Journal of
Sensor and Actuator Networks

MDPI

Article

Moving Towards Body-to-Body Sensor Networks for Ubiquitous Applications: A Survey

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Received: 18 March 2019; Accepted: 30 April 2019; Published: 10 May 2019

Abstract: Thanks to their arising abilities to influence the human lifestyle, along with reducing the healthcare systems' cost, wireless body area networks (WBANs) still form a strongly growing research field. Recent advances focus on the opportunities of coexistence and communication between a group of WBANs, that will forward the sensing data, using persons as network relays, until reaching a remote analysis server or cloud servers via the Internet, forming thus a body-to-body network (BBN). Such new-style networks support a range of innovative and promising applications, including ubiquitous healthcare (U-health), interactive games, and military, to cite a few. In this paper, we first present the evolution of the single WBAN concept to the cooperative network of multiple WBANs, giving rise to the BBN concept. A synopsis of the WBAN and BBN respective standards and applications is given, and the emerging BBN challenges are highlighted. Then, we present and discuss the existing WBAN proposals, especially the candidate WBAN protocols that could be adapted and used in BBNs, focusing on four intrinsically related axes of great importance for BBN design: energy efficiency, *mobility prediction*, quality of service (QoS) and security. Further BBN open issues are also investigated, namely, the wireless propagation between humans carrying wearable devices, the interference, storage and privacy issues as well as the heterogeneity of BBN devices and traffic.

Keywords: WBAN; BBN; U-health; energy-efficiency; quality of service; mobility prediction; wireless channel; security; routing

1. Introduction

Due to the growing need of current internet of things (IoT) infrastructures, in terms of connectivity and network capacity, connected people have an aspiring potential to form an imminent access network that extends the IoT coverage, through achieving ubiquitous and real-time applications (healthcare, social interactions, sports and entertainment, etc.), thus ensuring anywhere and anytime people connectivity.

In this context, using network subscribers themselves as relays could complement and extend existing infrastructure networks, while improving network capacity and promoting radio spectrum usage. Indeed, each user will be equipped by a wireless body area network (WBAN), which is a wireless network of small computing devices. These sensor devices can be embedded inside the human body or under the skin, mounted on the body (wearable), or carried by humans as portable devices.

Around 1995, the idea of using wireless personal area networks (WPAN) as transmission technology among humans started, to enable communications on, around, and next to the human body [1,2]. Nowadays, WBANs have evolved into an interdisciplinary area that provides real-time healthcare services with reduced costs and ubiquitous medical records in the network servers. This area relies on the feasibility of fixing (implanting) very small biosensors on (inside) the human body that are comfortable and that do not impair normal activities. The biosensors are fixed or implanted on/inside the human body comfortably and without altering the normal activity of the individual. Then, sensors collect the human sensing information which allows us to monitor the health status of the patient whatever his location. The sensing data is transmitted over wireless links to a remote processing unit. In case of emergency threat, an alert is generated to prevent the patient and the medical staff. WBAN solutions have gradually developed over the last years through the implementation of novel WBAN-based applications, giving rise to body-to-body networks (BBNs) that we can characterize as a group of WBANs, interacting between them, so as to guarantee a range of services that satisfy genuine social advantages. Indeed, network operators, that are already planning for the IoT and cloud computing technologies integration, should also think about this new possibility of creating a new type of mobile ad hoc network, so that a radio device situated on one person gathers the sensor data from the sensor nodes worn by that person, and transmit them to a transceiver situated on another person in the nearby area, in order to be processed or relayed to other BBN users. Furthermore, the other motivation behind BBNs is to overcome the problems of coexistence and performance degradation of closely located WBANs, by involving them in mutual interactions and cooperation [3]. In this survey, we review and synthesize the relevant features of WBANs in order to exploit the opportunities of cooperation between them, forming a BBN. This survey is an exhaustive extension of our previous work done in [4].

WBAN issues have been tackled by a number of surveys that investigate the fundamental mechanisms of WBAN including architecture and topology, types of WBAN sensors, low-power medium access control (MAC), implant communication and routing protocols.

Authors in [5,6] discussed some solutions for WBANs at physical (PHY), MAC, and network layers. Power consumption of WBAN wireless transceivers and microprocessors was thoroughly discussed and investments in increasing sensor battery capacities were also explored [7], such as energy harvesting from ambient sources, sunlight or vibration.

WBAN antenna design is also a prominent issue that has been considered by several researchers. Some focused on the electrical properties of the body tissue and the in-body antenna design to meet the requirements of the MICS band (402-405 MHz) designated for in-body communications [8,9]. Others have been interested in the on-body antenna design [10,11] yielding channel models or scenario-based approaches, so that to enhance the average channel gain measured for each on-body link (head-to-belt, head-to-wrist, belt-to-wrist, etc.). Few works have been carried out to characterize the off-body [12–14] and body-to-body [15,16] channel models involving indoor and outdoor environments, body shadowing and human mobility, in the unlicensed industrial, scientific, and medical (ISM) band (2.45 GHz).

Others classified the WBAN technologies, with respect to the WBAN communication architecture, into three components: intra-WBAN, inter-WBAN and beyond-WBAN communications, and addressed the different issues related to each [6,17].

In most of the literature studies, WBAN applications were highlighted and classified into medical and non-medical [6,18,19], or in-body and on-body applications [5,9,19].

Furthermore, the growing trend of using humans as network relays gave rise to new concepts, such as the internet of everything and everybody [20], or the internet of people (IoP) [21], along with their related design requirements, especially the data handling and management in next generation internet (NGI). Indeed, such human-centric technology should involve additional data processing criteria to the NGI devices and protocols.

Recent works turned towards the integration issue of WBANs into the existing information technology infrastructures [22–26]. Indeed, according to the nature of WBAN services, which range from entertainment and gaming to high priority emergency traffic, the network resources should provide the ability to aggregate hierarchical information and priority-based data dissemination. Thus, a crucial collaboration between technology engineers and medicine experts to help defining the specifications and priorities of WBAN services, severely constrains the BBN opportunities.

Indeed, such a network presents several challenges like the problem of heterogeneous devices and traffic, interference and coexistence, wireless environment properties, etc. Among the more challenging issues in BBNs, we focus on four principal axes: the energy-efficiency, the quality-of-service (QoS), the human mobility prediction, and the data security.

Energy-efficiency: is one of the foremost challenges of BBNs. The energy efficiency consists of reducing the amount of energy required to provide the different services, so that frequent replacement of the batteries should be avoided, especially for implanted sensors [27]. In this paper, we study a number of works that propose solutions, protocols and mechanisms to reduce energy consumption. The main objective of these solutions is to increase the lifetime of the network and balance the energy consumption among WBANs/sensor nodes.

Quality-of-service (QoS): is the set of characteristics involved in a telecommunication service that ensure its ability to meet the user needs and requirements [28]. In this paper, we present a number of QoS-aware protocols that are in use today, and that compete in optimizing the whole network throughput, delay and traffic priority management, in order to ensure a better QoS in the WBAN communications.

Mobility prediction: in mobile scenarios, WBANs connectivity could be altered, and the whole network performance would degrade consequently [29]. If the WBAN mobility could be predicted prior to service breakdown, most of the link failures would be avoided, which could promote the quality of BBN applications. The mobility prediction mechanisms are crucial for the network layer to ensure reliable routing and for network resource allocation.

Security: security and privacy preoccupations are a hot topic for BBNs, due to the implication of human information. Indeed, biomedical sensors implanted in the human body for healthcare monitoring, will communicate with neighboring WBANs as well as with external networks; this increases the BBN security risk [30]. There are different studies that bring out the limitations of the current proposed security solutions that need, therefore, further research. In this survey we present and discuss different security solutions intended to be applied to some BBN applications.

A number of these issues has been considered in the literature, and synthesized by several surveys in order to discuss and compare them [19,31–34]. Namely, a recent survey [31] summarizes the WBAN routing protocols, while classifying them into posture-based, energy-efficient, QoS-based, mobility-based, etc., and highlighting the network design considerations provided by each. Besides, authors of [19] provide a comprehensive overview of the existing WBAN protocols covering the latest advances in architecture, energy, security and application aspects. Nevertheless, all of the aforementioned works provide WBAN solutions in the intra-WBAN context, either to optimize the energy consumption, to implement QoS-aware data management, to ensure secure transmissions, or to handle dynamic scenarios, in the communications between the body sensors and the sink, belonging to a single WBAN.

Few works tackled the body-to-body concept and investigate a single or limited design axes [3,15,16,35,36]. For example, real testbed-based experiments are conducted in [35] to explore the connectivity behavior in body-to-body communications under different network parameters (radio technology, interference conditions, mobility, data dissemination scheme, etc.). A body-to-body pointed study is also present in [3], especially a distributed routing protocol is introduced using an adaptive CSMA/CA cross-layer mechanism. Some other studies focused on the body-to-body channel characterization such as [15,16,36]. Even fewer works tackled the inter-WBAN coexistence issue [32,37–39], some of which are discussed in detail in this survey hereafter.

Yet, to the best of our knowledge, this survey is the first to synthesize the existing WBAN and BBN solutions to provide an overview of the candidate protocols that are suitable for BBN deployment, and to discuss the opportunities of their enhancement and adaptation to fit the BBN specific requirements. We would like to emphasize that all the previous issues, namely the energy, QoS, mobility and security design axes, will be carefully addressed and discussed in the tremendously challenging context of BBNs, and therefore our survey makes the big difference from all existing surveys on WBANs and co-existence of WBANs in the literature.

To summarize, the main contributions of this survey are twofold. One is to synthesize existing WBAN surveys in order to extract relevant techniques and protocols suitable for BBNs. More specifically, *the first goal* of our survey is to investigate the research trends in WBANs and draw the most suitable mechanisms for BBNs, which have additional particularities different from those of single WBANs. Indeed, it is generally presumed that a WBAN is not a dynamic network structure, sensor nodes are fixed on the human body, and intra-WBAN transmissions could be handled by time division multiple access (TDMA)-based MAC, for example [37]. However, in BBN context we would rather presume a dynamic structure where each WBAN member can join and leave the BBN network seamlessly, and without the need for any centralized infrastructure which would present additional constraints for inter-WBANs transmissions. Yet this survey differs from the existing WBAN surveys in underlying the latest and relevant results in this area and providing targeted requirements to pave the way for practical BBN use.

The second goal is to present and discuss some open issues, which are of significant concern for BBNs, keeping in mind the emergence of new paradigms, such as IoT and cloud computing. We focus on five pillar issues: (A) wireless channel propagation in indoor and outdoor environment, (B) interference and coexistence of WBANs, (C) storage and privacy of health data in IoT/Cloud environment, (D) heterogeneity of wireless devices and traffic and finally (E) the ethical issue.

This paper is organized in the following manner. In Section 2, we present the WBAN and BBN concepts. In Section 3, we discuss the BBN design considerations. In Section 4, we present a synthesis of the studied solutions and protocols, along with a discussion on several key open issues, and finally, Section 5 concludes the paper.

2. From WBANs to BBNs

Motivated by the emergence of remote healthcare solutions in developed countries, especially to support the ceaselessly increasing aged population and lower the cost of such services, WBANs are still a strong research focus, mainly with the development of the IEEE 802.15.6 standard. Yet, moving from single-operating WBANs towards a network of cooperative WBANs forming a large-scale BBN, is liable to several challenges, some of which will be addressed in this section.

2.1. Overview of WBAN

A WBAN is a wireless body area network composed of various types of sensors that monitor the body functions. These sensors could be fixed on the body or could be implanted under the skin. The implanted ones are comfortable and do not disturb normal activities. Figure 1 illustrates an example of a patient monitoring system using a WBAN.

The main tasks of the sensor nodes are to collect body activity information and to forward them to remote servers for analysis. Actuator sensors could also process the collected data and perform subsequently. A WBAN allows continuous health monitoring in real time and we can access to the medical records remotely. If an emergency is detected we can immediately inform the patient/the medical staff by sending messages or alarms.

2.1.1. Architecture

In [40], communication devices in a hospital are classified into three categories, defining three communication models. In communication tier 1, each sensor node of the WBAN collects data and sends them to the WBAN Coordinator. In communication tier 2, the WBAN forwards data for a next hop, which can be a WBAN, a medical display coordinator, a nursing station coordinator, or a cellular device. Finally, communication tier 2 forwards to tier 3 communication devices which can be a 3G tower, a nurse device, an application server, or any cloud servers through the Internet. Other taxonomy used for WBAN architecture talks about intra-WBAN, extra-WBAN and beyond-WBAN communications to designate almost the same communication models.

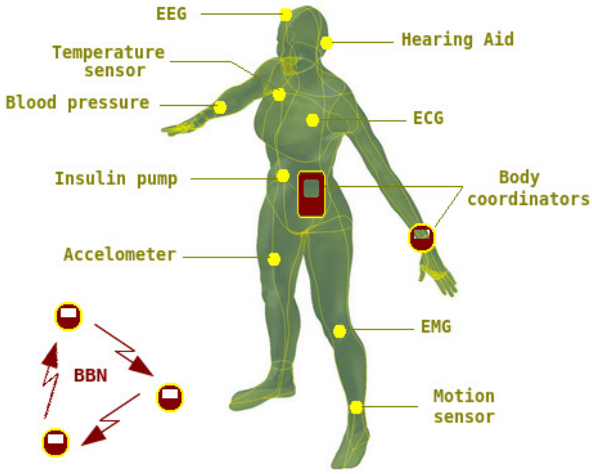


Figure 1. Example of a patient monitoring using a wireless body area network (WBAN).

2.1.2. Standards

There are different standards that are used in WBANs in order to permit the communications between the different sensor nodes and between the WBAN coordinator and external devices. The most known and used standard in the industry is IEEE 802.15.6 [41,42], which is a low-power wireless technology intended for short-range transmissions of WBANs, with around 10 Mbps of data rates. This standard provides capabilities to reduce the signal radiation absorption rate (SAR), caused by body movements. Then, IEEE 802.15.4 (ZigBee) [43] is a well-known standard for WBANs, that deals with the interconnection of low-data rate communication devices, with low-power and long battery life, which could provide low-complexity short-range radio frequency (RF) transmissions. Furthermore, other standards are also used in WBANs, like the Bluetooth Low Energy (BLE) standard [44], that operates on center frequencies that allows it to reduce the overlapping with channels 1, 6 and 11 of the IEEE 802.11 standard, and thus mitigate interference with them.

2.1.3. Applications

WBAN applications are classified according to their area of use. In the following, we present the major categories [42].

- Medical treatment and diagnosis: there are several cases of WBAN use in diagnostic and treatment of diseases, and many researches are conducted in this field. Use case example: cardio–vascular disease (CVD), diabetes, asthma, Parkinson's disease, etc.
- Training schedules of professional athletes: through the use of equipments helping athletes in training and monitoring of the progress and advancement of their performances.
- Public safety and prevention of medical accidents: a large number of people dies every year due to medical accidents, then, using a sensor node to maintain a log of previous medical accidents can reduce the number of deaths.
- Safeguarding of uniformed personnel: WBAN can be used by firefighters, policeman or military to keep them monitored in hazardous environments. For example, in the case of firefighters involved in stopping a fire, the WBAN can detect the existence of a dangerous gas and its level in the air, and relay this information to these team members.
- Consumer electronics and entertainment: some WBAN devices can be integrated in electronic equipments, head-mounted displays, microphone, camera, etc.

2.2. Body-to-Body Network Concept

A BBN is a set of WBANs that communicate with their neighboring WBANs, through the coordinator device, which plays the role of a gateway sharing the sensor data among the WBANs. Then, a BBN is theoretically a mobile ad hoc network that uses humans to transmit data within a bounded geographic zone. Thus, the wireless signal keeps transmitting from one WBAN to the nearest WBAN, using BBN-enabled Smartphones or Smartwatches, and so on until reaching the destination.

The BBN is an emerging solution for communication between patients and the medical staff, and exchange of data between WBANs, which provides the possibility to share data in order to perform estimation, statistics or just route to a given destination. A BBN network for the monitoring of a group of cyclists is depicted by Figure 2.

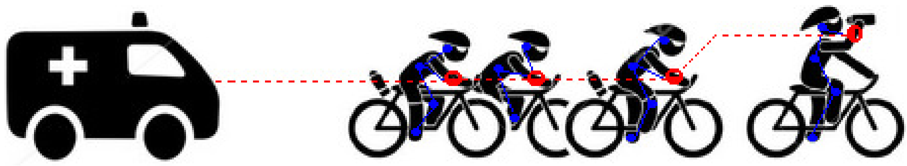


Figure 2. Body-to-body network for the performance monitoring of a group of athletes © [2019] IEEE. Reprinted, with permission, from [4].

In a BBN, all users should cooperate and contribute of their network resources to relay data to the other network users, creating thus vast cooperative body-to body communications, for the great benefit of the network. In densely populated areas, a BBN could allow cellular providers to truly achieve "anytime and anywhere" connectivity and gigabit data rates, especially with the emergence of the IoT, giving rise to real-time applications with growing demands on data rates. For example, authors of [45] investigate IoT-based approaches to enable smart healthcare solutions, redesigning modern healthcare by using WBANs with technological, economic, and social prospects. A Health-IoT ecosystem is also formulated in [23] within a healthcare-based cloud, accessed by remote patients through an in-home healthcare station (IHHS). In a more recent study [46], an energy-efficient body-to-body communication was implemented for cloud-assisted WBANs to relay the patients' sensor data to the nearest APs in order to access the cloud resources. Indeed, the link quality between WBANs and APs deteriorates as the distance increase. Thus, body-to-body communications are necessary to maintain the connectivity and increase the data transmission rate in such situations.

Alike the single WBAN, a BBN uses different communication standards such as 802.15.4 (Zigbee), 802.15.6, 802.15.1 (Bluetooth), 802.11 (WiFi) or 4G. Moreover, the emerging Long Range (Lora) technology [47] could be involved in the BBN space. Especially, LoraWAN is a low cost communication protocol based on chirp spread spectrum (CSS) modulation, to keep the power level characteristics, instead of the frequency shifting keying (FSK) modulation which commonly increases the communication range. LoraWAN is projected to support billions of IoT devices, and BBN could be considered as one of the promising solutions to be integrated to such systems in order to extend and enhance the connectivity of the IoT-based health services.

2.3. BBN Challenges

Compared to single WBANs, BBNs present further challenging features. First, the energy problem become more constraining when the WBAN coordinator plays also the role of a gateway that transmits the sensing data to the neighboring WBANs within the BBN. Furthermore, the aforementioned standards used for BBN communications are not optimal and do not provide a secure communication. Thus, implementing a security system that helps to protect and limit the access to the data transmitted between the WBAN and the destination is necessary. Indeed, people may consider BBNs as a threat on their personal data and their own privacy, their approval is the key of the achievement of BBNs. Then, a third issue consists of the routing of sensor data while supporting WBANs mobility and ensuring

QoS considerations. Finally, all data aggregated by the WBANs coordinators should be collected and processed seamlessly, without affecting the activity of the person. Patient records may be fragmented and transmitted through different nodes without any effort or knowledge from the person.

2.4. BBN Applications

BBNs are intended for providing genuine social advantages, for example, remote medicinal services, monitoring of sport teams, accuracy communications of rescue teams in hazardous situations or soldiers on a battlefield, and so on. Indeed, a BBN can be deployed either for medical or non-medical applications. The novel trend of medical systems relies on ubiquitous healthcare services, and could be ensured by BBNs through the remote monitoring of patients relaying each other's physiological data collected by their own body-carried sensors, until the medical central unit. This will make the government's aim of ubiquitous and low-cost healthcare services come true. By embedding tiny sensors into clothes, vehicles, portable devices, glasses or helmets, people no longer need to be in the range of the cellular network to communicate or send data, in addition to the environment and health benefits that could be afforded by such low-power network.

Figure 3 sorts the different WBAN and BBN applications into medical and non-medical. We just describe some medical BBN scenarios, for example to ensure remote health monitoring out of the 3G/4G coverage area, this could apply to track the vital signs of a rescue team in a disaster area or a group of soldiers in a battlefield. Also, for remote or disabled people, it will be possible to alert his neighbors and broadcast a call for help in an urgent situation. In [48], we proposed a BBN-based epidemic control framework, in mass gathering areas, that differentiates WBANs traffic and ensures real-time quarantine strategies in response to epidemic outbreaks in contaminated areas.

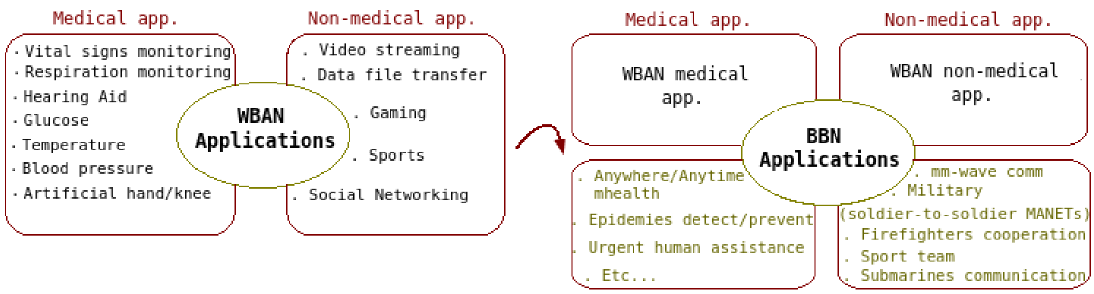


Figure 3. Application area extension from WBAN to body-to-body networks (BBN).

3. BBN Design Considerations

The design of new mechanisms for BBNs is subject to a number of challenges. Actually, few WBAN-based techniques could apply to BBNs, unless some specific customization and adaptation are made. In this section, we investigate some WBAN solutions, proposed in the literature, and we discuss their suitability to BBN scenarios. We mainly focus on four interrelated axes: energy efficiency, QoS, mobility management and security.

3.1. Energy-Efficiency for BBN

WBAN energy constraints have been long discussed in the literature. Naturally, if WBANs are energy-constrained, BBNs are more so. Indeed, the communication and sharing of sensor data among coexisting WBANs, will give rise to further energy consumption.

Authors of [49] presented a comparative study of existing WBAN routing protocols for healthcare. The studied scenario consists of a ZigBee network having static IEEE 802.15.4 star topology, taking into account the energy consumption as well as the following QoS metrics: the average end-to-end delay, the throughput, the jitter and the packet delivery rate. The simulation of the ad hoc on demand distance vector (AODV) protocol testifies higher throughput, minimum jitter and reduced delay, in both mobile and stationary situations of WBANs. AODV is then enhanced to an energy-aware

AODV protocol (EAAODV), that builds routes on-demand by flooding route request (RREQ) packets. EEAODV routing relies on mobility metrics and the remaining energy to select the next WBAN as forwarder of the RREQ. In fact, each sensor node defines energy and mobility thresholds and selects the next hop sensor with maximum residual energy and minimum mobility.

EAAODV outperforms AODV in terms of energy consumption, and then could provide an appropriate routing for the energy-constrained network of multiple WBANs. Thus, EAAODV is a candidate routing protocol for BBNs.

Authors of [50] propose a mobility-supporting adaptive threshold-based thermal-aware energy-efficient multi-hop protocol (M-ATTEMPT) for WBANs, with a prototype using heterogeneous sensors on a single WBAN. An M-ATTEMPT protocol enables a direct link between the sensors and the sink for both real-time and on-demand data, and a multi-hop transmission for normal data. Multi-hop strategy preserves energy consumption, since less energy is required for routing through short distances. The thermal-aware algorithm includes mobility support and energy management. Indeed, it detects link hotspots of implanted sensors and avoids them while transmitting to help them save energy. In addition, the algorithm detects patient mobility and deals efficiently with links disconnections. For normal data, M-ATTEMPT protocol implements a TDMA schedule so that the sensor nodes could transmit data to the sink during the allocated time slots. In case of WBAN mobility, extra energy is used by sensors to maintain the connectivity.

The M-ATTEMPT protocol performs for intra-WBAN communication to ensure energy and QoS-aware routing. In BBN context, M-ATTEMPT could be adapted to transmit data between sinks, provided that the traffic data classes and the scheduling scheme would be customized for BBN use. Furthermore, M-ATTEMPT should implement a mobility management process to support inter-WBANs communications in dynamic scenarios. Indeed, the major limitation of this protocol consists of the disconnections caused by sensors mobility that requires restructuring of the WBAN tree topology.

A stable increased-throughput multi-hop protocol for link efficiency (SIMPLE) routing protocol was proposed in [51] for intra-WBAN communications. It optimizes the energy-consumption, reliability and throughput of multi-hop communications between sensor nodes and the sink, in comparison to M-ATTEMPT. This protocol provides better stability of the intra-WBAN communications for a long time and under a high speed of the WBAN. It could be extended to apply to BBN communications with further QoS considerations, where each WBAN sink would represent either the parent or the forwarder for the inter-WBANs routing. Nevertheless, for the transmission and reception, the authors have chosen the radio model of Heinzelman [52], where d is the separation between the transmitter and the receiver, and d^2 models the energy waste due to the transmission channel, corresponding to the free space path loss, which is actually very specific and not suitable for WBANs/BBNs. Instead, the wireless channel propagation between distant WBANs is discussed in Section 4.1 and a BBN path loss model is reported.

In [53], authors presented a low overhead tree-based energy-efficient routing scheme (EERS) with a multi-hop routing and low overhead in WBANs based on the collection tree protocol (CTP), considering adaptive power control to save energy and keep sensor node for a long time. Upon simulations, authors conclude that EERS outperforms CTP with 30% lower delay, 10% lower energy consumption and reaching 0.95 of packet reception rate (PRR).

The EERS routing protocol is proposed for intra-WBAN multi-hop communications, it ensures a good balance of QoS (reliability, delay) and energy parameters. It could be extended to a BBN routing protocol, with adding a mobility management/prediction module and more detailed data traffic classification.

Further detailed expressions of the WBAN power consumption are provided in other works. For example, authors of [54] formulate the energy consumed by a sensor node as an equation of the different energy components corresponding to each task performed by the sensor in the transmission process. The main advantages of this model are:

- Generic: it does not depend on the type of MAC protocol and thus, it could be used in a heterogeneous WBAN network, like a BBN scenario.
- Expanded: each energy component appears clearly in the model and could be optimized to minimize the total energy consumed by a sensor node.

However, this model did not take into account the topology constraints and the routing task, and their corresponding energy. Our previous work [55] deals with the topology problem and provides an energy-aware topology design for wireless body area networks (EAWD) that minimizes the number of relay nodes and the total energy consumption. Furthermore, the EAWD model explicitly formulates each energy component by displaying both circuitry and amplifier dissipated energy. The transmission process is split into three instances: (i) sensors transmitting to relays, (ii) relays forwarding to relays and (iii) relays forwarding to sinks. The same for the reception process: (i) relays receiving from sensors, (ii) relays receiving from relays and (iii) sinks receiving from relays.

Thereby, EAWD provides more accurate transmission and reception energy values in accordance with topology features, together with sensor roles (node, relay or sink). This is a foremost of EAWD that could apply to BBN context. Then, in the BBN energy profile, sinks should indicate the energy consumed for transmission and reception with the other sinks of the network. Also, two further node roles could be specified in a BBN context, namely: sinks forwarding to sinks and sinks receiving from sinks. Nonetheless, EAWD lacks some important components that were considered in [53], namely the retransmission energy, the MAC access energy and the signaling energy.

In a more recent study [56], a cross-layer design optimal (CLDO) scheme optimizes the transmission power balance, among the WBAN nodes, through the use of a relay selection algorithm which relies on two interdependent parameters: the residual energy and the size of the transmitted data packet. However most of CLDO simulations were run with a fixed WBAN topology; just slight body movements have been simulated, at the end, to study the transmission reliability in the presence of body disturbances. Therefore, extensive performance evaluation of CLDO scheme, in dynamic scenarios, is needed to conclude about its suitability for use in BBNs.

A similar cross-layer protocol, the autocorrelation-based adaptive transmission (AAT), is proposed in [57]. The main advantage of AAT is the use of adaptive power control, which is the current trend in energy-efficiency research. Therefore, the AAT scheme was proved to ensure a good trade-off between transmission reliability, energy consumption and network delay, in terms of which it outperforms CLDO. Indeed, compared to AAT, CLDO introduces additional delay due to the complexity of its energy theoretical analysis. The second advantage of AAT protocol is the channel state estimation, which makes it possible to handle real WBAN scenarios, taking into account the human body movement and the WBAN topology changes. However only two-hop star topology is considered. The off-body link is not in the scope of AAT protocol. Then, despite its good achievement, AAT is restricted to intra-WBAN communications.

Another energy key feature is the duty cycle, implemented in [58] for WBANs. The duty cycle minimizes the amount of extra overhead, by removing the need of idle listening for clear channel, using the TDMA MAC protocol in such a way to reduce communication time relatively to power down time, and this is the major benefit of the duty cycle. However, its major limitation is the assumption of WBAN static topology, which leads to a second assumption, i.e., the synchronization can be simplified since the WBAN has almost fixed topology and the same sensor functions. Although the duty cycle mechanism could be beneficial for BBN use, by reducing the traffic overhead while routing sensor data among WBANs, the static topology assumption does not outfit the dynamic nature of BBNs.

Table 1 recapitulates the salient features of the aforementioned energy-aware protocols for intra-WBANs communications.

Table 1. Energy-aware candidate protocols for body-to-body networks (BBNs). © [2019] IEEE. Reprinted and modified, with permission, from [4].

Protocol	Layer	Topology	Advantages	Limitations
EAAODV [49]	Network	Single-hop	On-demand Routing Mobility management	Results only for ZigBee MAC Model.
M-ATTEMPT [50]	Network	Single-hop/ Multi-hop	Mobility management Traffic priorities Intra-WBAN routing	Disconnection during sensor node mobility
SIMPLE [51]	Network	Multi-hop	Reliability, High throughput On-demand intra-WBAN routing	No mechanism to handle mobility
EERS [53]	Network	Multi-hop	Joint Routing and Adaptive power control. Low overhead. Prolong the lifetime of the overall network.	Only focus on the data transmission energy. Sensing and reception energy are assumed constant.
EAWD [55]	Network	Multi-hop	Topology-aware energy-efficiency. Minimizing the number of relay nodes. Minimizing the energy consumption. Generic (separate energy components).	Absence of retransmission energy, MAC access energy and signaling energy components.
CLDO [56]	MAC PHY	Multi-hop	Transmission reliability Energy efficiency with suitable packet size Prolong WBAN lifetime.	Do not handle topology changes.
AAT [57]	MAC PHY	Two-hop	Adaptive power control Channel link estimation Transmission reliability Reduced delay.	Handle only two-hop topology relaying.
Duty-cycle [58]	MAC	Single-hop	Guard time: no overlaps, data reliability. Reduce idle listening. TDMA synchronization.	Hardware dependent.

3.2. QoS-Aware Traffic Management for BBN

The applications targeted by the design of the BBN should benefit from high quality communications, that should be ensured by a QoS-aware inter-WBAN routing protocol. Such protocol should then fulfill stringent QoS requirements by defining an application-dependent QoS-aware routing metrics.

The Qos-aware peering routing protocol for reliability (QPRR) is proposed in [59]. QPRR uses end-to-end QoS and redundant paths to ensure reliability in the WBAN. Authors showed, by simulating real hospital scenarios, that QPRR performs effectively for both stationary and mobile patients. They classified the devices used in WBAN communications into three energy-based classes: Nursing Station Coordinator (NSC), which is directly connected to the power source, medical display coordinator (MDC), which uses replaceable batteries, and WBAN coordinator, which has limited energy availability.

The simulations of QPRR protocol verify successful transmission rate, reduced traffic load, energy consumption and latency. The QPRR reliability is above 88% for low density stationary WBANs and 75% for mobile WBANs. The scalability is also ensured for a large number of nodes and the reliability is above 74%. However, QPRR is an infrastructure-based network, which is a major limitation in a BBN distributed system where WBANs play independently the role of sources and destinations. Besides, neither bandwidth consideration is made in the route selection, nor fault detection. Indeed, the reliability of the WBAN link with his neighbor is evaluated upon receipt of transmission acknowledgments, the protocol is unable to detect congestion or predict link disconnections.

In a subsequent study [40], the same authors improved the QPRR protocol by adding a delay module and implementing an enhanced version of the protocol referred as ZEQoS, which integrates energy and QoS-aware modules. The targeted application of the new protocol is the hospital indoor service and the WBAN sensor data is classified into : ordinary packets (OPs), delay-sensitive packets (DSPs) and reliability-sensitive packets (RSPs). The path selection mechanism of ZEQoS improves the throughput for all data types, since it calculates the communication costs of all possible paths and selects the best path that fulfills the QoS demands. ZEQoS also provides good achievements of throughput, with reduced overhead and packet loss than comparable protocols, namely the Data-centric multiobjective QoS-aware routing protocol (DMQoS) [60].

Despite the QoS considerations, no energy and no mobility management are involved in ZEQoS; only static topology is assumed and the overlapping issue is tackled for fixed WBANs. The model could be extended to a BBN scenario to minimize the interference between neighboring WBANs, with more specific investigations, especially with traffic priorities compliant to the BBN application. For instance, military QoS is different from sport team QoS, and QoS mapping schemes are needed in case of heterogeneous BBN scenarios, where WBANs could use different transmission technologies.

It is worth to cite another recent work [61] that focuses on the delay as the ultimate QoS parameter to optimize. Authors propose a lightweight routing protocol for dynamic (LRPD) topology changes in WBANs. The sensor data are also classified according to delay priorities, into general packets (GP) and delay-sensitive packets (DP). The typical feature of LRPD is the decomposition of the total delay into the different delay components throughout the whole transmission process, i..e, queuing, transmission, propagation and procession delays are calculated and minimized consecutively. However, the major drawback of LRPD is the increased energy consumption due to the minimum hop routing used to forward DP packets.

QoS parameters (throughput, delay and priority) have also been used in [62] as a utility function in a game-theoretical approach to resolve the overlapping issue of WBANs that coexist in a limited geographic area. Each player submit its own QoS requirements within the contention free period. A Cournot model was then proposed to share fairly the network resources between the WBAN players. The WBAN traffic priorities are reported by Figure 4. Upon simulations, it was observed that the utility function of the WBAN player increases proportionally to the throughput and conversely to the delay, in accordance with the Cournot model.

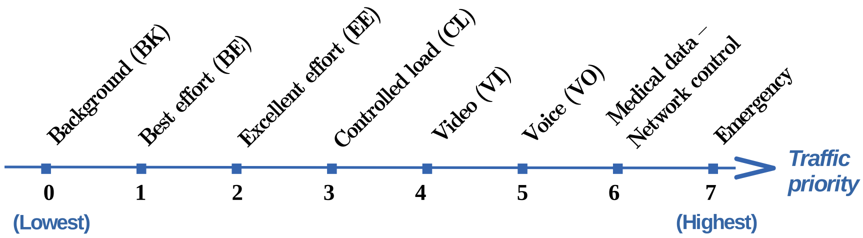


Figure 4. WBAN traffic priorities according to [62].

In [63], authors proposed a multi-constrained MAC protocol (McMAC) with energy-aware QoS provisioning that supports WBANs heterogeneous traffic. Delay and reliability are considered as the most important QoS metrics in a WBAN. McMAC classifies the intra-WBAN traffic into five classes, based on the delay and the reliability: emergency traffic with hard QoS constraints (life-critical situations), soft QoS traffic with acceptable reliability and delay (electrocardiogram for example), high reliability traffic with no delay constraint (respiration monitoring), high delay traffic with no reliability constraint (telemedicine video streaming applications), and finally non-constrained traffic like the human physiological information (temperature, respiration rate, etc.).

The McMAC protocol introduces the "transmit-whenever-appropriate" superframe structure, a novel superframe structure based on principle which guarantees multi-constrained QoS. Either in the contention access period or contention-free period, the WBAN nodes and coordinator handle the emergency packets and ensure an energy-efficient delivery with minimum delay and maximum reliability. Only single-hop transmissions are performed by McMAC, which is almost enough for intra-WBAN communications, but multi-hop is necessary for inter-WBANs scenarios in BBNs.

The problem of single-hop and minimum hop encountered in LRPD and McMAC, was resolved by [64], using the two-hop extension of the IEEE 802.15.6 standard. Then, a QoS control scheme in a multi-hop WBAN is proposed to optimize the energy efficiency, the packet delivery failure ratio (PDFR) and the number of transmissions instead of the delay.

The solution in [65] consists of a random contention based resource allocation (RACOON) protocol that ensures QoS for multiple WBANs with mobility management. RACOON is a bandwidth control mechanism integrated into a MAC layer. To ensure the multi-WBAN QoS, RACOON has two major features. First, it utilizes a centralized control scheme, by the central processing node (CPN), to minimize energy consumption of WBANs, to prevent inter-WBAN interference and packet collisions. RACOON also implements a probing-based inter-WBAN interference detection scheme to decrease energy waste in the WBANs, which simplifies QoS controls. To this end, RACOON uses two channels: one is intended to negotiate the sharing of network resources, the other is for the transmission of polling messages and sensing data between the sensors and CPN. Second, RACOON implements an iterative bandwidth control mechanism with respect to users' priorities, so that high priority WBANs get better bandwidth than low priority WBANs.

The main advantage of the RACOON protocol is that it considers a multi-WBAN design, with inter-WBAN interference and inter-WBAN priorities considerations, based on polling messages. Moreover, RACOON deals with WBANs mobility, collisions and the energy waste that may result. This could be a promising protocol for BBNs to define each WBAN priority with respect to his energy and service requirements. Nevertheless, RACOON should support inter-WBANs communications and the related specific QoS and mobility requirements to apply to BBNs. A comparison of the aforementioned protocols is given by Figure 5.

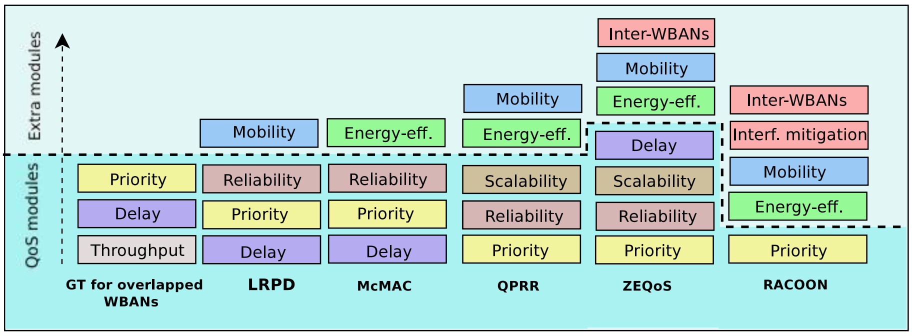


Figure 5. Quality-of-service (QoS) modules of WBAN QoS protocols suitable for future BBNs. © [2019] IEEE. Reprinted and modified, with permission, from [4].

3.3. Mobility Management for BBN

If accurate mobility management is crucial for mobile networks, it is more so for BBNs, especially to handle the ubiquitous service-oriented applications. For example, vital medical data should be routed seamlessly among mobile WBANs, without being affected by links disconnections, apart from the other critical tasks related to healthcare as well as other BBN ubiquitous applications.

Mobility management is mandatory in a dynamic environment, such as BBNs, where the network topology is changing in a regular or irregular basis, and the mobility of coexisting WBANs could impact the performance of a WBAN of interest. Several works have investigated the mobility prediction for mobile networks [66–71].

In the absence of previous works on mobility management and prediction for BBN scenarios, we review in this section the most relevant studies undertaken for WBANs and mobile ad hoc networks, with consideration of specific constraints of BBNs, since they have several aspects in common. In [66], we find a threefold classification of the mobility prediction methods according to the movement history, the physical topology and the logical topology. These methods are detailed and compared in Table 2, with their possible application in BBNs.

An optimized handover mechanism for WBANs, based on mobility prediction, is proposed in [67], using stable routes and a hop-by-hop strategy to reach the sink in dynamic scenarios.

Authors of [68] implemented a prediction-based secure and reliable routing framework (PSR) that relies on the regular aspects of body movements in some physical activities (jogging, swimming, etc.), which may guarantee the link quality and predict topological changes.

A WBAN-based heart monitoring application is implemented in [69], using a novel mobility handling routing protocol (MHRP). The WBAN topology considered by authors is somehow special, where a backup group of nodes composed of one sink, two relays and one acquisition node is placed symmetrically to another identical group of nodes, on the same WBAN. The redundant group of nodes would handle the data transmission and ensure reliability in case of link failures due to body movements. The major disadvantage of this solution is the discomfort inflicted to the human body, apart from the installation cost of such double infrastructure. A preferable alternative to deal with node's mobility could be found in [72], where a mobility-based temperature-aware routing protocol (MTR) is proposed. Indeed, in the WBAN topology, the nodes are classified into static and dynamic nodes, with respect to their location on the human body. Thus, the sensor data of dynamic nodes are saved in the node cache, for a prospective retransmission in case of link failure due to the node movement.

Table 2. Comparative study of mobility prediction methods for BBNs. © [2019] IEEE. Reprinted, with permission, from [4].

Category	Advantages	Disadvantages	BBN Application
Movement History-Based Mobility Prediction			
	Exploit the regularity in human movement behavior within a defined period of time.	Unpredictable changes in user's behavior. Limited feasibility for supporting high quality services.	U-health monitoring for some sports/Athletes
Physical Topology-Based Mobility Prediction			
Link expiration time estimation	Estimate the expiration time of the wireless link. Routes are reconfigured before disconnecting.	Support simple mobility pattern, no sudden changes in velocity and moving directions	U-health in indoor environments (hospital, rest home)
Link availability estimation	Immediate rerouting in link failure case. Select more reliable neighbors to form more stable clusters.	Difficulties in learning the changes in link status due to nodes movements. In highly volatile environments, increase of the control overhead.	U-health in accidents and emergencies. (Patient transportation, sharing emergency information, and vital signs monitoring.)
Group mobility and network partition prediction	Prevent disruptions caused by the network partitioning. Low-complexity clustering algorithm accurately determines the mobility groups and their mobility	Assume that the velocity of the mobile group of nodes is invariant over time. Non realistic assumption.	U-Health for a rescue team in a disaster area
Cluster change based prediction	The mobile node position and the direction of its movement in the cluster are used to predict future cluster switching.	This prediction process needs an accurate location. The use of GPS is needed to locate the mobile nodes.	U-health monitoring of a group of soldiers. The position and mobility of each soldier are function of those of his neighbors.
Logical Topology-Based Mobility Prediction			
Neighboring Nodes Relative Mobility Based Prediction	Based on past measurements. A linear model is implemented by mobile nodes to estimate the distance from their next cluster head (CH).	Do not consider node mobility during CH election.	U-health in indoor environments (hospitals), or u-health monitoring of a sport team or a rescue team in outdoor/indoor environment.
Information theory based mobility prediction	Assume virtual clusters, no fixed geographical area. Online learning to predict the next cluster.	Recurrent CH switching due to node mobility. Node's mobility is deduced from the frequency of its neighborhood changeability over time.	U-health in indoor environments, or U-health monitoring of a sport team or a rescue team in a limited geographical area.
Evidence based mobility prediction	No GPS use is required. Accurate prediction of the user trajectory. The distance between mobile nodes is estimated by the signal strength. Applied to the Zone Routing Protocol.	Only applied by the border nodes to predict the next cluster.	Feasible in outdoor environments, for U-health monitoring of freely moving patients or any group of persons in an outdoor/indoor environment.

The study in [70] analyzes two prerequisites of mobility support in WBANs. First, the location independence, which consists of decoupling the different TDMA transmission phases. This would let a subset of WBAN coordinators or BBN routers transmit acknowledgments so that biological sensors or mobile WBANs are not constrained to be in the proximity of a specific receiving coordinator or router for an acknowledgment. The second requirement is the clock drifting resilience which emerges in large-scale networks with random mobility, namely BBNs. In such networks, critical protocol timing needs increased clock drifting resilience.

Yet, the two requirements are applicable to BBNs to ensure quite high mobility of patients in both indoor and outdoor environments. The number of acknowledgments (ACKs) in the location independence process should be customized according to the BBN application and the different WBANs' QoS demands. Clock drifting is also needed in large scale BBN scenarios.

An extensive WBAN mobility model (MoBAN) is presented in [71], to deal with intra and extra-WBAN communications, for different WBAN and individual node postures. Extra-WBAN protocols take care of communications between a WBAN and its environment, with potentially several WBANs as well as an ambient network. The mobility prediction is based on a Markov model. The local motions of sensor nodes are defined by the individual posture, and the whole WBAN mobility by global WBAN posture, in order to plot the connections of the sensor nodes with each other and the WBAN with the surrounding environment. Authors use a one-level Markov template to model random posture patterns, in any location. As an example, different rooms in a building can be thought of as having statistically different posture patterns. The posture pattern in a bedroom is surely different from the pattern in the living room or the kitchen. The great benefit of MoBAN is the support of extra-WBAN mobility. Since BBNs are intensively affected by WBAN's movements, MoBAN could be a good candidate to provide mobility information that could be used as a routing parameter for BBNs, and according to WBANs specific needs/applications, this information could represent a mobility prediction parameter.

In addition to the topology changes and/or mobile WBAN location considerations, that are usually made in reactive routing schemes, accurate mobility prediction methods should be adapted to anticipate the route reconstruction before that topology changes occur. Then genuine ubiquitous BBN applications could be fulfilled with high link quality and reliable data delivery.

3.4. Security Policies for BBN

Given their restricted resources, especially in terms of energy supply, often body sensors are vulnerable to data injection attacks, that aim to consume the resources of a target WBAN by flooding its nodes with false data. Especially, when a WBAN roams from one BBN to another, a handover mechanism takes place increasing the risk of the physical capture of the WBAN. Thus, mostly invasive attacks happen during the mobility of WBANs beyond the BBN borders or APs' coverage zone. Yet, issues related to security must be investigated in BBNs, and security schemes should be designed in accordance with the intended applications and their possible threats. In a U-healthcare context, holistic security scheme is, above all, a mandatory requirement for U-health BBN application design, since human lives are definitely at stake. Privacy measures, as well as intrusion detection mechanisms, are mandatory in such networks. Therefore, through the implementation of tough data encryption and constant network monitoring, WBANs could preserve their own privacy.

Very few works investigate the security issue in BBNs, such as [73], where a chaotic compressive sensing (CCS) is implemented to solve three major issues in BBNs: storage space, energy saving and data security. Chaotic compression is intended, specially, to encrypt images, as it is a highly recommended function of BBNs, in order to report real-time situations in remote healthcare, rescue or military applications.

In [74] the authors proposed a hybrid security solution based on preloaded keys and biometric-generated keys. It provides an efficient solution for intra-WBAN and inter-WBAN communications:

- Intra-WBAN: the sensors measure physiological values (PVs) of the human body and then the keys are generated using those PVs to secure communications.
- Inter-WBAN: preloaded keys are used. The technique is memory-saving since it combines auto-generation and preloading key to enhance security. Any personal server (PS) can use biometric information to generate a key pool that it shares to the WBANs. The medical server (MS) assigns the responsibility of refreshing the key to any PS generator.

This hybrid solution averts from different attacks like outsider attack, PS compromise, sensor node compromise, etc., and ensures the confidentiality, authentication and integrity of WBAN communications. Such a solution could be useful for a BBN scenario, since it considers the inter-WBAN communications, which include the communication among the PSs to deal with situations when a PS is out of range of the MS. However, this hybrid security mechanism does not consider dynamic scenarios where WBANs are mobile and, thus, could encounter further security threats, due to their position changes.

Yet, authors of [75] proposed a cluster-based security mechanism for intra and inter-WBAN communications in a healthcare context. It takes into consideration the mobility of WBANs to the extent that it implements a WBAN neighborhood discovery mechanism, re-clustering in case of cluster head leaving or new arrival WBAN configuration, and WBAN addition or eviction. The proposed security mechanism consists of an energy-efficient key management scheme for WBANs that monitors the energy level of the node during the key management process. This framework supports both intra and inter-WBAN security and is then highly recommended for BBNs.

On the other hand, authors in [76] proposed a new method to improve WBAN security by decreasing the required memory, control packets complexity, control buffers and mend the existing damages resulting from the high speed of transferring data between nodes. To ensure these goals, ref [76] proposes a cryptography scheme to secure the intra-WBANs communications, by combining the advanced encryption standard (AES) and sensor node bio-signals.

Besides, there are several security proposals in the literature for WBANs and their applications, the work in [77] reviews some of them. First, the security mechanism for WBANs must be adjusted to the subsequent major security necessities which are divided into three classes (Figure 6):

- Data storage:

Confidentiality: while storing WBAN data, it should be encrypted and protected by access control lists.
Integrity: WBAN data should be kept intact, unbroken while storage is performed.
Dependability: WBAN data should be recovered after network incidents (link failure, deleted data, etc.).
Privacy: unauthorized access to the stored WBAN data should be prohibited by the data storage policy.

- Data access:

Accountability: every malicious WBAN, that would access illegally to others' secured data, should be retrieved and held responsible of his actions.
Revocability: malicious WBANs should be underprivileged at once.
Non-repudiation: a source WBAN should not deny the generation of its own data.

- Other security requirements:

Authentication: any source WBAN should be authenticated by the destination, before sending the sensing data.
Availability: the WBAN data should be available and accessible whenever it is needed.

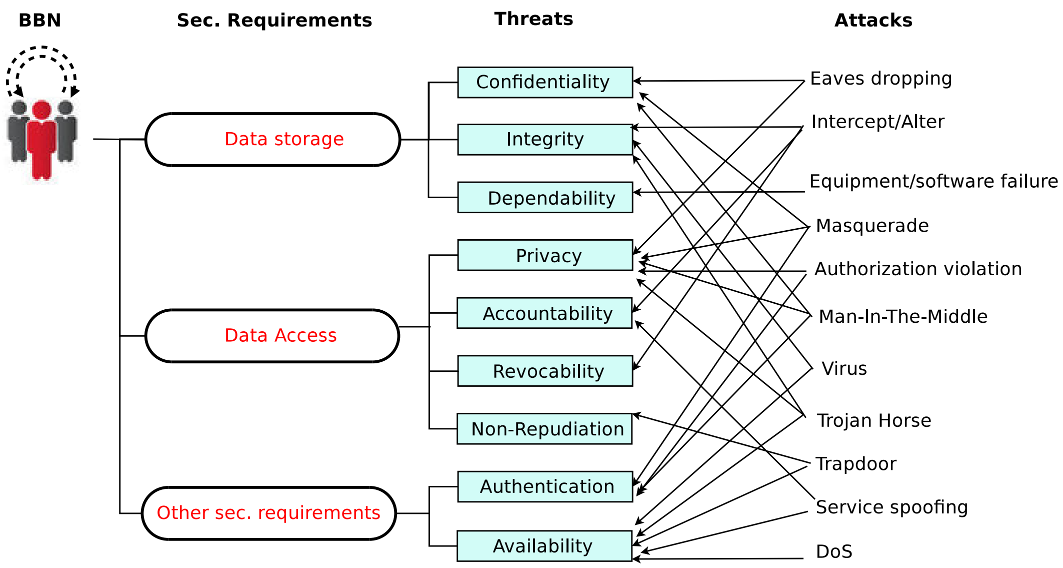


Figure 6. Major security requirements in BBNs.

Then, specific mechanisms should be implemented to ensure a secure environment around the WBAN, which will detect, prevent and reinforce the WBAN against attacks. Existing security mechanisms for WBANs could be developed into seven aspects:

1. Cryptography: cryptographic functions are used to ensure the safety and security of the information collected by sensor nodes (vital signs of a patient). Choosing the cryptographic system depends on the WBAN application and its energy consumption.
2. Key management: cryptographic keys are generated and shared to the WBANs to ensure secure communications. Three types of key management protocols can be found: the trusted server, considering a trusty base station to validate the key agreement, the key pre-distribution or the symmetric key cryptography, and finally, the public-key infrastructure.
3. Secure routing: the sensor node collects physiological information and sends this data to alternative devices. A number of routing protocols are proposed in the literature for sensor networks, but most of them suffer from security vulnerabilities that should be addressed to prevent inconsistency in the routed data.
4. Resilience to node capture: this is a major issue in WBANs, especially in real-time applications. For example, the public hospital environment could be targeted by malicious behaviors from the inside or the outside. To resolve this problem, one feasible solution is to use inviolable network hardware.
5. Trust management: corresponds to the partnership between two trustworthy WBANs that relay their respective data.
6. Secure localization: to facilitate mobility for patients, the authors specify in [78] localization procedures that operate over three steps: distance estimation, angle estimation and position computation.
7. Robustness to communication denial-of-services: the denial-of-service (DoS) attack can be implemented in the WBAN by broadcasting high-energy signals. Therefore, an energy-based security mechanism should be implemented to deal with this vulnerability.

Finally, a number of industry and research projects have paid a special attention to the security issue in WBANs. In healthcare industry, the European MobiHealth project presented in [79] provides a detailed end-to-end ambulatory application using Bluetooth or ZigBee-based communication device, and is a single-hop network. The solution is deployed by UMTS and GPRS networks. The major issues are reliability and QoS guarantees.

In the same context, CodeBlue project, introduced in [80], consists of the design of an ad hoc sensor wireless infrastructure to be deployed for emergency healthcare, in order to ensure efficient allocation of medical resources and seamless transfer of sensor data. Intended to scale to high-density networks, connecting a wide range of heterogeneous devices, CodeBlue places the security issue on the spotlight of interest and implements a flexible and decentralized security model that allows the emergency medical technicians to be authenticated by the network before receiving patient information. A handoff mechanism is also performed to ensure transparent authentication when the patient is transferred to the hospital. The Biosec project [81] also addresses the security constraints of the communications among biosensors operating in extremely stringent environments. The idea is to derive biometric inputs from the human body for the security module. Therefore, keying material is computed using biometrics from the body, which would drop the security overhead for the benefit of reliable sensing and energy saving. Another interesting proposal could be found in [82], which consists of a lightweight authentication scheme based on zero-knowledge proof (ZKP) [83] for WBANs, implemented on TinyOS-based sensors, referred to as TinyZKP. Originally, ZKP is a cryptographic protocol with low computational requirements and simple key management. TinyZKP mechanism relies on the cryptographic strength of ZKP. Thus, with such authentication protocol, it is impossible to inject malicious data within the communication between the base station and the authenticated WBAN. Another recent study, BANZKP [84], also implemented ZKP authentication for WBANs, together with a commitment scheme to deal with replay attacks. BANZKP has been proved to be more efficient than TinyZKP in terms of memory requirement, execution time and energy consumption.

4. BBN Design Challenges and Open Issues

A synopsis of the aforementioned WBAN solutions is given by Table 3, with a global view on the different network features which are tightly related to future BBN requirements. Apart from the BBN design challenges discussed in this survey, further research issues are not of lesser significance, some of which are tackled hereinafter.

4.1. Wireless Channel Propagation

The propagation of the wireless signal between humans carrying wearable devices still present a non-deterministic research field. Recent propagation models have been established in the 2.45 GHz ISM band [85–87], based on the human body physical characteristics, such as mobility, body postures; line-of-sight (LOS), non-line-of-sight (NLOS), body shadowing, fading, etc. Indeed, the feasibility of upper layers design relies on the understanding of the physical layer characteristics.

In [15,16,87], some experiments were performed at the ISM frequency of 2.45 GHz, to illustrate the human body impact on signal propagation in BBNs through different scenarios. It is assumed that the antennas are positioned on two distant persons. To estimate signal loss over distance, two additional parameters are added to the log-distance path loss model, which are the body shadowing (X_{BS}) and the small physiological movements (X_{SM}). Yet the BBN path loss model of the signal propagation in free space, is given by [87]:

$$P(d) = P_0 + 10nlog(d/d_0) + X_{BS} - X_{SM} \quad (dB),$$

where P_0 represents the path loss measured at a reference distance ($d_0 = 1$ m), n is the path loss exponent and d is the distance between the transmit and receive antennas. The observed results of the signal propagation between two BBN users could be reported for both stationary and mobile scenarios [16]:

Table 3. Comparison of existing wireless body area network (WBAN) solutions to be extended to the BBN environment. © [2019] IEEE. Reprinted and modified, with permission, from [4].

Protocol	Energy-eff.	Reliability	QoS	Mobility	Security	Intra-WBAN	Inter-WBAN
EAAODV [49]	✓		✓	✓		✓	
SIMPLE [51]	✓	✓				✓	
EERS [53]	✓	✓				✓	
M-ATTEMPT [50]	✓		✓	✓		✓	
EAWD [55]	✓	✓		✓		✓	
CLDO [56]	✓	✓	✓			✓	
AAT [57]	✓	✓	✓			✓	
MoBAN [71]				✓		✓	✓
McMAC [63]	✓	✓	✓			✓	
LRPD [61]		✓	✓	✓		✓	
QPRR [59]		✓	✓			✓	
ZEQoS [40]	✓	✓	✓			✓	✓
RACOON [65]		✓		✓		✓	✓
PSR [68]		✓		✓	✓	✓	
MHRP [69]	✓	✓	✓	✓		✓	
MTR [72]	✓	✓		✓		✓	
CCS [73]	✓				✓	✓	✓
MobiHealth [79]		✓	✓	✓	✓	✓	
Hybrid Security Mechanism [74]	✓				✓	✓	✓
Cluster-based sec. mechanism [75]	✓			✓	✓	✓	✓

4.1.1. BBN Users in Stationary Positions

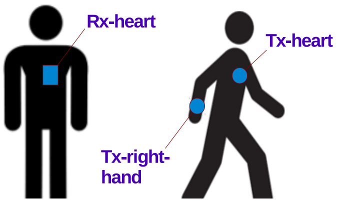
- Involuntary slight movements of two persons in LOS position, may result in noticeable variations of the body-to-body signal level, in comparison to the log-distance pathloss model prediction.
- In outdoor NLOS situation, when one person turns his body back to the other person, the direct signal path is shadowed and the received signal level decreases consequently.

4.1.2. BBN Users in Movement

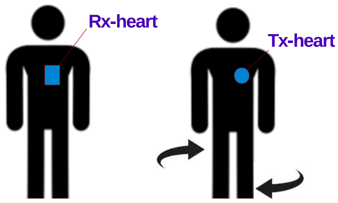
- Rotation movements significantly alter the average signal level (up to 50 dB attenuation), especially when the person turns on the spot and obstructs the LOS position with the other person.
- During tilt movements, the received signal is as much impacted as the vicinity between the two persons is reduced.
- Finally, in LOS and NLOS walking situations, when one person starts moving during the body-to-body signal propagation, body shadowing and path loss components increase in comparison to stationary scenarios.

In outdoor mobile communication channels, the small-scale fading is modeled by a Rayleigh fading, which is defined as the sum of the different scattered signals, due to the surrounding obstacles, received with arbitrary amplitudes. Whereas in BBNs, on-body reflection or direct communication link could give rise to a dominant signal component. Thus the fading component X_{SM} is assimilated to the Ricean fading, with the Ricean-K factor $K = A^2/2s^2$, where A is the dominant component and $2s^2$ is the average scattered power. Indoor measurements have also been performed in [85], where the fading envelope was associated to the walking LOS/NLOS scenarios and assimilated to a Nakagami distribution, which is described by the couple of parameters: the shape (μ) and the spread (ω) [88]. The body shadowing effect was considered for the rotation scenarios performed at different distances separating two WBANs from each other, and top loaded monopole (TLM) antennas have been proved to be less affected by body shadowing, in indoor environments, than other types of body antennas, such as wideband planar monopole (PM) antennas, that have also been considered in the channel measurement campaign of [85].

The different signal propagation BBN scenarios for outdoor and indoor environments are reported, respectively, in Tables 4 and 5, with the corresponding fading components, represented by the Ricean K-factor (A and s parameters) for outdoor scenarios and Nakagami parameters for the indoor environment. The shadowing (X_{BS}) is represented, for the outdoor signal, by the μ and σ parameters of the lognormal probability distribution function (PDF). The shadowing standard deviation σ_s characterizes the shadowing component for the indoor rotation scenario. We have reported those results for TLM antennas considering the scenarios described by Figure 7. It is worth to note that S.L. Cotton et al. have conducted a number of experiments in [15] over five wireless channel modeling distributions: Nakagami [88], lognormal [89], Rice [90], Weibull [91], and $k - \mu$ [92], among which the $k - \mu$ distribution was proved to better characterize the indoor small-scale fading in body-to-body channels, but this study is earlier than [85].



(**a**) Scenario 1



(**b**) Scenario 2

Figure 7. Scenario 1: walking line-of-sight (LOS)/non-line-of-sight (NLOS) Rx-heart/Tx-right-hand. Scenario 2: rotation Rx-heart/Tx-heart.

Table 4. BBN scenarios of the wireless signal propagation in outdoor environment.

BBN Scenario	Description	Human Body Effect	n	P_0	X_{BS}	X_{SM}
Stationary LOS	Person A and person B are facing and stationary at a distance of 15 m	Increased variability in path loss caused by slight body movements.	2.1	39.8	$\mu = 0.00$ $\sigma = 0.05$	$A = 1.00$ $s = 0.04$
Stationary NLOS	Person A and person B have their bodies rotated through 180° and keep stationary	The path loss significantly increases with an extra 40 dB attenuation compared to the LOS state, due to the spread of the X_{BS} component.	1.9	77.9	$\mu = 0.00$ $\sigma = 0.11$	$A = 1.00$ $s = 0.04$
Rotation	Person A performs a full 360° rotation, turning from LOS to NLOS position	Received signal under the noise threshold of the receiver. The magnitude of the X_{SM} increases due to the varying propagation links transmitting the wireless signal.	-	-	-	$A = 0.96$ $s = 0.14$
Tilt	Person A tilts his position through a 45° angle	At 1 m, a variation of 10 dB in the signal level is recorded due to the distance between the two persons.	-	-	-	$A = 1.00$ $s = 0.04$
Walking LOS	Person A walks at a normal pace (0.88 m/s) towards person B until reaching a distance of 1 m.	When person A is walking, the path loss exponent n increases compared to the stationary scenario, because of the body shadowing.	2.9	29.6	$\mu = 0.00$ $\sigma = 0.20$	$A = 1.00$ $s = 0.05$
Walking NLOS	Person A turned 180° from person B and walks from an initial distance of 1 m to 15 m.	The constantly changing propagation paths impact the received signal level. The spread of the standard deviation σ and s parameter noticeably increase compared to previous scenarios.	1.5	79.6	$\mu = 0.02$ $\sigma = 0.28$	$A = 0.98$ $s = 0.16$

Table 5. BBN scenarios in indoor environment.

BBN Scenario	Description	n	P_0	Nakagami Fading	Indoor Shadowing
Stationary LOS	Person A stands at a distance $d = 8$ m from person B and performs two forward walkings and two backward walkings, into the average speed of 0.8 m/s, reproducing in that way LOS and NLOS conditions.	2.46	−43.70	$\mu = 0.98$ $\omega = 1.8$	-
Stationary NLOS		1.91	−52.46	$\mu = 0.87$ $\omega = 1.97$	-
Rotation	Person B realizes full rotations beside person A, starting from $\alpha = 0°$ to $\alpha = 180°$, turning from LOS to NLOS position, and inversely.	-	-	-	$\sigma_s = 4.24$

Furthermore, recent studies [93,94] evaluated the impact of the body mass index (BMI), which is a function of the height and weight of a person, characterizing the body fat, on the body-to-body signal propagation. A channel measurement campaign was conducted within UWB MIMO array system, in the 2–10 GHz frequency band, to evaluate the BMI-dependence of channel metrics, i.e., the gain, the shadowing and delay spread. It was concluded that parameters obtained with BMI for humans with large body sizes are notably different from those with standard BMI. Definitely, further researches are needed to accurately characterize the impact of the human body on the wireless signal propagation in BBNs.

4.2. Interference and Coexistence

Due to the restricted number of channels of the radio spectrum, multiple wireless technologies (i.e., ZigBee, WiFi, Bluetooth, etc.) are constrained to share and manage the wireless resources. Hence, in order to preserve the link quality and do not alter the wireless signal, while implementing inter-WBAN communications, it is crucial to enable an interference mitigation mechanism to deal simultaneously with mutual and cross-technology scenarios.

Three interference mitigation mechanisms are considered by the IEEE 802.15.6 standard to deal with coexisting WBANs, namely [42]:

- Beacon shifting: by using a beacon shifting sequence not used by his neighbors, a WBAN could avoid co-channel allocation conflicts. Yet, each WBAN will periodically transmit within a scheduled interval and is characterized by its beacon shifting sequence index and the length of its beacon period.
- Channel hopping: the WBAN is allocated a wireless channel for a fixed number of superframes. Then, it should hop to another channel according to his channel hopping sequence, which is different from his neighbors. Thus, WBANs could not reserve indefinitely a wireless channel.
- Active superframe interleaving: two neighboring WBANs could share the same channel by interleaving their active superframes, i.e., alternating between them during their inactive periods.

Also, the Bluetooth low energy (BLE) standard [44] defines an adaptive frequency hopping mechanism to avoid overlapping with neighboring wireless links. But these keep standard-specific techniques, and do not deal with cross-interference scenarios, in a BBN context. Number of recent works [38,39,95–97] investigate the inter-WBANs interference problem with different alternatives. For example, authors of [95] enhanced the existing frequency hopping mechanism of WPANs to ensure coexistence with WiFi devices. A WiFi system is assumed to rarely change its operating channels, thus they implemented a novel scheme that monitors the packet error rate (PER) within the network to find out the channels that should be excluded from the hop set. From another perspective, in [96], a power control game theoretical approach is implemented, considering the signal-to-interference-plus-noise-ratio (SINR) as utility function to model the interference between coexisting WBANs. An almost blank subframe (ABS) scheduling technique is proposed in [38], for a

WBAN-based machine-to-machine (M2M) medical system. Each WBAN could then avoid interference with his neighbors by specifying the type of the transmitted subframe: normal or ABS, with respect to the load status of the M2M system. In [39], the interference-aware coexistence of multiple WBANs is tackled by considering the mobility of sensor nodes within the single WBAN, and the movement of WBANs in their surrounding environment, based on social interaction detection, so as to ensure spectral reuse and power efficiency.

The cross-technology interference mitigation (CTIM) problem is considered in [97], involving node mobility, to characterize and solve the interference problem that results on the utilization of different wireless technologies in the same radio spectrum, namely the ISM band. Three heuristic approaches are proposed to solve the CTIM problem, and have been proved to be efficient for large-scale BBN scenarios.

In the same perspective, a game-theoretical approach called the socially-aware interference mitigation (SIM), has been proposed in our previous work to deal with this issue and considers the mutual interference as well as the cross-technology interference scenarios [98,99].

Besides, a recent channel selection approach for interference mitigation (CSIM) [100] enables the WBAN operation within IoT environment. The CSIM protocol involves a BLE transceiver together with a cognitive radio module within the WBAN coordinator, so as to inform the WBAN through announcements of the frequency channels used in its vicinity, allowing him to switch to another wireless channel providing less interference within his surrounding.

4.3. Storage and Privacy of Health Data in IoT/Cloud Environment

The communication and cooperation between a group of WBANs are driven by the continuous expansion of the IoT infrastructures and cloud-computing market. Yet, BBNs could benefit from the data storage capabilities of the existing infrastructures, but should pay special attention to the related privacy issues. Already, in [101], the idea of including WBANs to extend the infrastructures coverage area, had been tackled. WBAN packets are expected to be translated into IP datagrams by the WBAN coordinator, that could be a smartphone able to transmit over multiple network interfaces, to ensure the connectivity of the WBAN with the outside world. Existing technologies such as short message services (SMS), general packet radio services (GPRS), email, Bluetooth personal area networking, IPv6 over low power wireless personal area networks (6LoWPAN), and IP for smart objects (IPSO), are expected to enhance and speed up the data transfer. Today, it will be possible to ensure this task by creating a new type of ad hoc network, where network users themselves are used as ad hoc base stations, able to forward real-time information among co-located persons carrying body sensors. Then, with the emergence of the IoT, ubiquitous healthcare, WBAN data storage, and other management services could be performed remotely by a powerful computing platform at a distant location (Figure 8).

In [102,103], it is argued that the standardization of the technologies in IoT is important and urgent, in order to ensure the interactions among the networked things and help accelerate the spread of IoT technology. Yet, to deal with the lack of IoT standardization, global collaboration between existing standards is necessary. The objective, in the long term, is to ensure the integration of objects with sensors in the cloud-based Internet, and then the fusion of sensing and Internet, where all of the networked devices should be autonomous and smart enough to support the ubiquitous services. The other major requirement to enable the integration of WBANs within an IoT platform would be the security of health data storage and transmissions across the networked objects [22,104]. Wan et al. in [22] proposed a cloud-enabled WBAN architecture to transmit vital sign data using joint cloud resource allocation and cloud data security, along with an energy-efficient routing. The integration of WBANs and mobile cloud computing (MCC), in order to provide and facilitate pervasive healthcare services, is driven in the scope of the cloud-enabled WBAN platforms (wMCC). Data storage encryption, data partitioning, access control, user diversity, scalability and mobile access are the more challenging constraints to be held to enable wMCC services. These security issues are also investigated in [30], especially to ensure secure access control and distributed data storage for sensitive medical data. The goal is to overcome the weaknesses of classical key management approaches, for example the shared public keys should be centralized in a trusted server outside the cloud, or decentralized/distributed among users, rather than centralized in the cloud provider. Besides, in [104], IoT security and resilience challenges are analyzed in order to ensure the IoT - Cloud convergence in the context of Smart City deployment.

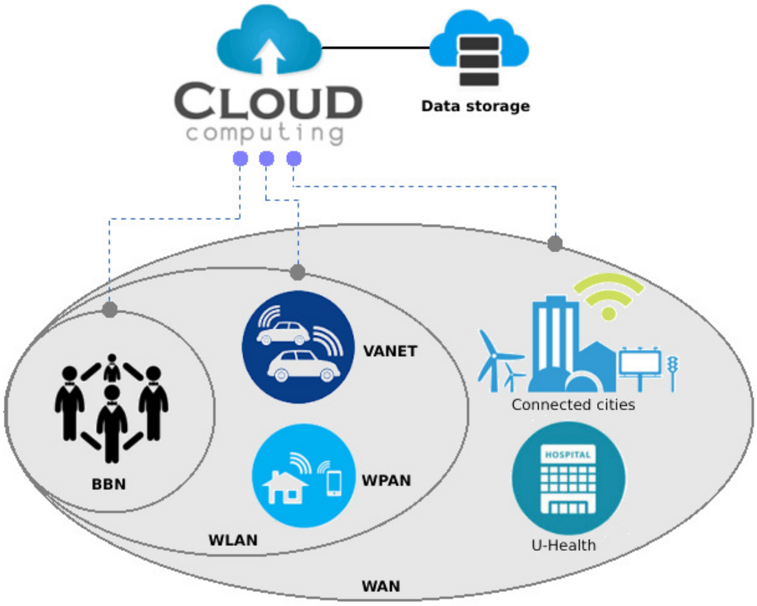


Figure 8. Internet of things (IoT) landscape including body-to-body networks.

Another example of applications using WBANs in a cloud environment is proposed in [105], and consists of a cloud health management system which includes six subsystems; electronic health record, health information collection, health risk assessment, health intervention, health education and telemedicine system, that are all assisted by an Android mobile phone application. In general, an adequate storage solution solution must be robust, secure, compatible with existing infrastructures and low cost.

4.4. Heterogeneous Devices and Traffic

In future BBNs, the WBAN coordinators could be any type of portable devices and should communicate and forward heterogeneous traffic; plain text data as well as video or audio contents. Furthermore, the entry of a new device or the disconnection of a WBAN due to roaming, should be systematically handled, without altering the neighboring WBANs operating.

Yet, in BBNs, a service-oriented architecture (SoA) is recommended for the service providers and users in order to ensure the interoperability among the heterogeneous devices, that are interconnected within the BBN. The SoA is a kind of middleware that provides access to heterogeneous resources in a deployment independent manner [103,106]. The key role of such middleware is to allow the interconnection between the things and the application layer through the abstraction of the heterogeneous functionalities of the devices into a common set of services [107,108]. Thus, the BBN middleware can be divided into a set of layers: object abstraction, service management, service composition, and application [109]. Due to the advantages of such layered architecture, SoA could provide extensible, scalable and modular BBN services.

4.5. Ethical Challenges

While strict ethical guidelines are set up by the government for the medical profession, it is not the case for U-health services where trendy issues about privacy and ethics are increasingly rising [110]. Apart from the user trust problem, real threats could impact the U-health sector, as well as other BBN-based services, that could deviate from their worthy goals to become a compromising technology. Hence, ethical considerations for BBNs become a moral imperative. In the information and communication technology (ICT) industry, threats and countermeasures should be investigated to handle security issues including privacy, equity, liability and responsibility to the error. Actual legislative efforts should be made to enable pervasive surveillance by data analysts and machine learning techniques that could be well-coupled with BBN networks.

5. Conclusions

In this survey, we provided a brief overview of the current proposals related to WBANs and their possible application in BBNs. Four design challenges have been tackled: energy efficiency, mobility prediction, QoS, and security. The existing WBAN and BBN-related works have been discussed and compared in order to highlight the key features for BBN design. The energy issue is definitely a hot topic for WBANs and more so for BBNs. In addition to the single WBAN sensing activity, further energy is consumed for the sensor data relaying among coexisting WBANs. Then, the BBN energy profile should take into account the sink-forwarding-to-sink energy component, and should also support the WBAN topology changes and the mobility of WBANs in the BBN vicinity. The most appealing QoS requirement for BBNs is the QoS mapping, in case of heterogeneous BBN devices and traffic, apart from the ultimate delay and reliability constraints, that could have a vital impact on the health-based applications. Accurate mobility management is also mandatory to ensure seamless transfer of sensor data in dynamic scenarios. The main mobility features to take up are: the need of a handover mechanism for the WBAN roaming to handle channel switching and prevent link failures. Also, the WBAN mobility patterns could take advantage from the regular aspects of the human body movements, and should consider differently the indoor and outdoor scenarios, since the wireless channel propagation characteristics are not the same. Above all the aforementioned issues, tough security policies are required in BBNs, first to prevent the energy-constrained resources from malicious attacks, and second to secure the BBN activity itself, especially in health-oriented applications, since human lives are directly implicated. Finally, a number of candidate protocols have been identified, and further research issues have been also discussed. Hence, by enabling inter-WBAN communications, BBNs could extend the existing infrastructures, bringing innovative services with great social benefits, ranging from gaming and entertaining to ubiquitous healthcare, rescue teams in hazardous situations or military applications, etc. In fulfilling these goals, our ongoing work is about compiling the aforementioned proposals to implement an inter-WBAN routing protocol in order to boost the research incentives of BBN effective deployment.

Author Contributions: Am.M., J.E., and Ah.M. conceived the presented topic. Am.M. and J.E. developed the original draft. Am.M took the lead in the study, investigation and writing of the manuscript with close participation of J.E. J.E. and Ah.M. supervised the findings and theoretical syntheses of this work. All authors provided critical review and editing of the paper.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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