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Review Article

A Review on Human Body Communication: Signal Propagation Model, Communication Performance, and Experimental Issues

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Human body communication (HBC), which uses the human body tissue as the transmission medium to transmit health informatics, serves as a promising physical layer solution for the body area network (BAN). The human centric nature of HBC offers an innovative method to transfer the healthcare data, whose transmission requires low interference and reliable data link. Therefore, the deployment of HBC system obtaining good communication performance is required. In this regard, a tutorial review on the important issues related to HBC data transmission such as signal propagation model, channel characteristics, communication performance, and experimental considerations is conducted. In this work, the development of HBC and its first attempts are firstly reviewed. Then a survey on the signal propagation models is introduced. Based on these models, the channel characteristics are summarized; the communication performance and selection of transmission parameters are also investigated. Moreover, the experimental issues, such as electrodes and grounding strategies, are also discussed. Finally, the recommended future studies are provided.

1. Introduction

The prevalence of chronic diseases (e.g., heart diseases, diabetics, and strokes) and escalating of aging population have become public health concerns and challenges of healthcare system. According to world health organization (WHO), millions of people suffer from chronic diseases and die, for instance, in 2012, cardiovascular diseases led to 17.5 million deaths and diabetes caused 1.5 million deaths [1]. Moreover, the absolute number of people aged 60 years and over will increase from 900 million to 2 billion from year 2015 to 2050 [2], and aging population is fueling the prevalence of chronic disease as elder people are more prone to have chronic diseases [3]. To effectively control the chronic diseases and improve the quality of life for patients, continuous health monitoring [4] is required. For high risk group people, the continuous monitoring of physiological data helps to early detect and prevent the diseases [5]. For instance, brain and muscles activities need to be continuously monitored in patients with Parkinson's disease and blood glucose is monitored in patients with diabetes. The promising solution to enable the continuous physiological data monitoring is to deploy the body area network (BAN) [6, 7], where tiny-size sensors and actuators are utilized to monitor the physiological data and provide the therapeutic functions (i.e., administrate the insulin dosage, control the rates of cardiac pacemaker, etc.) [6, 8, 9].

The structure of BAN is shown in Figure 1. The sensor nodes including both the on-body and in-body nodes (implantable devices), generally perform the monitoring function (pulse oximeter measures SpO2; blood pressure sensor measures blood pressure). The physiological data from these nodes over a period of time are delivered privately and reliably to a relay node or aggregator mounted on the body, such as a smart-watch or smart wristband [10, 11], which are emerging devices in the biomedical industry due to their convenience to control and constantly wear behavior. The data are then forwarded to the hub and the central control point, from where the data are available to hospital, professional staff, and emergency center or for personal usage.

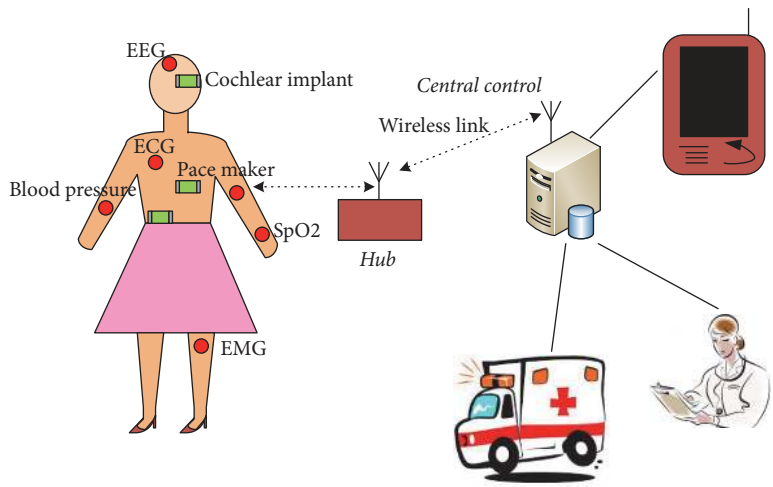


Figure 1: Structure of body area network.

Human centric is the major characteristic for BAN, the communication among sensors scattered on/in the human body and aggregator should be accomplished by wired connection or short distance wireless communication techniques. Obviously, wired connection is not a good choice since wire can break and is inconvenient for patients' movement. The short range radio frequency (RF) wireless techniques such as Zigbee, Bluetooth, and Ultrawide Band (UWB) are the preferable candidates. However, these approaches have the intrinsic drawbacks since they are not designed for human centric health monitoring data transmission. For instance, the RF techniques are prone to electromagnetic interference and suffer from large signal leakage and easy eavesdropping. Furthermore, human body is primarily (65%) composed of water, which is a blocking material for RF signals [12]. Thus the RF wireless signals transmitted around or in the human body will suffer from body-shadowing effect, which will lead to significant signal attenuation [13, 14]. Moreover, the RF techniques radiate the signal via antenna, which is challenged for miniaturization. Another potential candidate is the inductive wireless coupling technique. However, its coupling efficiency (0.4% with 3 cm distance [15]) is low and coil size (typical dimensions of 25 mm × 10 mm for rectangular coil, diameter 20 mm for circular coil) [16] is large. Also the coil is a problem for miniaturization. It is evident that new communication techniques targeted for human centric healthcare monitoring data transfer are required for the medical BAN.

Human body communication (HBC, also termed intrabody communication) is a novel transmission technique using the human body as the transmission medium for electrical signal transfer [17]. HBC has become one of three physical layers (another two are narrow band and UWB) for BANs proposed by IEEE 802.15.6 task group 6 [18]. HBC can be implemented in two ways: capacitive coupling method and galvanic coupling method. It has the following desirable characteristics.

(a) Little Signal Leakage-High Security. The signal is confined to the surface of the body and with little energy radiated into the surrounding environment (avoid the body acting as antenna to radiate energy) [19, 20]. Therefore, the security of information is guaranteed for its avoidance of eavesdropping, and the interference among different individuals can be minimized as well.

(b) Low Signal Attenuation-Low Transmission Power. Compared with air channel, human body channel obtains high channel gain [21], which can lower the transmission power. And thus it may potentially lower the power consumption of the system and helpful for miniaturization.

(c) Low Carrier Frequency. HBC operates in low frequency (especially for galvanic coupling HBC), which can potentially simplify the design, minimize the power consumption (in HBC system, the detected circuit, filter, and power amplifier have the component of CMOS circuit, in which the dynamic power is proportional to the carrier frequency. Also power consumption of CPU and frequency synthesizer is proportional to operation frequency) [22, 23], and reduce the size of devices due to the low requirement on amplifiers, capacitors, and inductors. Meanwhile, the lower carrier frequency requires low-intermediate-frequency receiver, which can potentially achieve the crystal-less receivers due to its better tolerance to the frequency deviation [24]. The crystal-less transceiver could further reduce the size and power consumption, since crystal oscillator is bulky, power-hungry, and fragile components. In addition, HBC does not require the antenna, which can minimize the size of chip.

The comparisons of HBC and other wireless techniques are shown in Table 1. To serve as a suitable communication technique for BAN, HBC has been attempting to become a prospective candidate due to its low interference, high security (signal intercept requires body touch), suitable transmission range, and potentially higher degree of miniaturization.

Table 1: Comparison of wireless communication techniques.

Technique	Frequency (GHz)	Data rate (Mbps)	Power (dBm)	Distance	Inf
Zebee [93]	2.4, 0.865	0.25	−3~10	10 m	high
Bluetooth [94]	2.4	0.721~24	<20	10 m	high
UWB	3~10	0.85~20	−41	10 m	high
ICL	0.001~0.4 [15]	0.0001–4 [95]	—	0.5~3 cm	low
Cap-HBC	0.01~0.1	0.002~10	−15~5	5 cm~2 m	low
Gal-HBC	0.0001~0.01	0.0009~2	−30~ −4	5 cm~40 cm	low

Inf: interference; ICL: inductive coupling link; Cap-HBC: capacitive coupling HBC; Gal-HBC: galvanic coupling HBC.

By using HBC for data transfer among the wearable or implantable healthcare monitoring devices, the low power transmission is important, not only for avoiding information leakage or interference to other BANs, but also for saving power (the decrease of transmission power can lower the power consumption of power amplifier, which accounts for a significant portion of the HBC system power consumption). This is especially true for implantable devices, as the leakage of important information (e.g., pacing speed and pacing threshold setting of pacemaker) to unintended receiver will lead to life-threatening events. In addition, low transmission power is of importance as it can also extend the lifetime of battery [25], which requires costly and invasive surgical operation for replacement.

To achieve low transmission power, it is necessary to minimize transmission power and optimize its communication performance. Certainly, the reliable data transmission should be at the same time maintained. Then the transmission parameters correlated with the transmission power, such as data rate, modulation method, bandwidth, and frequency band, should be selected suitably. That motivates us to summarize the channel characteristics and find out the rule of communication performance (i.e., bit error rate BER) for different modulation schemes. Of course, the experimental issues to obtain the channel characteristic are also of significant. Therefore, having a survey on the above issues is of importance for the deployment of HBC. In what follows, the history and development of HBC are reviewed. Then the signal propagation model is summarized in Section 3; based on the models, the channel characteristics and communication performance are provided in Section 4. The experimental issues are discussed in Section 5. Finally, the conclusions and future studies are addressed in Section 6.

2. The Development of Human Body Communication

2.1. The History of Electrical Property and Human Tissue. In the history of human beings, the interests on body tissues were inevitable. Many researchers devoted their efforts and thoughts to investigate the muscles and their electrical properties and biomechanics. There are generally two forms of bioelectrical assessment of muscle, one is to investigate the electrical signal originated in muscle and another is the properties of muscle by applying electrical signals.

The relationship between electricity and muscle contraction was first observed by the Italian physician Luigi Galvanic in the mid-1780s. Luigi Galvanic performed the experiment of connecting the nerves of recently dead fog to a long metal wire and pointed it towards the sky during thunderstorm, the frog's legs twitched and jumped as if they were alive with flash of lighting, from which Galvanic pointed out that recently dead muscle tissue can respond to external electrical stimuli. Since then, more and more researchers investigated the response of human tissue to electric current, the tissue impedance, and dielectric properties. For example, the nerve, muscle, and gland can be stimulated to produce anesthesis [26] by milliampere electric currents. The early extensive literature reviews on dielectric properties have been provided by Geddes and Baker [27], who summarized the early reports on the specific resistance of tissues. Later, the intensive research on tissue dielectric property was reported by Gabriel et al. [28]. And further experiments were conducted by Gabriel et al. to study the dielectric properties of human and animal tissue in the frequency range 10 Hz to 20 GHz [29]. Based on these measurements, a parametric model with four Cole-Cole type dispersions was developed to describe the dielectric properties of tissue as a function of frequency [30]. These electrical properties have been utilized by the researchers to facilitate the recent research and applications. For instance, electrical impedance tomography (EIT) has been developed to image the internal organs and structure of body for medical diagnosis; electrical stimulation has been adopted for medical therapy and prosthesis. Until 1995, human body as a transmission medium was proposed to be utilized for data transmission. This type of telemetry, called capacitive coupling HBC [17], was developed to enable data transmission on or around the human body.

The pioneer researches of HBC focused on the feasibility of implementing HBC. After that, the signal propagation models were emerging to investigate the signal propagation mechanism and channel characteristics. Later, experiments and prototypes were developed to investigate their communication performance. Generally, HBC can be implemented in two ways: capacitive coupling method and galvanic coupling method. In what follows, the details will be presented.

2.2. HBC Coupling Methods and Their First Attempts

2.2.1. Capacitive Coupling HBC. In 1995, Zimmerman [17] did the research to perform the position measurement of

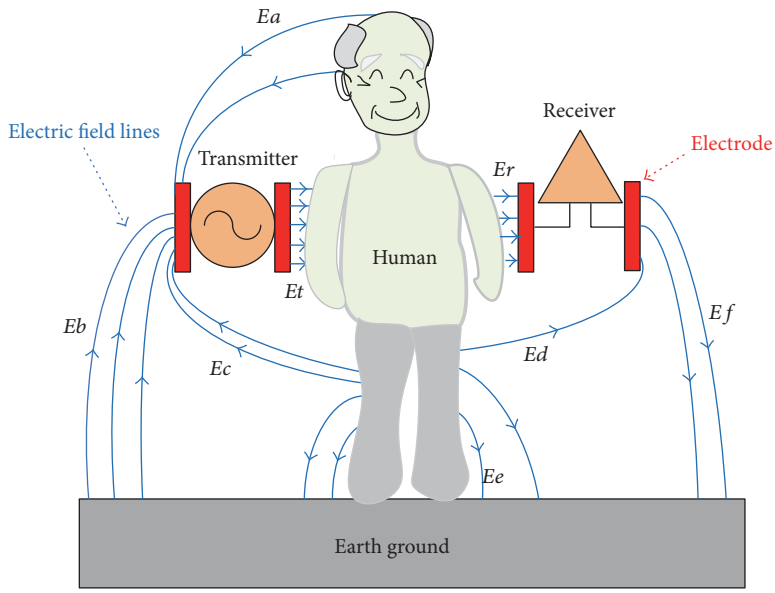


Figure 2: Principle of capacitive coupling HBC.

Yo-Yo Ma's cello bow. It was discovered that placing one's hand in electric field attenuates the received signal significantly. Based on these facts and principle, he proposed the concept of Personal Area Network (PAN), a wireless system that allows electronic devices on and near the human body to exchange digital information through HBC, which does not need the sophisticated antenna to radiate the signal into air; instead, electrodes are used to couple the electric signal to human body, which is then served as the medium to convey the signal. Zimmerman also developed a prototype as an initial attempt to implement HBC technology. This prototype validates the feasibility of using HBC for data transfer.

The capacitive coupling HBC, also called near-field coupling [31], and electrostatic coupling [17, 32] are described in Figure 2. The signal electrodes at both transmitter and receiver are attached on the human skin, while the ground electrodes are floating in air. A large electric field *Et* is introduced to the human body via the signal electrode of transmitter [31]. The conductivity of human body not only couples electric field to environment (i.e., *Ee*) but also serves as a conducting plate that induces electric fields (i.e., *Ea*, *Ec*, and *Ed*) to other conducting plates (ground electrodes) [33, 34]. The return path of the transmitted signal is formed by the electric fields *Ea*, *Ec*, *Ee-Eb*, *Er-Ef-Eb*, and *Ed-Ef-Eb*. In other words, the electric fields in environment or through external earth ground serve as the return path [35]. At the receiver, the received signal as electric potential difference between *Er*, *Ef*, and *Ed* is allowed to be detected as *Er* is much larger than *Ef* and *Ed* (conductivity of human body is much higher than that of air) [34]. On the other hand, the electric potential difference is small due to the escaped electric fields *Ee*, *Ea*, and *Ec*. Furthermore, the detected signal is unstable and highly influenced by the environment on accounting that the electric fields *Ef* and *Ee* vary along with environment changes [17] (e.g., the appearance of metallic furniture, wires, water, and office equipment will change the backward capacitance [36]).

To avoid the human body's antenna effect of radiating signal ($\lambda/2$ dipole is around 1 m), the operating frequency should be lower than 150 MHz [31]. And most of the electric field will concentrate around the tip of arm wearing transmitter [19]. Capacitive coupling HBC is suitable for those applications requiring higher operating frequencies (approximately tens of MHz) and longer body transmission distances (usually along the whole body). Nevertheless, capacitive coupling HBC is vulnerable to external interferences and other unpredictable effects, such as the subjects' movements [37].

2.2.2. Galvanic Coupling HBC. The galvanic coupling HBC was firstly reported in 1997 by the Japanese researchers Handa et al. [38]. The ECG signal from the chest was modulated into micro-Ampere electric current, coupled into human body by electrodes, and detected by a pair of receiving electrodes on the wrist. The transmitting and receiving electrodes were in direct contact with the body, resulting in galvanic coupling signal transmission. This system worked with small power consumption, only 8 μW. The results suggest that data transmission with low transmission power is possible by using galvanic coupling HBC.

In 1998, Lindsey et al. [39] tested the galvanic coupling HBC between an implantable device and an external data acquisition system. In the system, two platinum electrodes (each 0.38 mm in diameter, separated by 2.5 mm) were used to inject sinusoidal currents with frequencies of 2–160 kHz and amplitudes of 1–3 mA into the leg of a human cadaver. EMG electrodes on the surface of the leg were deployed to detect the voltage differences. The human body channel resulted in attenuation within 37–47 dB. This prototype

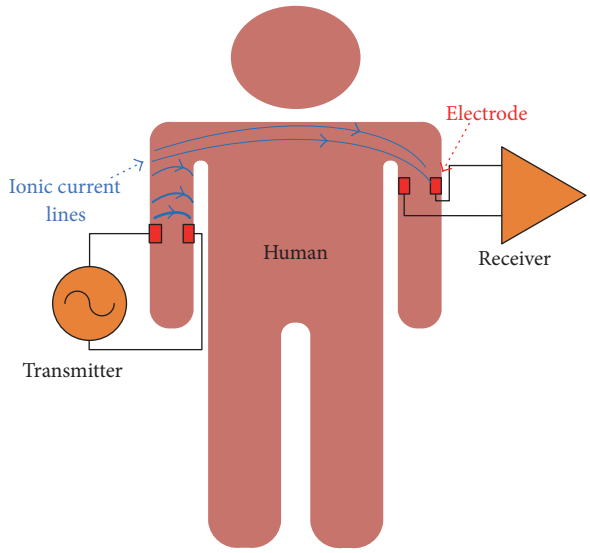


Figure 3: Principle of galvanic coupling HBC.

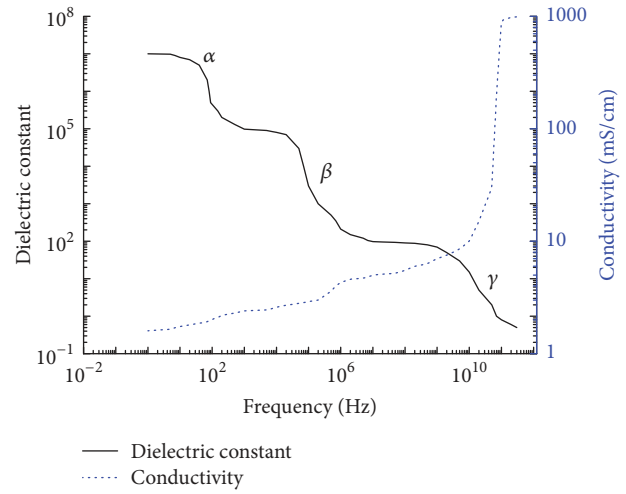


Figure 4: Dielectric constant and conductivity of tissue and cell [48].

demonstrates that it is feasible to utilize galvanic coupling HBC for data transmission between implantable device and body surface mounted sensors.

Galvanic coupling HBC, also termed waveguide HBC [40], utilizes the ionic fluids in body and volume conduction properties of tissues [39] to convey electrical signal. The simplified model is depicted in Figure 3. A major ionic current is generated within the tissue close to the transmitter. With a separation distance to the transmitter, the current will decrease due to the impedance of human tissue. The small current induces electric potential that can be detected at the receiver by a high-gain differential amplifier. The existing experiments or prototypes are usually performed on human limb. Since the signal propagation principle is based on the ionic current, the operation frequency should be low (i.e., <1 MHz [41]). And in such low frequency, the signal radiation or leakage into the space can be negligible [20].

Compared with capacitive coupling HBC, galvanic coupling HBC operates in lower frequency and is less influenced by the environment, which makes the signal transmission much more stable and reliable. Therefore, galvanic coupling HBC is more suitable for the vital physiological signal transmission, especially for implantable device communication. Certainly, it trades off data rate. Fortunately, the data rate requirements for the vital physiological signal transmission are relatively low, for example, 75 kbps in ECG, 1.6 kbps in SpO2, and <100 kbps for both pacemaker and implantable glucose sensors [42]. Therefore, galvanic coupling HBC is also a promising candidate for the vital physiological data transmission among wearable and implantable devices.

3. Electrical Properties of Human Tissues and HBC Signal Propagation Models

After the pioneering work of successfully implementing HBC, considerable researches have been conducted by research groups to investigate the channel gain at different distances and regions of body such as arm, thorax, leg, and the back [43, 44]. Accompanying with the experimental investigations, the theoretical researches on the transmission mechanism have become a major research topic. The signal propagation model includes numerical model and analytical model. The numerical method can achieve more accurate calculation for the realistic structure and geometric of human body, but sacrificing computation time and cost. The numerical model for HBC includes the finite difference time domain (FDTD) simulation model (e.g., [19]) and finite element method (FEM) simulation method (e.g., [20, 35, 41]) model. On the other hand, the analytical model saves computation time but is limited to simple structures such as circle and cylinder. The analytical model mainly includes the simplified circuit model [31, 41, 44, 45], asymmetric distributed circuit model [37, 46], and quasistatic field model [47].

3.1. Electrical Property of Tissues. The signal propagation models in HBC are generally based on the electrical properties of human tissues. The frequency dispersion mechanism of human tissue was first introduced by Schwan [48]. Three main dispersion regions denoted by α, β, and γ region at respective frequencies of low frequency range, RF range, and gigahertz frequency range, response for the behavior of tissue. As depicted in Figure 4, the three dispersion regions are as follows.

α Dispersion (Low kHz). It is not known well and is related to the polarization of counterion atmosphere near charge surfaces in the tissue or polarization of large membrane-bound structures in the tissue. Or it is associated with ionic diffusion process at the site of cellular membrane. It is apparent in permittivity and hardly noticeable in conductivity.

β Dispersion (0.1–10 MHz). Relaxation effects are caused by proteins, lesser extended amino acid residues, and the bioimpedance (capacitance of membrane and resistance of

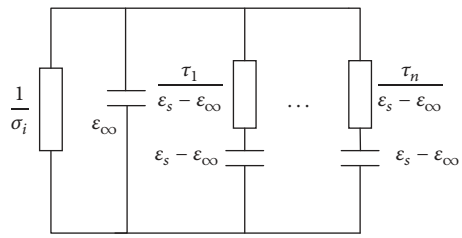


FIGURE 5: Circuit model of the tissue (multiple Cole-Cole model).

fluid) of organelles inside the cell, cell nuclei, and mitochondria. As the cell membranes have negligible impedance, charging of cell membranes through intracellular and extracellular becomes easier. The current passes through the extracellular and intracellular media; therefore, the conductivity becomes higher.

γ Dispersion (Above 1 GHz). High conductivity region is mainly caused by a variety of tissues (amino acids, nucleic) and protein solution.

Based on many reported experimental data of tissues, the Cole-Cole equation is adopted to predict the change of dielectric properties of a tissue over frequency:

$$\varepsilon^*(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + (j\omega\tau_n)^{1-a_n}}, \tag{1}$$

where τ is the relaxation time constant of the polarization mechanism in the relaxation regions and ε_∞ and ε_s are the permittivity at frequencies $\omega\tau \gg 1$ and $\omega\tau \ll 1$, respectively. Equation (1) encompasses a frequency independent part ε_∞ due to ion conduction and a frequency dependent part related to dielectric relaxation. However, the dispersion region may be broadened by many mechanisms due to the complexity of both the structure and composition of biological material. The tissue spectrum may therefore be more appropriately described by multiple Cole-Cole dispersion:

$$\varepsilon^*(\omega) = \varepsilon_\infty + \sum_n \frac{\varepsilon_s - \varepsilon_\infty}{1 + (j\omega\tau_n)^{1-a_n}} + \frac{\sigma_i}{j\omega\varepsilon_0}, \tag{2}$$

where σ_i is the static ionic conductivity. The complex conductivity and impedance of tissue are calculated by

$$\sigma^* = j\omega\varepsilon_0\varepsilon^*, \qquad z^* = \frac{1}{\sigma^*}. \tag{3}$$

Based on (2) and (3), the electrical properties of tissue can be modelled by equivalent circuit with conventional resistors and capacitors as shown in Figure 5.

3.2. HBC Signal Propagation Models

3.2.1. Circuit Model. Wegmueller [41] developed a simple four-terminal circuit model with six body tissue impedances and four electrode-skin impedances for low frequency (<1 MHz) galvanic coupling HBC. The simplified circuit model is shown in Figure 6. This model takes into account the impedance of human limb, such as longitudinal (Z_t) and cross (Z_b) channel impedances, as well as electrode-skin impedance (Z_e), input (Z_{in}) and output impedances (Z_{out}). The channel transfer function can be described as follows:

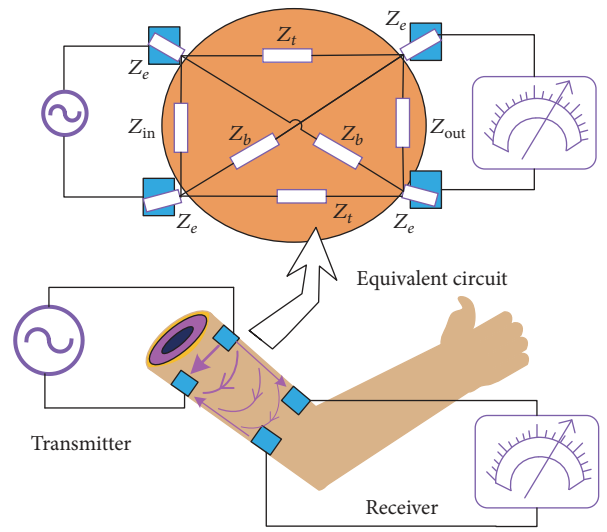


FIGURE 6: Simplified circuit model for galvanic coupling HBC.

$$H = \frac{Z_{\text{out}}(Z_b - Z_t)}{2Z_tZ_b + Z_{\text{out}}Z_b + Z_{\text{out}}Z_t}$$

$$H_{\text{total}} = \frac{H}{1 + Z_e\left[1/Z_t + 1/Z_b + H\left(1/Z_b + 1/Z_{\text{in}} - 2/Z_t\right)\right]}. \tag{4}$$

Besides the simplified circuit model, Wegmueller [41] described the body impedance by equivalent parallel circuit of resistance and capacitance according to the Cole-Cole reference model. Then a more complex layered tissue (skin, muscle, and bone) model was developed. Each layered tissue was composed by transversal and longitudinal impedances with Cole-Cole circuits connected in a mesh. It was reported that a smaller portion of current would flow through the skin layer between the electrodes, whereas the majority would be conducted by the deeper muscle tissue.

The circuit model of skin for both capacitive coupling and galvanic coupling HBC was developed by Amparo Callejón et al. [37, 46]. In the model, the equivalent circuit model of skin can be seen as a lossy transmission line without inductive element. And for capacitive coupling method, the model parameter (propagation constant and characteristic impedance) also depends on the capacitance effect from the external ground return path [37]. It was reported that attenuation increased up to 200 kHz and remained approximately constant for higher frequencies in galvanic coupling HBC. For capacitive HBC, a bandpass profile was observed within 1~100 MHz. The circuit model for these two coupling methods was also addressed in [44], and it was found that two-electrode arrangement achieved higher gain than the four-electrode arrangement.

Recently, Kibret et al. [45] developed an equivalent circuit model with subject specific anthropometric measures. The gain was found to rise slowly as frequency increased from 200 kHz to 10 MHz, and phase fell from 50° to 10° as frequency increased.

3.2.2. Finite Difference Time Domain (FDTD) Method. Fujii et al. utilized the FDTD method to calculate the electric field distribution in human body [19, 49, 50]. It was found that most part of the electric field was concentrated around the tip of the arm, and biological tissue-equivalent solid phantom was sufficient to mimic the human body [19]. Similar results were found in [51] that dominant signal was on the surface of the arm.

3.2.3. Finite Element Method (FEM) Method. Xu et al. [35] proposed a circuit coupled FEM model for capacitive coupling HBC. The human body was considered as a circuit of lumped resistors paralleled with lumped capacitors. The channel gain satisfied high-pass profile and the return path capacitance was dependent on the transceiver ground, as well as external ground. Recently, Callejon et al. [20] investigated the electric field distribution and current density using FEM. It is found that the electric field is mainly confined to the outer layer of the arm, and the radiation could be neglected. The majority of electric current in the galvanic coupling HBC travels through muscle.

3.2.4. Analytical Electromagnetic Model. The analytical electromagnetic model is developed by solving Maxwell's equations and specific boundary conditions. A theoretical model, wherein the electric field was assumed to be composed of near field, inductive field, and far-field, was proposed by Bae et al. [52] for the capacitive coupling HBC. The quasistatic field modelling of galvanic coupling HBC was developed by Pun et al. [47, 53]. The channel gain follows the high-pass characteristic in sub-MHz, and the signal radiation into space is negligible.

The summary of signal propagation models and their main results are depicted in Table 2. From the table, the signal propagation models are based on the static body behavior. While for dynamic body behavior, the signal propagation model is not yet developed.

4. Channel Characteristics and Communication Performance of HBC Systems

Besides the signal propagation model, one important issue that related to data transmission is the channel characteristic, which generally guides us to select the suitable transmission parameters, such as frequency band and modulation methods. In what follows, the channel characteristics are discussed.

4.1. Channel Characteristics and Transmission Parameters. From the main results of signal propagation model, the channel gain is generally analyzed. The channel gain behaves generally as bandpass [37] or high-pass [31, 45]. Besides, the channel characteristics in static body behavior that in dynamic body behavior are of important. That is due to the fact that HBC system permits the doctors or physicians to access the physiological data without interrupting the patients' everyday life, in which the human body moves and posts different gestures (such as grasping cup to drink), which is expected to affect the data transmission. From the experimental investigation, it was found that the large scale body behavior, such walking, sitting, and standing, has little effect on the channel [54, 55]. The joint behavior, such as joint flexion or extension, can cause gain variate in 2~5 dB [56, 57], while phase is little affected [57]. The channel characteristics' analysis is shown in Table 3. As shown in Table 3, the other channel characteristics such as phase, linearity of channel, and noise in channel are little discussed. From the recent investigation, the phase in galvanic coupling HBC channel follows a decreased trend [45, 58], while the noise in the channel is assumed to be mainly from electronic components [41] and electrode-skin interface [59], which are assumed to follow the additive white Gaussian noise (AWGN) property.

The transmission parameters, which are either for testing conditions of experiments or specifications (i.e. narrow band or wideband) that they chose for the demo system or for achieving the best performance, are generally selected based on the results of channel gain profile. The parameters' selections in some typical literatures are summarized in Table 4. The transmission parameters such as carrier frequency and modulation method, which are involved in the physical layer design, have been selected based on the empirical results and analysis of channel characteristics. For instance in [17], the carrier frequency and bandwidth were determined via the −3 dB frequency response. In [32], 10 MHz was suggested to be the suitable carrier frequency due to its maximum channel gain. Similarly in [60], suitable frequency range (from 200 MHz to 600 MHz) for transmission was determined corresponding to the lowest path loss. Owing to the relative flat and high channel gain, a carrier frequency of 256 kHz and bandwidth of 100 kHz were chosen in [41]; meanwhile the transmission power was averagely allocated within this band. To show the feasibility of achieving biomedical applications in clinical trials, BPSK and QPSK were selected to be implemented in the HBC prototype [61]. QPSK was chosen as suitable modulation method based on the results of hardware complexity analysis [41]. Based on the comparison measurements, BPSK was selected as the optimal modulation method among BPSK, QPSK, MSK, and 16QAM [62]. From Table 4, the transmission parameters' selection is generally based on the empirical and scattering measurement results. Recent investigation [63] offers an innovative view to select the transmission parameter based on the theory of channel capacity; however, further experimental verification of the theory and analysis is needed.

4.2. Communication Performance of HBC Systems. The communication performance of HBC systems was investigated by using simulations [37] and experiments [17, 61, 64, 65]. Also many prototypes [32, 41, 60] have been developed to achieve different communication performance. Various transmission parameters (carrier frequency, modulation scheme, and

Table 2: Signal propagation models and results.

Model	Coupling method	Model mechanism	Main results
Equivalent circuit model, Hachisuka et al. [44]	Cap-HBC & Gal-HBC	Four-terminal circuit model with six impedances	Higher gain in Cap-HBC
Multilayer tissue model, Wegmueller [41]	Gal-HBC	Equivalent Cole-Cole circuits	Muscle conduct majority current
Distributed circuit model, Amparo Callejón et al. [37]	Cap-HBC & Gal-HBC	Lossy transmission line	Cap-HBC: bandpass gain in 1–100 MHz Gal-HBC: peak gain in 20–50 kHz
Circuit model, Kibret et al. [45]	Gal-HBC	Simplified layered tissue circuits	High-pass profile in gain in 0.2–10 MHz
Distributed RC model, Cho et al. [31]	Cap-HBC	Cascaded blocks of RC circuit	High-pass profile in gain in 0.1–100 MHz
FEM model, Xu et al. [35]	Cap-HBC	Body path with π circuit model	High-pass gain in 10–100 MHz, body can reduce return path capacitance
FEM model, Callejon et al. [20]	Gal-HBC	Time-harmonic charge-continuity equation, Gauss' law	Electric field mainly in outer layer of arm, electric current mainly in muscle layer, 20 dB attenuation with additional 5 cm channel length
FDTD model, Fujii et al. [19]	Cap-HBC	FDTD	TX GND electrode strengthen signal, electric field confined at the tip of arm
Quasistatic field model, Pun et al. [47]	Gal-HBC	Quasistatic field, Maxwell's equation	High-pass gain in sub-MHz
Electromagnetic field model, Bae et al. [52]	Cap-HBC	Time harmonic electromagnetic field Maxwell's equation	Near-field region: signal attenuation depend on $(1/r)^3$, far field region: signal attenuation satisfy $1/r$

Table 3: Channel characteristics from the literature.

Gain	Phase	Linearity of channel	Noise in channel	Gain
Capacitive coupling HBC				
Static body behavior	Bandpass profile [31] Influence by electrode [35] Better results in limbs [54] TX GND electrode strengthen signal [19]	Non	Non	Non
Dynamic body behavior	Movement sensitive [54, 55] Joint flexion cause gain variate in 2 dB [96]	Non	Non	Non
Galvanic coupling HBC				
Static body behavior	Higher gain in trunk and back [54] High-pass profile [45] High-pass profile [59]	Decrease [45]	Linear channel [59]	AWGN [41, 59, 92]
Dynamic body behavior	Not sensitive in sitting & waling [54] Increase as joint flexion [56] Joints and biceps muscle have a great effect [57]	Decrease trend [57] Not sensitive by movement [57]	Non	AWGN [57]

transmission power) were adopted to achieve different data rates.

For capacitive coupling HBC, narrowband modulation on-off keying (OOK) and wideband signaling direct sequence spread spectrum (DSSS) were examined in [17]. The OOK was found to be more effective and easier to be implemented, and a data rate of 2.4 kbps was obtained with carrier frequency 330 kHz and bandwidth 400 kHz. The data rate was extended to 9.6 kbps by using frequency shift keying (FSK) modulation in [66, 67]. A higher data rate of 38.4 kbps was achieved with carrier frequency of 160 kHz in [68]. Since 2006, experiments sprung up to obtain data rate around Mbps. According to Ruiz and Shimamoto [69], the received power could be modelled as a normal distribution. The modulation methods BPSK, QPSK, 8PSK, 16QAM, and MSK provided symbol rates range from 100 ksps to 5 Msps with transmission power of 15 dBm and carrier frequency of 200 MHz [21, 65]. Although MSK achieved the best performance [65], it was the most sensible modulation scheme so that the modulation quality decreased as symbol rate

Table 4: Transmission parameters selection from literatures.

Literature	Suitable carrier frequency		Suitable modulation method		Objective of selection
	Frequency	Guideline	Modulation	Rule	
Zimmerman [17]	300 kHz	−3 dB band	OOK	Simple	Test narrow band transmission
Hachisuka et al. [32]	10.7 MHz	Maximum gain	FSK	Simple	Minimize power consumption
Ruiz and Shimamoto [65]	200 MHz	Maximum gain	MSK	Empirical results	Find suitable modulation method
Wegmueller [41]	256 kHz	High gain	QPSK	Hardware complexity	Test HBC transceiver
Wegmueller et al. [61]	128 kHz	High gain	BPSK, QPSK	Empirical results	Test clinical trials in transceiver
Zhang et al. [62]	10.7 MHz	Maximum gain	BPSK	Empirical results	Determine optimal modulation
Lin et al. [60]	200–600 MHz	Low path loss	OOK	Saving power	Optimization of SoC chip

increased [21]. A data rate of 5 Mbps was achieved in [70] by using OOK/FSK modulation. By using the delay-locked-loop based BPSK demodulator, a data rate between 164 kbps and 1.313 Mbps was achieved with transmission power of 1.4 mW in the HBC transceiver developed by Cho et al. [71]. Later, a 65 nm CMOS process HBC transceiver [72] for both entertainment and healthcare was implemented by this research group; for the latter case, a data rate of 100 kbps was achieved with low transmission power of 21 μW. By using a wideband pulse system on chip (SOC) transceiver was implemented by Song et al. [73], and the chip obtained a data rate of 2 Mbps within the frequency band from 10 kHz to 100 MHz. By using DSSS and frequency hopping FSK modulation, the data rate was extended to 10 Mbps in [74] and in [75]. With other wideband modulation such as frequency selective Walsh spread and UWB, the data rates were up to 2 Mbps [76] and 5 Mbps [77, 78]. Recently, a wideband signaling HBC transceiver with high data rate between 1 Mbps to 40 Mbps was developed by Chung et al. [79].

For galvanic coupling HBC, the first prototype achieved only 0.9 kbps by employing pulse width modulation (PWM) [38]. A data rate of 9.6 kbps was obtained by using FSK modulation with carrier frequency of 10.7 MHz [32, 40]. The new component electrooptic sensor was introduced in the transceiver by Shinagawa et al. [80]; a data rate of 10 Mbps was reached. The comparison of modulation schemes FSK and BPSK was conducted by Wegmueller et al. [43]. It was found that, with input current of 2 mA, BPSK and FSK obtained a data rate of 255 kbps and 128 kbps, respectively. With a SNR of 6 dB [61], both BPSK and QPSK achieved a data rate of 64 kbps and BER of 10^{-4}. BPSK and QPSK were the suitable modulation schemes among PSK, FSK, and QAM [41] in galvanic coupling HBC. According to Zhu et al. [64], a minimum transmission power of −17.8 dBm was utilized to achieve data rate of 10 Mbps and BER of 10^{-6}. The SOC prototype from Lin et al. [60] obtained a data rate of 2 Mbps by using OOK with transmission power −4 dBm.

The data rates in the experiments and prototypes are presented and compared in Table 5. There is a general trend that the data rate increases from kbps to Mbps since 2000. Generally, the transmission distance of capacitive coupling HBC system is in several tens to even hundreds of centimeters. However, galvanic coupling HBC transmits with shorter distance around tens of centimeter and lower data rate than capacitive coupling HBC. It is noted that capacitive coupling HBC can transmit with wideband signaling, which can obtain high data rate but requires large bandwidth.

4.3. Applications of HBC. The HBC prototypes have been applied in the healthcare data transmission. For instance, Handa et al. [38] developed a galvanic coupling HBC prototype to transmit the ECG signal from chest to limb. Later, a prototype [40] of galvanic coupling HBC has been applied to transmit the heart rate and SpO2. Yoo et al. [81] implemented a HBC system to transmit the ECG and blood pressure. And a SOC chip for transferring the ECG signal was developed by Lin et al. [60].

Recently, the channel characteristics in HBC, such as gain and phase, were found to have great relevance with some physiological parameter, such as muscle contraction or relaxation, body fluid hydration, and dehydration. Based on these principles, the galvanic coupling HBC system has been adopted to conduct some physiological parameter measurement. For instance, the qualitative hydration and dehydration rate affected by the physiological state and metabolic equilibrium can be accessed by the galvanic coupled HBC signal propagation [82]. This mechanism has been utilized to evaluate the body fluid [82] and help to aid diagnosis and treatment of fluid disorders such as lymphoedema. According to Chen et al. [57], the gain variation has great relevance with the joint flexion. The relationship between joint angle and channel gain variation has been accessed by using the polynomial curve fitting method [83]. The obtained relationship is then adopted to perform the joint angle estimation [83], which can be applied in prosthesis control and gait analysis.

5. Safety Considerations and Experimental Issues

During *in vivo* HBC experiment, the electric signals are applied into the human body by the electrodes, which would pose potential health risks to the human body, such as the danger of electrical shock and safety issue of using electrodes.

Table 5: Communication performance of HBC system.

Literature (authors, year)	TX power	Channel capacity	Data rate	TX distance	Modulation method
Capacitive coupling HBC					
Zimmerman [17], 1995	—	417 kbps	2.4 kbps	—	OOK
Post et al. [66], 1997	20 dBm	50 kbps	9.6 kbps	200 cm	FSK
Matsushita et al. [67], 2000	—	—	9.6 kbps	—	FSK
Partridge et al. [68], 2001	—	—	38.4 kbps	200 cm	FSK
Shinagawa et al. [80], 2004	—	—	10 Mbps	150 cm	—
Song et al. [73], 2006	—	—	2 Mbps	—	Wideband
Zhu et al. [64], 2009	−14 dBm	—	10 Mbps	15 cm	QPSK
Cho et al. [75], 2009	−5 dBm	—	10 Mbps	120 cm	Wideband
Zhang et al. [62], 2010	—	—	0.1~10 Mbps	10~150 cm	BPSK
Nie et al. [70], 2012	−15~5 dBm	—	5 Mbps	10~50 cm	OOK
Hyoung et al. [78], 2012	—	—	2 Mbps	170 cm	Wideband
Cho et al. [71], 2014	1.4 dBm (or 1.4 mW)	—	164 kbps~1.313 Mbps	—	BPSK
Cho et al. [72], 2015	−16.7 dBm (or 21 μW)	—	100 kbps	—	OOK
Chung et al. [79], 2016	—	—	1 Mbps~40 Mbps	—	Wideband
Galvanic coupling HBC					
Handa et al. [38], 1997	−21 dBm	—	0.9 kbps	40 cm	PWM
Hachisuka et al. [40], 2003	−10 dBm	—	9.6 kbps	28 cm	FSK
Wegmueller et al. [43], 2005	−3 dBm	—	255 kbps	10~15 cm	BPSK
Ruiz and Shimamoto [65], 2006	15 dBm	—	2 Mbps	20 cm	QPSK
Wegmueller [41], 2007	−6 dBm	1.23 Mbps	64 kbps	10~25 cm	QPSK
Lin et al. [60], 2011	−30~−4 dBm	—	2 Mbps	—	OOK
Li et al. [92], 2013	−5 dBm	—	200 kbps	6 cm	QPSK

5.1. Safety Guidelines. Whenever any form of energy is introduced into the human body, it is important to understand what risks might result from applying energy to internal tissue. The most obvious effect is heating. Since a significant portion of energy is absorbed and converted into heat during signal propagation, this would potentially lead to temperature increase. More importantly, the induced current intensity at specific frequency determines the intensity of the electrical shock through the body. The applied electric current or voltage on human body must follow IEEE Std. C95.1 2005 [84] and International Commission on Nonionizing Radiation Protection (ICNIRP) guidelines [85]. The IEEE Std. C95.1 2005 is more detailed about the safety levels with respect to the human body exposure to radio frequency electromagnetic field. For instance, the restriction of electric field between 100 kHz and 3 GHz within localized human body such as extremities and pinnae should be 4^c W/kg (where c is defined as tissue volume in the shape of a cube) [84]. The maximum harmless induced current in HBC should be lower than 20 mA at frequency range of 100 kHz to 110 MHz (general public exposure) [85].

5.2. Electrodes. HBC operates without the antenna; instead the electrodes are used to couple the signal into the human body. From the literature, the Ag/AgCl electrodes are generally utilized in the HBC systems [44, 54, 60, 86]. For Ag/AgCl electrode, the major process that occurs at the electrode-skin interface is a transformation of charge carriers between electrons and ions. And the transformation is governed by the reduction and oxidation chemical reaction [87], which can be described as follows:

$$\mathrm{Ag} \longleftrightarrow \mathrm{Ag}^+ + \mathrm{e}^- \quad (5)$$

$$\mathrm{Ag}^+ + \mathrm{Cl}^- \longleftrightarrow \mathrm{AgCl} \quad (6)$$

The electrodes with materials safety for human body are also recommended, such as carbon/graphite electrodes [57, 59]. The Pt electrodes were used in [39], since Pt electrode is commonly used for signal stimulation [88]. Some other electrodes, such as copper and aluminium, were utilized [54].

5.3. Grounding Strategies. The results of HBC theoretical models or analysis are required to be verified by *in vivo* or *in vitro* experiments, in which the measurement system generally includes the earth-grounded electrical devices such as signal generator, oscilloscope, network analyzer, and spectrum analyzer. More than one ground connection path between two pieces of equipment (such as signal generator at transmitter and oscilloscope at the receiver) leads to different places of "Ground" points that are expected to be at the same potential, but actually, they may have different potentials due to the nonzero impedance of the interconnected cables. The difference of system ground impedance makes the ground potential at the receiver input BNC connector not the same as the ground of the system or transmitter. This potential difference or unwanted ground path signal can range from microvolts to as high as hundreds of millivolts. This unwanted ground path signal generally exists in parallel with the true

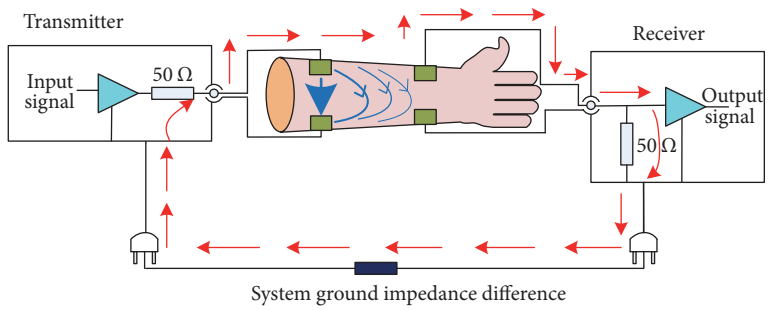
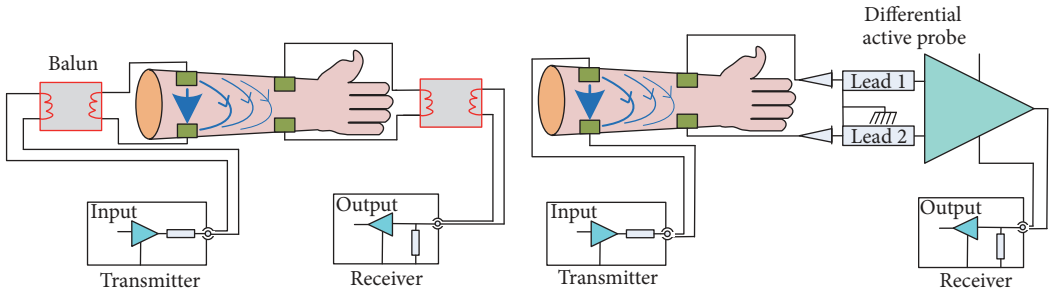


Figure 7: Grounding problems in HBC measurement system.



(a) With balun (b) With differential probe

Figure 8: Grounding strategy with balun transformer (a) or differential probe (b).

return ground path of HBC signal (note that this unwanted ground path signal does not exist in the real HBC system with independent battery-powered transceiver). Figure 7 illustrates the ground path signals of a typical galvanic coupling HBC measurement system. The receiver refers the measurement from the shell of the input BNC connector; the displayed waveform may not represent the real signal at the probe input, which may therefore cause incorrect measurement results at the receiver.

To minimize or reduce the unwanted ground path signal, suitable grounding strategies are required. Generally, the balun transformer or differential amplifier should be adopted. A typical measurement system with baluns at both transmitter and receiver for the galvanic coupling HBC is shown in Figure 8(a). In the measurement system with balun transformer, the reduction of unwanted ground path signal is influenced by the interwinding capacitance (IWC) between primary and secondary windings [34, 89, 90]. Lower IWC achieves lower measured results [89]. According to the recent investigations, the measured result is also influenced by the symmetry to ground of the balun transformer [91]. The typical measurement systems using balun are [54, 64]. A setup of the measurement system with differential probe is shown in Figure 8(b). The detected potential at the respective lead of differential probe refers to the same/common ground point, which eliminates the common-mode voltage picked up by the system ground impedance. By using the differential probe, which always contains a differential amplifier with several dB gain, satisfactory receiving performance will be obtained. Generally, differential probe is always utilized in galvanic coupling HBC system, such as [57, 59, 92].

6. Conclusions and Future Studies

The history and development of HBC have been reviewed in this paper. HBC is a short range non-RF wireless communication technique specified by the IEEE 802.15.6 using the human body as a transmission medium. In this work, we surveyed the current HBC coupling methods, various signal propagation models, and communication performance. Finally, the issues on *in vivo* experiment such as types of electrodes and grounding problems have been elaborated so that it can make the *in vivo* experiment safe and accurate.

From recent HBC systems, capacitive coupling HBC operates in higher frequency band, and, thus, higher data rate can be achieved. Galvanic coupling HBC operates in relatively lower frequency band and achieves lower data rate, but it has the advantages of minimizing the interference from the environment. The channel gain of HBC behaves as band-pass or high-pass in different frequency band, which indicates that a rule or guideline to select the suitable frequency band for data transmission requires to be proposed. As it stands, the HBC technique potentially offers a more power efficient and naturally secured communication method for BAN. The signal is mainly conveyed within the muscle tissue. Although HBC has many advantages, many challenges and future studies are still required to be addressed.

6.1. Channel Modelling. A suitable channel model considering the effects of joint (i.e., the structure and electrical properties of the joint) should be developed. Moreover, the change of joint angle leads to variation of channel gain; hence, developing a channel model that can cover the channel characteristics

in dynamic body behavior would be a good research topic. Also, suitable channel model should be developed for HBC channel with longer transmission distance (i.e., the whole upper limb, from left hand to right hand). Besides the on-body channels, channel model for the implantable data transmission should be a future research topic. Moreover, the HBC channel characteristics have been evaluated on the young subjects in the literature. However, the investigation on elder people has not yet been addressed. And designing the HBC system to satisfy all the individual channel property, such as the fat, thin, young, and elder subject's HBC channel is challenging. In addition, the signal propagation models are investigated in the single channel applications, such as ECG only or blood pressure only. However, how to apply the channel model in the multiple channel applications has not been discussed yet.

6.2. System Design. Considering the HBC system design, achieving the channel capacity is challenging. Even though the multicarrier system with optimal power allocation can achieve the capacity, the multicarrier system can lead to high peak-to-average power ratio. Therefore, it is preferable to develop the single carrier system for HBC applications. Then how to design a single carrier system to achieve channel capacity and satisfy the special requirements on applications (high QoS, low power consumption, and low hardware complexity) is a future research topic.

6.3. MAC Layer Design. To build a BAN, the point-to-point data transmission is the basis. The reality BAN is generally a point-to-multipoint topology. How to apply the results on HBC channel (point-to-point data transmission) to enable the point-to-multipoint performance analysis is a future research topic. Besides the physical layer design, the design of protocol in higher layers, that is, MAC layer, should be addressed. For the network issue, the security and power management are suggested to be studied.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Jian Feng Zhao conceived the study and helped to draft the manuscript and handled the acquisition of funding. Xi Mei Chen designed and carried out the experiments, analyzed the data, and drafted the manuscript. Bo Dong Liang helped to collect the data and draft the manuscript. Qiu Xia Chen helped to collect the data, handled the acquisition of funding, and justified the authorship. All authors have read and approved this manuscript.

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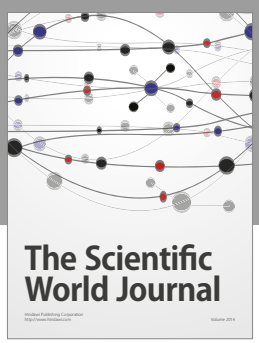

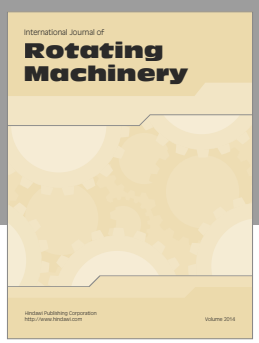

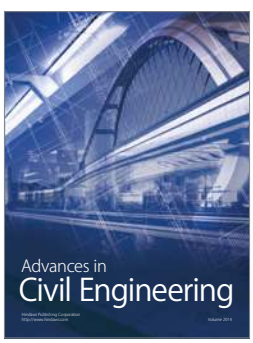

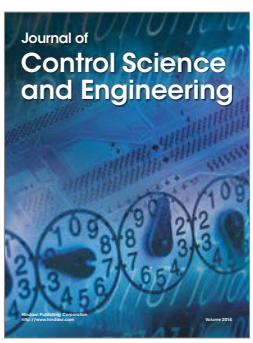

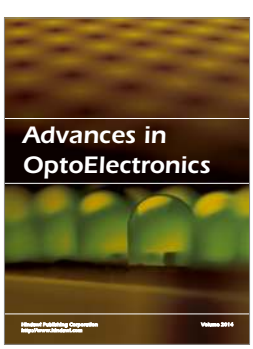

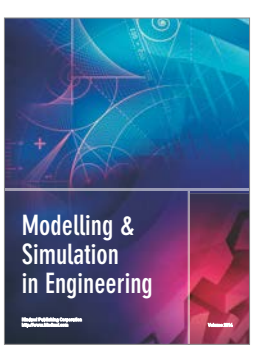

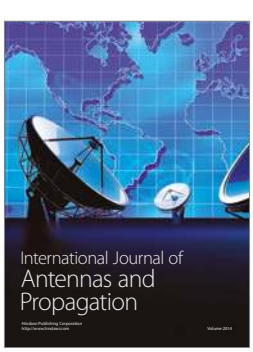

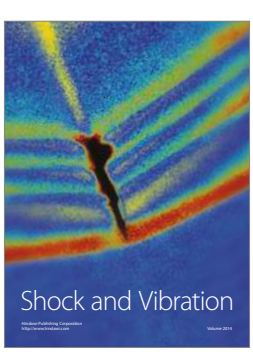

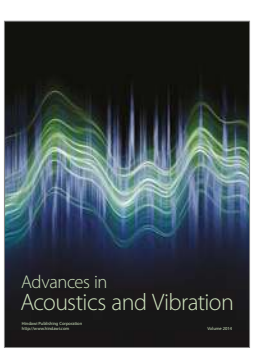

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