi, and 2.45/5.8 GHz used for ISM, can be a useful option for wireless communication [60].

Azim, Rezaul, et al. designed a planar ultra-wideband antenna with a circular patch design for 5G communication below 6 GHz. The antenna's circular patch and ground plane eliminate the need for an encapsulated element or large system ground plane. To get the appropriate operating frequency range, a rectangular slot was inserted into the top edge of the ground plane. Experiments show that the antenna functions with a reflection coefficient (S11) of less than -10 dB from 3.05 to 5.82 GHz. This range covers all 5G below 6 GHz N77/N78/N79 frequency bands, WLAN, LTE, WiMAX, and wireless communication technologies [69].

6.2. 5G MIMO

Shoaib et al. proposed an 8×8 MIMO 5G wristwatch and dongle antennas [71]. The substrate's top layer has 3.4 mm2 of twisted H-shaped MIMO antennas. The design uses a 31.2×31.2×1.57 mm Rogers RT-5880 board with a 2.2 dielectric constant. The substrate has eight MIMO antennas on top and a ground plane at the bottom. The central frequency of MIMO antennas is 25.2 GHz with 15.6 % bandwidth. The antennas at resonance frequencies gain 8.732 dB, while the bandwidth gains 7.2 dB. The EBG structure increases efficiency, gain and Bandwidth [72]. Sufian, Md. Abu, et al. [73] present a 2×2 MIMO antenna with one element by translating each element orthogonally. Slots and metal strips with shorting pins of the supported structured antenna isolate MIMO elements. Shorting ground plane pins and slots reduces mutual coupling and electromagnetic field distribution. Advantages of the proposed antenna include 15.9 % 10 dB impedance, 3.3 to 3.87 GHz bandwidth, and 8.72 dBi peak gain. For 3.3–3.8 GHz (N78 band) frequency, 0.85 $\lambda 0 \times 0.85$ $\lambda 0 \times 0.038 \lambda 0$,compact size, 3.27 to 3.82 GHz operating bandwidth, S11 < 10. Anbarasu and Nithiyanantham [74] developed a 0.674×0.712-inch denim antenna with a 1.7 dielectric constant and 4 mm thickness. The antenna's S11 characteristics are below 10 dB and gain 15 dB. The antenna is an 8–12 GHz notch filter. The antenna radiates 4–18 and 24–58 GHz. The antenna has a 4 GHz bandwidth, exceeding 34 GHz. A 90° angle and 80 mm radius bent the antenna. The antenna supports WiMAX, 5G, and GPS.An antenna substrate of standard felt with a dielectric constant of 1.3 and two rectangular cotton fabric patches with 2.23 are used. Two forms of flexible and wearable dielectric increase microstrip sample bandwidth by 7 GHz. The recommended 5 GHz antenna size is 54×36×2.5 mm^3. Parametric studies on cotton fabric and standard felt. The wearable MIMO antenna's 5 GHz bandwidth and isolation are impacted by CF component dielectric constant changes. This substrate has a 1.2 dielectric constant. Bandwidth and isolation alter little when cotton fabric €r increases from 2 to 2.5. Dielectric constants exceeding 2.5 reduce bandwidth and isolation. The author parametrically examined the SF substrate to determine how SF dielectric constant variation affects bandwidth and isolation. With €r of SF 1–1.5, bandwidth and isolation stay constant. At €r 1.5, bandwidth and isolation decrease [61]. Addepalli, Tathababu, et al. [75] present a four-port MIMO antenna for 5G-NR spectrum applications covering bands n77 (3.30–4.20 GHz), n78 (3.30–3.80 GHz), and n79 (4.40–5.00 GHz). The design includes omnidirectional and dipole radiation patterns in both H- and E-planes, along with high impedance matching, isolation, and diversity analysis. Two antennas are analyzed: the four-port modified MIMO antenna and a single-element asymmetrically fed Calendula flower-shaped antenna.

In [76], the author introduces a novel flexible tri-band four-port MIMO antenna tailored for modern wearable applications in 5G/WIFI 6E. Spanning frequencies from 2.54 to 3.56 GHz, 4.28 to 4.97 GHz, and 5.37 to 8.85 GHz, it covers Chinese 5G bands n78 (3.4–3.5 GHz) and n79 (4.8–4.9 GHz), along with Wi-Fi 6E spectrum from 5.945 to 7.125 GHz. The design addresses the need for compact MIMO diversity antennas to support high-speed cellular 5G sub-6 GHz and WLAN applications, including NR bands N77, N78, and N79, and Wi-Fi 5 and Wi-Fi 6 standards.

7. Future scope for wearable antenna in 6G

According to projections, the implementation of 6G is expected to take place by 2030 or earlier, facilitated by the progress made in transition technologies. This represents a notable advancement compared to previous mobile transitions, when each generation required about a decade for deployment (e. g., 1G in the 1980s, 2G in the 1990s, 3G in the 2000s, 4G in the 2010s, and 5G in the 2020s) [78]. Figure 14 depicts the potential spectrum range for the sixth generation (6G) of wireless communication technology.

This paper provides an in-depth overview of phased-array antenna-on-display technology for use in wireless communication, radar, sensing, and other applications operating at microwave, millimeter-wave (mm-Wave), and sub-THz frequencies. Figure 15 illustrates the integration of an antenna, designed for use with 2.4 GHz Wi-Fi and Bluetooth technologies, into the OLED display of the wearable device, as recommended by the antenna-on-display technology [78].

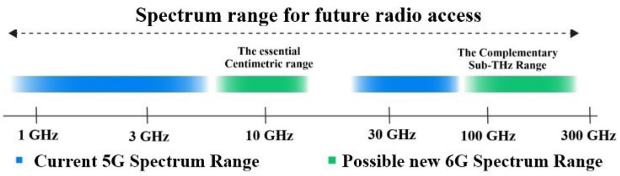


Figure 14 – Potential spectrum of 6G [77]

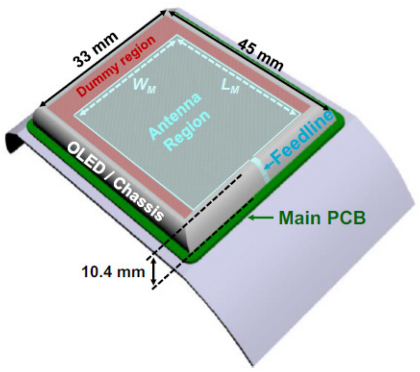


Figure 15 – Embedded optically invisible antenna inside the wearable device's organic light emitting diode display [78]

Conclusion

A detailed overview of wearable antennas for body centric wireless communication, focusing on the 5G sub-6GHz frequency spectrum. The sub-6 GHz frequency band, which is an essential element of the 5G spectrum, offers distinct advantages such as wider coverage and improved penetration capabilities. Consequently, it is proving to be a highly suitable option for the advancement of body centric wireless communication in the coming generation. The article begins by introducing the concept of body centric wireless communication, which encompasses three distinct modes: in-body, on-body, and off-body.

This article presents an in-depth review of several substrate materials employed in the development of wearable antennas. Additionally, it offers an overview of the corresponding fabrication steps and methods. This study examines the impact of varying radii on the bending behavior of antennas and evaluates their effects on the performance of wearable antennas. A detailed list of substrates having dielectric constants ranging from 1.17 and 3 is provided.

Different frequency bands are to be allocated for 5G communications.

Furthermore, the present study examines a range of 5G antennas operating at frequencies below 6 GHz, as well as multiple-input multiple-output antennas. This paper also addresses future opportunities for portable antennas in 6G.

Appendix

Abbreviations

MIMO	Multiple Input Multiple Output
BCWC	Body Centric Wireless Communication
IMD	Implantable Medical Device
WLAN	Wireless Local Area Network
ISM	Industrial Scientific and Medical
EBG	Electromagnetic Band Gap
UWB	Ultra Wide Band
PET	Polyethylene terephthalate
PTFE	Polytetrafluroethynyne
PVC	Poly vinyl Chloride
MTM	Metamaterial
LTE	Long Term Evolution
AVG	Autologous Vein Grafts
WBAN	Wireless Body Area Network
RFID	Radio Frequency Identification
SAR	Specific Absorption Rate

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