Comprehensive review of the human body communication system for wireless body area network applications

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ABSTRACT

The body area networks (BAN) structure is one of the advancements in health monitoring innovations and the sharp rise in healthcare demand. With the help of a network of constantly running sensors, BAN technology aims to monitor vital physiological and physical features like accessibility, respiration, and blood sugar levels. The achievement of BAN technology depends on wireless communication since it gives the user flexibility and versatility. Most BAN solutions have effectively employed radio frequency (RF) wireless technology, although these systems are battery-intensive, prone to electromagnetic interference, and have security weaknesses. The human body is the signal transmission medium in the alternative wireless communication technology called human body communication (HBC). HBC possesses traits that could logically deal with the problems with RF for wireless body area networks (WBAN) technology. This overview looks at the ongoing research in this field and highlights the principles of the HBC, the most recent studies of HBC, human body coupling approaches, the designs of HBC transceivers, and the unresolved research issues. HBC provides promising future possibilities for making WBAN technologies more useful.

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1. INTRODUCTION

The rapidly growing healthcare sector now uses wireless sensors to monitor patients remotely across a network continuously. These body area networks (BAN) and other infrastructure area networks prevent the need for a manual health system and guarantee that patients can manage their illnesses in the future. The BAN technology uses wireless sensors implanted in the body to track vital signs and stop serious illnesses. Due to the high demand for portable health monitoring devices, BAN technology is now the subject of many research and case studies [1]. Intrabody communication (IBC) is a conduit for electrical signals to connect minute electronic components in wireless BANs (WBANs) inside the human body. These tiny devices are communicated with each other in the human body and with central devices [2]. Three physical layers (PHY), including IBC, were suggested by the IEEE 80-2.15.6 standard for implementing the WBAN. IBC is also known as conductive communication, body-coupled communication, body channel communication, human-body communication (HBC), and in-body radio. The IBC addresses wavelength, skin depth, large-scale fading, and dielectric characteristics in relation to propagation and bio-electromagnetic mechanisms [3], [4]. When creating the HBC, many factors must be taken into account, including coupling strategies, the electrical characteristics of human tissues, signal propagation strategies, body channel characteristics, and the HBC's communication performance [5]–[7].

Minimum power needs constrain low-power gadgets attached to the body because of their short battery lives, and they should be wearable-sized. Managing such a heterogeneous network (from the perspectives of the various devices) and the highly dynamic traffic adds another level to the design difficulties. The severe environment, quality-of-service (QoS), and dependability of successful connectivity for the applications in question all add to the system's strict limitations. As a result, the state-of-the-art, including standards and protocol stacks, needs to be thoroughly reviewed from an application-oriented and associated concerns perspective in light of these new applications. Finally, it's important to comprehend the potential prospects and difficulties in this situation and the crucial limitations of the current solutions.

The following highlights the importance of this review work on HBC: the goal is to gather the most recent findings on an entirely novel technology for wireless communication, quickly gaining interest. The human body is the transmission channel for electrical impulses in HBC, a cutting-edge non-RF wireless data communication method. The recently approved IEEE 802.15.6 WBAN protocol has a definition for the HBC method. HBC users' suppression of communication with people around them reduces energy from being lost in the surroundings, which could result in reduced power consumption. According to research, HBC can transmit power at levels as low as 10 mW using software and below 200 mW using hardware approaches. This strategy may be intriguing as a short-range communications alternative because the HBC can boost data rates of more than 1 Mbps. The HBC's future directions and open research challenges are mentioned.

This exhaustive review of human body communication and its challenges is presented in this manuscript. The manuscript's organization is: the current works on HBC and its limitations are discussed in section 2. Section 3 overviews the IEEE 802.15.6 standard for WBAN. The HBC system is explained in section 4, including coupling approaches, architecture, recent works with performance comparison, and applications. The open research challenges and futuristic work are suggested in section 5. Lastly, the overall work is concluded in section 6.

2. LITERATURE REVIEW

This section discusses the current HBC or IBC system using different approaches for WBAN applications. Lee *et al.* [8] present the decision feedback equalization (DFE) based body channel communication to improve the data rate issues. The DFE compensates for the human body channel's intersymbol interference (ISI). The work obtains the 10 Mbps and 150 Mbps as the human body channel's lowest and highest data rates. The data rate will be improved by increasing the number of DFEs.

Chowdhury *et al*. [9] present the multi-integrating receiver (RX) frontends for lossy broadband channels. This work provides alternate communication links like HBC to avoid channel loss. The work realizes the theoretical analysis of several broadband RX modules to improve gain factors. Asan *et al*. [10] present the fat-intrabody communication (IBC) analysis using different body movements. The work analyzes path loss using locations, polarization, and fat-thickness. The system provides a frequency range from 3.2 to 7.1 GHz using waveguide probes with optimization in fat-IBC. Noormohammadi *et al*. [11] discuss the galvanic impulse-based IBC system to improve the power issues in wireless communication. The galvanic impulse approach is used to communicate the in-body and on-body devices. The system obtains the data rate of 64 kbps by consuming45 µW of power with an implant depth of 14 cm and a percentage bit error rate (BER) of 0.5.

Liao *et al*. [12] explain the HBC-based signal transmission to realize the path losses for wearable robot control. The work uses electroencephalogram (EEG) signal transmission in HBC to control the wearable robot. The impulse radio-based HBC transceiver is designed to evaluate computational performances. The system operates at 10 Mbps with a BER of 10^{-3} for a distance of 10 cm. Sacco *et al*. [13] describe the human body coupling in fifth-generation millimeter (mm) wave bands to realize the effects of aging and textiles. Skin-based model is used concerning the multi-beam radiating structures. The effects of clothing and aging concerning bare skin at 26 GHz and 60 GHz are realized to find the power density variation. Wagih [14] present the flexible textile single-wire transmission lines (SWTL) using on-body ultra-high frequency (UHF) to mm-wave surface wave links. This approach is used to resolve issues of human body shadowing. The SWTL is operated between 1 to 3 GHz over -10 dB. The SWTLs are capable of using in future BANs for high data-rate transmission. Sasaki and Ban [15] explain the Binary channel states based k-nearest neighbor classification (k-NNC) approach to improve the security in HBC. The k-NNC is a machine-learning approach to solving the binary classification problem. The work obtains the error-free classification by concerning different channel gain data.

Coviello *et al*. [16] discuss the fractional low-power synchronization algorithm (FLSA) based distributed full synchronized system (DFSS) for global health monitoring. The synchronization is the main issue while monitoring the complex system with high-density sensors. The FLSA-based DFSS provides a suitable solution to monitor a patient's health, like posture, heartbeat, and oxygen saturation analysis. Siddiqi *et al*. [17] explains the security enhancement of the IEEE 802.15.6 standard for WBANs. The work analyzes the security attributes and attacks in detail. The tradeoff between security, accessibility, resources, and usability are discussed in detail. The work is suitable to use in medical-based BAN applications. Musa *et al*. [18] describe the compact dual-band wearable antenna for WBAN devices. The gain and antenna bandwidth is enhanced using radial patterns. The work is evaluated under federal communications commission (FCC) to meet the specific absorption rate (SAR) limits. Memon *et al*. [19] present the enhanced probabilistic route stability (EPRS) protocol designs for WBAN applications. The EPRs protocol provides reliable data transmission throughout the human body. The work also evaluates the link assessment cost (LAC) and meets the quality of services (QoS) requirements. Cacheda *et al*. [20] discuss the detailed architecture of interconnecting the nano and BANs for cardiovascular health applications. The cardiovascular events are prevented by bridging the nano and BAN devices using suitable network architecture. This work built the channel and coverage zone model to realize the path loss of the chest area. The summary of the current HBC works are tabulated in Table 1.

Table 1. Summary of the current HBC works

Author, year	Research problem	Design approach	Limitations or future scope
Lee *et al*. [8], 2020	Data rate improvement in the human body.	DFE-based body channel communication.	Obtains a higher BER, body channel distance has to be improved.
Chowdhury *et al*. [9], 2021	Avoiding channel loss in communication links.	Multi-integrating RX frontend modules.	Power consumption and energy efficiency are more during lossy channel analysis.
Asan *et al*. [10], 2021	Signal path loss improvement.	Fat-IBC approach using body movements.	Offers lower data rate at a higher frequency range.
Noormohammadi *et al*. [11], 2021	Power issues in IBCs.	Galvanic impulse-based IBC.	BER is more.
Liao *et al*. [12], 2021	Path loss analysis in wearable devices.	HBC-based signal transmission for wearable robot control.	BER is more and less coverage distance.
Sacco *et al*. [13], 2021	Aging and textile impact on the power absorption in the Human body.	Human body coupling using 5G mm waves bands.	Power density is more when the thickness of the air gap between the textile and the skin.
Wagih *et al*. [14], 2022	On-body transmission is an issues duo body shadowing.	Flexible textile single-wire transmission lines (SWTL) using on-body UHF to mm-wave surface wave links.	Complexity will be more when SWTL is applied to high-data-rate transmission.
Sasaki and Ban [15], 2022	Security in HBC.	Binary channel states based nearest neighbor classification approach.	Broad bandwidth may increase to classify the samples easily and enhance HBC security.
Coviello *et al*. [16], 2022	Reliability and monitoring the complex data and synchronization issues.	FLSA based DFSS.	The work is integrated with gait analysis to realize the efficiency of the treatment.
Siddiqi *et al*. [17], 2022	Security enhancement.	IEEE 802.15.6-based module for WBANs.	The work is limited to medical-based BAN applications.
Musa *et al*. [18], 2023	Gain and bandwidth issues in antenna.	Compact dual-band wearable antenna for WBANs.	The designed antenna is suitable to use in particular human body parts.
Memon *et al*. [19], 2023	Reliable data transfer is channeled through human body.	EPRS protocol design for WBANs.	Data rate and QoS have to be improvements.
Cacheda *et al*. [20], 2023	Prevention of Cardiovascular events.	Interconnecting the nano and BANs for health applications.	The work is limited to heart-related problems and unsuitable for other disease prevention.

3. OVERVIEW OF THE IEEE 802.15.6

The IEEE 802.15.6 is one wireless standard for WBAN applications. The IEEE 802.15.6 standard offers low-power, reliable, short-range wireless communication within the human body's surroundings. The IEEE 802.15.6 standard was developed to communicate low-power devices, and it will be implanted inside or on the human body for different applications. Three PHYs support the IEEE 802.15.6 standard concerning the narrowband (NB), ultra-wide-band (UWB), and HBC. The PHY layer provides a secured and reliable link between the WBAN transmitter and receiver by incorporating the encoding-decoding, modulation-demodulation, and error correction functionalities. The structure of the WBAN is illustrated in Figure 1.

The tiny devices can act in the body (implantable) and on body sensors in the human body. The sensors like electrocardiogram (ECG), blood pressure, body temperature, pulse asymmetry, motion sensor, and many more are used in the human body to sense particular human-related issues. The actuators receive information from the human body and provide some response. The gateway acts as the central device that collects the human body's information and provides it to the corresponding location (medical database, doctor, emergency unit) through an external wireless link. These links are provided by typically wireless standards like ZigBee, Bluetooth, and wireless local area networks (WLANs). A few wires standards are compared with WBANs, tabulated in Table 2.

The ZigBee is IEEE 802.15.4 standard and operates between 868/915 MHZ and 2400 MHz frequency bands. The ZigBee provides a data rate of up to 250 Kbps and covers a distance of up to 75 m with low power consumption. Bluetooth is IEEE 802.15.1 standard and operates in the 2400 MHz frequency band. Bluetooth offers a data rate of up to 1 Mbps and covers a distance of up to 100 m with moderate power consumption. The Wi-Fi is IEEE 802.11a/b/g standard and operates between 2400 and 5000 MHz frequency bands. The Wi-Fi offers a data rate of up to 150 Mbps and covers a distance of up to 250 m with high power consumption. The wireless personal area network (WPAN) or UWB is IEEE 802.15.4a standard and operates between 3100 MHz and 10.6 GHz frequency bands. The WPAN offers a data rate of up to 27.24 Mbps and covers a distance of up to 30 m with low power consumption. Lastly, the WBAN is 802.15.6 standard and operates between 402 MHz and 2.4 GHz frequency bands. The WBAN offers a data rate of up to 15.6 Mbps and covers a distance of up to 10 m with ultra-low power consumption [21]–[23].

The IEEE 802.15.6 standard supports different frequency bands with three levels of authentication and encryption. The PHY layer function converts the physical layer service data unit (PSDUs) into physical layer protocol data units (PPDUs) [24]. The NB provides the transmission and reception of data, activation and deactivation of the transceiver, and clear channel assessment (CCA) over networks. The NB is used in on-body communication due to the high power in wireless sensor nodes. The NB offers to send and receive the data concerning the different frequency bands. The NB PHY uses different frequency bands and modulation techniques like Gaussian minimum shift keying (GMSK) and differential phase shift keying (DPSK). The NB-PHY with GMSK operates at 420-450 MHz frequency bands. The NB-PHY with DPSK operates at 402–405 MHz and 863–2483.5 MHz frequencies with different bandwidths. The UWB is divided into high and low-frequency bands. The low bands have three channels, and the high bands have eight channels. The UWB in IEEE 802.15.6 operates between 3.1 GHz to 10.6 GHz. The UWB offers good performance with low power and allows communication with the medical implement communication system (MICS). The HBC provides the platform to communicate the electronic devices in the human body; Zimmerman originally developed it in 1995. The HBC operates between 5 to 50 MHz frequency bands. The HBC uses the electric-field coupling concept to communicate with the human body. The HBC PHY uses two frequency bands: i) 16 MHz with 4 MHz bandwidth and ii) 27 MHz with 4 MHz bandwidth, valid in America, Japan, and Korea countries. Most European countries use a 27 MHz frequency band for HBC [25]. The summary of the NB, UWB, and HBC are listed in Table 3.

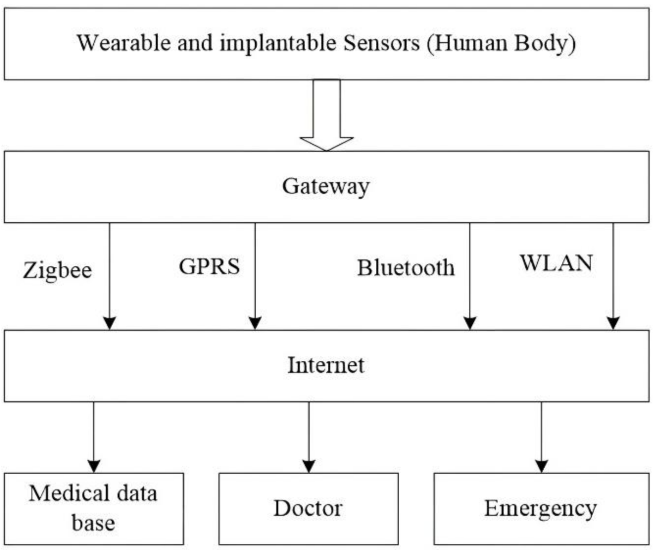


Figure 1. Structure of WBAN

Table 2. Comparison of WBAN with other wireless standards

Parameters	ZigBee	Bluetooth	Wi-Fi	UWB	WBAN
Standards	802.15.4	802.15.1	802.11a/b/g	802.15.4a	802.15.6
PHY layers	NB	NB	NB	UWB	NB/UWB/HBC
Frequency band (MHz)	868/915, 2400	2400	2400, 5000	3100–10600	402–2400
Transmission range	Up to 75 m	Up to 100 m	Up to 250 m	Up to 30 m	Up to 10 m
Data rate	250 Kbps	1 Mbps	150 Mbps	up to 27.24 Mbps	10 Kbps to 15.6 Mbps
Network topology	Adhoc, peer-to-peer, mesh, star	Adhoc, piconet, star	Mesh, single-hop	Peer to peer, piconet,	Half-hop Star
Power consumption	Low (up to 50 mW)	Medium (100 mW)	High (800 mW)	Low (< 50 mW)	Ultra-low (5 mW)

Table 3. Comparison of IEEE 802.15.6 standards

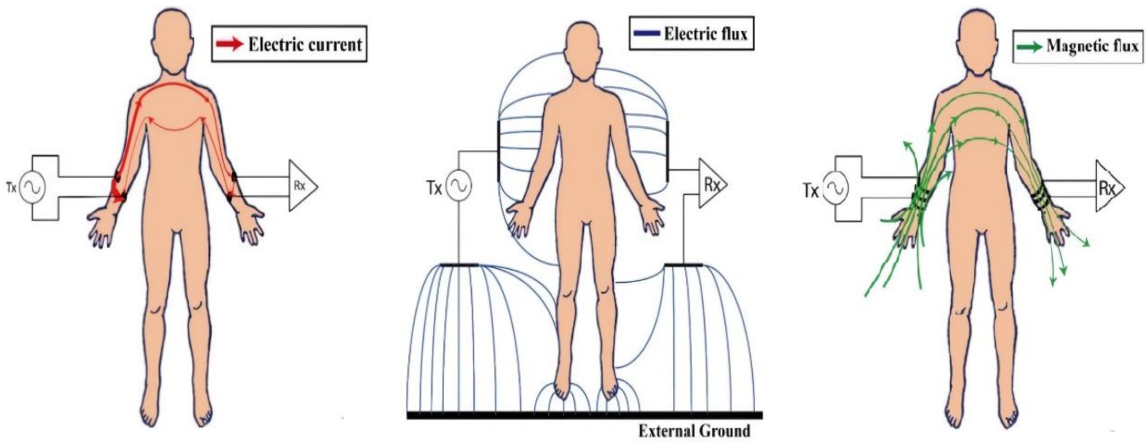
Parameters	NB/UWB	HBC
Frequency band (MHz)	402–2400	5–50
Transmission range	10 m	< 2 m
Data rate (Mbps)	< 15.6	< 2
communication medium	Air	Human body
Energy efficiency	Low	High
Conductivity	Low	High
Antenna (on-body)	Yes	No
Signal attenuation	High	Low

4. HUMAN BODY COMMUNICATION SYSTEM

This section discusses the HBC coupling approaches, architecture of the HBC transceiver system, recent works of HBC, performance metrics comparison, and applications. The HBC is a non-radio-frequency approach of WBANs. The human body is a transmission medium between electronic devices on and inside the body [26]. The human body communicates using three different coupling approaches, namely: i) galvanic coupling (GC), ii) capacitive coupling (CC), and iii) magnetic coupling (MC). The HBC approaches are illustrated in Figure 2. The GC, CC and MC approaches are shown in Figures 2(a) to (c) respectively.

4.1. HBC coupling approaches

Galvanic coupling: it is a technique that propagates an electrical signal made by a pair of connected electrodes using the human body as a medium (or channel). The current (alternating) is coupled inside the body. There are two electrodes placed on each transmitter and receiver side. The GC-based approach offers a lower transmission data rate and no need for a ground signal as a reference. The human body is constructed as a waveguide for signal conduction. The influence of the parasitic paths is less in GC [27]. The GC operates between the 1 to 10 MHz frequency ranges and covers up to 25 cm distance. The GC-based approach achieves a data rate of up to 1.56 Mbps. The GC-based approach is used in wearable and implantable applications.



(a) (b) (c)

Figure 2. Approaches of HBC: (a) GC, (b) CC, and (c) MC

Capacitive coupling: when two circuits that share an electric field produce an energy transfer from one circuit to the other, this is known as capacitive coupling (CC). The electric field of the body controls the induced current flow. Only signal electrodes are attached to the body (one each for the transmitter and receiver). The CC-based approach offers a higher transmission data rate and the need for a ground signal as a reference. The human body is constructed as a conductor in CC. The influence of the parasitic paths is high in CC. The GC operates between the 1 to 120 MHz frequency ranges and covers up to 150 cm distance. The CC-based approach achieves a data rate of up to 60 Mbps. The CC-based approach is used in most wearable applications.

Magnetic coupling: it is also known as resonant coupling due to the electromagnetic resonance properties, which generate the magnetic field throughout the human body. MC is used to drive the magnetic propagation to establish a relatively close wireless electrical transmission energy between two coils tied around various body parts [28]. The MC-based approach offers a moderate transmission data rate and less influence on the parasitic paths. The MC operates between the 1 to 50 MHz frequency ranges and covers up to 120 cm distance. The MC-based approach achieves a data rate of up to 15 Mbps. The MC-based approach is used in most wearable and implantable applications. The comparison of these coupling approaches [29] is tabulated in Table 4.

Table 4. Comparison of HBC coupling approaches

Characteristic’s	Galvanic coupling	Capacitive coupling	Magnetic coupling
Channel	Intrabody	Intrinsic and extrinsic	Intrabody
Parasitic paths influence	Less	High	Less
Electrodes contact	within the body	within body	contactless
Frequency (MHz)	1–10	1–120	Up to 50
data rate (Mbps)	0.1–1.56	60	< 15
Communication distance (cm)	< 25	< 150	< 120
Max. attenuation (dB)	65	65	35
Applications	Wearable and implantable	Wearable	Wearable and implantable
Analyzers used	Spectrum analyzer and signal generator	Vector network analyzer	Spectrum analyzer and signal generator

4.2. Architecture of the HBC system

The HBC system mainly contains an HBC modem, analog front-end module, and electrode, as shown in Figure 3. The HBC modem acts as a digital baseband transceiver for transmitting and receiving data signals from the human body via electrodes. The Analog front end (AFE) module converts the digital data signals and analog signals on the human body. Electrodes receive or transmit analog signals in the forming voltage to or from the human body using coupling approaches.

The HBC modem or digital baseband transceiver architecture is illustrated in Figure 4. The HBC transmitter (TX) contains four modules: data generator, preamble, header generator, and frequency selective (FS) spreading modules. The data is processed using the frequency selective digital transmission (FSDT) approach. The FS spreading module performs the modulation using Walsh codes. The preamble and header generation is performed based on IEEE 802.15.6 standards. The multiplexor receives preamble, modulated, and header data and produces the transmitted data. The HBC receiver (RX) receives the data signals from the human body via electrodes followed by AFE and stored in receiver first-in-first-out (FIFO). So, decompose the stored FIFO data for data and header recovery. Perform the demodulation operation on FS dispreading using Walsh codes to recover the data bits. The frame synchronization maintains the clock synchronization between the associated TX and RX modules. The header processor recovers the header information, and the data cyclic redundancy check (CRC) module recovers the final data bits. The transmitter enables (TXE) acts as an enable signal in TX and is further used in AFE for clock and data recovery (CDR) operation.

The AFE module for the HBC system is illustrated in Figure 5. The AEF module contains an RC filter, variable gain amplifier, operational amplifier (Opamp), comparator, and CDR module. The signal propagation loss of the human body in the channel is calculated using transmitter output voltage and received voltage. The RC filter attenuates the high-frequency interferences and filters the unwanted signals. The variable gain and operational amplifiers are used to amplify the filtered signal and maintain the voltage levels for further process. The comparator is used to convert the amplified signal to a binary state. The clock and data recovery module aligns the binary state data with the clock and generates the RX data.

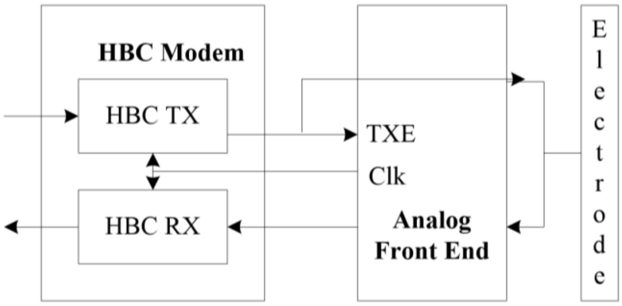


Figure 3. The complete HBC system

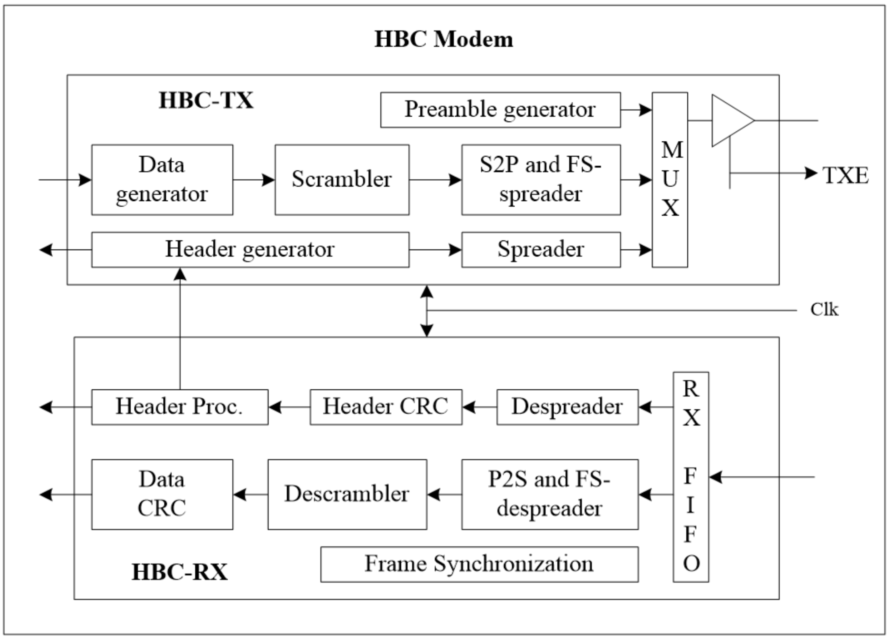


Figure 4. HBC modem or digital baseband transceiver

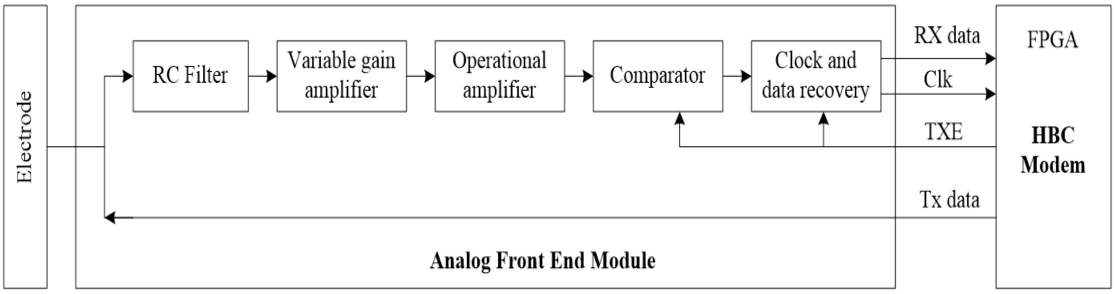


Figure 5. Analog frontend module for HBC system

4.3. Recent works on HBC system

This section discusses the recent works on the HBC transceiver system for different application viewpoints. Hyoung *et al.* [30] present the HBC transceiver using the FSDT technique on a 90 nm complementary metal oxide semiconductor (CMOS) environment. The HBC operates between 8 to 22 MHz frequency bands with an RX sensitivity of -74 dBm. The HBC achieves a data rate of 2 Mbps with a BER of 10^{-6} and consumes the power of 0.194 mW with an energy efficiency of 0.0097 nJ/b. Fazzi *et al.* [31] describe the body-coupled communication (BCC) transceiver using the pulse amplitude modulation (PAM) technique on a 130 nm CMOS technology. The BCC transceiver operates between 1 to 30 MHz frequency bands with an RX sensitivity of -78 dBm. The BCC achieves a data rate of 8.5 Mbps with a BER of 10^{-4} and consumes the power of 2.75 mW with an energy efficiency of 0.32 nJ/b. Huang *et al.* [32] explain the HBC transceiver with low-power wearable features on a 180 nm CMOS process. The HBC operates between 1 to 20 MHz frequency bands with an RX sensitivity of -88.32 dBm. The HBC achieves a data rate of 15 Mbps with a BER of 10^{-3} and consumes the power of 5 mW with an energy efficiency of 0.337 nJ/b. Song *et al.* [33] discuss the BCC transceiver with scalable features using the pulse position modulation (PPM), and direct-sequence spread spectrum (DSSS) techniques on a 180 nm CMOS process. The BCC transceiver operates between 10 to 70 MHz frequency bands with an RX sensitivity of -56.6 dBm. The BCC achieves a data rate of 10 Mbps with a BER up to < 10^{-7} and consumes the power of 2.6 mW with an energy efficiency of 0.26 nJ/b. Liu *et al.* [34] present the multi-standard transceiver (MS-TX) for Bluetooth/ZigBee/802.15.6 for WBAN applications using the offset quadrature phase-shift keying (OQPSK) technique on a 90 nm CMOS process. The MS-TX operates between 1 to 30 MHz frequency bands with an RX sensitivity of-90 dBm. The MS-TX achieves a data rate of 2 Mbps with a BER up to < 10^{-3} and consumes the power of 9.2 mW with an energy efficiency of 4.1 nJ/b. Lee *et al.* [35] explain the HBC transceiver with energy-efficient features using the FSDT technique on a 90 nm CMOS environment. The HBC operates at 21 MHz frequency with an RX sensitivity of -88.32 dBm. The HBC achieves a data rate of 1.3125 Mbps with a BER of 10^{-4} and consumes the power of 0.88 mW with an energy efficiency of 6.76 nJ/b.

Manchi *et al.* [36] present the NB and HBC transceiver on a 90 nm CMOS environment. The NB-TX operates between 1 to 4 MHz frequency bands and achieves a data rate of 0.455 Mbps, and consumes the power of 0.17 mW with an energy efficiency of 0.0372 nJ/b. The HBC operates at 42 MHz, achieves a data rate of 1.3125 Mbps, and consumes a power of 0.864 mW with an energy efficiency of 0.661 nJ/b. Ali *et al.* [37] describe the HBC baseband transceiver using the FSDT technique on a 130 nm CMOS environment. The HBC operates at 42 MHz frequency and achieves a data rate of 1.3125 Mbps with BER of 10-4 and consumes the power of 1.307 mW with an energy efficiency of 0.661 nJ/b. Saadeeh *et al.* [38] discuss the Pseudo orthogonal frequency division multiplexing (P-OFDM) with miniaturized frequency shift keying (M-FSK) based BCC transceiver on a 65 nm CMOS technology. The BCC transceiver operates between 1 to30 MHz frequency bands with an RX sensitivity of -78 dBm. The BCC achieves a data rate of 1 Mbps with a BER of 10^{-7} and consumes the power of 2.5 mW with an energy efficiency of 2.5 nJ/b. The ground-effect resilient features-based BCC transceiver [39] is designed on a 65 nm CMOS process. The BCC achieves a data rate of 2 Mbps with a BER of 10^{-7} and consumes the power of 1.88 mW with an energy efficiency of 0.94 nJ/b. Zhao *et al.* [40] describe the HBC transceiver with digital-sigma–delta Infinite-impulse-response (SDIIR) mask shaping on a 65 nm CMOS environment. The HBC operates at 22 MHz frequency with an RX sensitivity of -72 dBm. The HBC achieves a data rate of 5.25 Mbps with a BER of 10^{-7} and consumes the power of 4.14 mW with an energy efficiency of 0789nJ/b.

Park *et al.* [41] explain the HBC transceiver using the FSDT technique on a 130 nm CMOS environment. The HBC operates at 32 MHz frequency with a data rate of 6 Mbps and consumes the power of 3.7 mW with an energy efficiency of 0.616 nJ/b. The HBC transceiver [42] uses the FSDT technique on a 90 nm CMOS environment. The HBC operates between 8 to 22 MHz frequency bands with an RX sensitivity of -82.8 dBm. The HBC achieves a data rate of 2 Mbps with a BER of 10^{-6}. The magnetic HBC (M-HBC) [43] using the on-off-keying (OOK) technique on a 65 nm CMOS process. The M-HBC operates at 42.5 MHz frequency with an RX sensitivity of -56.6 dBm. The M-HBC achieves a data rate of 5 Mbps with a BER of 10^{-3} and consumes the power of 0.0602 mW with an energy efficiency of 0.0121nJ/b. Jeon *et al.* [44] present the galvanically-coupled BCC transceiver on a 180 nm CMOS environment. The GC-BCC operates between 1 to 100 MHz frequency bands. The GC-BCC achieves a data rate of 100 Mbps with a BER of 10^{-9} and consumes the power of 3.155 mW with an energy efficiency of 0.0316 nJ/b. Yoo [45] discuss the BCC transceiver using the FSK technique on a 65 nm CMOS technology. The BCC transceiver operates at a 30 MHz frequency with an RX sensitivity of -78 dBm. The BCC achieves a data rate of 1 Mbps with a BER of 10^{-7} and consumes the power of 2.5 mW with an energy efficiency of 2.5 nJ/b. Maity *et al.* [46] explain the broadband (BB) HBC transceiver using time domain interference rejection (TDIR) and non-return-zero (NRZ) codes on a 65 nm CMOS technology. The BB-HBC transceiver operates at 30 MHz frequency with an RX sensitivity of -63.3 dBm. The BB-HBC achieves a data rate of 1 Mbps with a BER of 10^{-7} and consumes the power of 0.191 mW with an energy efficiency of 0.0633 nJ/b.

Vijayalakshmi and Nagarajan [47] discuss the BCC transceiver using the hamming encoding digital transmitter (HEDT) and FSK techniques on a 65 nm CMOS technology. The BCC transceiver operates at 100 MHz frequency with an RX sensitivity of -56 dBm. The BCC achieves a data rate of 60 Mbps with a BER of 10^{-2} and consumes the power of 1 mW with an energy efficiency of 0.016 nJ/b. Ali *et al.* [48] describe the autoencoder-based HBC transceiver on a 45 nm CMOS environment. The HBC operates at 42 MHz frequency. The HBC achieves a data rate of 5.25 Mbps with a BER of 10^{-3} and consumes the power of 1.468 mW with an energy efficiency of 0.028 nJ/b. Chung *et al.* [49] present the BBC transceiver in a 45 nm CMOS environment. The BBC operates at 100 MHz frequency with an RX sensitivity of -18.87 dBm. The BBC achieves a data rate of 3.125 Mbps with a BER of 10^{-8} and consumes a power of 158 mW with an energy efficiency of 50.56 nJ/b. Wei *et al.* [50] discuss the GC-intra-body communication (GC-IBC) transceiver using differential phase shift keying (DPSK) on a 90 nm CMOS process. The GC-IBC transceiver operates at 30 MHz frequency with an RX sensitivity of -20 dBm. The GC-IBC achieves a data rate of 1 Mbps with a BER of 10^{-4}. Chen *et al.* [51] present the DSSS-DPSK-based GC-IBC transceiver on a 90 nm CMOS environment. The GC-IBC operates at a 2 MHz frequency. The GC-IBC achieves a data rate of 0.05 Mbps with a BER of 10^{-6}. Cho and Park [52] explain the NB-IBC using FSK with security features on the 90 nm CMOS process. The NB-IBC operates at 50 MHz frequency. The NB-IBC achieves a data rate of 0.014 Mbps with a power consumption of 0.48 mW. Tang *et al.* [53] describe the HBC transceiver using FSK on a 90 nm CMOS environment. The HBC operates at 60 MHz frequency with an RX sensitivity of -86 dBm. The HBC achieves a data rate of 2 Mbps with a BER of 10^{-9}. The performance summary of the above transceiver approaches [30]–[53] is summarized and tabulated in Table 5.

The performance comparison of existing transceiver approaches on the field programmable gate array (FPGA) platform is tabulated in Table 6. The type of physical transceiver (PHY-TR), FPGA, selected coding approach, covered distance, obtained data rate, chip area utilization slices and look-up tables (LUTs), total power consumption, and obtained bit error rate (BER) parameters are considered for performance comparison. The ultra-wideband (UWB) impulse-radio (IR) based transceiver [54] is designed on Virtex-6 FPGA using multi-pulse position modulation (MPPM) approach. The UWB-IR transceiver covers up to 70 m distance by achieving a 2 Mbps data rate. The UWB-IR transceiver utilizes > 23 % slices and LUTs with BER of 10^{-3} on Virtex-6 FPGA. The narrowband (NB) based transceiver [55] is designed on Spartan-6 FPGA using BCH coding approach. The NB-TR covers up to 5 m distance by achieving a data rate of 0.188 Mbps. The NB-TR utilizes 2843 slices and consumes power of 192 mW with BER of 10^{-3} on Spartan-6 FPGA. The NB based transceiver [56] of IEEE 802.15.6 WBAN is designed on Virtex-6 FPGA using BCH coding approach. The NB-TR covers up to 3 m distance by achieving a data rate of 0.111 Mbps. The NB-TR utilizes 2668 slices, LUTs of 3161, and consumes power of 117 mW with BER of 10^{-2} on Virtex--6 FPGA. The NB based transceiver [57] with robust low-power features is designed on Virtex -6 FPGA using BCH coding approach. The NB-TR covers up to 4 m distance by achieving a data rate of 0.972 Mbps. The NB-TR utilizes 846 slices, LUTs of 1293, and consumes power of 162 mW with BER of 10^{-4} on Virtex--6 FPGA. The HBC transceiver [58] is designed using Walsh coding approach on Artix-7 FPGA. The HBC transceiver covers up to 5 m distance by achieving a 9.52 Mbps data rate. The HBC transceiver utilizes < 2 % slices and LUTs, a power of 101 mW, and a BER of 10^{-4} on Artix-7 FPGA.

Table 5. Performance summary of existing transceiver approaches [30]–[53]

Ref.	Transceiver	Modulation	CMOS technology (nm)	Frequency band (MHz)	Voltage (V)	Sensitivity (dBm)	Data rate (Mbps)	BER	Power (mW)	Energy efficiency (nJ/b)
[30]	HBC	FSDT	90	8 to 22	1.2	–74	2	10^{-6}	0.194	0.097
[31]	BCC	PAM	130	1 to 30	1.2	–78	8.5	10^{-4}	2.75	0.32
[32]	HBC	NA	180	1 to 20	1.8	-88.32	15	10^{-3}	5	0.33
[33]	BCC	PPM + DSSS	180	10 to 70	0.9/1.8	-56.6	10	$<0^{-7}$	2.6	0.26
[34]	MS-TX	OQPSK	90	1 to 30	1.2	–90	2	10^{-3}	9.2	4.1
[35]	HBC	FSDT	90	21	1.2	-88.32	1.3125	10^{-4}	0.88	6.76
[36]	NB-TX	NA	90	1 to 4	1.1	NA	0. 455	NA	0.17	0.372
[36]	HBC	FSDT	90	42	1.1	NA	1.3125	NA	0.864	0.661
[37]	HBC	FSDT	130	42	1.1	NA	1.3125	10^{-4}	1.307	0.996
[38]	BCC	FSK	65	1 to 30	001.1	-78	1	10^{-7}	2.5	2.5
[30]	BCC	FSK	65	30	1.1	-83.1	2	10^{-7}	1.88	0.94
[40]	HBC	FSDT	65	21	1.2	-72	5.25	10^{-7}	4.14	0.789
[41]	HBC	FSDT	130	32	1.2	NA	6	NA	3.7	0.616
[42]	HBC	FSDT	90	8 to 22	1.2	-82.8	2	10^{-6}	NA	NA
[43]	M-HBC	OOK	65	42.5	0.6	-56.6	5	10^{-3}	0.0602	0.0121
[44]	GC-BCC	NA	180	1-100	1	NA	100	10^{-9}	3.155	0.0316
[45]	BCC	FSK	65	30	1.1	-78	1	10^{-7}	2.5	2.5
[46]	HBC	NRZ	65	30	1	-63.3	30	10^{-3}	0.191	0.0633
[47]	BCC	H-FSK	65	100	1.1	-56	60	10^{-2}	1	0.016
[48]	HBC	NA	45	42	1.2	NA	5.25	10^{-3}	1.468	0.0280
[49]	BCC	FSDT	45	100	1	-18.87	3.125	10^{-8}	158	50.56
[50]	GC-IBC	DPSK	90	30	1.2	-20	1	$< 0^{-4}$	NA	NA
[51]	GC-IBC	DSSS-DPSK	90	2	1.2	NA	0.05	$< 0^{-6}$	NA	NA
[52]	NB-IBC	FSK	90	50	5	NA	0.014	NA	0. 480	0.03428
[53]	HBC	FSK	90	40-60	1.2	–86	2	10^{-9}	NA	NA

4.4. HBC applications

Intra-body communication (IBC) or HBC is used in most WBAN applications. Examples of the IBC touching voice system, blind person assistance system, and speech assistance for dump people. The IBC or HBC is used in emergency and rescue management, workforce safety, and health management. Health-related applications like ECG, pulse rate, body temperature, respiratory rate, blood flow, and sugar level checking on the human body. The non-medical applications like voice, video, motion sensors, high-quality (HD) audio, global positioning system (GPS) positions, and many more. A few of the particular applications from the recent works of the HBC system are discussed below and tabulated in Table 7.

Table 6. Performance comparison of existing transceiver approaches on FPGA platforms

Parameters	[54]	[55]	[56]	[57]	[58]
PHY-TR	UWB-IR	NB-TR	NB-TR	NB-TR	HBC
FPGA	Virtex-6	Spartan-6	Virtex-6	Virtex-6	Artix-7
Coding approach	MPPM	BCH	BCH	BCH	Walsh
Distance (m)	70	5	3	4	5
Data rate (Mbps)	2	0.188	0.122	0.972	9.52
Slices	10049	2843	2668	846	196
LUTs	17918	NA	3161	1293	1137
Power (mW)	NA	192	117	162	101
BER	10^{-3}	10^{-2}	10^{-2}	10^{-4}	10^{-4}

Remote patient monitoring: the aging of the global population and rising healthcare expenses are driving forces behind telemedicine networks to deliver various medical treatments. Investigators, doctors, and other healthcare providers can treat additional patients due to remote transmission of patient care via unified medical data systems and communication technology. Applications for tracking patients typically regulate necessary signals and offer real-time feedback and data to aid the patient's rehabilitation. In such a case, physicians can keep the patient under medical supervision in their typical state of mind without interfering with their daily activities or causing them significant harm. While in-hospital monitoring concentrates on circumstances in which patients must remain in a hospital for prolonged treatment and assessments, often for a protracted period, daily-life activity tracking focuses on the activity during the everyday life of patients with particular specific disorders. A WBAN can offer uninterrupted biophysical indicator metrics; such a system for remote surveillance will be less expensive, safer, and more realistic.

Table 7. Applications of the HBC

Ref.	HBC applications
[19]	Low-power wearable devices
[20]	Body sensor applications
[25]	Binaural hearing aids
[27]	Electrocardiography (ECG)
[27]	Electromyography (EMG)
[28]	Wireless capsule endoscopy
[29]	Hi-Fi audio streaming application
[30]	Bionic arms
[33]	Body wire
[39]	Securing electronic authentication
[59]	Parkinson's disease monitoring
[60], 61]	Heartbeat
[62]	E-Health
[63]	Security

Ambient assisted living: the need for cutting-edge assisted living facilities technology for secure and independent aging is driven by the aging population, the rising cost of formal health care, and people's significance in living independently. Thanks to home automation, applications in this area enhance the quality of life so people can continue living more independently. Thanks to ongoing cognitive and physical monitoring, an ambient sensor network can sense and regulate the elements of the living space and then transmit bodily data to a central station.

Rehabilitation and biofeedback: after being released from the hospital, rehabilitation aims to enable patients to return to regular functioning by providing them with the necessary rehabilitative care. A home-based rehabilitation program makes it crucial and required to detect and track human mobility. Biofeedback is now feasible to remotely monitor one's body utilizing WBANs to obtain sensor data. With the use of biofeedback occurrences like temperature evaluation, blood pressure identification, electrocardiography (ECG), electromyography (EMG), and many more, sensors are implanted or placed in the human body to track certain behaviors or illnesses to assist individuals with maintaining their health.

5. OPEN RESEARCH CHALLENGES

The HBC, or IBC, was developed for more than two decades. Many research articles were published on channel characteristics, signal propagation approaches, HBC transceiver design, and applications. But still, some of the technical challenges are open to establishing in the HBC system and are listed:

- Long-term usage effect in the human body, transmission performance based on subject movement, automatic model approaches to improving communication performance, and energy-efficient HBC transceiver designs.
- Most of the current HBC approaches are focused more on the communication of low-rate data appliances like ECG, pulse oximetry, Blood pressure, and motions. However, in the future, the realization of high-data-rate implantable sensors in HBC is required
- HBC is used in most medical and healthcare applications. However, the HBC has to incorporate biochemical reactions, nano-materials, and flexible electronics applications.
- Higher Frequency in most communications systems involves a higher data rate, which is challenging with IBC owing to antenna and body temperature effects.
- Networking issues like data security, Quality of service, mobility, and the interrelationship between different environmental conditions are open research issues in HBC
- Human movement-based channel models are necessary, and measurement setup is needed to know the effects of the APE and other component devices in HBC.
- A new approach is needed to operate in lower-frequency ranges to improve the data rates. The human channel model needs to understand the functionalities and motion of the human body.

6. CONCLUSION

A comprehensive review of human body communication is discussed in this manuscript. The HBC is a new non-RF wireless standard with short-range features issued by IEEE 802.15.6. The human body is a transmission medium between transmission and reception in HBC. The HBC offers energy-efficient, short-range communication and low-data rate compared to RF-based wireless standards. This work discusses the comparative discussion of the different PHY layer standards like NB, UWB, and HBC. The HBC-based coupling approaches like galvanic, capacitive, and magnetic are discussed. The HBC system architecture, digital baseband transceiver, and analog front-end modules are discussed in detail. The recent works of the HBC, IBC, or BCC transceiver are discussed in detail with performance comparison. In addition, the performance comparison of the FPGA-based PHY transceiver is explained. Lastly, the open research challenges of the HBC system are highlighted, which requires improving the HBC system in the future direction. The current HBC has included a few works to accommodate future research directions. New methods are needed to increase data rates in lower-frequency regions. Mathematical models to comprehend the limits and properties of the body channels. While the body is moving, human channel modeling is required. Studies on the long-term tissue impacts of IBC use, such as malignancy. In designing new IBC transceivers, WBAN specifications must be considered; in contrast to conventional IBC systems, a new transceiver architecture is built on strong security, low power use, improved data rate, and a tiny form factor.

REFERENCES

[1] M. Seyedi, B. Kibret, D. T. H. Lai, and M. Faulkner, “A Survey on Intrabody Communications for Body Area Network Applications,” *IEEE Transactions on Biomedical Engineering*, vol. 60, no. 8, pp. 2067–2079, Aug. 2013, doi: 10.1109/TBME.2013.2254714.

[2] D. N. -Hernández, A. C. -Leblic, Ž. L. Vasić, M. Seyedi, and Y.-M. Gao, “Past Results, Present Trends, and Future Challenges in Intrabody Communication,” *Wireless Communications and Mobile Computing*, vol. 2018, no. 8, pp. 1–39, Mar. 2018, doi: 10.1155/2018/9026847.

[3] L. Maoyuan, S. Yong, Z. Xu, Y. Chen, and C. Tang, “A Review of Implant Intra-Body Communication,” *Journal of Beijing Institute of Technology (English version)*, vol. 31, no. 01, pp. 1–29, 2022, doi: 10.15918/j.jbit1004-0579.2021.076.

[4] J. Pourbemany, Y. Zhu, and R. Bettati, “A Survey of Wearable Devices Pairing Based on Biometric Signals,” *IEEE Access*, vol. 11, pp. 26070–26085, 2023, doi: 10.1109/ACCESS.2023.3254499.

[5] A. Celik, K. N. Salama, and A. M. Eltawil, “The Internet of Bodies: A Systematic Survey on Propagation Characterization and Channel Modeling,” *IEEE Internet of Things Journal*, vol. 9, no. 1, pp. 321–345, Jan. 2022, doi: 10.1109/JIOT.2021.3098028.

[6] J. F. Zhao, X. M. Chen, B. D. Liang, and Q. X. Chen, “A Review on Human Body Communication: Signal Propagation Model, Communication Performance, and Experimental Issues,” *Wireless Communications and Mobile Computing*, vol. 2017, pp. 1–15, Oct. 2017, doi: 10.1155/2017/5842310.

[7] D. Muramatsu and K. Sasaki, "Transmission Analysis in Human Body Communication for Head-Mounted Wearable Devices," *Electronics*, vol. 10, no. 10, p. 1213, May 2021, doi: 10.3390/electronics10101213.

[8] J.-H. Lee *et al.*, "A Body Channel Communication Technique Utilizing Decision Feedback Equalization," *IEEE Access*, vol. 8, pp. 198468–198481, 2020, doi: 10.1109/ACCESS.2020.3034999.

[9] R. Chowdhury, M. Antroy, S. Shovan, and Shreyas, "Theoretical Analysis of Multi Integrating RX Front-Ends for Lossy Broad-Band Channels," *IEEE Open Journal of Circuits and Systems*, vol. 2, pp. 363–379, 2021, doi: 10.1109/OJCAS.2021.3078176.

[10] N. B. Asan *et al.*, "Fat-IntraBody Communication at 5.8 GHz: Verification of Dynamic Body Movement Effects Using Computer Simulation and Experiments," *IEEE Access*, vol. 9, pp. 48429–48445, 2021, doi: 10.1109/ACCESS.2021.3068400.

[11] R. Noormohammadi, A. Khaleghi, and I. Balasingham, "Galvanic Impulse Wireless Communication for Biomedical Implants," *IEEE Access*, vol. 9, pp. 38602–38610, 2021, doi: 10.1109/ACCESS.2021.3064206.

[12] W. Liao, K. Muramatsu, and J. Wang, "Path Loss Analysis and Transceiver Development for Human Body Communication-Based Signal Transmission for Wearable Robot Control," *IEEE Access*, vol. 9, pp. 20127–20135, 2021, doi: 10.1109/ACCESS.2021.3055261.

[13] G. Sacco, D. Nikolayev, R. Sauleau, and M. Zhadobov, "Antenna/Human Body Coupling in 5G Millimeter-Wave Bands: Do Age and Clothing Matter?," *IEEE Journal of Microwaves*, vol. 1, no. 2, pp. 593–600, Apr. 2021, doi: 10.1109/JMW.2021.3063256.

[14] M. Wagih, "Broadband Low-Loss On-Body UHF to Millimeter-Wave Surface Wave Links Using Flexible Textile Single Wire Transmission Lines," *IEEE Open Journal of Antennas and Propagation*, vol. 3, pp. 101–111, 2022, doi: 10.1109/OJAP.2021.3136654.

[15] A. Sasaki and A. Ban, "Nearest Neighbor Classification of Binary Channel States for Secure Human Body Communication," *IEEE Transactions on Instrumentation and Measurement*, vol. 71, pp. 1–14, 2022, doi: 10.1109/TIM.2022.3209796.

[16] G. Coviello, A. Florio, G. Avitabile, C. Talarico, and J. M. W. -Roveda, "Distributed Full Synchronized System for Global Health Monitoring Based on FLSA," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 16, no. 4, pp. 600–608, Aug. 2022, doi: 10.1109/TBCAS.2022.3173586.

[17] M. A. Siddiqi, G. Hahn, S. Hamdioui, W. A. Serdijn, and C. Strydis, "Improving the Security of the IEEE 802.15.6 Standard for Medical BANs," *IEEE Access*, vol. 10, pp. 62953–62975, 2022, doi: 10.1109/ACCESS.2022.3181630.

[18] U. Musa *et al.*, "Design and Analysis of a Compact Dual-Band Wearable Antenna for WBAN Applications," *IEEE Access*, vol. 11, pp. 30996–31009, 2023, doi: 10.1109/ACCESS.2023.3262298.

[19] S. Memon *et al.*, "Enhanced Probabilistic Route Stability (EPRS) Protocol for Healthcare Applications of WBAN," *IEEE Access*, vol. 11, pp. 4466–4477, 2023, doi: 10.1109/ACCESS.2023.3235837.

[20] R. A. -Cacheda, L. M. Correia, C. G. -Pardo, K. Wojcik, K. Turbic, and P. Kulakowski, "Bridging Nano and Body Area Networks: A Full Architecture for Cardiovascular Health Applications," *IEEE Internet of Things Journal*, vol. 10, no. 5, pp. 4307–4323, Mar. 2023, doi: 10.1109/JIOT.2022.3215884.

[21] S. Saleem, S. Ullah, and K. S. Kwak, "A Study of IEEE 802.15.4 Security Framework for Wireless Body Area Networks," *Sensors*, vol. 11, no. 2, pp. 1383–1395, Jan. 2011, doi: 10.3390/s110201383.

[22] M. Alam and E. Hamida, "Surveying Wearable Human Assistive Technology for Life and Safety Critical Applications: Standards, Challenges and Opportunities," *Sensors*, vol. 14, no. 5, pp. 9153–9209, May 2014, doi: 10.3390/s140509153.

[23] M. Ghamari, B. Janko, R. Sherratt, W. Harwin, R. Piechockic, and C. Soltanpur, "A Survey on Wireless Body Area Networks for eHealthcare Systems in Residential Environments," *Sensors*, vol. 16, no. 6, p. 831, Jun. 2016, doi: 10.3390/s16060831.

[24] S. A. Salehi, M. A. Razzaque, I. T. -Reyes, and N. Hussain, "IEEE 802.15.6 standard in wireless body area networks from a healthcare point of view," in *2016 22nd Asia-Pacific Conference on Communications (APCC)*, IEEE, Aug. 2016, pp. 523–528, doi: 10.1109/APCC.2016.7581523.

[25] S. Ullah, M. Mohaisen, and M. A. Alnuem, "A Review of IEEE 802.15.6 MAC, PHY, and Security Specifications," *International Journal of Distributed Sensor Networks*, vol. 9, no. 4, p. 950704, Apr. 2013, doi: 10.1155/2013/950704.

[26] M. Seyedi, Z. Cai, and D. T. H. Lai, "Characterization of Signal Propagation through Limb Joints for Intrabody Communication," *International Journal of Biomaterials Research and Engineering*, vol. 1, no. 2, pp. 1–12, Jun. 2011, doi: 10.4018/ijbre.2013070101.

[27] W. J. Tomlinson, S. Banou, C. Yu, M. Stojanovic, and K. R. Chowdhury, "Comprehensive Survey of Galvanic Coupling and Alternative Intra-Body Communication Technologies," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 2, pp. 1145–1164, 2019, doi: 10.1109/COMST.2018.2879643.

[28] J. Park and P. P. Mercier, "Magnetic human body communication," in *2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, IEEE, Aug. 2015, pp. 1841–1844. doi: 10.1109/EMBC.2015.7318739.

[29] G. A. A. -Botero, Y. K. H. -Gomez, C. E. Tellez, and J. F. Coronel, "Human body communication: Channel characterization issues," *IEEE Instrumentation & Measurement Magazine*, vol. 22, no. 5, pp. 48–53, Oct. 2019, doi: 10.1109/IMM.2019.8868277.

[30] C.-H. Hyoung, S.-W. Kang, S.-O. Park, and Y.-T. Kim, "Transceiver for Human Body Communication Using Frequency Selective Digital Transmission," *ETRI Journal*, vol. 34, no. 2, pp. 216–225, Apr. 2012, doi: 10.4218/etrij.12.0111.0178.

[31] A. Fazzi, S. Ouzounov, and J. van den Homberg, "A 2.75mW wideband correlation-based transceiver for body-coupled communication," in *2009 IEEE International Solid-State Circuits Conference - Digest of Technical Papers*, IEEE, Feb. 2009, pp. 204-205, doi: 10.1109/ISSCC.2009.4977379.

[32] J. Huang, L. Wang, C. L. -Kang, and Z. Y. -Ting, "A low power wearable transceiver for human body communication," in *2009 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, IEEE, Sep. 2009, pp. 3802–3805, doi: 10.1109/IEMBS.2009.5335208.

[33] S.-J. Song, N. Cho, S. Kim, J. Yoo, S. Choi, and H.-J. Yoo, "A 0.9V 2.6mW Body-Coupled Scalable PHY Transceiver for Body Sensor Applications," in *2007 IEEE International Solid-State Circuits Conference. Digest of Technical Papers*, IEEE, Feb. 2007, pp. 366–609, doi: 10.1109/ISSCC.2007.373446.

[34] Y.-H. Liu *et al.*, "A 1.9nJ/b 2.4GHz multistandard (Bluetooth Low Energy/Zigbee/IEEE802.15.6) transceiver for personal/body-area networks," in *2013 IEEE International Solid-State Circuits Conference Digest of Technical Papers*, IEEE, Feb. 2013, pp. 446–447, doi: 10.1109/ISSCC.2013.6487808.

[35] H. Lee, S.-J. Song, N. Cho, J. Bae, and H.-J. Yoo, "Human Body Communication Transceiver for Energy Efficient BAN," 2015, pp. 281–311, doi: 10.1007/978-3-319-14714-7_9.

[36] P. K. Manchi, R. Paily, and A. K. Gogoi, "Design and Implementation of Low-Power Digital Baseband Transceivers for IEEE802.15.6 Standard," in *2016 29th International Conference on VLSI Design and 2016 15th International Conference on Embedded Systems (VLSID)*, IEEE, Jan. 2016, pp. 581–582, doi: 10.1109/VLSID.2016.19.

[37] A. Ali, A. Shalaby, M. S. Sayed, and M. A. -Zahhad, "Low power HBC PHY baseband transceiver for IEEE 802.15.6 WBAN," in *2017 29th International Conference on Microelectronics (ICM)*, IEEE, Dec. 2017, pp. 1–4, doi: 10.1109/ICM.2017.8268857.

[38] W. Saadeh, M. A. Bin Altaf, H. Alsuradi, and J. Yoo, "A Pseudo OFDM With Miniaturized FSK Demodulation Body-Coupled Communication Transceiver for Binaural Hearing Aids in 65 nm CMOS," *IEEE Journal of Solid-State Circuits*, vol. 52, no. 3, pp. 757–768, Mar. 2017, doi: 10.1109/JSSC.2016.2639536.
[39] W. Saadeh, M. A. Bin Altaf, H. Alsuradi, and J. Yoo, "A 1.1-mW Ground Effect-Resilient Body-Coupled Communication Transceiver With Pseudo OFDM for Head and Body Area Network," *IEEE Journal of Solid-State Circuits*, vol. 52, no. 10, pp. 2690–2702, Oct. 2017, doi: 10.1109/JSSC.2017.2713522.
[40] B. Zhao, Y. Lian, A. M. Niknejad, and C. H. Heng, "A low-power compact IEEE 802.15.6 compatible human body communication transceiver with digital sigma-delta IIR mask shaping," in *ESSCIRC 2017 - 43rd IEEE European Solid State Circuits Conference*, IEEE, Sep. 2017, pp. 380–383, doi: 10.1109/ESSCIRC.2017.8094605.
[41] M. Park *et al.*, "Low-Power, High Data-Rate Digital Capsule Endoscopy Using Human Body Communication," *Applied Sciences*, vol. 8, no. 9, p. 1414, Aug. 2018, doi: 10.3390/app8091414.
[42] K. Park, M. J. Jeong, J. J. Baek, S. W. Kim, and Y. T. Kim, "BER Performance of Human Body Communications Using FSDT," *IEICE Transactions on Communications*, vol. E102.B, no. 3, pp. 522–527, Mar. 2019, doi: 10.1587/transcom.2018EBP3053.
[43] J. Park and P. P. Mercier, "A Sub-10-pJ/bit 5-Mb/s Magnetic Human Body Communication Transceiver," *IEEE Journal of Solid-State Circuits*, vol. 54, no. 11, pp. 3031–3042, Nov. 2019, doi: 10.1109/JSSC.2019.2935549.
[44] Y. Jeon *et al.*, "A 100Mb/s Galvanically-Coupled Body-Channel-Communication Transceiver with 4.75pJ/b TX and 26.8 pJ/b RX for Bionic Arms," in *2019 Symposium on VLSI Circuits*, IEEE, Jun. 2019, pp. C292–C293, doi: 10.23919/VLSIC.2019.8778040.
[45] J. Yoo, "Energy-Efficient Body Area Network Transceiver Using Body-Coupled Communication," in *The IoT Physical Layer*, Cham: Springer International Publishing, 2019, pp. 127–139, doi: 10.1007/978-3-319-93100-5_8.
[46] S. Maity, B. Chatterjee, G. Chang, and S. Sen, "BodyWire: A 6.3-pJ/b 30-Mb/s −30-dB SIR-Tolerant Broadband Interference-Robust Human Body Communication Transceiver Using Time Domain Interference Rejection," *IEEE Journal of Solid-State Circuits*, vol. 54, no. 10, pp. 2892–2906, Oct. 2019, doi: 10.1109/JSSC.2019.2932852.
[47] S. Vijayalakshmi and V. Nagarajan, "Design and Implementation of Low Power High-Efficient Transceiver for Body Channel Communications," *Journal of Medical Systems*, vol. 43, no. 4, p. 81, Apr. 2019, doi: 10.1007/s10916-019-1204-x.
[48] A. Ali, K. Inoue, A. Shalaby, M. S. Sayed, and S. M. Ahmed, "Efficient Autoencoder-Based Human Body Communication Transceiver for WBAN," *IEEE Access*, vol. 7, pp. 117196–117205, 2019, doi: 10.1109/ACCESS.2019.2936796.
[49] C.-C. Chung, D. Sheng, and M.-H. Li, "Design of a human body channel communication transceiver using convolutional codes," *Microelectronics Journal*, vol. 100, p. 104783, Jun. 2020, doi: 10.1016/j.mejo.2020.104783.
[50] Z. Wei, W. Chen, M. Yang, Y.-M. Gao, Z. L. Vasic, and M. Cifrek, "Design and Implementation of Galvanic Coupling Intra-Body Communication Transceivers using Differential Phase Shift Keying," in *2020 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, IEEE, May 2020, pp. 1–6, doi: 10.1109/I2MTC43012.2020.9129050.
[51] W. K. Chen *et al.*, "Design of Galvanic Coupling Intra-Body Communication Transceiver Using Direct Sequence Spread Spectrum Technology," *IEEE Access*, vol. 8, pp. 84123–84133, 2020, doi: 10.1109/ACCESS.2020.2991206.
[52] S. Cho and D. Park, "Robust Intra-Body Communication Using SHA1-CRC Inversion-Based Protection and Error Correction for Securing Electronic Authentication," *Sensors*, vol. 20, no. 21, p. 6056, Oct. 2020, doi: 10.3390/s20216056.
[53] H. Tang *et al.*, "A 2Mbps Human Body Communication Transceiver Based on Body Antenna Effect," *Journal of Beijing Institute of Technology (English version)*, no. 1, pp. 39–52, 2022, doi: 10.15918/j.jbit1004-0579.2021.083.
[54] Y. Shimizu, D. Anzai, and J. Wang, "Performance evaluation on FPGA-implemented UWB-IR receiver for in-body to out-of-body communication systems," in *2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, IEEE, Aug. 2014, pp. 6981–6984, doi: 10.1109/EMBC.2014.6945234.
[55] Y. Liang, Y. Zhou, and Y. Li, "The Design and Implementation of IEEE 802.15.6 Baseband on FPGA," 2014, pp. 231–235. doi: 10.1007/978-3-319-03005-0_59.
[56] P. Mathew, L. Augustine, D. Kushwaha, V. Desalphine, and A. D. Selvakumar, "Implementation of NB PHY transceiver of IEEE 802.15.6 WBAN on FPGA," in *2015 International Conference on VLSI Systems, Architecture, Technology and Applications (VLSI-SATA)*, IEEE, Jan. 2015, pp. 1–6, doi: 10.1109/VLSI-SATA.2015.7050452.
[57] A. M. El-Mohandes, A. Shalaby, and M. S. Sayed, "Robust low power NB PHY baseband transceiver for IEEE 802.15.6 WBAN," in *2015 27th International Conference on Microelectronics (ICM)*, IEEE, Dec. 2015, pp. 91–94, doi: 10.1109/ICM.2015.7437995.
[58] S. B. Lokanatha and S. B. B. Prashanth, "Design and performance analysis of human body communication digital transceiver for wireless body area network applications," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 12, no. 3, p. 2206, Jun. 2022, doi: 10.11591/ijece.v12i3.pp2206-2213.
[59] N. Keranen *et al.*, "IEEE802.15.6 -based multi-accelerometer WBAN system for monitoring Parkinson's disease," in *2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, IEEE, Jul. 2013, pp. 1656–1659, doi: 10.1109/EMBC.2013.6609835.
[60] R. Matias, B. Cunha, A. Mota, and R. Martins, "ECG monitoring via Capacitive Body Coupled Communications," in *2014 IEEE International Symposium on Medical Measurements and Applications (MeMeA)*, IEEE, Jun. 2014, pp. 1–6, doi: 10.1109/MeMeA.2014.6860047.
[61] F. Solt *et al.*, "Energy Efficient Heartbeat-Based MAC Protocol for WBAN Employing Body Coupled Communication," *IEEE Access*, vol. 8, pp. 182966–182983, 2020, doi: 10.1109/ACCESS.2020.3028800.
[62] J. Ormanis and A. Elsts, "Towards Body Coupled Communication for eHealth: Experimental Study of Human Body Frequency Response," in *2020 IEEE International Conference on Communications Workshops (ICC Workshops)*, IEEE, Jun. 2020, pp. 1–7. doi: 10.1109/ICCWorkshops49005.2020.9145205.
[63] R. Negra, I. Jemili, and A. Belghith, "Wireless Body Area Networks: Applications and Technologies," *Procedia Computer Science*, vol. 83, pp. 1274–1281, 2016, doi: 10.1016/j.procs.2016.04.266.

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