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ORIGINAL PAPER

A Comprehensive Survey of Wireless Body Area Networks

On PHY, MAC, and Network Layers Solutions

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Abstract Recent advances in microelectronics and integrated circuits, system-on-chip design, wireless communication and intelligent low-power sensors have allowed the realization of a Wireless Body Area Network (WBAN). A WBAN is a collection of low-power, miniaturized, invasive/non-invasive lightweight wireless sensor nodes that monitor the human body functions and the surrounding environment. In addition, it supports a number of innovative and interesting applications such as ubiquitous healthcare, entertainment, interactive gaming, and military applications. In this paper, the fundamental mechanisms of WBAN including architecture and topology, wireless implant communication, low-power Medium Access Control (MAC) and routing protocols are reviewed. A comprehensive study of the proposed technologies for WBAN at Physical (PHY), MAC, and Network layers is presented and many useful solutions are discussed for each layer. Finally, numerous WBAN applications are highlighted.

Keywords Implant communication · Physical · WBAN · MAC · Networking · Routing · Survey

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Acronyms and abbreviations

ALTR	Adaptive Least Temperature Routing
AES	Advanced Encryption Standard
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CAP	Contention Access Period
CFP	Contention Free Period
CCA	Clear Channel Assessment
C1/C2	Control Channels
CE	Consumer Electronics
CTR	Counter
CBC	Cipher-block Chaining
CCM	Counter with CBC
CRC	Cyclic Redundancy Check
CAB	Coefficient of Absorption and Bioeffects
CICADA	Cascading Information Retrieval by Controlling Access with Distributed slot Assignment xprotocol
CBR	Constant Bit Rate

DTDMA	Reservation-based Dynamic TDMA Protocol
ERP	Effective Radiated Power
ECG	Electrocardiogram
FCC	Federal Communication Commission
FDTD	Finite Difference Time Domain
GDP	Gross Domestic Product
GTS	Guaranteed Time Slot
H-MAC	Heart-beat Driven MAC Protocol
HEC	Hydroxyl Ethyl Cellulose
H-V	Horizontal-Vertical Polarisation
H-H	Horizontal-Horizontal Polarisation
IEEE	Institute of Electrical and Electronics Engineers
ISM	Industrial, Scientific, and Medical band
LPL	Low Power Listening
LBT	Listen Before Talking
LOS	Line Of Sight
LTR	Least Temperature Routing
LTRT	Least Total Route Temperature
MAC	Medium Access Control
MICS	Medical Implant Communications Service
MAC (bold letters)	Message Authentication Code
MN	Master Node
MS	Monitoring Station
NIST	National Institute of Standards and Technology
NLOS	Non-line Of Sight
NS2	Network Simulator 2
PHY	Physical Layer
PB-TDMA	Preamble-based TDMA Protocol
QoS	Quality of Service
RF	Radio Frequency
REMCOM	a software company (http://www.remcom.com/)
SAR	Specific Absorption Rate
TDMA	Time Division Multiple Access
TSRP	Time Slot Reserved for Periodic Traffic
TSRB	Time Slot Reserved for Bursty Traffic
TARA	Thermal Aware Routing Algorithm
TIP	Temperature Increase Potential
UWB	Ultra-wide Band
V-V	Vertical-Vertical Polarisation
V-H	Vertical-Horizontal Polarisation
WBAN	Wireless Body Area Network
WMTS	Wireless Medical Telemetry Services
WASP	Wireless Autonomous Spanning Tree Protocol
WSN	Wireless Sensor Network
XFDTD	a 3d Electromagnetic simulation software package
XOR	Exclusive OR

Introduction

Current healthcare systems are facing new challenges due to the rate of growth of the elderly population (persons 65 years old and over) and limited financial resources. According to the US Bureau of the Census, the number of old people (65–84 years old) is predicted to double from 35 million to 70 million by 2025 [1]. This trend shows that the world elderly population will double from 375 million in 1990 to 761 million in 2025. Furthermore, overall healthcare expenditure in the US was $1.8 trillion in 2004, and this number is projected to be triple by 2020, or 20% of the US Gross Domestic Product (GDP) (http://www.who.int/) [2]. The impending health crisis attracts researchers, industrialists, and economists toward optimal and quick health solutions. The non-intrusive and ambulatory health monitoring of patient's vital signs with real time updates of medical records via the internet provides economical solutions to the challenges that health care systems face. The remote monitoring of body status and the surrounding environment is therefore becoming more important for sporting activities, members of emergency, military and health care services. The levels of fitness required for the very competitive international sporting events require athletes to be at the very pinnacle of fitness with every muscle used to its utmost. Furthermore, many body functions are traditionally monitored and separated by a considerable period of time. This can give an incomplete picture of what is really happening.

Consider a patient visiting a doctor for a blood pressure check; he/she may be anxious and thus have elevated pressure resulting in an inaccurate diagnosis. If, however, the patient can be fitted with a simple monitoring system that requires no intervention, then a picture can be built up of how the pressure changes throughout the day when he/she goes about their normal business. This gives a better picture of what is happening and remove inaccurate results caused by going to visit the doctor. To achieve these requirements, monitoring of movement and body functions are essential. This monitoring requires the sensors and wireless system to be very lightweight and to be integrated unobtrusively into the clothing.

A Wireless Body Area Network (WBAN) allows the integration of intelligent, miniaturized, low-power sensor nodes in, on, or around a human body to monitor body functions and the surrounding environment. Each intelligent node has enough capability to process and forward information to a base station for diagnosis and prescription. A WBAN provides long term health monitoring of patients under natural physiological states without constraining their normal activities. It can be used to develop a smart and affordable health care system and can be a part of diagnostic procedure, maintenance of chronic condition, supervised recovery from a surgical procedure and can handle emergency events [3]. Generally WBAN consists of in-body and on-body area networks. An in-body area network allows communication between invasive/implanted devices and a base station. An on-body area network, on the other hand, allows communication between non-invasive/wearable devices and a base station. In this paper we present a comprehensive study of the proposed technologies for WBAN at Physical (PHY), Medium Access Control (MAC), and Network layers. To the best of our knowledge, no study has been conducted to analyze the behaviour of these layers for WBAN. Different technologies proposed at different layers are thoroughly studied and many useful solutions are discussed for each layer. Since many researchers including those involved in the IEEE 802.15.6 are focusing on PHY/MAC standardization, the network layer has received limited concentration. We therefore study the importance of network protocols (i.e. routing protocols) for WBAN and explain how these protocols can be used to improve the lifetime of a network.

The rest of the paper is categorized into six sections. Section "WBAN architecture" introduces WBAN architecture and the traffic model. Section "PHY layer communication" is related to the implant communication (at the PHY layer) and presents a brief discussion on in-body RF communication and the propagation pattern in or around a human body. Section "MAC layer communication" discusses low-power mechanisms and the proposed MAC protocols for WBAN. Section "Network layer communication" presents a discussion on routing protocols for WBAN followed by future research directions. The final section concludes our work.

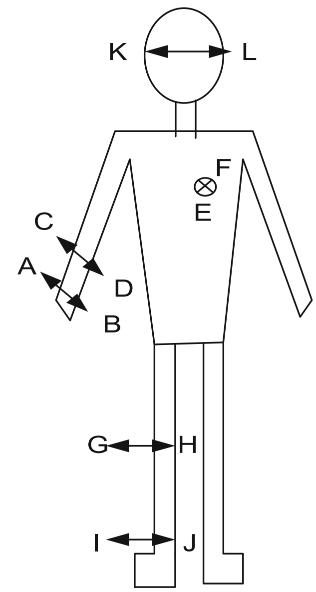


Fig. 1 On-body nodes distribution

WBAN architecture

A WBAN consists of in-body and on-body nodes that continuously monitor a patient's vital information for diagnosis and prescription. Some on-body nodes can be used for multimedia and gaming applications. These nodes can have different topologies such as star, tree, and mesh topologies. However, the most common is a star topology where the nodes are connected to a central coordinator in star manner. Depending on the application, several nodes are sometimes combined to process and transfer data to a central coordinator. Since

Table 1 On-body nodes links description [4]

Link	Description
A–B	Through the hand
C–D	Through the wrist
E–F	Torso, front to back
G–H	Through the thigh
I–J	Through the ankle
K–L	Left ear to right ear
M–N	Glucose sensor to Glucose pump

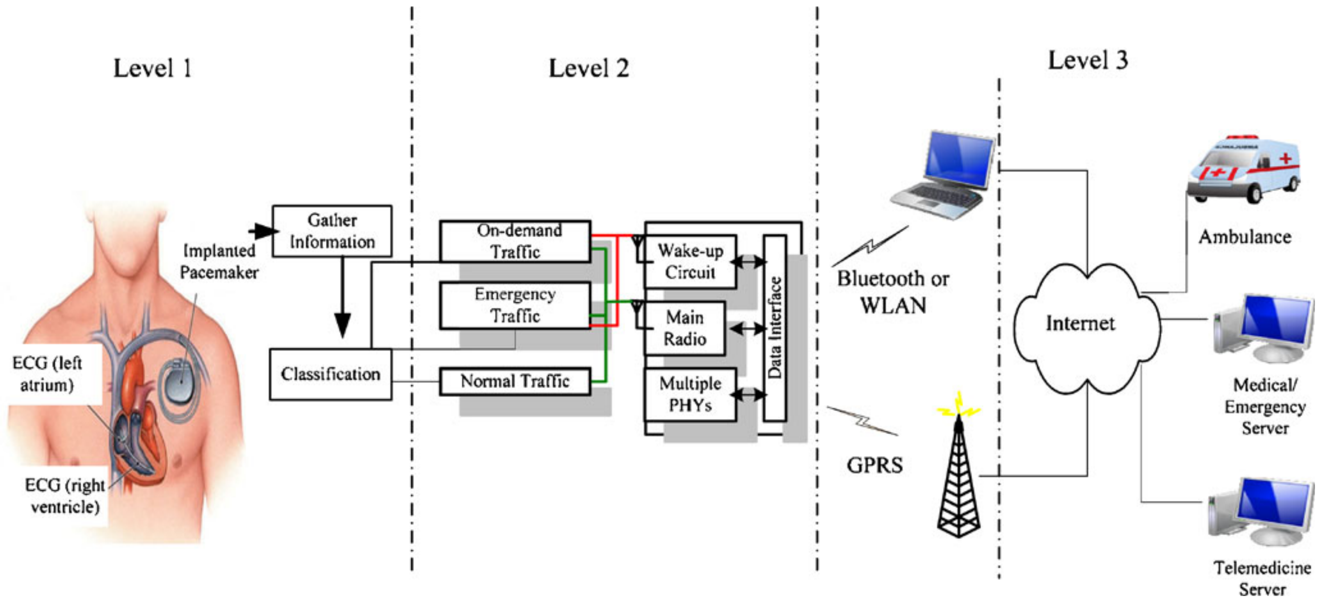


Fig. 2 WBAN architecture for medical and non-medical applications

some parts of the human body move relative to each other, this trend should be considered when deploying on-body nodes. Figure 1 shows a simple example of on-body nodes deployed on a human body [4]. The nodes for audio and video transmission should be carefully deployed keeping in consideration the sensitivity of head nerves. Furthermore, sensitivity of eye to Specific Absorption Rate (SAR)[1] should be considered. The nodes located on the torso and head do not move much relative to each other. However, the nodes located on extremities such as legs and arms, torso and the head, may move relative to each other. Table 1 shows the possible links between on-body nodes. The in-body and on-body nodes are quite low power and are not able to generate power available for the whole body SAR. However, these nodes are in close proximity to or inside the human body and therefore the localized SAR could be quite large if all the available power is deposited in a small volume. As a result, the localized SAR into the body must be minimized [4].

A WBAN uses Wireless Medical Telemetry Services (WMTS), unlicensed Industrial, Scientific, and Medical (ISM), Ultra-wideband (UWB) and Medical Implant Communications Service (MICS) bands for data transmission. WMTS is a licensed band used for medical telemetry system. The Federal Communication Commission (FCC) urges the use of WMTS for medical applications due to fewer interfering sources (http://wireless.fcc.gov/services). However, only authorized users such as physicians and trained technicians are eligible to use this band. Furthermore, the restricted WMTS (14 MHz) bandwidth cannot support video and voice transmissions. The alternative spectrum for medical applications is the 2.4 GHz ISM band that includes guard bands to protect adjacent channel interference. But this band is also used by other technologies, such as Bluetooth, Zigbee, and WiFi. A licensed MICS band (402–405 MHz) is dedicated to implant communication. Figure 2 shows the WBAN architecture for medical and non-medical applications where the WBAN traffic is classified into On-demand, Emergency, and Normal traffic. On-demand traffic is initiated by the coordinator or doctor to acquire certain information, mostly for the purpose of diagnostic recommendations. This is further divided into continuous (in case of surgical events) and discontinuous (when occasional information is required). Emergency traffic is initiated by the nodes when they exceed a predefined threshold and should be accommodated in less than one second. This kind of traffic is not generated on regular intervals and is totally unpredictable. Normal traffic is the data traffic in a normal condition with no time critical and on-demand events. This includes unobtrusive and routine health monitoring of a patient and treatment of many diseases such as gastrointestinal tract, neurological disorders, cancer detection, handicap rehabilitation, and the most threatening heart disease. The normal data is collected and processed by the coordinator. Depending on the application requirements, the coordinator may contain a wakeup radio circuit to accomodate life-critical

[1] Energy absorbed by the body when exposed to RF waves and is measured in watts per kilogram

events and an additional circuit to connect multiple physical layers (see Section "A power-efficient MAC protocol for WBAN"). The coordinator is further connected to telemedicine and medical servers for relevant recommendations.

PHY layer communication

There are several ways to communicate with a human body implant, including methods that use electromagnetic coupling and Radio Frequency (RF) communication. Both are wireless and their use depends on the applications. Comprehensive details about the implant communication are presented in [5]. In this section, we briefly discuss electromagnetic coupling, in-body RF communication, antenna design, and the propagation pattern in or around a human body. This section is concluded with useful remarks.

Electromagnetic coupling

Electromagnetic coupling means that the transponder and the antenna are coupled by the magnetic flux through coils, much like a transformer. Different applications still use electromagnetic coupling to provide a communication link to implanted devices, with an external coil held very close to the patient that couples to a coil implanted just below the skin surface. The implant is powered by the coupled magnetic field and requires no battery for communication. Data is transferred from the implanted device by altering the impedance of the implanted loop that is detected by the external coil and electronics. This type of communication is commonly used to identify animals that have been injected with an electronic tag. Electromagnetic induction is commonly used when continuous, long-term communication is required, such as for a cochlear implant used to restore hearing. It achieves the best power transfer when using large transmit and receive coils. However, it is impractical when space is an issue or devices are implanted deep within the patient. This technique does not support very high data rate applications and cannot initiate a communication session from inside of the body. For further details, see [6].

In-body RF communication

RF communication enables a two-way data link that allows an implant to initiate a communication session. This requires an implanted battery, electronics, and a suitable antenna. Earlier, some in-body communication systems used the ISM bands, but the MICS band is gaining worldwide acceptance for in-body communication systems. This band has a power limit of 25 μW in air and is split into ten wide channels where each channel has 300 KHz bandwidth.

The human body is a medium that poses numerous wireless transmission challenges. The body is composed of various components that are not predictable and will change as the patient ages, gains or loses weight, or even changes posture. While there are simple formulas for designing free-space communications, it is very difficult to calculate the performance of an in-body communication system, as each individual is different [5]. Generally, the implant operates in a wide variety of environments and positions that change with time. Before considering any in-body data transmission, the effects of the human body on the RF signal must be understood. Unlike the usual communication through constant air, the various tissues and organs within the body have their own unique conductivity, dielectric constant and characteristic impedance. As a result, signal level and propagation from an implanted device to a remote receiver is unpredictable. Typical dielectric constant ε_r, conductivity ρ and characteristic impedance $Z_0(\Omega)$ properties of muscle and fat are shown in Table 2. Not only do these values vary from person to person, they also change as a patient moves, changes weight and ages. The high dielectric constant ε_r works to reduce the physical size of any antenna.

Antenna design

According to [5], an in-body antenna needs to be tuneable using an intelligent transceiver and routine. This enables the antenna coupling circuit to be optimized and to obtain the best signal strength. Often size constraints dictate the choice of a non-resonant antenna. A non-resonant antenna has lower gain and therefore is less sensitive on the receiving side and radiates low power generated by the transmitter. This makes design of the antenna coupling circuit even more important.

A patch antenna can be used in the implants with a $0V$ RF backplane. Generally, patch antennas are comprised of a flat substrate coated on both sides with a conductor. The substrate is typically alumina or a similar

Table 2 Body electrical properties

Frequency	Muscle			Fat		
	(ε_r)	ρ (S.m^{-1})	$Z_0(\Omega)$	(ε_r)	ρ (S.m^{-1})	$Z_0(\Omega)$
100	66.2	0.73	31.6	12.7	0.07	92.4
400	58	0.82	43.7	11.6	0.08	108
900	56	0.97	48.2	11.3	0.11	111

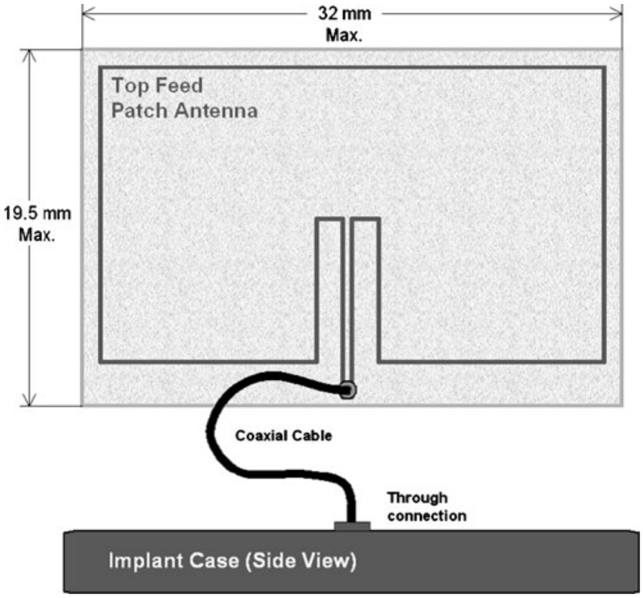


Fig. 3 Patch with top surface connection

body-compatible material, with a platinum/iridium coating on both surfaces. The upper surface is the active face and is connected to the transceiver. The back face is typically connected to the implant $0V$. The connection to the transceiver needs to pass through the case where a hermetic seal is maintained, requiring a feed-through. The feed-through must have no filter capacitors present. The connection to the top (active) surface can be established by a hole through the substrate or by a wire connected to the top, as given in Fig. 3. The back face can be connected to the case with conductive epoxy if it is attached to $0V$.

REMCOM conducted several experiments to compute the input impedance, radiation gain pattern, and SAR of a patch antenna inside a human body using XFDTD (http://www.remcom.com/xfdtd/). They considered a patch antenna of 19.2 mm × 32 mm dimensions and 2 mm thickness with a substrate of lossless dielectric permittivity 9.5. Initial calculations for the patch antenna were performed in free space, resulting an input impedance of 0.175 + j 11.8 Ohms with 100% efficiency as given in Fig. 4a. However, when the same patch antenna was embedded inside the human body, it resulted in 4.05 + j 15.61 Ohms impedance with an efficiency of 0.23% as given in Fig. 4b. The reduction in the gain was due to the loss in the body tissues.

Another option is to use a loop antenna in the implants. The loop antenna operates mostly in the magnetic field, whereas the patch operates mostly in the electric field. The loop antenna delivers comparable performance to that of a dipole, but with smaller size.

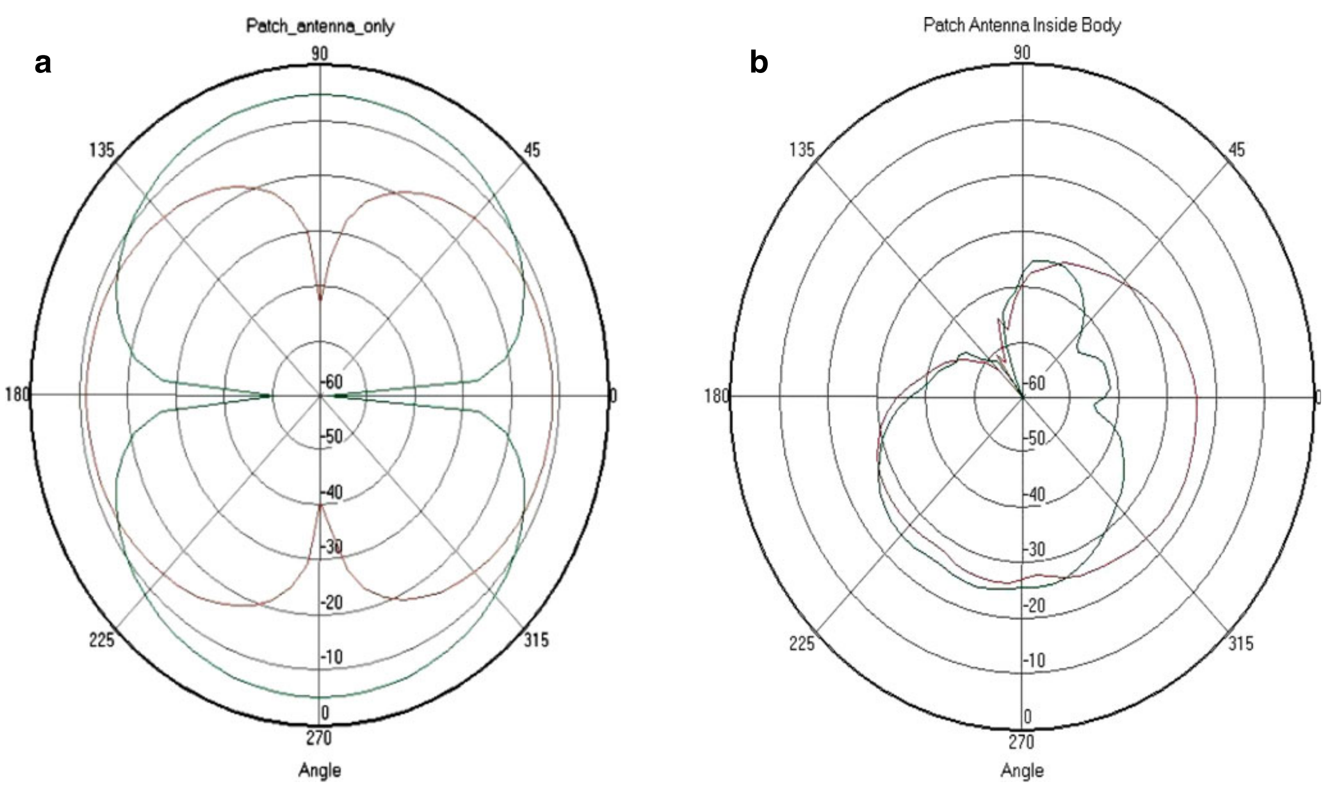


Fig. 4 **a** Patch antenna gain in free space. **b** Patch antenna gain inside body

Also the magnetic permeability of muscle or fat is very similar to that of air, except the dielectric constant that varies considerably. This property enables an antenna to be built and used with much less need for retuning. A loop antenna can be mounted on the case in a biocompatible structure.

Further details of antenna design can be found in [7–9], and [10]. Generally, the performance of an implant inside a human body is difficult to predict or simulate. There are no reliable equations to consider and therefore only limited simulation models can be used. The simulations provide a guide to the propagation in or around a human body but do not guarantee performance. Accurate approximation to a human body can be made using a body phantom (see Section "Implant materials") filled with a liquid that mimics the electerial properties of the human body.

Antenna testing

Before designing a matching network for the antenna or transceiver interface, it is necessary to measure the impedance of the antenna within a representative medium. Testing an implant antenna in air does not represent the in-body impedance. To measure the in-body impedance, a phantom comprising a tank of liquid is used. The liquid is a mixture of water, sodium chloride, sugar and Hydroxyl Ethyl Cellulose (HEC), which mimics muscle or brain tissue [11] in the frequency range 100 MHz to 1 GHz as given in Table 3. A way of measuring an antenna with a low radiation resistance is described in [12].

Matching network

Once the impedance of the antenna is known it can be matched to the transceiver. When implanted, the transceiver needs to be capable of optimization by having access to an array of capacitors that can be switched in or out across RF terminals. These can be controlled by an automatic routine within the transceiver or by a microcontroller. This enables the transceiver performance to be optimized. Antenna tuning circuits are required to present optimum load impedance to the transmitter. It should be noted that this does not necessarily lead to a conjugate impedance match. The design of matching networks is discussed in [13].

Table 3 Body tissue recipes

Ingredient	% of weight (100 MHz to 1 GHz)	% of weight (1.5–2.5 GHz)
Water	52.4	45.3
Sugar	45.0	54.3
Salt (NaCl)	1.5	0.0
HEC	1.1	0.4

Base station antennas

The implant and the base-station antennas are often very different. A base-station, with a 2.45 GHz wakeup transmitter and 403 MHz communication function, typically uses two separate antennas as shown in Fig. 5. These can be as large as aesthetics can allow. Base station antennas result in a higher gain than the small implanted antenna. The base station could also use more than one antenna to overcome the effect of multi-path fading and polarization, as discussed in [14], and to reduce the signal strength. If space permits, an arrangement of four antennas with suitable switching and software optimization can be employed.

Implant materials

An implant case is typically made of titanium or implant-grade stainless steel. In-body wires are made of platinum and iridium, which have conductivities in the order of 9.52 MS m^{-1} and 5.2 MS m^{-1}, respectively. The conductivity of copper is 58 MS m^{-1}. At present these are the only two metals that can be used for conductors to contact the body. The low value of electrical conductivity should be compensated by using the thickest material possible. The substrate needs to be non-toxic, mechanically stable and insoluble in blood

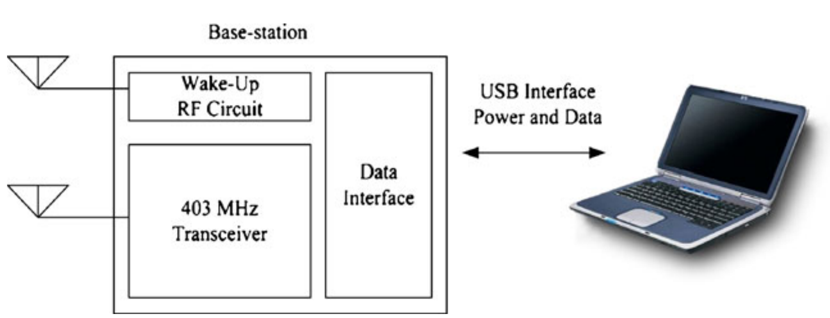


Fig. 5 Base station and PC

or other body fluids. Alumina is a material found to be acceptable. Earlier titania, ziconia and multi-layer substrates have been considered. The entire implant is often coated in a passive material such as parylene. Table 4 shows Parylene has good water resistant properties compared to other materials and is acceptable for in-body use. Typical coatings are in the order of a few microns thick. Coating cannot be used to isolate a conductor from the body, as blood will dissolve most plastics or coating and will become porous.

Signal propagation

The propagation pattern of the antenna is required to predict the performance of an implant. Measurements can be made using a body phantom and immersing a battery test implant into it. The authors of [15] conducted several experiments to analyze the performance of an implant inside a human body/phantom. The phantom was filled with a liquid that mimicked the electrical properties of the human body tissues. The distance from the body phantom to the base-station was 3 m. Further details can be found in [15] where the authors made useful measurements over a set distance with all combinations of implant and test antenna polarisations, i.e., Vertical-Vertical (V-V), Horizontal-Vertical (H-V), Vertical-Horizontal (V-H), and Horizontal-Horizontal (H-H) polarisations. Typical results are shown in Fig. 6 where the Effective Radiated Power (ERP) is calculated from the received signal power and the antenna characteristics. It can be seen that there is a significant difference in signal levels with polarisation combinations and depth. From the results and known antenna parameters the ERP can be calculated. The V-V polarisation combination shows an increase in signal level at 4 cm depth and then shows a decline. From the Figure it can be seen that signal level is affected by the depth and different polarisation combinations. Such a test needs to be done with an antenna that is to be used in the final product.

Although most of the performance of an implant link is assessed by measurement using the body phantom, simulation can also help to understand the propagation

Table 4 Water uptake and other parameters of various polymers, noting these are not all biocompatible [5]

Material	ε_r	Loss tangent	Water absorption (%)
Parylene (C type)	2.9	0.013	0.01
Polyether ketone	3.4	0.005	0.11
Polyether imide	3.2	0.0026	0.25
Polyether ether ketone	3.3	0.0035	0.11

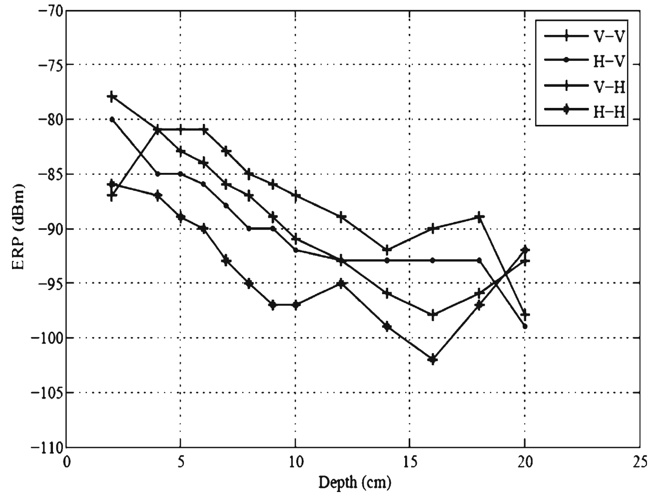


Fig. 6 ERP vs. depth of polarisation combinations

pattern. K.Sayrafian et al. carried out extensive simulations at National Institute of Standards and Technology (NIST) to characterize the MICS path loss for communication to/from an implant or between two implants inside a human body [16]. The model was based on 4 near surface implants and 2 deep tissue implants for a typical male body. Figure 7 shows the MICS path loss for different communication scenarios, where the near surface implants reside within a definable distance (20 mm in the figure) from the body surface and the deep tissue implants completely reside inside the body. It can be seen that direct communication between two deep implants results in an increasing path loss. There-

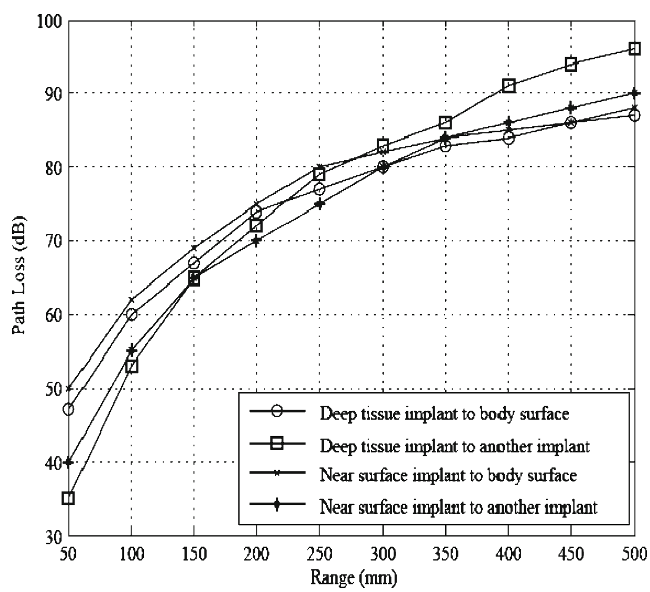


Fig. 7 Path loss model vs. Distance scatter plot

fore, peer to peer communication between the implants should not considered. However, an indirect communication through a central coordinator is possible.

In case of on-body communication systems, signals often propagate across the body surface. This propagation may be a combination of surface waves, creeping waves, diffracted waves, scattered waves and free space propagation depending on the antenna position [17]. Like implantable antennas, the design of on-body antennas and the signal propagation on the human body is becoming increasingly important. Unlike in-body communication, antennas required for on-body communication should direct the radiation along the body surface with the appropriate polarisation. Several groups studied the nature of on-body propagation where characterization of path loss with distance and path gain are examined at several frequencies. Kamarudin et al. performed the measurements of the path loss of various antennas for on-body communication and concluded that for the majority of antenna positions and body postures, monopole antennas yield the lowest loss [18]. However, thin wire monopoles are susceptible to damage, and therefore antennas in the form of buttons are developed for 2.4 GHz and 5.8 GHz ISM bands, and for the UWB band, respectively.

A study conducted at the University of Birmingham concluded that some on-body links achieve benefit from diversity [19]. The stationary body results in some multipath fading but body movement gives rise to fading. Table 5 shows the diversity gain in two channels obtained by using a diversity antenna consisting of two quarter wavelength monopoles spaced by 5.3 cm on a continuous ground plane. The transmit antenna was fixed on the belt. The table shows that diversity gain is greater for the belt-to-head channel than that of the belt-to-ankle. For other postures the diversity gain is comparatively less. Further details about on-body antennas and propagation are present in [20, 21], and [22].

Discussion

While designing an implant, careful consideration must be given to propagation pattern of the antenna, the implant case, and the materials used. There are a number of antenna options to be used in a given network. Testing to determine antenna characteristics is important to ensure the effective design of a matching network. Additionally, multiple antennas can be used if there is a polarisation or multi-path fading problem. With careful measurement and observation (including a clear understanding of the above topics), a number of implants can be effectively designed in high volume and can be integrated into a patient monitoring system for unobtrusive health monitoring.

The above discussion only considered communication to or from a single implant. When multiple implants are deployed in a human body, it requires energy conserving mechanisms to efficiently utilize and share the channel. In other words, it requires a power efficient MAC protocol that should control the channel access and the dominant sources of energy waste. The next sections present a comprehensive discussion on MAC layer communication in WBAN.

Table 5 Diversity gain at 2.4 GHz ISM band for jogging postures

Diversity gain	Rx placement right head	Rx placement ankle
Selection combining	8.57	5.14
Equal gain combining	9.62	6.13
MRC	10.28	6.46

MAC layer communication

In this section, we discuss the role and importance of MAC protocols for WBAN. We first outline major MAC requirements of WBAN. Then we analyze and compare many existing low-power mechanisms such as Low Power Listening (LPL), Contention and scheduled-contention, and Time Division Multiple Access (TDMA) mechanisms for WBAN. Additionally, we overview a number of proposed MAC protocols for WBAN including a case study of our proposed protocol and discuss their strengths and weaknesses . The final section presents the discussion.

General overview

In WBAN, the RF part of the sensor consumes most of the energy and hence becomes one of most important entities to be considered. The MAC protocol plays a significant role in controlling/duty cycling the RF module and in reducing the average energy consumption of the sensor node. In other words, the MAC protocol is required to achieve maximum throughput, minimum delay, and to maximize the network lifetime by controlling the main sources of energy waste, i.e., collision, idle listening, overhearing, and control packet overhead. A collision occurs when more than one packet transmits data at the same time. The collided packets have to be retransmitted, which consumes extra energy. The second source of energy waste is idle listening, meaning that a node listens to an idle channel to receive data. The third source is overhearing, i.e., to receive packets

Table 6 CSMA/CA vs. TDMA protocols

Performance metric	CSMA/CA	TDMA
Power consumption	High	Low
Traffic level	Low	High
Bandwidth utilisation	Low	Maximum
Scalability	Good	Poor
Effect of packet failure	Low	Latency
Synchronisation	Not applicable	Required

that are destined to other nodes. The last source is control packet overhead, meaning that control information are added to the payload. A minimal number of control packets should be used for data transmission.

Generally MAC protocols are grouped into contention-based and schedule-based MAC protocols. In contention-based MAC protocols such as Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) protocol, nodes contend for the channel to transmit data. If the channel is busy, the node defers its transmission until it becomes idle. These protocols are scalable with no strict time synchronization constraint. However, they incur significant protocol overhead. In schedule-based protocols such as TDMA protocol, the channel is divided into time slots of fixed or variable duration. These slots are assigned to nodes and each node transmits during its own slot period. These protocols are energy conserving protocols. The duty cycle of the radio is reduced and there is no contention, idle listening and overhearing problems. However, these protocols require frequent synchronization. Table 6 compares CSMA/CA and TDMA protocols [23].

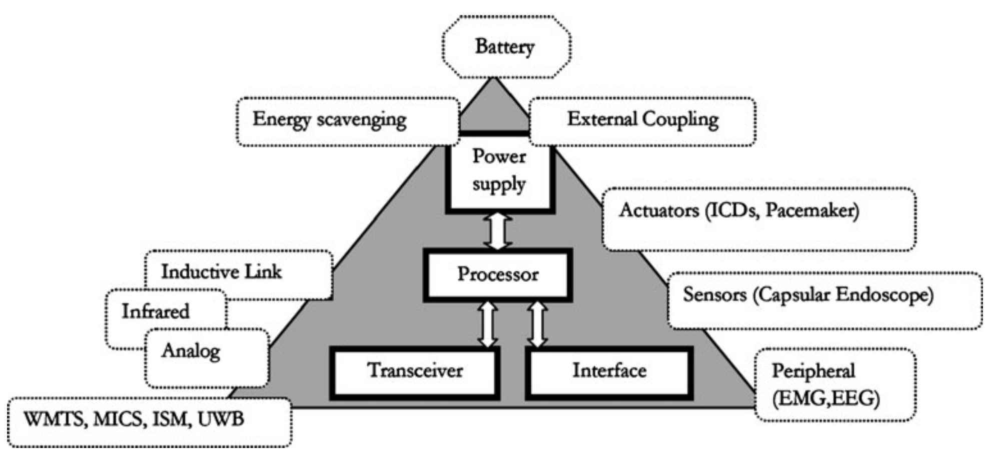
MAC requirements

As comprehensively discussed in [23], the most important attribute of a good MAC protocol for WBAN is energy efficiency. In some applications, the device should support a battery lifetime of months or years without interventions, while others may require a battery life of tens of hours due to the nature of the applications. For example, cardiac defibrillators and pacemakers have a lifetime of more than 5 years while swallowable camera pills have a lifetime of 12 h [4]. Power-efficient and flexible duty cycling techniques are required to solve the idle listening, overhearing and packet collisions problems. Furthermore, low duty cycle nodes should not receive frequent synchronization/control packets (beacon frames) if they have no data to send or receive. The WBAN MAC should satisfy the MAC transparency requirements, i.e., to operate on multiple physical layers (MICS, ISM, and WMTS) simultaneously. Figure 8 shows some of the potential issues of a MAC protocol for WBANs.

The Quality of Service (QoS) is also an important factor of a good MAC protocol for WBAN. This includes point-to-point delay and delay variation. In some cases, real-time communication is required for many applications such as fitness and medical surgery monitoring applications. For multimedia applications, latency should be less than 250 ms and jitter should be less than 50 ms. However, reliability, latency, and jitter requirements depend on the nature of the applications. For emergency applications, the MAC protocol should allow in-body or on-body nodes to get quick access to the channel (in less than one second) and to send the emergency data to the coordinator. One such example is the detection of irregular heartbeat, high or low blood pressure or temperature, and excessively low or high blood glucose level in a diabetic patient. Another example is when the node is dying. Reporting medical emergency events should have a higher priority than non-medical emergency (battery dying) events.

Since most of the traffic in WBAN is correlated [24], a single physiological fluctuation triggers many

Fig. 8 Potential issues of a MAC protocol for WBAN



sensors at the same time. In this case, a CSMA/CA protocol encounters heavy collisions and extra energy consumption. Additionally, in CSMA/CA protocol the nodes are required to perform Clear Channel Assessment (CCA) before transmission. However, the CCA is not always guaranteed in the MICS band since the path loss inside the human body due to tissue heating is much higher than in free space. Bin et al. studied the unreliability of a CCA in WBAN and concluded that for a given −85 dBm CCA threshold, the on-body nodes cannot see the activity of the in-body nodes when they are away at 3 m distance from the surface of the body [25]. The behavior of the CSMA/CA protocol for WBAN is studied in [26] where the authors concluded that the CSMA/CA protocol encounters heavy collision problems for high traffic nodes. TDMA-based protocols provide good solutions to the traffic correlation, heavy collision, and CCA problems. These protocols are energy conserving protocols because the duty cycle is reduced and there are no contention, idle listening, and overhearing problems. However, common TDMA needs extra energy for periodic time synchronization. All the sensors (with and without data) are required to receive control packets periodically in order to synchronize their clocks.

Low-power mechanisms in WBAN

Low-power mechanisms play an important role in the performance of a good MAC protocol for WBAN. They are categorized into Low Power Listening (LPL), Contention and scheduled-contention, and TDMA mechanisms. The following sections briefly explain each mechanism in the context of WBAN with examples. Further details about these mechanisms can be found in [23].

Low power listening

In the Low Power Listening (LPL) mechanism, nodes wake up for a short duration to check the channel activity without receiving any control packet(s). If the channel is idle the nodes go into sleep mode, otherwise they stays on the channel to receive the data. This is also called channel polling. The LPL is performed on a regular basis regardless of synchronization among nodes. The sender sends a long preamble before each message in order to detect the polling at the receiver. The BMAC [27] protocol is based on the LPL mechanism where an adaptive preamble sampling technique is used to minimize idle listening and overhearing. The LPL method has several advantages and disadvantages. The periodic sampling is efficient for high-traffic nodes and performs well under variable traffic conditions. However, it is ineffective for low-traffic nodes, especially for in-body nodes, where periodic sampling is not preferred due to strict power constraints. Since the WBAN topology is a star topology and most of the traffic is uplink, using LPL mechanism is not an optimal solution to support both in-body and on-body communication simultaneously.

Contention and scheduled-contention

In the Contention-based mechanism, nodes contend for the channel to transmit data regardless of any predefined schedule. The CSMA/CA protocol is a best example of the contention-based mechanism. However, in some cases we need to use a hybrid approach to access the channel, i.e., a combination of contention and scheduling mechanisms called a scheduled-contention mechanism. In this mechanism, scheduled and contention based schemes are combined to incur scalability and collision avoidance. The nodes adapt a common schedule for data communication. The schedules are exchanged periodically during a synchronization period. If two neighbouring nodes reside in two different clusters, they keep the schedules of both clusters, which results in extra energy consumption. The SMAC [28] protocol is a good example of a scheduled-contention mechanism designed for multi-hop Wireless Sensor Networks (WSNs). The scheduled-contention mechanism reduces idle listening using sleep schedules and performs well for multi-hop WSNs. However, considering this mechanism for WBAN reveals several problems for low-power in-body/on-body nodes such as pacemakers and defibrillator implants, which should not wake up periodically in order to exchange their schedules with other nodes. Furthermore, scheduled-contention mechanism may perform well for on-body applications but it does not provide reliable solutions to handle sporadic events including emergency and on-demand events. Handling sporadic events (emergency) require innovative solutions that allow in-body/on-body nodes to update the coordinator within strictly limited amount of time.

TDMA

In the TDMA mechanism, the channel is bounded by a superframe structure that consists of a number of time slots allocated by a base-station or a coordinator. Each node is assigned at least one slot enough to complete the transmission. Multiple slots can be assigned depending on the data volume. This mechanism is probably the best for WBAN since the time slots can be allocated to the nodes according to their traffic requirements. Although it performs well in terms of power consumption but consumes limited energy due to frequent synchronization. The Preamble-based TDMA (PB-TDMA) protocol is based on the TDMA mechanism [29] where nodes are assigned specified slots for collision-free data transmission using the preamble. As discussed in Section "MAC requirements", the CSMA/CA protocol is not a reliable protocol for WBAN due to unreliable CCA, traffic correlation, and heavy collision problems. The alternative is to adapt a TDMA protocol that can solve the aforementioned problems in a power-efficient manner. However, traditional TDMA protocols such as PB-TDMA have several problems, e.g., preamble overhearing and limitation of handling sporadic events. Solving these problems (including many others) for WBAN can reliably accommodate the heterogeneous traffic requirements.

Comparison of low-power mechanisms

Table 7 presents the characteristics of the LPL, schedule-contention, and TDMA mechanisms for WBAN. It shows that the LPL and the scheduled-contention are unable to accommodate the heterogeneous WBAN traffic including sporadic events. Although it is possible to develop new MAC protocols based on these mechanisms, they will not be able to satisfy all the requirements. For example, LPL mechanisms may perform well in case of periodic traffic but they are unable to accommodate aperiodic (unpredictable sporadic events) traffic and low duty cycle nodes in WBAN. Furthermore, the scheduled-contention mechanisms are unable to accommodate in-body nodes that do not require frequent synchronization or exchange of their schedules. The TDMA mechanisms provide good solutions to the variable WBAN traffic. The slots can be assigned according to the traffic volume of a node. Although in traditional TDMA protocols, nodes are required to synchronize at the beginning of each superframe boundary, this approach can be optimized for nodes that do not require frequent synchronization. One of the design approaches is to skip the synchronization control packets such as beacons and receive them whenever the nodes have data to send/receive. A detailed comparison of MAC protocols based on LPL, scheduled-contention, and TDMA mechanisms for WBAN is presented in [23] and summarized in Appendix A.

Proposed MAC protocols for WBAN

The following sections give a brief overview of different MAC protocols proposed for WBAN and highlight their strengths and weaknesses.

IEEE 802.15.4 MAC protocol

IEEE 802.15.4 is a low-power standard designed for low data rate applications [30]. It offers three operational frequency bands: 868 MHz, 915 MHz, and 2.4 GHz bands. There are 27 sub-channels allocated in IEEE 802.15.4, i.e., 16 sub-channels in 2.4 GHz

Table 7 Comparison of LPL, scheduled-contention, and TDMA mechanisms for WBAN [23]

LPL	Scheduled-contention	TDMA
10 times less expensive than listening for full contention period	Listening for full contention period	Low duty cycle
Asynchronous	Synchronous	Synchronous-Fine grained time synchronisation
Sensitive to tuning for neighbourhood size and traffic rate	Sensitive to clock drift	Very sensitive to clock drift
Poor performance when traffic rates vary greatly (Optimised for know periodic traffic)	Improved performance with increase in traffic	Limited throughput and number of active nodes
Receiver and polling efficiency is gained at the much greater cost of senders	Similar cost incurred by sender and receiver	Require clustering >>cost incurred more on cluster head
Challenging to adapt LPL directly to new radios like IEEE 802.15.4	Scalable, adaptive, and flexible	Limited scalability and adaptability to changes on number of nodes
Unable to accommodate aperiodic traffic (unpredictable sporadic events) and low duty cycle nodes in WBAN. Very hard to satisfy the WBAN traffic heterogeneity requirements	Low duty cycle nodes do not require frequent synchronization/exchange of schedules in WBAN. Hard to satisfy the WBAN traffic heterogeneity requirements	Low duty cycle nodes do not require frequent synchronization at the beginning of each superframe. Easy to satisfy the WBAN traffic heterogeneity requirements

band, 10 sub-channels in 915 MHz band and one sub-channel in the 868 MHz band. IEEE 802.15.4 MAC has two operational modes: a beacon-enabled mode and a non-beacon enabled mode. In a beacon-enabled mode, the network is controlled by a coordinator, which regularly transmits beacons for device synchronization and association control. The channel is bounded by a superframe structure as illustrated in Fig. 9a. The superframe consists of both active and inactive periods. The active period contains three components: a beacon, a Contention Access Period (CAP), and a Contention Free Period (CFP). The coordinator interacts with nodes during the active period and sleeps during inactive period. There are maximum seven Guaranteed Time Slots (GTS) in the CFP period to support time critical traffic. In the beacon-enabled mode, a slotted CSMA/CA protocol is used in the CAP period while in the non-beacon enabled mode, unslotted CSMA/CA protocol is used.

IEEE 802.15.4 has remained the main focus of research during the past few years. Some of the main reasons of selecting IEEE 802.15.4 for WBAN are low-power communication and support of low data rate WBAN applications. Nicolas et al. investigated the performance of a non-beacon IEEE 802.15.4 for low upload/download rates (mostly per hour) [31]. They concluded that the non-beacon IEEE 802.15.4 results in 10 to 15 years sensor lifetime for low data rate

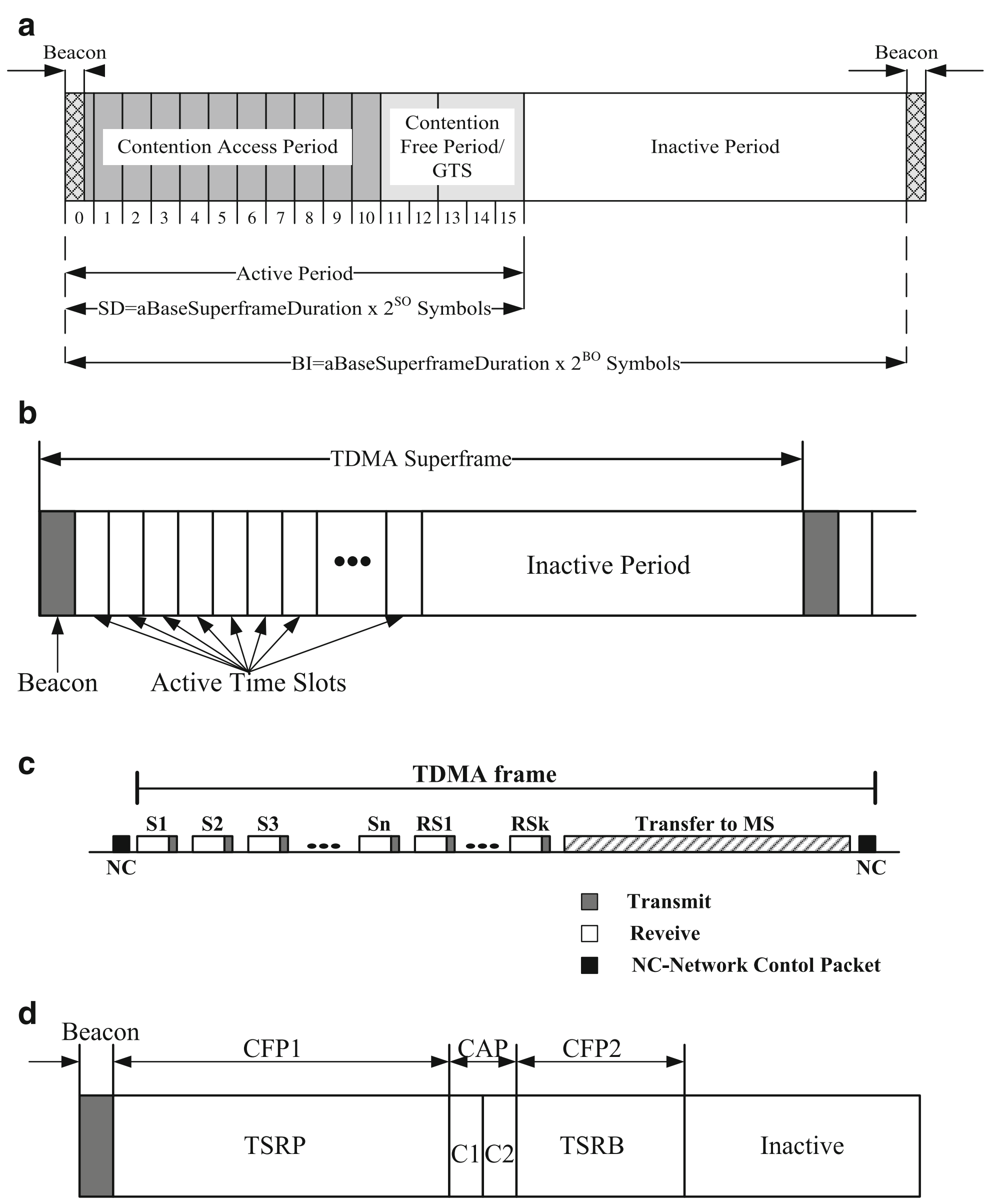


Fig. 9 **a** IEEE 802.15.4 superframe structure. **b** TDMA superframe structure of battery-aware TDMA protocol [36]. **c** TDMA timing of energy-efficient TDMA MAC protocol [38]. **d** Superframe structure of priority-guaranteed MAC protocol [39]

and asymmetric WBAN traffic. However, their work considered data transmission on the basis of periodic intervals, which is not a real WBAN scenario. Furthermore, the data rate of in-body and on-body nodes varies ranging from 10 Kbps to 10 Mbps, which reduces the lifetime of the sensor nodes. Li et al. studied the behaviour of slotted and unslotted CSMA/CA mechanisms and concluded that the unslotted mechanism performs better than the slotted one in terms of throughput and latency but with high cost of power consumption [32]. Additionally, Dave et al. studied the energy efficiency and QoS performance of IEEE 802.15.4 and IEEE 802.11e [33] MAC protocols under two generic applications: a wave-form real time stream and a real-time parameter measurement stream [34]. A series of experiments to evaluate the impact of IEEE 802.11 and microwave ovens on the IEEE 802.15.4 transmission are carried out in [35]. Other details about IEEE 802.15.4 for WBAN can be found in [23].

Battery-aware TDMA protocol

The authors of [36] proposed a battery-aware TDMA protocol for WBAN, which takes into account the battery discharge dynamics, wireless channel models, and packet queuing characteristics. The battery's recovery capacity effects [37] are considered to maximize the idle periods of sensor nodes while maintaining the required QoS. In addition, the proposed protocol utilizes the electrochemical properties of batteries and the characteristics of wireless fading channels. The channel is bounded by TDMA superframe structures as given in Fig. 9b, where each superframe consists of a beacon, an active period, and an inactive period. The beacon is used to indicate the length of the frame period and helps to estimate the channel information. The sensor nodes receive the beacons periodically and subsequently transmit data in the active period. No data transmission takes place in the inactive period. The low duty cycle nodes can decide whether or not to receive beacons and to utilize the channel at different superframes. Although this protocol efficiently recovers the battery's capacity and prolongs the lifespan of sensor nodes, it has several drawbacks. First, the average delay and the packet drop rate are high since in some cases the nodes hold the packets in their buffers for long time. Second, there is no reliable mechanism for life-critical sporadic or emergency events. Third, the current version of the protocol is not suitable for implants however it can be easily improved to achieve reliable communication in the MICS band. Finally, the protocol considers Nakagami distribution, which does not accurately represent the complexity of real-time WBAN applications.

Energy-efficient TDMA-based MAC protocol

This protocol [38] is mainly developed for streaming large amount of data. The authors of the paper exploited the fixed network structure (static topology) of WBAN and implemented an effective TDMA strategy with little amount of overhead and no overhearing. Since the target topology is static and does not change frequently in time, no complex synchronization mechanisms are required. The network topology is hierarchical with a number of sensor nodes, a Master Node (MN) that coordinates the synchronization and transmission to the sensor nodes, and a Monitoring Station (MS) that gathers data from the MNs directly for further analysis. Figure 9c shows the TDMA frame structure of the protocol. The timeslots S_n are allocated to n different nodes. The slots are separated by a guard interval, which is necessary to prevent overlapping of transmission form different sensor nodes. Extra slots RS_n are reserved for retransmission. The protocol defines two options for communication between MN and MS. First, when the MN has one transceiver, enough time should be given to complete communication between MN and MS. Second, when the MN has two transceivers. This allows the MN to communicate both with the sensor nodes and the MS simultaneously. The second option is complex in terms of implementation, however it can be used to support communication on multiple physical layers simultaneously and can easily satisfy the MAC transparency requirement of WBAN. It is shown in the paper that the proposed protocol is energy efficient for streaming communication as well as for sending short bursts of data. The shortcomings include: First, It has limited superframe structure (only CFP) based on pure TDMA mechanism with no CAP period. The CAP period can be used to send short data frames (when TDMA slot duration exceeds the data transmission duration) including command frames. Second, WBAN topology is not always static (as considered by the protocol) and sometimes sensor nodes can be deployed for short period of time, e.g., an endoscope which is expelled probably after 12 h. The proposed protocol does not respond well when the WBAN topology is dynamic. However this can happen very often and is not a serious problem. Finally, the protocol lacks a proper wake up mechanism for low duty cycle nodes in case of on-demand events.

Priority guaranteed MAC protocol

In this protocol [39], the superframe structure is a combination of CAP and CFP periods and is defined by the beacon boundaries as given in Fig. 9d. The CAP period is further divided into two control periods (C1 and C2), which are used for life-critical medical applications and Consumer Electronics (CE) applications, respectively. The C1 and C2 periods use randomized slotted ALOHA for resource allocation. The use of two separate and dedicated control periods isolates life-critical medical communication from much busier CE traffic. The CFP period is divided into Time Slot Reserved for Periodic Traffic (TSRP) and Time Slot Reserved for Bursty Traffic (TSRB) periods. The TSRP and TSRB periods are used for periodic and bursty traffic, respectively. The TDMA slots in the TSRP and TSRB periods are allocated on demand using the control periods. As demonstrated by the simulations, this protocol showed significant improvements on throughput and power consumption as compared to IEEE 802.15.4 MAC protocol. The drawbacks of this protocol are its complex superframe structure and its inadaptability to emergency and on-demand traffic.

Others MAC protocols for WBAN such as Heartbeat Driven MAC (H-MAC) [40], Reservation-based Dynamic TDMA (DTDMA) [41], and BodyMAC [42] are briefly discussed in [23].

A power-efficient MAC protocol for WBAN

In this section, we discuss our proposed power-efficient MAC protocol for WBAN. This protocol accommodates normal, emergency, and on-demand traffic in a reliable manner [43]. Additionally, it has two wakeup mechanisms, a traffic-based wakeup mechanism, which accommodates normal traffic by exploiting the traffic patterns of the nodes, and a wakeup radio mechanism, which accommodates emergency and on-demand traffic by using a wakeup radio. Like the previous protocols, the channel is bounded by the superframe structures. The superframe is divided into CAP and CFP periods. The CAP period uses slotted-ALOHA and is used for resource allocation. The CFP period is used for data transmission including real-time communication. In the traffic-based wakeup mechanism, the operation of each node is based on traffic patterns. The initial traffic pattern is defined by the manufacturer/coordinator and can be changed later. These patterns are repeated per BAN day, BAN hour, BAN minute, BAN second, and BAN millisecond. This categorization allows simple representation of the traffic levels. For example, a high traffic node sends data x times per BAN minute or BAN millisecond. The coordinator can change the traffic levels from low to high (vice-versa) by simply changing the traffic patterns. The traffic patterns of all nodes are organized into a table called traffic-based wakeup table. In the wakeup radio mechanism, a separate control channel is used to send a wakeup radio signal. The coordinator and the node initiates sending the wakeup radio signal in on-demand and emergency case, respectively. Further details can be found in [43].

We simulated the protocol using the Monte Carlo method. Poisson and deterministic traffic generators were used to generate aperiodic (emergency and on-demand) and periodic (normal) traffic, respectively. For the deterministic traffic, the Gaussian distribution was used to incorporate randomness in the relative offsets of the nodes. The average power consumption and delay were presented as a function of packet and beacon inter-arrival time. If more than one node appeared to have the same traffic patterns, the priority concept was used to ensure fair resource allocation. The performance of the protocol was compared to the low-power WiseMAC [44] protocol. Figure 10a shows the average power consumption of the proposed protocol and compares it with the WiseMAC protocol. It can be seen that the average power consumption of the proposed protocol outperforms WiseMAC protocol since the nodes are required to wake up whenever they have data to send/receive. The extra power consumption used for preamble sampling in the WiseMAC protocol is avoided. Since we used two generators (Deterministic and Poisson), the arrival of Poisson traffic affects the average power consumption of the protocol as indicated by a slight curve change in the figure. For normal traffic only (with no emergency and on-demand events), the proposed protocol provides relatively low-power consumption as shown in the figure. In the WiseMAC protocol, if a node has a packet to send/receive, it waits until the medium is sampled. This increases the delay of the WiseMAC protocol if the medium is busy or if the sampling period is high. However, in the proposed protocol, a node wakes up whenever it has a packet to send/receive. It does not have to wait for resource allocation information/beacon since the traffic patterns are pre-defined and known to the coordinator. This results in a reasonable delay as shown in Fig. 10b.

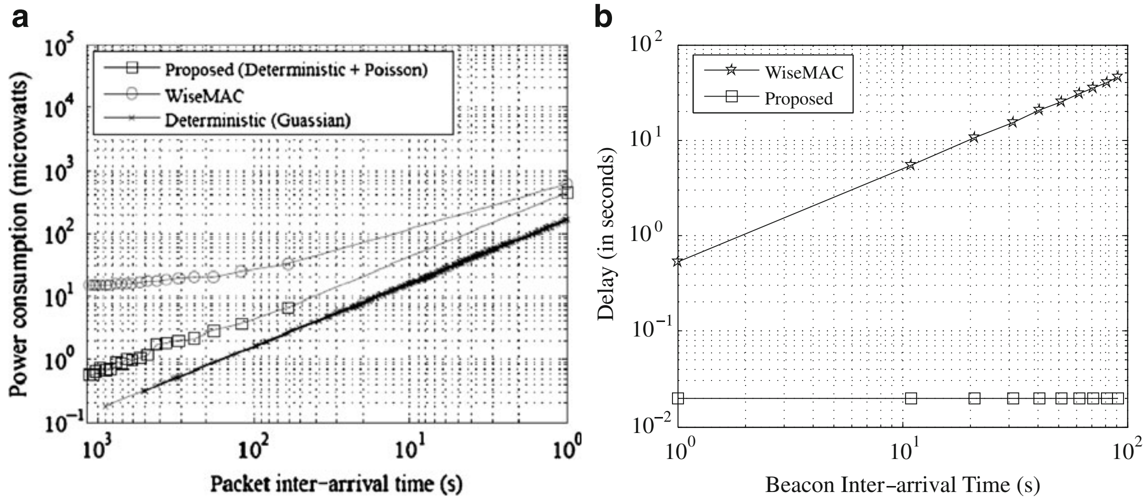


Fig. 10 **a** Average power consumption of the proposed protocol. **b** Average delay of the proposed protocol

MAC security

The deployment of WBAN for medical and non-medical applications must satisfy stringent security and privacy requirements [45]. These requirements are based on different applications ranging from medical (heart monitoring) to non-medical (listening to MP4) applications. In the case of medical applications, security threats may lead a patient to dangerous conditions, and sometimes to death. Thus, a strict and scalable security mechanism is required to prevent malicious interaction with WBAN. A secure WBAN should include confidentiality and privacy, integrity and authentication, key establishment and trust set-up, secure group management and data aggregation. However, the integration of a high-level security mechanism in a low-power and resource-constrained sensor increases computational, communication and management costs. In WBAN, both security and system performance are equally important, and thus, designing a low-power and secure MAC protocol for WBAN is a fundamental challenge to the designers.

Generally, the application layer is used to explicitly enable the security by adjusting certain control parameters. For example, in IEEE 802.15.4 the application layer has a choice of security modes that control different security levels. Each security mode has different security properties, protection levels, and frame formats. The IEEE 802.15.4-based security modes can be used/improved for WBAN according to the application requirements. Table 8 lists different security modes described in the IEEE 802.15.4 standard, broadly classified into no security, encryption only (AES-CTR), authentication only (AES-CBC), and encryption and authentication (AES-CCM) modes. The following sections shortly discuss AES-CTR, AES-CBC, and AES-CCM modes for WBAN.

AES-CTR

The Counter (CTR) (also known as Integer Counter Mode) mode can be used in WBAN in order to encrypt data. It breaks the cleartext into 16-byte blocks $b_1, b_2, ...b_n$ and computes $c_i = b_i \oplus E_k(x_i)$, where c_i is the cipher text, b_i is the data block, and $E_k(x_i)$ is the encryption of the counter x_i. The coordinator recovers the plaintext by computing $b_i = c_i \oplus E_k(x_i)$. Figure 11a shows the CTR encryption and decryption process.

Table 8 Security modes in IEEE 802.15.4

Name	Description
Null	No security
AES-CTR	Encryption only, CTR mode
AES-CBC-**MAC**-128	128 bit **MAC**
AES-CBC-**MAC**-64	64 bit **MAC**
AES-CBC-**MAC**-32	32 bit **MAC**
AES-CCM-128	Encryption and 128 bit **MAC**
AES-CCM-64	Encryption and 64 bit **MAC**
AES-CCM-32	Encryption and 32 bit **MAC**

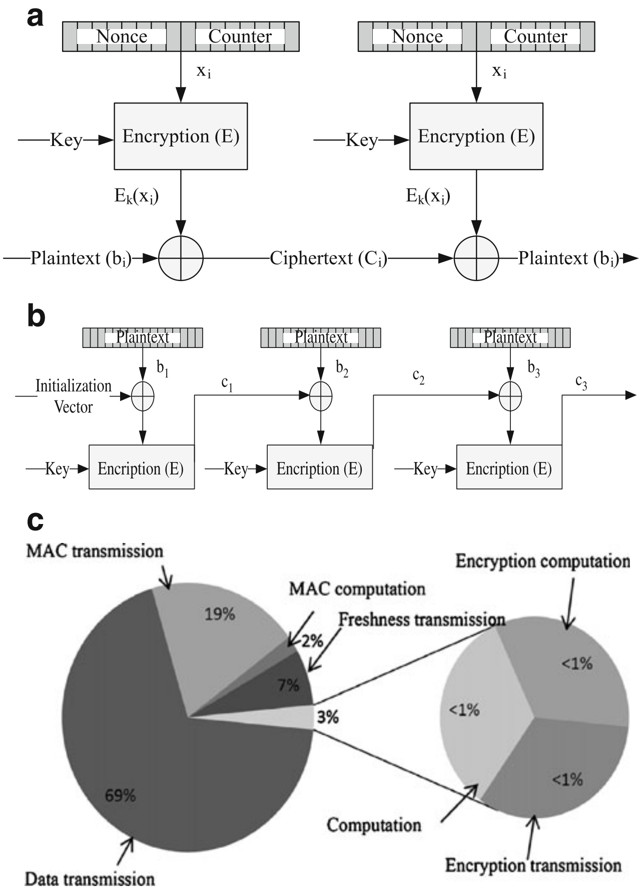


Fig. 11 **a** CTR encryption and decryption. **b** CBC-MAC operationc. **c** Energy cost of security protocols [46]

AES-CBC-MAC

In the Cipher-block Chaining Message Authentication Code (CBC- **MAC**)[2] mode, the plaintext is XORed with the previous cipher text until the final encryption is achieved. This mode provides authentication and message integrity by allowing the WBAN nodes to compute either 32 bits, 64 bits, or 128 bits Message Authentication Code (**MAC**). The coordinator computes its own **MAC** and compares it with the node's **MAC**. The coordinator accepts the packet if both **MACs** are equal. The mathematical representation of the CBC-**MAC** is given by: $c_i = E_k(b_i \oplus c_{i-1})$ for generating ciphertexts and $b_i = D_k(c_i) \oplus c_{i-1}$ for generating plaintexts. Figure 11b shows a block diagram of the CBC-**MAC** operation.

[2]To differentiate it from the term Medium Access Control (MAC), Message Authentication Code (**MAC**) is represented in bold letters.

AES-CCM

The Counter with CBC-**MAC** (CCM) mode combines CTR and CBC modes in order to ensure high-level security that includes both data integrity and encryption. The nodes first apply the integrity protection to the MAC frames using CBC-**MAC** mode and then encrypts the frames using CTR mode. This mode can be used to send or receive sensitive information such as updating programs in pacemakers and implantable cardiac defibrillators.

Generally, the addition of security protocols to WBAN consumes extra energy due to overhead transmission required by the protocols as given in Fig. 11c [46]. The best way is to use a stream cipher for encryption, where the size of the ciphertext is exactly the same as the plaintext. In this case, the **MAC** uses 16 bytes of 60 bytes data frame. Moreover, the Cyclic Redundancy Check (CRC) is not required since the **MAC** itself achieves data integrity. Law et al. concluded that the most energy efficient cipher is Rijndael [47]. They examined the number of CPU cycles during they key setup and encryption/decryption procedures. The summary of different ciphers is given in Appendix B.

Discussion

MAC protocols play a significant role in determining the energy consumption in WBAN. The existing low-power MAC mechanisms do not satisfy the WBAN MAC requirements. The LPL and schedule-contention mechanisms are unable to accommodate unpredicted sporadic events as well as low duty cycle nodes. The TDMA mechanism, on the other hand, is a good alternative to be used in WBAN. Therefore most of the existing MAC protocols for WBAN are based on TDMA mechanisms. As discussed above, these protocols have several pros and cons in the context of a real WBAN system. None of them considered the MAC transparency requirement, i.e., to allow communication on multiple physical layers simultaneously. In addition, these protocols are not targeted for MICS band perhaps due to Listen Before Talking (LBT) criteria and FCC restrictions [23]. Security is also one of the most important issues in WBAN since the devices are used to collect sensitive (life-critical) information and may operate in hostile environments. The current IEEE 802.15.6 is working on the standardization of WBAN including the development of a unified MAC protocol. The new standard will target all the requirements mentioned in Section "MAC requirements".

Although MAC protocols can solve a variety of problems, they do not consider addressing nor do they ensure end-to-end packet delivery. It is therefore important to consider the network layer and more specifically the routing in WBAN. The next sections focus on network layer communication in WBAN.

Network layer communication

Developing efficient routing protocols in WBANs is a nontrivial task because of the specific characteristics of the wireless environment on the human body.

1. The available bandwidth is limited, shared and can vary due to fading, noise and interference. As a result, the network control generated by the protocol should be limited.
2. The nodes that form the network can be very heterogeneous in terms of available energy or computing power. As a result, node energy should also be taken into account.
3. An extremely low transmit power per node is needed to minimize interference to cope with health concerns and to avoid tissue heating [48].
4. The devices are located on the human body that can be in motion. WBANs should therefore be robust against frequent changes in the network topology.

In this section, we give an extensive overview of existing solutions for routing in WBAN. First, we discuss its relationship to WSNs. Second, the most ideal topology is discussed. Third, an overview of existing WBAN routing solutions is given. The routing solutions are grouped in three different strategies: temperature aware routing, cluster based routing and cross layer routing. The cross layer protocol is discussed in more detail. Finally, this section is concluded with future research directions.

Routing: WSN vs. WBAN

A lot of research is being done towards energy efficient routing in ad hoc networks and WSNs [49] but the proposed solutions are inadequate for WBANs. For example, in WSNs maximal throughput and minimal routing overhead are considered to be more important than minimal energy consumption. Energy efficient adhoc network protocols only attempt to find routes in the network that minimize energy consumption in terminals with small energy resources, thereby neglecting parameters such as the amount of operations (measurements, data processing, access to memory) and energy required to transmit and receive a useful bit over the wireless link. Even worse, loss of a sensor is not considered to be problematic. In WBAN, the number of devices worn by a patient should be very low in order to have good patient comfort. Most protocols for WSNs only consider networks with homogeneous sensors, an assumption that is incorrect when considering different devices in WBAN, each with their different required data rate. In many cases the network is considered as static. In contrast, WBAN has heterogeneous mobile devices with stringent real-time requirements due to the sensor-actuator communication. The mobility in sensor networks is considered on a scale of meters or tens of meters, however movements of tens of centimeters can cause mobility in WBANs. In brief, although challenges faced by WBANs are in many ways similar to WSNs, there are intrinsic differences between the two, requiring special attention.

Network topologies

Network topology is defined as the logical organization or arrangement of communication devices in the system. The selection of a proper network topology in WBAN is important as it significantly affects the overall system performance and protocol design. It influences the system in many ways, for example in power consumption, the ability to handle heterogeneity, the robustness against failures and the routing of data etc.

There has been very little research about the most optimal network architectures in WBAN. Most researchers assume that a single-hop topology, where every sensor directly communicates with the personal device, is the best solution. Hence, almost all current implementations in WBAN assume single-hop communication. However, the devices used in these implementations are not fitted for WBAN as they are too big to allow easy use by the person wearing the WBAN [50]. In this overview, we will focus on energy efficiency and reliability of topologies.

Energy efficiency

In [51], a first attempt is done to justify the use of multi-hop in WBAN, where intermediate hops are used for reaching the receiver. They use an energy model that is only applicable for an energy usage comparison of UWB communication from a node on the back of a person to a node on the chest. It is concluded that whether to use a multi-hop strategy or not depends on the ratio of the energy consumption needed for decoding/coding and receiving/generating a UWB-pulse. In [52], a preliminary study based on simulations of the physical layer showed the necessity for multi-hop networking. This work only considered the energy consumption of the entire network, not taking into account the individual nodes. Both studies focused on maximizing the lifetime of the network and concluded that in some cases a multi-hop topology is more energy efficient. In [53], different topologies are evaluated for a TDMA-based MAC protocol for WBAN. It is concluded that a cluster based topology is more energy efficient. However, they use a simplified propagation protocol which does not take into account the large losses experienced on the human body.

A more profound study about energy efficiency in WBANs has been performed in [54] where the authors showed that single-hop communication is inefficient, especially for nodes located far away from the sink. Their analysis is based on path loss models derived for communication on the human body, where path loss is very high compared to free space propagation. When the sender and receiver are in Line Of Sight (LOS), a path loss exponent of about 3 to 4 is found in [55]. On the other hand, when the communication is Non-line Of Sight (NLOS), e.g., when the sender is placed on the back and the receiver on the chest, a path loss exponent of 7 is found in [56] as given in Fig. 12a and b. This means that the path loss around the human body may thus tremendously exceed the path loss for propagation in free space, where usually a path loss exponent of 2 is considered. Due to these high losses in NLOS situations, direct communication between the sensors and the sink will not always be possible. This is especially the case when one wants to lower the radio's transmission power. Hence, multi-hop networking becomes advantageous and sometimes even an absolute requirement to ensure connectivity of the network.

These models are used in [54] for determining whether multi-hop or single-hop is the most energy efficient approach in a line or a tree topology. Figure 13 shows the ratio of multi-hop energy usage over single-hop energy usage for a scenario with 4 nodes and changing distances between the nodes. The results show that the nodes closest to the sink do not perform well when using multi-hop: they become hot spots using more than 10 times the energy of single-hop. This is shown in Fig. 14, which explicitly plots the energy consumption in single-hop and multi-hop. In the single-hop architecture, nodes 1 and 2 consume more energy when they send their data directly to the central device. The proposed solution is to use the residual energy of nodes 3 and 4 for relaying data from other nodes. Stated otherwise, to let the nodes cooperate in the network. Indeed, by breaking into this energy supply, the lifetime of the network will be higher as the advantages of a

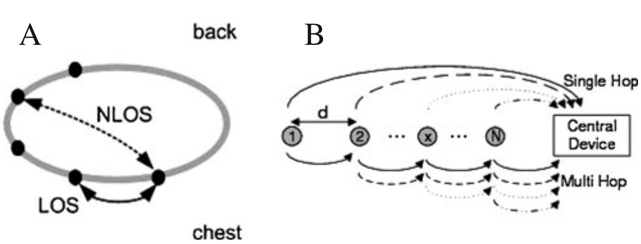


Fig. 12 **a** Communication path on the body. **b** The resulting line topology

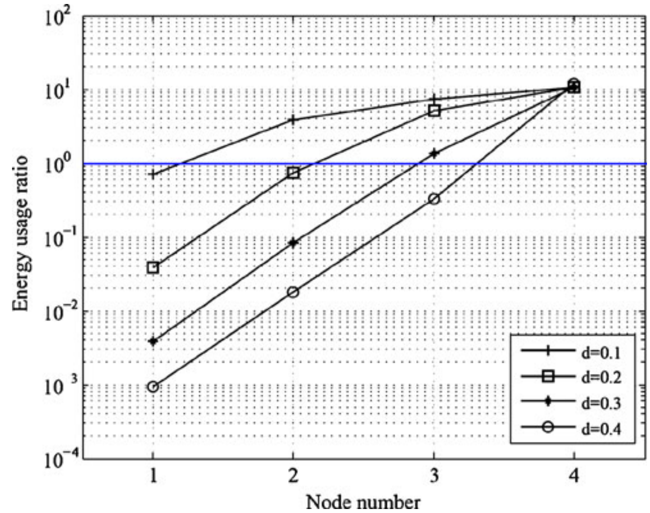


Fig. 13 Comparison of the energy usage when using single-hop and multi-hop communication in the line scenario with 4 nodes. The distance (d) between the nodes is varied from 0.1–0.4 m. The ratio of the energy usage of the multi-hop and single-hop communication is given. When the ratio is above the *horizontal line*, single-hop is the most energy efficient

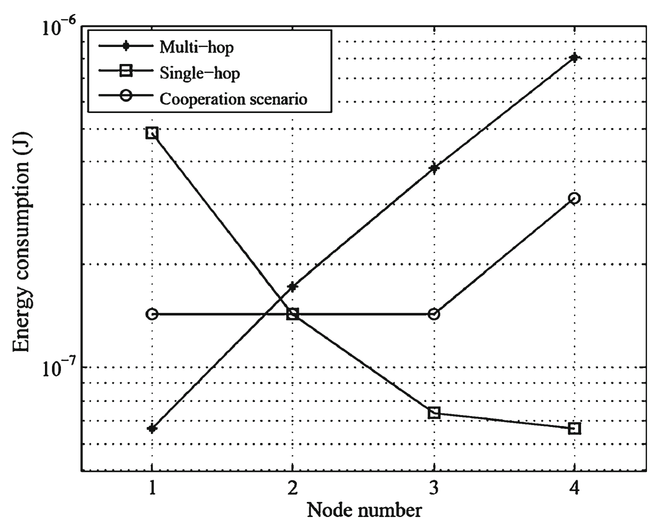


Fig. 14 Energy usage when using cooperation compared to single-hop and multi-hop energy consumption

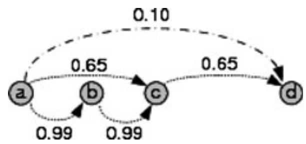


Fig. 15 Example of a connection probability in a single-hop and a multi-hop scenario. The distance between node **a** and **b** is 10 cm and between node **c** and **d** 20

multi-hop network for nodes 1 and 2 is combined with the available energy at nodes 3 and 4. Thus, instead of only forwarding data to the most nearby node, the data is transported more intelligently and the burden of forwarding the data is more equally spread among the nodes. The architecture no longer only considers the naive approach of only sending data to the direct neighbours of a node.

Reliability

Earlier, reliability was not considered. In [57] reliability is experimentally investigated by measuring the packet delivery ratio without imposing a MAC-protocol. A multi-hop strategy turns out to be the most reliable. In order to develop an intuition for why there might be a room for improvement in multi-hop routing, it is helpful to consider Fig. 15.

Different nodes are placed on one line and different routes are shown for communication between nodes A and D. The numbers above the communication links show the link probability between the 2 nodes. At one extreme, node A could send directly to D in one hop and at the other extreme, A could use the 3-hop route through B and C. In the example, it is clear that the 3-hop communication has a communication probability of 63.7% whereas the single-hop communication only is 10%. On the other hand, in multi-hop communication nodes C and D will hear many of the packets sent from A to B and it is wasteful that node B forwards these packets. This example shows the trade-off between the reliability and energy efficiency.

In general, we consider WBAN to be a converge cast network: all data is generated at the nodes and sent to a central device, the sink. From a network traffic point of view, this can be considered as an asymmetric structure. Most of the data will flow to the sink, while a limited amount of control traffic will go in the other direction. Routing algorithms can exploit this very specific topology. A more dynamic WBAN should also make sensor-to-sensor or sensor-to-actuator traffic feasible. In a basic asymmetric, converge cast network, this is possible by routing all traffic between two nodes over the sink. Routing should be optimized to avoid this triangular routing situation. Overall, based on the previous, it can be concluded that a multi-hop architecture is the best choice for WBAN and that one has to deal with a trade-off between energy efficiency and reliability.

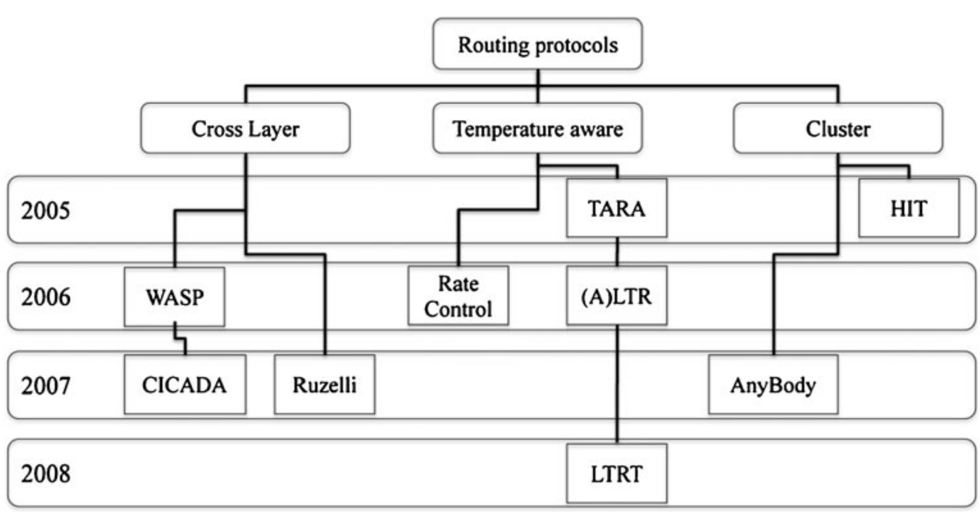
Routing strategies in WBAN

In this section, we give an overview of existing routing strategies for WBAN. These can be categorized as follows: Temperature based routing, Cluster based routing and Cross layer based routing. An overview can be found in Fig. 16.

Temperature routing

When considering wireless transmission around and on the body, important issues are radiation absorption and heating effects on the human body [58]. To avoid heat generation, five thermal aware routing protocols are proposed in the existing literature.

Fig. 16 Schematic overview of routing protocols in WBAN



To reduce tissue heating, the radio's transmission power can be limited or traffic control algorithms can be used. In [59], the authors proposed a model for the bioeffect caused by biosensors to the human body, both for near-field and far-field communication, using the SAR. They showed that the bioeffects caused by radio frequency radiation are highly related to the incident power density, network traffic and tissue characteristics. Based on this observation, they derived a guideline for designing WBAN: the normalized bioeffect metric or Coefficient of Absorption and Bioeffects (CAB). A price-based rate allocation algorithm further showed that the bioeffects can be reduced via power scheduling and traffic control algorithms.

Another approach is to balance the communication over the sensor nodes, which is used by Thermal Aware Routing Algorithm (TARA), Least Temperature Routing (LTR) and Adaptive Least Temperature Routing (ALTR). The TARA routes data away from high temperature areas due to focusing data communications, defined as hot spots [60]. In order to quickly calculate the temperature increase, the authors defined the Temperature Increase Potential (TIP), which is based on the SAR. Each node monitors neighbours packet counts and calculates the communication radiation and power consumption to derive the current temperature of the neighbours. When the temperature of a neighbouring node is above a certain threshold, i.e., the node is becoming a hot spot, the packets will no longer be forwarded to the node but will be withdrawn and rerouted through alternate paths. The algorithm leads to a better temperature distribution over all the nodes in the network. However, TARA only considers the temperature as a metric. Consequently, it suffers from low network lifetime, a high ratio of dropped packets and low reliability, which is problematic for WBAN.

Improvements of TARA are LTR and ALTR [61]. Unlike TARA, LTR always chooses the neighbouring node with the lowest temperature as the next hop for routing. In order to maintain the network bandwidth, a predefined maximum hop count is used. When the number of hops exceeds this maximum, the packet is discarded. Loops are avoided by maintaining a list in the packet with the recently visited nodes. Thus, when the coolest neighbour is already on the list, the packet will be forwarded to the second coolest neighbour, if it is not in the list. ALTR is similar to LTR with the difference that when the packets exceeds the maximum hop count, it can use shortest hop routing to take the packet to the destination as quickly as possible. An example of LTR and ALTR is given in Fig. 17. Both LTR and ALTR suffer from the same problem as TARA: they do not optimize their routing in terms of energy efficiency, reliability or delay. In larger sensor networks almost half of the generated packets are be dropped due to excess hop count [62], leading to low packet delivery ratio, wastage of energy and even rise in the temperature in the network. (A)LTR can be considered as a greedy algorithm that is not globally optimized. The simulations in [61] further showed that TARA, LTR and ALTR have shorter lifetime than shortest path routing due to the rerouting of the packets.

A smarter combination of LTR and shortest path routing is Least Total Route Temperature (LTRT) [62]. LTRT selects a least temperature route instead of only considering the next hop. The node temperatures are converted into graph weights and minimum temperature routes are obtained using Dijkstra's algorithm. The node's temperature rises by 1 unit when a packet is received and decreases by 1 unit when no packet is received during a predefined time interval. LTRT experiences a lower hop count per packet, a lower number of packets dropped and a lower temperature rise is obtained. LTRT has as main disadvantage that a node needs to know the temperature of all nodes in the network. Neither the overhead of obtaining this data nor energy consumption was investigated.

In general, temperature routing can be considered as a specific case of weight based routing. Results are promising, but reliability and energy efficiency can be hard to guarantee.

Cluster based routing

Anybody [63] is a data gathering protocol that uses clustering to reduce the number of direct transmissions to the remote base station. It is based on LEACH [64] that randomly selects a cluster head at regular time

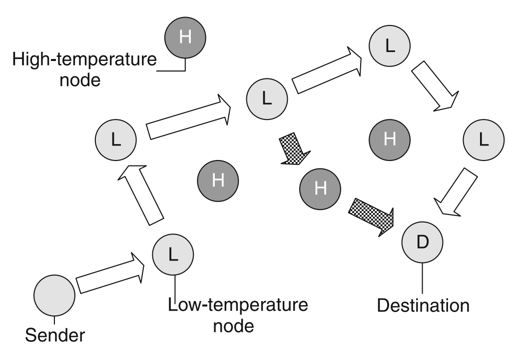


Fig. 17 An example of LTR and ALTR. The *white arrows* indicate the LTR-path. The *shaded arrows* show the adapted path of ALTR. When the path has three hops, the routing algorithm switches to shortest path routing. Remark that if the maximum hop count were limited to five or less, the packet would have been dropped

intervals in order to spread the energy dissipation. The cluster head aggregates all data and sends it to the base station. LEACH assumes that all nodes are within the sending range of the base station. Anybody solves this problem by changing the cluster head selection and constructing a virtual backbone network of the cluster heads. Energy efficiency is not thoroughly investigated and reliability is not considered. The authors only focus on the number of cluster heads, depending on the scale. A more profound problem lies in the fact that simulations are based on networks where nodes have hundreds of neighbours and communication ranges of up to 250 m.

Another improvement of LEACH is Hybrid Indirect Transmissions (HIT) [65], which combines clustering with forming chains. In doing so, the energy efficiency and as a consequence network lifetime is improved, specifically in sparse WBAN. Reliability, however, is not considered. Another open problem with HIT is the conflicting interaction between its communication routes and those desirable for application of the defined fusion operator. As a result, HIT requires more communication energy in a dense network.

Cross-layer protocols

Cross-layer design is a way to improve the efficiency of and interaction between the protocols in a WSN by combining two or more layers from the protocol stack. This research has gained a lot of interest in WSNs [66, 67]. However, little research has been done for WBANs. Ruzelli et al. proposed a cross-layer energy efficient multi-hop protocol built on IEEE 802.15.4 [68]. The network is divided into timezones where each timezone takes turns in the transmission. The nodes in the farthest timezone start the transmission. In the next slot, the farthest one sends its data and so on until the sink is reached. The protocol almost doubles the lifetime compared to regular IEEE 802.15.4. The protocol is developed for regular WSNs, but the authors claim its usefulness for WBANs. The primary reason is the absence of direct connectivity between nodes when located at opposite sides of a human body or when radio transmission power is limited to save energy. The Wireless Autonomous Spanning Tree protocol (WASP) [69] sets up a spanning tree and divides the time axis in slots. The slot allocation is done in a distributed manner. Every node sends out a proprietary WASP-scheme to its children to inform them of the following level when they are allowed to send. It achieves a high packet delivery ratio while keeping the energy efficiency low. Two-way communication is not supported. An improvement is the Cascading Information retrieval by Controlling Access with Distributed slot Assignment protocol (CICADA) [70], explained in more detail in the following section.

Another approach for cross layering is completely discarding the layered structure and implementing the required functionality in different modules, which interact with each other [71]. The authors claim that the modular approach has the following advantages: (1) Duplication of functionality can be avoided; (2) Heterogeneity is supported as more modules can be added depending on the capabilities of the node; (3) Cross layer optimizations are possible, leading to more energy efficient protocols; (4) modules can be easily adapted or replaced. A first attempt to use the modular approach for WBANs is described in [70]. The authors presented a modular framework and describe the most important modules. However, the discussion is only theoretical and the framework has not been implemented and properly evaluated.

The discussion above clearly shows that the development of routing protocols for WBANs is an emerging area of research. The protocols described above were only developed in the last four years. Several approaches exist, each with their own advantages and disadvantages. Combining the positive elements of these approaches will lead to better routing protocols.

CICADA: a cross layer protocol for WBAN

As an example of a cross-layer protocol specifically designed for WBANs, we briefly describe CICADA in this section.

General overview

CICADA is a cross-layer protocol specifically designed for WBANs, based on a multi-hop TDMA scheduling approach [70]. It uses the same packets to take care of both medium access as well as routing. The packets are used to detect the presence or absence of the children and to control medium access. The protocol sets up a spanning tree and divides the time axis in slots grouped in cycles in order to lower the interference and to avoid idle listening. The assignment of the slots is done in a distributed way. Synchronization of slots is possible because a node knows the length of each cycle. With the tree structure, each node informs its children when they are allowed to send their data. Routing itself is not complicated in CICADA as data packets are routed up the tree which is set up to control the medium access. The network is considered to be convergecast, but traffic between individual nodes in the network is possible as well by routing over the sink.

Slot assignment and data transfer in CICADA are defined by a sequence of cycles. At the beginning of each cycle, the slots in the remainder of the cycle are assigned. The slot allocation is done by sending a scheme from a parent node to a child node. A node calculates its own scheme based on the scheme it has received from his parent. Each cycle is divided in two parts: the control subcycle and the data subcycle. Each subcycle has its own scheme for slot allocation: the control scheme and the data scheme respectively. These schemes are both sent in the control subcycle. This subcycle is used to propagate the schemes from the parents to their children, to assign all slots in the cycle. When all nodes have received their scheme, the control cycle ends and the data cycle starts.

Each node is assigned one slot in the control subcycle. When a node has received a scheme packet from its parent in a slot in the control subcycle, it can sleep as no more packets will arrive in that slot. Furthermore, in the control subcycle, it will only be awake in the slot where it sends its own scheme to its children. The data subcycle is used to forward the data from the nodes to the sink. The first nodes to start sending data, are the nodes at the bottom of the tree. In doing so, all data can be sent to the sink in one cycle. This lowers the end-to-end delay tremendously.

In Fig. 18, a small example and its corresponding tree structure is given. Table 9 gives an overview of which slots each node is allowed to send in during the control and data subcycle. The arrows show that during the control subcycle, control information is sent downwards from the sink to all nodes in the control subcycle. In the data subcycle, all data is sent upwards to the sink. The last slot of each data scheme is a contention slot (represented by X) which is used to allow new children to join the network.

CICADA can add an inactive period after the data subcycle, for example when the data traffic in the network is low. In these inactive periods, the radios can be shut down, resulting in a better energy efficiency. The length of the active period is expressed by Δ, where a cycle without an inactive period has a $\Delta = 100\%$, and a cycle where the active period and the inactive period have the same length as $\Delta = 50\%$.

Joining and leaving the network

In each data subcycle, a contention-based slot is included to allow nodes to join the tree. A new node will send a JOIN-REQUEST packet in the contention slot of its desired parent, using in-slot ALOHA. This JOIN-REQUEST packet contains the number of slots a node needs to transmit its own data, to enable immediate optimal resource allocation. When the parent receives the join, it will include the node in the next cycle. With this simple join mechanism, quickly adding nodes is possible. This also gives CICADA basic support for mobility and changing topologies.

To support leaving and detection of loss of a connection, each node will send at least two packets per cycle: its schemes in the control subcycle and a data packet or a HELLO packet in the data subcycle. If a parent does not receive any packet from a child for 2 or more consecutive cycles, the parent will assume that the child is lost. Likewise, if a child does not receive packets from its parent for 2 or more consecutive cycles, the child will assume that the parent is gone and will try to join a new parent.

Results

CICADA is evaluated on an example network where some sensors are placed on the body, as can be seen in

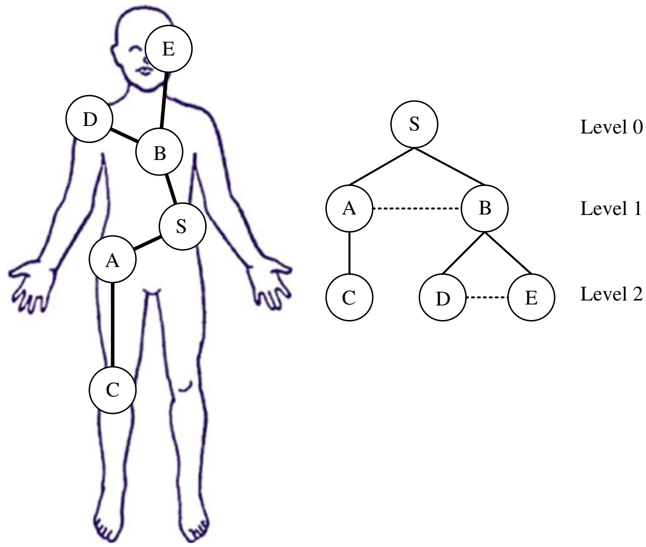


Fig. 18 Example network: the *lines* indicate the tree structure

Table 9 Steady-state cycle scheme for the example network, for both the control and data subcycle

1	2	3	4	5	1	2	3	4	5	6	7	8	9
S													
A						X							
B							X						
C					X								
D					X								
E					X								

The arrows indicate in which slot a node sends, where down means the node broadcasts to its children and up means it unicasts to its parent. The X-es represent contention slots, used for joining the network

Fig. 19a. Figure 19b shows the generic tree view of this network. Thirteen nodes each are sending a Constant Bit Rate (CBR) stream to the sink with radios capable of transmitting up to 1 Mbps.

CICADA is compared with SMAC, a frequently used CSMA-style protocol for sensor networks. In SMAC, nodes synchronize time by building virtual clusters and employ a fixed duty cycle to reduce idle listening overhead. SMAC includes carrier sensing, collision avoidance (RTS/CTS signaling), and overhearing avoidance. The SMAC available in NS2 is considered with the default parameters (a duty cycle of 10%) and with static (optimal) routing. In doing so, any overhead and delay caused by the routing protocol is avoided.

The sleep ratio is shown in Fig. 20. The sleep ratio drops for high packet rates, which is expected as more traffic is sent in the network. However, when the packet rate is too high, the sleep ratio rises again. More packets are lost due to buffer overflows, thus fewer packets are actually sent. For lower duty cycles, the sleep ratio rises up to 95%. Compared with SMAC (duty cycle of 10%) CICADA performs better when the duty cycle is set to 20% or lower.

The example network is also used to evaluate the packet loss for varying packet rates and different duty cycles. Packet generation time is defined as the time between the reception of packets from the application layer. In Fig. 21, it can be seen that compared with SMAC, CICADA performs a lot better. Further, CICADA has a packet loss of 0% as long as at most one packet per cycle is generated. The main reason for packet loss when too much data is generated is that the node is not aware of the application's traffic pattern (i.e. the sensor rate). The node can only reserve slots for data received from the application layer. For example, when the nodes start transmitting packets, two packets will be reserved in the first cycle as at least two packets are generated per cycle. The cycle length increases, but the traffic rate stays the same. As a result, more packets are generated during the cycle, so more slots have to be reserved. This mechanism creates an avalanche effect in the length of the duty cycle. Currently, CICADA does not take this problem into account. A possible solution is to implement a traffic predictor which can more precisely predict the packet rate.

The results above show that CICADA has a high sleep ratio, especially when the duty cycle is reduced

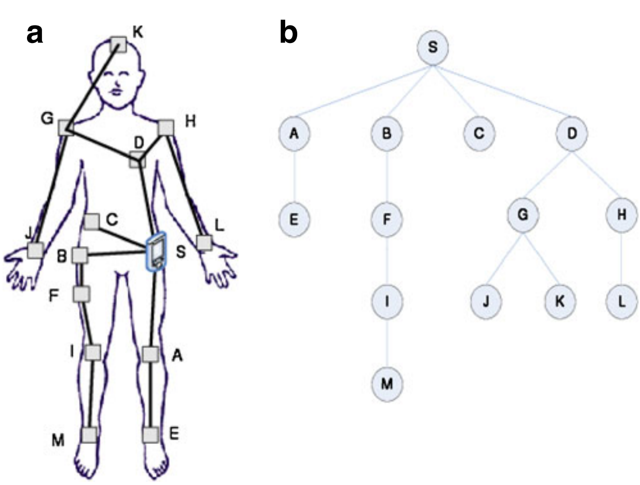


Fig. 19 **a** Sensors place on the body. **b** Resulting network topology used in the simulation

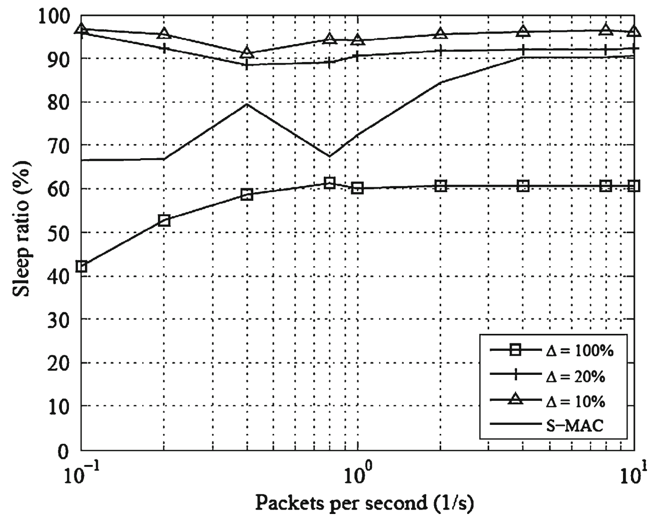


Fig. 20 Sleep ratio experienced by SMAC and CICADA for the network of Fig. 19b. The duty cycle Δ and the number of packets sent per second are varied

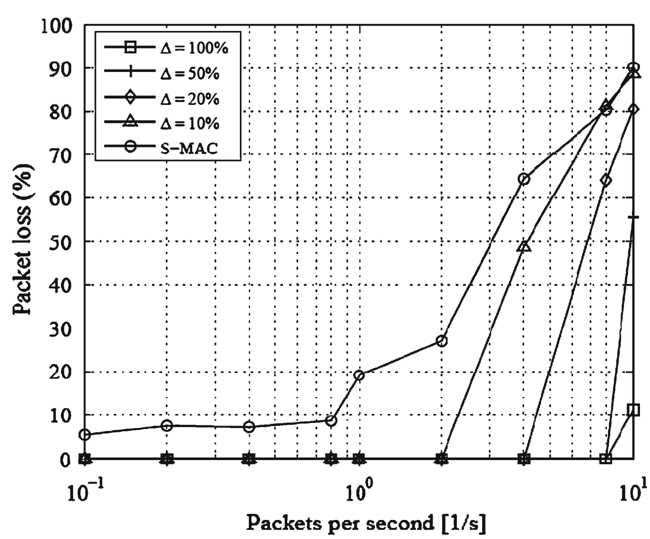


Fig. 21 Packet loss experienced by SMAC and CICADA for the network of Fig. 19b. The duty cycle Δ and the number of packets sent per second are varied

to 50% or lower. Longer duty cycles, however, lead to packet loss when the packet generation rate is too high. When deploying WBAN using CICADA, one thus has to balance the desired throughput and the energy efficiency.

Discussion

Currently, not many protocols for WBANs exist. Protocols specifically designed for WBANs like AnyBody and CICADA do resolve some of the issues that are typically encountered in WBANs, however there is still a lot of work to do. As shown before, temperature aware routing protocols are very interesting for WBAN. Incorporating energy efficiency and reliability support would largely improve the applicability of these results, as now the development is much focused on temperature. One important issue, from an application point of view, is offering QoS. Currently, protocols like BodyQoS [72] do offer basic QoS. However, integration into existing MAC and especially routing protocols is not optimal. When tackling the specific QoS requirements of WBANs, integration with all layers should be strong. Given the difficult environment, where the path loss is high and as a result bandwidth is low, QoS protocols should expect and use all information about the network that is available.

Another interesting research challenge is energy efficient routing in mobile networks. Because of the small scale and the low allowed transmission power, a simple movement of the human body can cause large mobility at the network level. Suddenly, links will break and new links will appear. Existing routing protocols are either well suited for mobility but highly energy inefficient from a sensor point of view, or they do not support fast mobility. We believe this is still a large hurdle to be overcome to completely start using WBANs. The complex trade-off between energy efficiency and fast routing in this mobile network should be overcome.

WBAN applications

WBANs have great potential for several applications including remote medical diagnosis, interactive gaming, and military applications. Table 10 shows some of the in-body and on-body applications. In-body applications include, monitoring and program changes for pacemakers and implantable cardiac defibrillators, control of bladder function, and restoration of limb movement [73]. On-body medical applications include monitoring ECG, blood pressure, temperature, and respiration. Furthermore, on-body non-medical applications include monitoring forgotten things, establishing a social network, and assessing soldier fatigue and battle readiness. Some of the WBAN applications are discussed below.

Cardiovascular diseases

Traditionally, holter monitors were used to collect cardio rhythm disturbances for offline processing without real-time feedback. Also transient abnormalities are sometimes difficult to capture. For instance, many cardiac diseases are associated with episodic rather than continuous abnormalities, such as transient surges in blood pressure, paroxysmal arrhythmias or induced episodes of myocardial ischemia and their time cannot be accurately predicated [74]. WBAN is a key technology that can be used to prevent the occurrence of myocardial infarction, monitor episodic events or any other abnormal condition and also can be used for ambulatory health monitoring.

Table 10 In-body and on-body applications [73]

Application type	Sensor node	Date rate	Duty cycle (per device) % per time	Power consumption	QoS (sensitive to latency)	Privacy
In-body applications	Glucose sensor	Few kbps	<1%	Extremely low	Yes	High
	Pacemaker	Few kbps	<1%	Low	Yes	High
	Endoscope capsule	>2 Mbps	<50%	Low	Yes	Medium
On-body medical applications	ECG	3 kbps	<10%	Low	Yes	High
	SpO2	32 bps	<1%	Low	Yes	High
	Blood pressure	<10 bps	<1%	High	Yes	High
On-body non-medical applications	Music for headsets	1.4 Mbps	High	Relatively high	Yes	Low
	Forgotten things monitor	256 kbps	Medium	Low	No	Low
	Social networking	<200 kbps	<1%	Low	Low	High

Diabetes

Worldwide, more than 246 million people suffer from diabetes, a number that is expected to rise to 380 million by 2025. Frequent monitoring enables proper dosing of medicines and reduces the risk of fainting and in later life blindness, loss of circulation and other complications.

Cancer detection

Cancer remains one of the biggest threats to the human life. According to National Center for Health Statistics, about 9 million people had cancer diagnosis in 1999 (http://www.cdc.gov/nchs/Default.htm). A set of miniaturised sensors capable of monitoring cancer cells can be seamlessly integrated in WBAN. This allows a physician to diagnose tumours without biopsy.

Asthma

WBAN helps millions of patients suffering from asthma by monitoring allergic agents in the air and providing real-time feedback to the physician. Chu et al. proposed a GPS-based device that monitors environmental factors and triggers an alarm in case of detecting an environment the patient is allergic to [75].

Telemedicine systems

Existing telemedicine systems either use dedicated wireless channels to transfer information to the remote stations, or power demanding protocols such Bluetooth that are open to interference by other devices working in the same frequency band. These characteristics limit prolonged health monitoring. WBAN can be integrated into a telemedicine system that supports unobtrusive ambulatory health monitoring for long period of time. Figure 22 shows a real-time telemedicine infrastructure for patient rehabilitation.

Artificial retina

Retina prosthesis chips can be implanted in the human eye that assists patient with limited or no vision to see at an adequate level [76].

Battlefield

WBANs can be used to connect soldiers in a battlefield and report their activities to the commander, i.e., running, firing, and digging. The soldiers should have a secure communication channel in order to prevent ambushes.

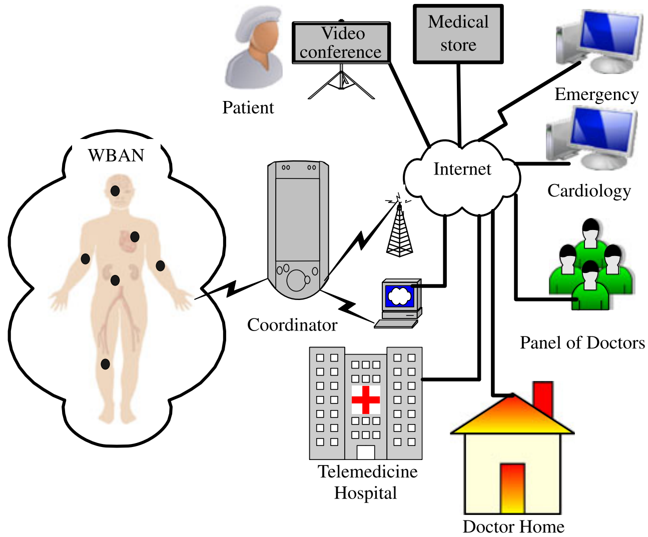


Fig. 22 A real-time telemedicine infrastructure for patient rehabilitation

Conclusions

In this paper, we studied the fundamental mechanisms of WBAN at PHY, MAC, and Network layers. Each section was concluded separately with useful remarks. Starting from the system architecture, for the PHY layer, we reviewed different methodologies of wireless communication to/from an implant including RF communication, in-body antennas, and propagation patterns. For the MAC layer, we discussed several low-power mechanisms in the context of WBAN and concluded that the TDMA mechanism is suitable and more appropriate for WBAN. We further discussed our proposed low-power MAC protocol for WBAN followed by important suggestions. For the Network layer, the possible network topologies for WBAN were discussed, taking into account the required energy efficiency and reliability. Then a classification of existing routing strategies was given with future research directions. Finally, numerous WBAN applications were presented.

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Appendix A

Table 11

Table 11 Comparison of low-power MAC protocols for WBAN [26]

Low-power mechanisms	Protocols	Channels	Organization and basic operation	Advantages and disadvantages	Adaptability to WBANs/Comments
Low power listening	WiseMAC	1	Organized randomly and operation is based on listening	Scalable and adaptive to traffic load, Support mobility, low and high power consumption in low and high traffic conditions, and low delay	Good for high traffic applications, not suitable for low duty cycle in-body/ on-body nodes
	BMAC	1	Organized in slots and operation is based on schedules	Flexible, high throughput, tolerable latency, and low power consumption	Good for high traffic applications
	STEM	2	Organized randomly having two channels (control + data channel) and operation is based on wakeup schedules	Suitable for events based applications	Good for periodic traffic especially for low traffic applications. Suitable to handle sporadic events due to a separate control channel. But hard to handle sporadic events when the traffic load is high
Scheduled-contention	SMAC	1	Organized in slots and operation is based on schedules	High transmission latency, loosely synchronized, low throughput	Good for high traffic applications. Suitable for applications where throughput is not a primary concern such as in-body medical applications
	TMAC	1	Organized in slots and operation is based on schedules	Queued packets are sent in a burst thus achieve better delay performance, loosely synchronized	Good for high traffic applications. Early sleep problems allow the nodes to loose synchronization
	PMAC	1	Organized in hybrid mode and operation is based on listening	Adaptation to changes might be slow, loosely synchronized, high throughput under heavy traffic	Good for delay-sensitive applications
	DMAC	1	Organized in slots and operation is based on schedules	Better delay performance due to Sleep schedules, loosely synchronized, optimized for data forwarding sink	On-body nodes can be prioritized according to their application requirements and a data tree can be built, where the WBAN coordinator will be a cluster node
TDMA	FLAMA	1	Organized in frames and operation is based on schedules	Better end-to-end reliability and energy saving, smaller delays, improved energy saving, high reliability	Good for low power applications. Adaptable to high traffic applications.
	LEACH	1	Organized in clusters and operations is based on TDMA scheme	Distributed protocol, no global knowledge required, extra overhead for dynamic clustering	TDMA schedules should be created by the WBAN coordinator. Cluster head should not change (depending on minimum communication energy) as in the traditional LEACH
	HEED	1	Organized in clusters and operations is based on TDMA scheme	Good for energy efficiency, scalability, prolonged network lifetime, load balancing	The WBAN coordinator acts as a cluster head. Unlike traditional HEED, the WBAN network size is often defined (by the physician)

Appendix B

Table 12

Table 12 Performance summary of different ciphers [47]

	Size: optimized			Speed: optimized		
Rank	Code mem	Data mem	Speed	Code mem	Data mem	Speed
By key setup						
1	RC5-32	MISTY1	MISTY1	RC6-32	MISTY1	MISTY1
2	KASUMI	**Rijndael**	**Rijndael**	KASUMI	**Rijndael**	Rijndael
3	RC6-32	KASUMI	KASUMI	RC5-32	KASUMI	KASUMI
4	MISTY1	RC6-32	Camellia	MISTY1	RC6-32	Camellia
5	**Rijndael**	RC5-32	RC5-32	**Rijndael**	Camellia	RC5-32
6	Camellia	Camellia	RC6-32	Camellia	RC5-32	RC6-32
By encryption (CBC/CFB/OFB/CTR)						
1	RC5-32	RC5-32	**Rijndael**	RC6-32	RC5-32	**Rijndael**
2	RC6-32	MISTY1	MISTY1	RC5-32	MISTY1	Camellia
3	MISTY1	KASUMI	KASUMI	MISTY1	KASUMI	MISTY1
4	KASUMI	RC6-32	Camellia	KASUMI	RC6-32	RC5-32
5	**Rijndael**	**Rijndael**	RC6-32	**Rijndael**	**Rijndael**	KASUMI
6	Camellia	Camellia	RC5-32	Camellia	Camellia	RC6-32

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