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A comprehensive review of wearable antenna design for On-Body and Off-Body communication

Gaurav Kumar Soni, Dinesh Yadav*, and Ashok Kumar

***Abstract*—Today age of advancement one of the fastest growing fields of the technology is wearable electronics and device. In the recent advancement the wearable devices for on and off body communication is going expeditiously. For the wearable wireless communication, wearable antennas are mostly used due to its compact size, self powered, light weight, low profile, portable wireless communication and sensing. This paper throws light on wearable antennas for on body and off body communication including their applications, advantages and disadvantages. A comparative study is conducted on designing of different on body and off body wearable antennas and parameters of designed antenna such as their size, shape, gain, SAR have been compared and analyzed. In this paper also discussed the impact of the wearable antenna on human body and impact of human body on antenna.**

***Keywords*—Wearable Device; Wearable Antenna; On body; Off body; SAR; Portable Device; WBAN; WPAN; Wireless Sensor Networks (WSN); ISM; MICS**

I. INTRODUCTION

IN recent years, there has been a significant surge in demand for wearable electronics and related technologies. This can be attributed to several factors, such as the reduction in size of wireless devices, the development of high-speed wireless networks, and the availability of ultra-compact, low-power System-on-Chips (SoCs) and the continued development of battery technology are some of the major advancements that have fueled this trend. These days, wearable electronics have a wide range of uses, and the majority of these uses rely on various antenna types to sense, gather, and wirelessly transmit data with a host device or an IoT gateway [1]. Products that incorporate electronic technology and computing equipment into their daily operations are known as wearable electronics. Currently, the market for these goods is expanding significantly, particularly for gadgets aimed at the average customer [2]. WPAN, WSN and WBAN all play a significant role in body centric wireless networks (BCWN). The three primary areas of BCWN are on-body, off-body and in-body based on the location of wireless sensor nodes. The communication inside the on body network and wearable device is done in on-body communication, for off body communication it done between the off bodies and on body system or device, and in-body communication the communication is done within the body using implant technology [3-5].

II. WEARABLE ANTENNA

Antennas that may be worn are known as wearable's. These antennas are frequently utilized in bio-medical RF and wearable wireless communication systems. Within the context of WBAN, wearable antennas are deployed. The main element of a WBAN that facilitates wireless communication, including in, on and off-body communication is the antenna [6]. A WBAN creates a wireless communication channel between sensors, actuators and IoT device on or at the skin, clothing, or human body. People of various ages and patients can use wearable antennas for continuous monitoring of biomedical signals like oxygen level, stress level, blood pressure and more [7]. Up till Wearable antenna are in high demand to be used for on-body and off-body communication. In the wearable antenna technology mostly used the microstrip antenna, monopole antenna, printed dipole antenna, printed loop antenna, plannar inverted F antenna (PIFA) as shown in fig 1.

When designing and developing wearable device, the three main considerations are safety, health, and way of life. The wearable antenna simplifies and improves the comfort of human living. Although people are concerned about their health and security, body worn antennas have emerged and are now utilized on a regular basis [8]. The characteristics of the wearable antenna technology are display in fig 2.

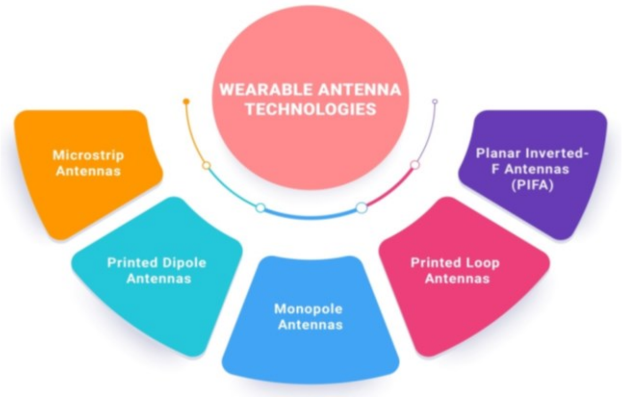

Fig 1. Wearable antenna technology

Gaurav Kumar Soni and Dinesh Yadav are with Department of Electronics and Communication Engineering, Manipal University Jaipur, Jaipur, Rajasthan, India (e-mail: gksoni2709@gmail.com, dinesh.yadav@jaipur.manipal.edu).

Ashok Kumar is with Department of Electronics and Communication Engineering, Government Mahila Engineering College, Ajmer, Rajasthan, India (e-mail: kumarashoksaini@gmail.com).

Fig 2. Characteristics of wearable antenna technology

The specific absorption rate (SAR) refers to the speed at which RF electromagnetic energy is transferred to a unit mass of a biological body. It quantifies the rate of energy absorption by the body following exposure to an RF electromagnetic field. Knowing the induced field (in V/m) that impacts a tissue is required to calculate SAR.

SAR is then determined as:

$$\text{SAR}= (\Sigma \times E^2)/M_D \qquad (1)$$

Where, σ is material conductivity, E is electric field (RMS) and m_d is density of mass.

The FCC/IC has established a SAR limit of 1.6W/kg averaged over 1 gram of real tissue. The European Union Council has set a SAR limit of 2.0W/kg averaged over 10g of real tissue.

Ultimately, these antennas must be able to function with the least amount of deterioration when close to the human body. These requirements make designing wearable antennas difficult, especially when taking into various factors like their compact size, the impact of structural deformation and connection to the body, as well as the complexity and accuracy of fabrication [9].

A. *Wearable Antenna for On Body Communications*

The number of body-centric wireless applications has dramatically expanded over the course of the last few years. These applications have the flexibility to cover various areas, including professional sports and entertainment systems, as well as security and healthcare applications, is one of their main driving forces [10]. As per the ITU-R Recommendation SA.1346, the usage of the 401 to 406 MHz band is proposed for Medical Implant Communications Services (MICS), depending on the specific system [11]. Currently, the MICS band is regulated by both the US Federal Communications Commission (FCC) [12] and the European Radiocommunications Committee (ERC) [13]. Additional recommended frequency bands for biomedical applications include 433.1 to 434.8 MHz, 0.608 to 0.614 GHz, 868 to 868.6 MHz, 0.9028 to 0.928 GHz, 1.395 to 1.4 GHz, 1.427 to 1.432 GHz, and 2.4 to 2.5 GHz, commonly known as ISM bands and wireless medical telemetry service (WMTS) [14], up to 60 [15] and 94 GHz [16].

The existence of the client, along with the interaction between the antenna and the absorbing medium of the on-body channel, is a shared characteristic among these systems, despite their variations. This fact poses a challenge to the systematic evolution of these systems as it becomes difficult to differentiate between the antenna's characteristics and the channel itself, considering the propagation conditions in free space. To describe the complete transmission connection in a free space scenario, one can utilize the directional characteristics of the transmitting antenna, the effective aperture of the receiving antenna, and an analytical or stochastic model of the channel. The Friis formula (shown in eq.2), for instance, can thus be used to determine the path loss directly.

Friis' transmission formula in free space is

$$W_r/ W_t = (G_rG_t\lambda)^2 / (4\pi R)^2 \qquad (2)$$

This equation is based on following assumptions:

- The antennas are „pointing” at one another in order to achieve maximize spatial response from each antenna, where Gr and Gt represent the maximum gains corresponding to an antennas
- The impedance matching between the transmitter, receiver and antenna is perfect.
- That the antennas used for transmission and receptions are completely co-polarized (have the same polarization, and aligned for that polarization).

Antennas and channel cannot be clearly differentiated in on-body propagations. As a result, for on-body communications, antenna metrics like the directivity and effective area are not readily available. The complete on body link, which consists of the broadcast antenna, on-body channel, and receive antenna, must therefore be taken into account [17-18].

In fig 3, shown the various application of the wearable antenna for on body communication.

Fig 3. Application of wearable antenna for on body communication

B. *Wearable Antenna for Off Body Communications*

Off-body communications are essential for integrating smart wearable's with external gadget [19]. Smart textile gadgets that communicate with other external gadgets are using off-body communication antennas [20]. Efficiency, manufacturing costs, and mechanical performance of the smart textile devices are significantly influenced by the topology and materials of these antennas (bending, crumpling, washing, and ironing) [21-22].

Off-body communication antennas must have the requisite impedance bandwidth, high radiation efficiency and compact size while minimizing front-to-back radiation levels [23]. The SAR is another important factor to take into account because of the users' health and safety concerns caused by the proximity of their bodies to the antenna [24-25].

In fig 4, shown the various application of the wearable antenna for off body communication.

Fig 4. Application of wearable antenna for Off body communication

III. Review of Previous Work Done on Wearable Antenna Design for On Body and Off Body Communication

A. For On Body Communication

Antennas designed for on-body environments need to be compatible with the human body and capable of withstanding frequency and polarization detuning. Understanding the most effective methods for specifying an antenna's radiation pattern becomes crucial when considering its placement in space and within a lossy body. It is also essential to comprehend how to specify the coupling of the antenna into propagation modes, which may include surface waves, free space waves, or a combination of both. To evaluate the impact of the human body's presence on the overall antenna performance, various on-body applications were subjected to a parametric review. This assessment encompassed aspects such as gain, efficiency, radiation patterns, return loss and impedance matching.

In [26] presented GCPW fed slot antenna works on 2.4GHz and 5.8GHz frequency and used for WLAN on body application. The simulated return loss for 2.4 and 5.8GHz frequency is -22dB and -18dB respectively and measured return loss is -11dB and -21.5dB respectively. The measured antenna efficiency is 65%-76%% for 2.4GHz and 88% for 5.8GHz. In [27] presented UC-EBG structure microstrip monopole antenna using PDMS substrate for 2.4GHz WBAN on body application. The presented antenna size is $40\times60\times3mm^3$ and return loss is -25dBi. In [28] AMC backed antenna is presented that is design using the lather material with size of antenna is $40.5\times40.5\times6$ mm^3. In this work different simulation and measurement is done on different human body part like on hand, chest, on head etc. In this work using AMC backed structure reduced the SAR value 96%. In [29] presented a wearable antenna using EBG structure with circular ring slot. The SAR value with EBG structure is 0.555 for 1g and 0.23 for 10g. The bandwidth of antenna is 14.7%, gain is 7.3dBi and antenna volume is $81\times81\times4mm^3$. In reference [30], a flexible PET substrate was employed to design an inkjet-printed circular monopole ultra-wideband (UWB) antenna. The antenna featured an inside-cut feed structure and was analyzed using HFSS. Its operating frequency range spanned from 3.04 GHz to 10.70 GHz, along with an upper Ku band range of 15.18 GHz to 18 GHz. The antenna demonstrated a return loss of 10 dB and VSWR of 2. It was constructed using a coplanar waveguide (CPW) feeding mechanism. The antenna's $47\times25\times0.135$ mm^3 size allowed it to radiate omnidirectionally across the whole impedance bandwidth with an average peak gain of 3.94dBi. The simulated antenna construction proved suitable for flexible and wearable IoT applications. In [31] describes a small, planar UWB antenna for wireless applications. A pentagon slot is placed inside a circular metallic patch in the suggested antenna, which is inspired by fractal geometry design. Iterations were carried out to attain the required broad bandwidth. The suggested antenna is designed using FR4 substrate and operates at a bandwidth of 12.1GHz (2.9–15GHz) and has dimensions of $32\times32mm^2$. When this antenna is positioned adjacent to the dispersive phantom model, the SAR, a measure of EM radiation exposure on human tissues, is observed. When the intended antenna is kept in close proximity to the human body, SAR and thermal effects resulting from EM exposure are examined. When the intended antenna is kept in close proximity to the human body, SAR and thermal effects resulting from EM exposure are examined. According to the study, the SAR values are far below the FCC's and other safety laws' limit, which qualifies the suggested antenna for a wide range of short-range wireless applications that are rapidly growing. SARs for 1g of tissue in various locations of body are calculated such as SAR for forearm for 5mm above the body is 0.003W/kg at 3.1 GHz, 0.004W/kg at 6.8GHz and 0.003W/kg at 10.6 GHz.

GCPW Slot Antenna [26]

UC-EBG Microstrip Monopole Antenna [27]

UWB Inkjet Printed Antenna [30]

AMC Backed Antenna Placement on Different Parts of Human Body [28]

Circular Ring Slot Antenna With EBG Structure [29]

Fig 5. Different Antenna Structure Used by different authors for on body communication [26-30]

TABLE I
OVERVIEW ON WEARABLE ANTENNA FOR ON BODY COMMUNICATION

Ref. No., Year	Antenna Structure	Substrate	frequency (GHz)	|Gain| (dBi)	SAR (1g) W/kg	Size (mm^3)	Application	Advantage	Disadvantage
[26], 2020	GCPW Slot Antenna	FR4	2.4 5.8	1.5 4.2	__	15×40×0.1	WLAN on body communication	Low Profile Fabrication and measurement is done. Human body model is used.	Lower Gain. SAR analysis is not done.
[27], 2019	UC-EBG microstrip monopole antenna	PDMS	2.48	5.6	0.0536	40×60×3	WBAN on body application	Low SAR. Banding analysis is done. Fabrication and measurement is done.	Low Gain.
[28], 2021	AMC	Leather	5.8	7.47	0.02298 on hand 0.01176 on chest 0.0246 on head	40.5×40.5×6	Biomedical Application	Low SAR. Banding analysis is done. Simulation and measurement results are analysis on different part of human body.	Low Gain. |S11| Response is may be more improved.
[29], 2018	Circular Ring Slot Antenna With EBG Structure	wool felt	2.4	7.3	0.554	81×81×4	WBAN	Bandwidth is good. Fabrication and measurement is done.	Large Size of Antenna. Banding analysis is not done.
[30], 2021	UWB Inkjet printed antenna	PET	10.6 18.5	4.25 5.7	__	47×25×0.135	Flexible wearable IoT applications	Different banding analysis is done. Antenna is flexible.	Human body analysis is not done. Low Gain. SAR value is not given properly.

[31], 2019	Planar UWB	FR4	3.1 6.8 10.6	—	0.003 0.004 0.003	32×32×1.6	Short Range Wireless Communication	Wide bandwidth. SAR value is good.	Bending Analysis is not done. Gain of antenna is missing.
[32], 2020	CPW fed Circular Monopole antenna	PET Paper	1.6 to 56.1	4.91	—	34×25×0.135	ISM band, WLAN, WiMAX, UWB application	Higher Bandwidth. Used for multiband application.	SAR analysis is not done. Banding analysis is not done.
[33], 2017	SSR Loaded CPW Antenna	Rogers RT 6002	2.45	1.06	—	35×35×1.6	EEG Monitoring	|S11| Response is good.	Gain is very poor. SAR analysis is not done. Fabrication measurement is not done.
[34], 2018	SSR loaded CB-CPW fed antenna	Teflon	2.45 3.5	10 4	—	20×20×1.6	Healthcare Monitoring	High simulated gain for 2.45GHz frequency. |S11| Response is good.	SAR analysis is not done. Fabrication measurement is not done.
[35], 2017	SRR Loaded CB-CPW Fed Diamond Shaped antenna	Teflon	2.48 3.54	2.5 3.57	—	20×20×1.6	ECG Monitoring	Compact antenna size. |S11| Response is good.	Gain is poor. SAR analysis is not done. Fabrication measurement is not done.
[36], 2019	UWB antenna	Felt	4 8	4.8 6	0.335 0.491	39×42×3.14	WBAN	Antenna measurement is done on different part of human body. Bandwidth is good. Bending analysis is done with different angles.	Low Gain. Complex Design.

B. *For Off Body Communication*

In [37] low profile monopole antenna is presented for biomedical off body application. the size of the presented antenna is 11×14×1.54mm^3, peak gain is 4.4dBi, bandwidth is 770MHz and SAR(1g) and (10g) value is 0.316W/kg and 1.22W/Kg respectively. In [38] presented footwear antenna is play major role in healthcare, motion monitoring and military field. It works on 0.433, 0.868 and 0.915GHz frequency range. In [39] presented a monopole antenna with slotted disc on PET substrate, and examined for early brain stroke detection at 2.45GHz ISM band. Due to its low loss tangent, flexibility, and moisture resistance, PET is employed as a substrate. By using the slotting approach, this antenna's size is decreased to 40×38mm^2. The printed antenna's 480MHz (19.55%) bandwidth spans the frequency range of 2.25GHz to 2.73GHz. It exhibits a 99 percent radiation efficiency and a realized gain of 2.78 dB at a frequency of 2.45 GHz. By comparing the differences in signals received from the head models with and without stroke, the Monostatic Radar (MR) method is thought to be able to identify brain stroke. The 2.45 GHz frequency of the antenna's SAR dispersion patterns was calculated. The simulated findings reveal that the computed values are 1.61W/kg and 0.8W/kg, respectively, for 1 g and 10 g of tissues. In [40] wearable textile antenna is presented for WiMax application and its work on 3.4GHz frequency and gain is 7.7dBi. A planar, lightweight UWB antenna designed for wearable IoT applications for WBANs was introduced in [41]. This antenna was designed by utilizing two different substrates (FR4 and denim), and the model's dimensions were 31×42 mm^2 and 70×56 mm^2 for FR4 and denim textile substrate respectively. The patch's size was 22.6×17 mm^2. The design is simplified by this patch such that the substrates' acquired impedance bandwidths of 7.71 GHz and 7.95 GHz for each may readily accommodate the current and upcoming generations of IoT gadget and WBAN transceiver systems. In this study, a symmetrically organised meander line antenna with truncated ground planes is suggested in [42] for wearable use. It is situated around a T-shaped junction. The developed antenna has a 69.04% bandwidth that covers the GSM 1800 band, 4G LTE band and the ISM 2.4-2.5 GHz spectrum. The antenna is small in size, measuring 30×40×1.6 mm^3. In the absence of any additional components, the specific absorption rate (SAR) is reduced. Both a head model and a homogeneous human dry skin model are utilized to approximate the behavior of the antenna. The design considers factors like size reduction, radiation patterns, and SAR limitations. The constructed antenna design is tested and proven suitable for practical applications. When a hand phantom is modeled in HFSS, it is observed that implementing a truncated ground plane in the suggested antenna reduces SAR levels. Specifically, at a distance of 15mm above the body, the SAR decreases from 1.31 Watts/Kg to 0.98 Watts/Kg. Additionally, for wearable applications, a low-profile monopole antenna with shaped pentagonal is developed and demonstrated in reference [43]. In this work major goal is to develop a miniature ultra wide band (UWB) monopole planar antenna that can operate effectively in space as well as on the surface of the human body. The proposed pentagonal monopole antenna is used to demonstrate how human tissues affect antenna performance. The overall antenna performance will be improved with a wide bandwidth ranging from 2.9 to 11GHz. The SARs at the different body location are calculated such as SAR for forearm for 5mm above the body is 0.038W/kg at 3.1 GHz, 0.0017W/kg at 6GHz and 0.0083W/kg at 10.5 GHz.(5mm above the body).

TABLE II
OVERVIEW ON WEARABLE ANTENNA FOR OFF BODY COMMUNICATION

Ref. No., Year	Antenna Type & Structure	Substrate	frequency (GHz)	Gain (dBi)	SAR W/kg	Size (mm^3)	Application	Advantage	Disadvantage
[37], 2023	Monopole antenna	Rogers 4003 C	5.8	4.4	0.316	11×14×1.54	Off-body WBAN communication systems	Large Bandwidth. SAR response is good. Low Profile.	Bending effect analysis is not done.
[38], 2022	textile slot antenna	wool felt	0.433 0.868 0.915	2.8	___	95×65×1.4	Footwear LoRa communication	Human body analysis is done with human foot phantom.	Low Gain. SAR analysis is not done.
[39], 2020	Inkjet Printed Slotted Disc Monopole Antenna	PET	2.45	2.8	1.61 (1g), 0.8 (10g)	40×38×0.135	Early Brain Stroke Detection	For simulation analysis 7 layer human tissue model is used. Fabrication and measurement is done. SAR value is good.	Low Gain.
[40], 2020	Textile antenna	Felt	3.5	7.7	0.772	70×70×2	WiMax	Human Body phantom analysis is done. Work for both on (2.4GHz) and off body (3.5GHz).	Bending effect analysis is not done.
[41], 2018	UWB Antenna	FR4 and Denim Textile	7.71 7.95	5.12 3.57	__	31×42×1.6 70×56×1	wearable IoT devices and WBAN	Low design complexity. Fabrication and measurement is done.	Low Gain. Banding effect and SAR value analysis is not done.
[42], 2017	T-shaped CPW-fed patch antenna	FR4	2.4	3	0.98	30×40×1.6	4G LTE & ISM Band	Large Bandwidth. Good radiation efficiency of 96.9%.	Banding effect is not analyzed. Gain is low.
[43], 2017	Low Profile UWB Monopole Antenna	FR4	2.9 GHz to 11GHz	1.8 to 5	0.038 at 3.1 GHz, 0.0017 at 6GHz and 0.0083 at 10.5 GHz	15×25×1.6	Wearable application.	Low Profile. Low SAR. Experiment analysis done on different part of human body.	Gain is low.
[44], 2012	Equilateral Triangular microstrip patch antenna array	ULA Textile	2.45	14.7	0.0124	480×180×3.55	Firefighter Suit	Active in disaster area. Mutual Coupling Measurements. Good simulated gain (14.7dBi) and measured gain 10.3 dBi.	Designed antenna is large in size.

IV. IMPACT OF WEARABLE ANTENNA ON HUMAN BODY AND VICE VERSA

Because of their near closeness to the human body in WBAN, wearable antennas encounter significant challenges, and vice versa.

- Electromagnetic radiation's effects on human body.
- The antenna's decreased effectiveness as a result of the radiation pattern being fragmented, the antenna's impedance changing, and frequency detuning.

When creating antennas for wearable technology, these aspects demand special consideration. When constructing wearable antennas, developers need to prioritize aspects such as structural integrity, accuracy, and precision in the production process, as well as consider the size requirements. Attention should be given to prevent structural deformation and ensure the antenna's overall quality and performance [45].

A. *Impact of Wearable Antenna on Human Body*

Non-ionizing radiations, such as microwaves, visible light, and sound waves, have the potential to increase the temperature of cells by inducing atomic movement or vibration, even without possessing sufficient energy to ionize atoms or molecules within the body. This rise in temperature, known as dielectric heating, can cause significant harm to human tissues. Dielectric heating occurs when the electromagnetic field induces rotations of polar molecules, leading to thermal effects from microwave radiation on dielectric materials [46]. In order to ensure radiation levels within the human body remain at acceptable levels, the FCC has implemented SAR standards for wireless devices. The SAR limit, set at 1.6W/kg averaged over 1g of actual tissue, has been exceeded by the European Union (EU) Council, which imposed a limit of 2W/kg averaged over 10g of real tissue. The rate of RF energy absorption by human tissues is measured using the SAR parameter. SAR values help to ensure that wireless smart gadgets and wearable technologies stay within the parameters of safe exposure [47].

Due to the fact that on-body antennas' SAR depends on near-field coupling to body, antennas without a ground plane have greater SAR values. As a result, changing the ground plane is a crucial component of many SAR value reduction solutions. To filter EM waves within certain frequency bands, one method includes using periodic conductive structures, such as EBG structures. By using high impedance surfaces, similar aid is given in the blocking of electromagnetic radiation within a specific frequency band. Wearable antennas are strategically placed in front of high impedance surfaces to increase the front-to-back radiation ratio and reduce the SAR (specific absorption rate) in the human body. These high impedance surfaces can effectively reflect electromagnetic waves without phase inversion and restrict the propagation of surface waves.

Additionally, utilizing an AMC (Artificial Magnetic Conductor) ground plane can serve as an isolator, further enhancing the antenna's performance.. Techniques for SAR reduction, including integrating metamaterials and ferrite sheets, are often used by antenna designers [48].

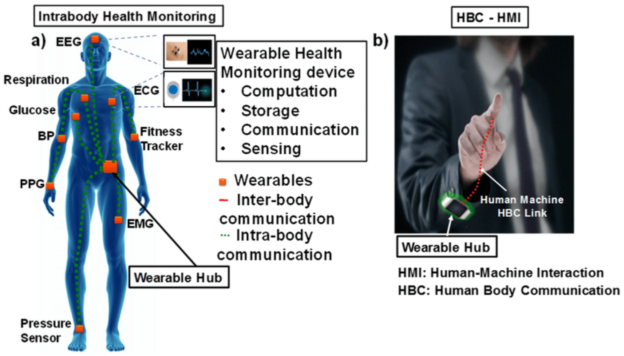

Fig 5. Human Impact Communication [48]

B. *Impact of Human Body on Wearable Antenna*

Wearable antennas are also affected to some extent by nearby human bodies. The human body's lossy, high dielectric constant characteristics could alter input impedance, alter frequency, and reduce antenna efficiency. There is a disruption in the communication path between the antenna and external host gadget [49].

The influence of the human body on antennas can be tackled using various approaches, which depend on the specific application. Among these approaches, the positioning and orientation of the antenna play a crucial role. Finding the optimal location, direction, and separation of the antenna from the body can significantly reduce the impact caused by the presence of the human body. Furthermore, advanced systems can incorporate automatic tunable circuits and programmable antennas to achieve high performance. Antenna designers also utilize high impedance surfaces and EBG ground planes to mitigate the effects of the body on wearable antennas.

V. CONCLUSION

One of the most rapidly advancing and growing fields in recent times is wearable electronics and devices, primarily due to their portability and ease of use. These wearable antennas and devices are employed for efficient on-body and off-body communication, thanks to their compact size, self-powered operation, lightweight nature, low profile, and portable wireless communication and sensing capabilities. In this paper, present a comparative study that explores various designs of wearable antennas for both on-body and off-body communication, along with their respective advantages and disadvantages. Additionally, we delve into the impact of the human body on wearable antennas and vice versa. Furthermore, a detailed overview is provided regarding different design parameters, antenna structures, gain, bandwidth, specific absorption rate (SAR), and operating frequencies of wearable antennas for both on-body and off-body communications.

REFERENCES

[1] N. H. M. Rais, P. J. Soh, F. Malek, S. Ahmad, N. B. M. Hashim and P. S. Hall, „A review of wearable antenna", IEEE 2009 Loughborough Antennas & Propagation Conference, pp. 225-228, 2009. https://doi.org/10.1109/LAPC.2009.5352373

[2] A. Chandravanshi, A. Rai and G. Chaitanya, „Wearable antenna: A critical review", 2016 IEEE 11th International Conference on Industrial and Information Systems (ICIIS), pp. 486-491, 2016. https://doi.org/10.1109/ICIINFS.2016.8262989

[3] P. S. Hall andY. Hao, "Antennas and Propagation for Body-Centric Wireless Communications", Norwood, MA, USA: Artech House, 2006.

[4] A. Pellegrini, A. Brizzi, L. Zhang, K. Ali; Y. Hao, X. Wu; C. C. Constantinou, Y. Nechayev, P. S. Hall, N. Chahat, M. Zhadobov and R. Sauleau, „Antennas and Propagation for Body-Centric Wireless Communications at Millimeter-Wave Frequencies: A Review [Wireless Corner]," in IEEE Antennas and Propagation Magazine, vol. 55, no. 4, pp. 262-287, Aug. 2013. https://doi.org/10.1109/MAP.2013.6645205

[5] Michal Mackowiak and Luis M. Correia, „A Statistical Model for the Influence of Body Dynamics on the Gain Pattern of Wearable Antennas in Off-Body Radio Channels", Wireless Personal Communications: An International Journal, Volume 73, Issue 3, pp. 381–399, December 2013. https://doi.org/10.1007/s11277-013-1193-x

[6] H. Xiaomu, S. Yan and G. A. E. Vandenbosch, „Wearable Button Antenna for Dual-Band WLAN Applications With Combined on and off-Body Radiation Patterns", IEEE Transactions on Antennas and Propagation, vol. 65, no. 3, pp. 1384-1387, March 2017. https://doi.org/10.1109/TAP.2017.2653768

[7] K. N. Paracha, S. K. Abdul Rahim, P. J. Soh and M. Khalily, „Wearable Antennas: A Review of Materials, Structures, and Innovative Features for Autonomous Communication and Sensing", IEEE Access, vol. 7, pp. 56694-56712, 2019.
https://doi.org/10.1109/ACCESS.2019.2909146

[8] V. Kumar, „Patch antenna for wearable electronics," IEEE 2017 2nd International Conference for Convergence in Technology (I2CT), pp. 636-640, 2017. https://doi.org/10.1109/I2CT.2017.8226207

[9] S. Alharbi, R. M. Shubair and A. Kiourti, „Flexible antennas for wearable applications: Recent advances and design challenges," 12th European Conference on Antennas and Propagation (EuCAP 2018), pp. 1-3, 2018.

[10] P. S. Hall and Y. Hao, "Antennas and Propagation for Body Communications Systems", 2nd ed. Norwood, MA, USA: Artech House, 2012. https://doi.org/10.1109/EUCAP.2006.4584864

[11] "International Telecommunications Union-Radiocommunications (ITU-R), Radio Regulations, SA.1346," ITU, Geneva, Switzerland; available online: http://itu.int/home

[12] "Medical Implant Communications Service (MICS) Federal Register," Rules Regulations, 64, 240, pp. 69926-69934, December 1999.

[13] "European Radiocommunications Commission (ERC) Recommendation 70-03 Relating to the Use of Short Range Devices," European Conference of Postal and Telecommunications Administration, CEPT/ERC 70-03, Annex 12, 1997.

[14] "International Telecommunications Union-Radiocommunications (ITU-R), Radio Regulations, Section 5.138 and 5.150," ITU, Geneva, Switzerland; available online: http://itu.int/home

[15] N. Chahat, G. Valerio, M. Zhadobov and R. Sauleau, "On-Body Propagation at 60 GHz," in IEEE Transactions on Antennas and Propagation, vol. 61, no. 4, pp. 1876-1888, April 2013. https://doi.org/10.1109/TAP.2013.2242034

[16] A. Kiourti and K. S. Nikita, "A Review of Implantable Patch Antennas for Biomedical Telemetry: Challenges and Solutions [Wireless Corner]", IEEE Antennas and Propagation Magazine, vol. 54, no. 3, pp. 210-228, June 2012. https://doi.org/10.1109/MAP.2012.6293992

[17] A. Pellegrini, A. Brizzi, L. Zhang, and Y. Hao, "Numerical and experimental analysis of the on-body propagation channel at W band," in Proc. 6th Eur. Conf. Antennas Propag. (EUCAP), Mar. 26–30, pp. 750–754, 2012. https://doi.org/10.1109/EuCAP.2012.6206635

[18] Q. H. Abbasi, A. Sani, A. Alomainy, and Y. Hao, "Numerical characterization and modeling of subject-specific ultra wideband body-centric radio channels and systems for healthcare applications," IEEE Trans. Inf. Technol. Biomed., vol. 16, no. 2, pp. 221–227, Mar. 2012. https://doi.org/10.1109/TITB.2011.2177526

[19] A Araghi, M. Khalily, A. A. Ghannad, P. Xiao and R. Tafazolli, "Compact Dual Band Antenna for Off-Body-Centric Communications", 2019 IEEE 13th European Conference on Antennas and Propagation (EuCAP), pp. 1-5, 2019.

[20] S. Agneessens, S. Lemey, T. Vervust and H. Rogier, ”Wearable small and robust: The circular quarter-mode textile antenna”, IEEE Antennas Wireless Propag. Lett., vol. 14, pp. 1482-1485, 2015. https://doi.org/10.1109/LAWP.2015.2389630

[21] S. Yan, P. J. Soh and G. A. E. Vandenbosch, ”Low-Profile Dual-Band Textile Antenna With Artificial Magnetic Conductor Plane”, IEEE Transactions on Antennas and Propagation, vol. 62, no. 12, pp. 6487-6490, Dec. 2014. https://doi.org/10.1109/TAP.2014.2359194

[22] M. E. Lajevardi and M. Kamyab, ”Ultra miniaturized metamaterial-inspired SIW textile antenna for off-body applications”, IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 3155-3158, 2017. https://doi.org/10.1109/LAWP.2017.2766201

[23] S. J. Boyes, P. J. Soh, Y. Huang, G. A. E. Vandenbosch and N. Khiabani, ”Measurement and performance of textile antenna efficiency on a human body in a reverberation chamber”, IEEE Trans. Antennas Propagation, vol. 61, no. 2, pp. 871-881, Feb. 2013. https://doi.org/10.1109/TAP.2012.2225817

[24] P. B. Samal, P. J. Soh and G. A. E. Vandenbosch, ”UWB All-Textile Antenna With Full Ground Plane for Off-Body WBAN Communications”, IEEE Transactions on Antennas and Propagation, vol. 62, no. 1, pp. 102-108, Jan. 2014. https://doi.org/10.1109/TAP.2013.2287526

[25] A. Smida, A. Iqbal, A. J. Alazemi, M. I. Waly, R. Ghayoula and S. Kim, ”Wideband Wearable Antenna for Biomedical Telemetry Applications”, IEEE Access, vol. 8, pp. 15687-15694, 2020. https://doi.org/10.1109/ACCESS.2020.2967413

[26] K. L. Wong, H. J. Chang, C. Y. Wang and S. Y. Wang, ”Very-Low-Profile Grounded Coplanar Waveguide-Fed Dual-Band WLAN Slot Antenna for On-Body Antenna Application”, IEEE Antennas and Wireless Propagation Letters, vol. 19, no. 1, pp. 213-217, Jan. 2020. https://doi.org/10.1109/LAWP.2019.2958961

[27] G. Gao, R. Zhang, C. Yang, H. Meng, W. Geng, B. Hu, ”Microstrip monopole antenna with a novel UC-EBG for 2.4 GHz WBAN applications”, IET Microwaves, Antennas & Propagation, Vol. 13 Iss. 13, pp. 2319-2323, 2019. https://doi.org/10.1049/iet-map.2019.0271

[28] P. Saha , D. Mitra, S. K. Parui, „Control of Gain and SAR for Wearable Antenna Using AMC Structure”, Radioengineering, Vol. 30, No. 1, pp. 81-88, 2021. https://doi.org/10.13164/re.2021.0081

[29] G. P. Gao, B. Hu, S. F. Wang and C. Yang, „Wearable Circular Ring Slot Antenna With EBG Structure for Wireless Body Area Network”, IEEE Antennas and Wireless Propagation Letters, vol. 17, no. 3, pp. 434-437, 2018. https://doi.org/10.1109/LAWP.2018.2794061

[30] Sharadindu Gopal Kirtania , Bachir Adham Younes, Abdul Rakib Hossain, Tutku Karacolak and Praveen Kumar Sekhar, “CPW-Fed Flexible Ultra-Wideband Antenna for IoT Applications”, MDPI Journal of Micromachines 12, 453, pp. 1-13, 2021. https://doi.org/10.3390/mi12040453

[31] Mohandoss Susila, Thipparaju Rama Rao, Karthik Varshini, Palaniswamy Sandeep Kumar, and Marudappa Pushpalatha, „Investigations of Specific Absorption Rate and Temperature Variations for an UWB Antenna for Wireless Applications”, Progress In Electromagnetics Research M, Vol. 78, 83–92, 2019. https://doi.org/10.2528/PIERM18111603

[32] Md. Rabiul Hasan, Manjurul Ahsan Riheen, Praveen Sekhar, Tutku Karacolak, „Compact CPW-fed circular patch flexible antenna for super-wideband applications”, IET Microwaves, Antennas & Propagation, Vol. 14 Iss. 10, pp. 1069-1073, 2020. https://doi.org/10.1049/iet-map.2020.0155

[33] K. Sajith, J. Gandhimohan and T. Shanmuganantham, „Design of SRR loaded octagonal slot CPW fed wearable antenna for EEG monitoring applications”, IEEE International Conference on Circuits and Systems (ICCS), pp. 49-53, 2017. https://doi.org/10.1109/ICCS1.2017.8325961

[34] K. Sajith, J. Gandhimohan and T. Shanmuganantham, „Multilayered and Dual-Band CB-CPW Fed Wearable Antenna for Healthcare Monitoring Applications”, IEEE International Conference on Current Trends towards Converging Technologies (ICCTCT), pp. 1-5, 2018. https://doi.org/10.1109/ICCTCT.2018.8551162

[35] K. Sajith, J. Gandhimohan and T. Shanmuganantham, „Design of SRR loaded CB-CPW fed diamond shaped patch on-body antenna for ECG monitoring applications”, 2017 IEEE International Conference on Circuits and Systems (ICCS), pp. 118-123, 2017. https://doi.org/10.1109/ICCS1.2017.8325975

[36] Purna B. Samal, Ping Jack Soh and Zahriladha Zakaria, „Compact Microstrip-Based Textile Antenna for 802.15.6 WBAN-UWB with Full Ground Plane”, Hindwai International Journal of Antennas and Propagation, pp. 1-12, 2019.

[37] R. Rabhi, H. Akbari-Chelaresi, M. Olaimat, A. Gharsallah and O. M. Ramahi, „Low-Profile off-Body Wearable Antenna for Biomedical Applications”, IEEE International Microwave and Antenna Symposium (IMAS), 2023, pp. 142-145, 2023. https://doi.org/10.1109/IMAS55807.2023.10066886

[38] R. Huang, W. Xia, L. Xing and F. Zhu, „A Dual-Band Footwear Textile Antenna for LoRa Off-Body Communication”, IEEE Conference on Antenna Measurements and Applications (CAMA), pp. 1-4, 2022. https://doi.org/10.1109/CAMA56352.2022.10002504

[39] Md. Ashikur Rahman, Md. Foisal Hossain, Manjurul A. Riheen, and Praveen K. Sekhar, „Early Brain Stroke Detection Using Flexible Monopole Antenna”, Progress In Electromagnetics Research C, Vol. 99, pp. 99–110, 2020. https://doi.org/10.2528/PIERC19120704

[40] H. Yang and X. Liu, „Wearable Dual-Band and Dual-Polarized Textile Antenna for On- and Off-Body Communications”, IEEE Antennas and Wireless Propagation Letters, vol. 19, no. 12, pp. 2324-2328, Dec. 2020. https://doi.org/10.1109/LAWP.2020.3032540

[41] Muhammad Mustaqim, Bilal A. Khawaja, Hassan T. Chattha, Kinza Shafique, Muhammad J. Zafar and Mohsin Jamil, „Ultra-wideband antenna for wearable Internet of Things devices and wireless body area network applications”, Welly International Journal of Numerical Modelling Electronic Networks Devices and Fields 32(2):e2590, pp. 1-12, 2018. https://doi.org/10.1002/jnm.2590

[42] Shankar Bhattacharjee, Monojit Mitra, and Sekhar R. Bhadra Chaudhuri, „An Effective SAR Reduction Technique of a Compact Meander Line Antenna for Wearable Applications”, Progress In Electromagnetics Research M, Vol. 55, pp. 143–152, 2017. https://doi.org/10.2528/PIERM16121501

[43] Srinivas Doddipalli, Ashwin Kothari, and Paritosh Peshwe, „A Low Profile Ultrawide Band Monopole Antenna for Wearable Applications”, Hindawi International Journal of Antennas and Propagation, pp. 1-9, 2017.

[44] Maria Lucia Scarpello, Luigi Vallozzi, Hendrik Rogier, and Dries Vande Ginste, „High-Gain Textile Antenna Array System for Off-Body Communication”, International Journal of Antennas and Propagation, pp. 1-12, 2012. https://doi.org/10.1155/2012/573438

[45] “Wearable Antennas – Applications, Technologies, and their Impact on Human Body”, https://www.mistralsolutions.com/blog/wearable-antennas-applications-technologies-impact-human-body/#:~:text=The%20human%20body%20also%20has,and%20reduced%20efficiency%20of%20Antenna

[46] Nurul Huda Abd Rahman, Yoshihide Yamada and Muhammad Shakir Amin Nordin, „Analysis on the Effects of the Human Body on the Performance of Electro-Textile Antennas for Wearable Monitoring and Tracking Application”, MDPI Journal of Materials 12, pp. 1-17, 2019. https://doi.org/10.3390/ma12101636

[47] Silvia Gallucci, Marta Bonato, Martina Benin, Emma Chiaramello, Serena Fiocchi, Gabriella Tognola and Marta Parazzini, „Assessment of EMF Human Exposure Levels Due to Wearable Antennas at 5G Frequency Band”, Sensors 23, pp. 1-13, 2023. https://doi.org/10.3390/s23010104

[48] S. Maity, D. Das and S. Sen, „Wearable health monitoring using capacitive voltage-mode Human Body Communication”, IEEE 39th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), pp. 1-4, 2017. https://doi.org/10.1109/EMBC.2017.8036748

[49] Yuanzheng Xu, Lei Mu, Yinfang Xu, Abdelhady Mahmoud, Yiying Wang and Omar M. Ramahi, „Wearable Directional Button Antenna for On-Body Wireless Power Transfer”, Electronics 12, pp. 1-12, 2023.