Future Body-to-Body Networks for Ubiquitous Healthcare: A Survey, Taxonomy and Challenges

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Abstract—**Smart mobile people have a great potential to extend the existing Internet of Things infrastructures by implementing genuine ubiquitous healthcare (U-health) applications, ensuring anywhere and anytime patients connectivity. Through the forwarding of sensing data from person to person until reaching a connected medical server, concrete U-health becomes true with the emerging of future Body-to-Body Networks. Indeed, the co-existence of multiple WBANs (Wireless Body Area Networks), the communication and interactions between them extend the classical concept of WBAN and present the new paradigm referred to as Body-to-Body Network (BBN). This paradigm supports a number of innovative applications such as U-health, entertainment, interactive gaming and military, to cite a few.**

In this paper, we present a survey of BBNs focusing on three principal axes: *energy efficiency*, *mobility prediction*, **and** *quality of service (QoS)*. **Then, we present and discuss different candidate protocols that can be used in BBNs, while illustrating main BBN design challenges and several open issues.**

Index Terms—*WBAN, BBN, U-health, Energy-efficiency, QoS, mobility prediction, routing.*

I. Introduction

A wireless body area network (WBAN) is a wireless network of wearable or implanted computing devices. Sensor devices can be embedded inside the body (implants), surface-mounted on the body in a fixed position (wearable), or carried by humans in different positions.

The development of such technology started around 1995 with the idea of using wireless personal area network (WPAN) technologies to implement communications on, next to, and around the human body. The WBAN field is an interdisciplinary area which could allow inexpensive and continuous health monitoring with real-time updates of medical records through the Internet. 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 sensors will collect the different information in order to monitor the patient's health status regardless of his location; this information will be transmitted wirelessly to an external processing unit. If an emergency is detected, an alert will be generated through the computer system to inform the patient and/or the medical staff.

Yet, WBAN applications have evolved over the time, and new WBAN-based networks have recently emerged, i.e., Body-to-Body Networks (BBNs), that we can define as a set of WBANs, which are able to communicate with each other,

in order to ensure various solutions that fulfill real social benefits. However, nowadays this kind of networks present numerous challenges like the system devices interoperability, interference, wireless environment properties, etc... But the more challenging issues in BBNs are the energy-efficiency, the human mobility prediction and the Quality-of-Service of these networks.

This paper is organized in the following manner. In section II, we present the WBAN and BBN concepts. In section III, we discuss the BBN design considerations. In section IV, we present a synthesis of the studied solutions and protocols as well as we discuss BBN open issues, and finally, section VI concludes the paper.

II. From WBAN to BBN

Motivated by the increasing need for remote and improved healthcare solutions, while decreasing the cost of supporting a continuously growing aging population in developed countries, WBANs still form a strongly growing research field, driven by the development of the IEEE 802.15.6 standard. Furthermore, the evolution of single-operating WBANs to a cooperative large-scale BBN, is subject to a number of design challenges, some of which will be addressed in this section.

1) BBN concept: A Body-to-Body Network (BBN) is composed by several WBANs, each communicates with its neighbor. The coordinator device plays the role of a gateway that shares the communication data with other WBANs. Body-to-Body Network is theoretically a mesh network that uses people to transmit data within a limited geographic area. Using devices such as a BBN-enabled Smartphones or Smartwatches, a signal is sent from the WBAN to the nearest BBN user, which is transmitted to the next-nearest BBN user and so on until it reaches the destination. Figure 1 illustrates an example of BBN network used for the U-Health monitoring of a group of cyclists.

2) Standards: Alike WBANs, a BBN uses the communication standards such as IEEE 802.15.6 [1], which is a low-power and short-range wireless standard used for devices operating inside or around the human body. This standard supports data rates up to 10 Mbps, while simultaneously complying with strict non-interference guidelines. Then, IEEE 802.15.4 (ZigBee) [2], which deals with compatible interconnection of communication devices using low-data rate, low-power, but very long battery life, and low-complexity short-range radio frequency (RF) transmissions. Nevertheless, it is possible to use other standards in BBNs, like 802.11 (WiFi) or 4G.

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Figure 1: Body-to-Body Network for U-Health monitoring of a group of cyclists.

3) Challenges: The major challenges for BBN are: the energy efficiency, when the coordinators will play the role of cluster head and will transmit the value or vital signs in the case of a medical application to other WBAN within a group. Then the routing of collected sensor data through neighboring WBANs until the destination, with QoS considerations and ability to support WBANs mobility, is a second issue. Yet, the data generated and transmitted in a BBN must have secure and limited access. Anyway, people can see the BBNs such as a threat sources on their data and private life, their acceptance is the key of the success of BBNs. Finally, all data residing in mobile WBANs or patient sensor nodes must be collected and analyzed in a seamless fashion. The vital patient datasets may be fragmented between some nodes, but if the node does not contain all known information the level of patient care may be not so good.

4) Applications: Body-to-body networks could represent emerging solutions ensuring real social benefits, such as re-mote healthcare, precision monitoring of athletes, rescue teams in a disaster area or groups of soldiers on a battlefield, etc. Yet, the BBN can be implemented in both medical and non-medical applications. Especially, BBNs represent the novel trend for the future ubiquitous healthcare systems, indeed the remote monitoring of patients carrying bodyworn sensors and relaying each other's physiological data up to the medical center, could greatly reduce the current strain on health budgets and make the Government's vision of ubiquitous healthcare for distant patients a reality. People would no longer need to be in range of a cellular tower to make a call or transmit data, apart from the health and environmental red tape associated with cellular peril issues that would be avoided with a low-power body-to-body network.

III. BBN Design Considerations

To design new, energy-efficient, QoS-based, and secure mechanisms for BBNs, there is a number of challenges one must overcome. Practically, few mechanisms proposed in the literature for WBANs could apply to BBNs, provided that further specific considerations of BBN applications should be well-respected. Thus, hereafter, we investigate some WBAN solutions and discuss their ability to suit BBN scenarios, focusing on three principal interrelated axes: energy efficiency, quality of service (QoS) and mobility management.

A. Energy-efficient routing for BBNs

Stringent resource constraints on devices within a WBAN have been long discussed in the literature. Indeed, while sensors in general are energy constrained, body sensors are more so. Furthermore, the interaction and routing of data among a group of WBANs within a BBN, result obviously in further energy consumption, in order to ensure inter-WBAN communication, and then introduce additional energy constraints.

Authors of [3] presented a comparative study between routing protocols for WBAN healthcare communication net-works. The simulation results showed that AODV (Adhoc On Demand Distance Vector) protocol provides higher throughput with minimum jitter and delay, with and without mobility of WBANs. Then, AODV was enhanced into an energy-aware routing protocol (EAAODV), which is an on-demand routing protocol that builds routes only on demand by flooding Route Request packets (RREQ). The selection of the neigh-boring WBAN for forwarding the route request is based on both mobility and the remaining energy. In comparison to AODV, EAAODV performs better in terms of energy con-sumption, and then presents a suitable routing protocol for the energy- and QoS-highly constrained networks of WBANs. Yet, EAAODV could be a candidate routing protocol for BBNs.

In [4], the authors proposed a new energy-efficient routing protocol for heterogeneous WBANs (M-ATTEMPT), defining a prototype to employ heterogeneous sensors on human body. The proposed protocol uses a direct communication with the sink for critical data (real-time) and on-demand data, and uses a multi-hop communication for normal data delivery. The thermal-aware algorithm detects link hot-spots corresponding to implanted sensors and avoids transmitting on these links in order to minimize energy consumption. Besides, patient mobility causes links disconnections, thus, mobility support and energy management are included in the solution.

The M-ATTEMPT protocol was proposed for an energy- and QoS-aware routing in intra-WBAN communications, but it could apply to inter-WBANs routing, i.e., to ensure data forwarding among sinks in a BBN scenario. Nevertheless, the QoS traffic classification and scheduling should be more investigated to fit specific BBN requirements. The negative aspect in this routing protocol is the disconnection during sensor node mobility, which requires the restructuring of the WBAN tree topology. Thus, M-ATTEMPT protocol needs the implementation of a robust mobility management mechanism to be able to ensure inter-WBAN communication within a BBN. Also in [5], the authors proposed the multi-hop topology to minimize the energy consumption of their routing protocol (SIMPLE), while ensuring higher throughput, more reliable and longer stability period, in comparison to M-ATTEMPT. This multi-hop protocol is based on a cost function to select

Protocol	Layer	Topology	Advantages	Limitations
EAAODV [3]	Network	Single-hop	On-demand Routing Mobility management	Results only for ZigBee MAC Model.
M-ATTEMPT [4]	Network	Single-hop/ Multi-hop	Mobility management Traffic data priorities Intra-WBAN routing	Disconnection during sensor node mobility.
SIMPLE [5]	Network	Multi-hop	Reliability, High throughput On-demand intra-WBAN routing	No mechanism to handle mobility.
EAWD [6]	Network	Multi-hop	Topology-aware energy-efficiency Minimizing relay nodes Minimizing installation cost Generic (separate energy components)	No consideration of retransmission energy, MAC access energy and signalling energy
Duty-cycle [7]	MAC	Single-hop	Guard time: no overlaps, reliable data transfer. Reduce idle listening Synchronization scheme for TDMA	Hardware dependent

Table I: Energy-aware candidate protocols for U-Health BBNs.

a parent node or a forwarder.

Other works proposed detailed expressions of the power consumption profile of a WBAN node, such as [8], where the authors focused on the MAC layer design to determine the energy profile of a sensor node. Thus, [8] provided the equation defining the total energy consumed by a WBAN node, which implements a number of energy components, each corresponding to a task performed by the node to transmit a packet. Nevertheless, this model did not consider the topology constraints and routing mechanisms that may introduce extra energy components. Yet, our previous work [6] provided an Energy-aware Topology Design (EAWD) for WBANs, that takes into consideration the topology problem, minimizing the number of relay nodes and thus the total energy consumption as well as the total network installation cost. Furthermore, the EAWD model explicitly formulates each energy component and separates the different transmission instances: i) sensors transmitting to relays, ii) relays forwarding to relays and iii) relays forwarding to sinks. As well as the different reception instances: i) Relays receiving from sensors, ii) relays receiving from relays and iii) sinks receiving from relays. This is a key feature of EAWD that allows it to apply to BBNs. Indeed, two energy components could be added to the sink energy expression, to specify the transmission and reception energy between sinks of neighboring WBANs, namely: i) sinks forwarding to sinks and ii) sinks receiving from sinks.

Another key feature of the energy efficiency in WBANs is the duty cycle considered in [7]. Indeed, this model removes the need of idle listening for clear channel, thus lowering the amount of unnecessary overhead and this by adopting TDMA MAC protocol. However, the major limitation of this model is the assumption of a static topology of the WBAN, which raises the major problem of TDMA, i.e., the need of a synchronization scheme to collect data efficiently from network sensors. Although the duty cycle mechanism is very useful for BBNs, where minimizing traffic overhead is necessary to ensure an energy-efficient routing among WBANs, the assumption of static topology is unsuited to a dynamic BBN where each WBAN member can join and leave the BBN network seamlessly, and without the need for any centralized

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

B. QoS-aware traffic management for BBN

In general, the design of a BBN is intended for specific applications (ubiquitous healthcare, sport team, group of fire-fighters, military, etc.), therefore, the routing protocol to be implemented, in order to ensure inter-WBAN communications within a BBN, should be able to fulfill the QoS demands of the WBAN application by using QoS-aware protocols.

In [9], the authors proposed a game theoretical approach using a QoS-based utility function to resolve the problem of overlapping between coexisting WBANs. The solution, based on the Cournot model, consists in fairly dividing the limited resources among the different players, where the player is the WBAN coordinator. The QoS parameters in this paper are throughput, delay and priority. The player's QoS demands are taken from the traffic specifications of the streams that are carried within the contention free period. It was verified that the player's utility increases with the increase of the throughput and decrease of the delay, according to the Cournot competition model.

Even though the utility function is based on QoS parameters, no energy efficiency parameter is considered and no mobility information is involved, WBANs are assumed fixed and the overlapping problem is only considered in a static topology.

The energy constraint was well-considered in [10], where the authors proposed McMAC which is a MAC protocol with multi-constrained QoS provisioning for heterogeneous traffic in WBANs. McMAC introduces a novel superframe structure based on the Transmit-whenever-appropriate principle. A handling mechanism for emergency traffic is used to ensure a delivery in the least possible delay and the highest reliability. Authors also described how the BC (wBAN Coordinator) and the nodes respond when there is an emergency packet in both cases, CAP (Contention Access Period) and CFP (Contention Free Period). McMAC is energy-efficient, and provides a QoS classification of the WBAN traffic, but only star topology is considered (single-hop). Multi-hop communications should
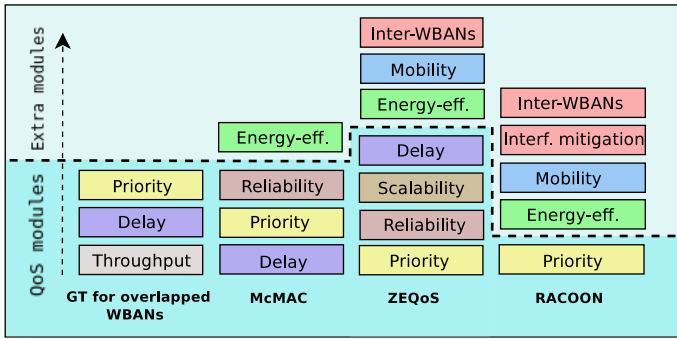
Figure 2: QoS modules of WBAN protocols candidate for future U-Health BBNs.

be considered, especially to be applicable to inter-WBAN communications in BBNs.

In this work, the network is infrastructure-based, with a Nursing Station Coordinator (NSC), Medical Display Coordinator (MDC), and mobile WBANs (patients), whereas in a BBN, we consider a completely distributed communication model with only WBANs as source and destination nodes. Furthermore, no specific bandwidth estimation/verification was considered in the path selection procedure, which is a relevant parameter in the QoS-constrained healthcare application. Besides, no fault detection procedure is implemented, the reliability module passes the information of successful data packets' transmission acknowledgments from MAC layer to the network layer to estimate the reliability of a link between the WBAN and its neighbor, and then it does not detect congestion or predict link failures.

In another recent study [11], authors proposed a novel integrated energy and QoS-aware routing protocol called ZEQoS which relies on two main layers: MAC layer and network layer. This protocol deals with the optimization of energy consumption, end-to-end latency and reliability requirements of the WBAN. ZEQoS classifies the data packets into three classes: ordinary packets (OPs), delay-sensitive packets (DSPs) and reliability-sensitive packets (RSPs), and calculates the best next hops for the three classes. It is intended to be used in hospital indoor environment. ZEQoS offers better performance in terms of higher throughput, fewer packets dropped on MAC and network layers, and lower network traffic than comparable protocols.

The solution in [12] consists in a Random Contention based Resource Allocation (RACOON) MAC protocol to support the QoS for multiuser mobile WBANs. It uses two distinct channels: one for inter-WBAN, to exchange the resource negotiation messages, and the other channel is for intra-WBAN, to transmit polling messages and data packets. RACOON also implements an iterative bandwidth control according to the users' priority index.The advantage of RACOON is that it considers multi-WBAN designs. Moreover, it takes into account the mobility feature of the WBANs in order to encounter the possible collisions and energy waste. Such mechanism could be used in BBNs to assign priorities to WBANs according to their requested services, and their energy status. Nevertheless,

RACOON does not consider inter-WBANs communications, which require further QoS considerations and mobility management to ensure the effective inter-WBANs routing.

Figure 2 illustrates a modular representation of the QoS modules of the aforementioned protocols, candidate for future U-Health BBNs, as well as the extra modules provided by these protocols.

C. Mobility management for BBNs

Mobility management can positively affect the service-oriented as well as the application-oriented aspects of mobile networks. Especially for BBN ubiquitous healthcare applications, accurate mobility prediction is necessary for critical tasks related to the routing of medical data among mobile WBANs, such as call admission control, congestion control, reservation of network resources, preconfiguration of services and QoS provisioning. Several works have considered the mobility prediction issue in mobile networks context [13], [14], [15], [16].

In [13] the mobility prediction methods are, first, classified into three main categories: movement history based methods, physical topology based methods and logical topology based methods, which are presented in detail and compared in Table II, the possible use cases of each method in the context of U-health BBN applications are also proposed.

Authors of [16] proposed an optimized WBAN handover strategy, a hop-by-hop method to reach the Sink, and a method to maximize the network throughput by using stable routes to avoid inter- and intra-flow interference based on mobility prediction.

In [15], a distributed Prediction-based Secure and Reliable routing framework (PSR) was proposed for emerging WBANs. It is observed that body sensors may exhibit regular mobility when a user's physical activity (e.g., swimming and jogging) contains repeated motions, and as a result, link quality and a sensor's neighbor set often present periodic changes. Using this model, the sensor node predicts the quality of its incidental links as well as the change of its neighbor set.

The work in [14] presents a comprehensive configurable mobility model (MoBAN) for evaluating intra and extra-WBAN communication. It implements different postures as well as individual node mobility within a particular posture. The selected posture also determines the local movement of sensor nodes and the global mobility of the whole WBAN. Therefore, it affects the connection between the nodes in the WBAN and the external network like other WBANs or the surrounding ambient sensor network. In addition to WBAN topology changes, the BBN topology is also subject to random changes due to WBANs' mobility. The advantage of MoBAN is that it considers both intra and extra-WBAN mobility, and is able to provide mobility information for both scenarios.

To maintain the high-quality, data routing should not only take into consideration the change of mobile WBANs locations or topology, as the reactive routing schemes do, but anticipate the movement behavior of mobile nodes employing proactive routing procedures. If each mobile WBAN's future location

Category	Advantages	Disadvantages	U-health 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 they disconnect.	Support simple node mobility with no sudden changes in the moving directions and speeds	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. Increase of the control overhead	U-health in accidents and emergencies. (Patient transportation 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 group and node velocities are time invariant, which is not a realistic assumption.	U-Health for a rescue team in a disaster area
Cluster change based prediction	Predict the next cluster change depending on the mobile node position in the cluster and its moving direction in the region.	This method needs an accurate location. The method requires the use of a GPS to build the sectors and locate the mobile nodes positions.	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. Mobile nodes use a linear model to estimate their future distance from their cluster head (CH).	Do not take node mobility into account during CH election.	U-health in indoor environments or monitoring of a sport team or a rescue team in outdoor/indoor environment.
Information theory based mobility prediction	The method does not make any use of a fixed geographical partition. Online learning of the probability model used for predicting the next neighborhood.	Frequent CH changes due to node mobility.	U-health in indoor environments, or monitoring of a sport team or a rescue team in a limited geographical area.
Evidence based mobility prediction	Does not require the use of a GPS. Accurately predict user traveling trajectory. The signal strength is used to estimate the distances among the mobile nodes.	This prediction process is performed only on the border nodes, to predict each mobile node's future cluster.	U-health in outdoor/indoor environments, for monitoring of freely moving patients.

Table II: Comparative study of mobility prediction methods for U-Health BBNs

and network topology changes can be predicted, then route reconstruction can be done prior to topology changes within BBNs.

IV. BBN DESIGN CHALLENGES AND OPEN ISSUES

In Table III, we summarize the aforementioned solutions, discussed in this paper in the context of their intended implementation in the future BBN systems for U-healthcare applications. Our survey focuses on three fundamental inter-related research issues: i) energy efficiency, ii) QoS and iii) mobility. Nevertheless, further issues have not been inspected in previous sections and are of significant concern, to cite a few:

- *Wireless channel propagation challenges:* At present, very little is known about the characteristics of wireless signal propagation between wireless wearable devices forming a human body-to-body network. Recent narrow-band studies at 2.45 GHz [17], [18], [19], have tried to establish some propagation models based on user's physical characteristics, including mobility and human bodies' effects (LOS, NLOS, shadowing, fading...). In fact, a greater understanding of the physical layer characteristics, the reliability and connectivity of wireless data paths will help in the design of upper layers, for example when allocating resources at the link layer or performing routing at network layer.

- *Interference and coexistence:* To identify and exploit opportunities for cooperation with neighboring WBANs, inter-body interference detection and subsequent mitigation are mandatory. Indeed, we should analyze the joint mutual and cross-technology interference problem due to the utilization of a limited number of channels by different transmission technologies (i.e., ZigBee, WiFi, Bluetooth, etc...) sharing the same radio spectrum. Yet, a game theoretic approach has been proposed in our previous work to deal with this issue [20], [21].

- *Storage and privacy of health data in a cloud environment:* The data exchange among a group of persons within a BBN could be motivated by the rapid growth of cloud-computing market. Nevertheless, the thought of one's sensitive health data, traveling from person to person until reaching a virtual server, is a bit unsettling, and it introduces further security issues for U-health applications.

- *Heterogeneous devices and traffic:* BBNs should be able to handle heterogeneous traffic, ranging from plain messages to real-time audio and video contents, and support diverse transmission rates, especially between the WBANs' coordinators. Moreover, special mechanisms should be implemented to handle new devices in the WBAN neighborhood, enabling the seamless addition or removal of WBANs during roaming or link failures, without affecting the BBN operation.

- *Ethical challenges:* whereas Medicine is a profession which is heavily regulated by government authority, computer science and ICT services are notoriously lacking in such regulations. Therefore, a number of ethical considerations, including privacy, equity, liability and responsibility to the error are involved.

Protocol	Energy-eff.	Reliability	QoS	Mobility	Security	Intra-WBAN	Inter-WBAN
EAAODV [3]	✓		✓	✓		✓	
SIMPLE [5]	✓	✓				✓	
M-ATTEMPT [4]	✓		✓	✓		✓	
EAWD [6]	✓	✓		✓		✓	
MoBAN [14]				✓		✓	✓
McMAC [10]	✓	✓	✓			✓	
ZEQoS [11]	✓	✓	✓	✓		✓	✓
RACOON [12]		✓				✓	✓
PSR [15]		✓		✓	✓	✓	

Table III: Summary and comparison of existing WBAN solutions which can be extended to BBN environment.

V. ACKNOWLEDGMENT

VI. CONCLUSION

In this survey, we have provided a brief overview of the current proposals related to WBANs and their possible application in body-to-body networks design. We mainly discussed the major challenges of inter-WBANs communications focusing on three principal axes: energy efficiency, quality of service (QoS) and mobility prediction. At the end, a list of candidate protocols is given and open research issues are discussed. Therewith, BBNs are expected to offer a potential wide range of ubiquitous healthcare benefits to patients, medical personnel and overall society, including numerous community activities. As part of our future work, we plan to design a routing protocol for inter-WBANs communications within a BBN, considering the aforementioned proposals which should be tailored to fit BBN specific requirements. Indeed, effective incentives are intended to improve the accuracy of BBN deployment and coexistence within the existing infrastructures, in order to ensure public safety and improve the Quality of Life for future human generations.

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