Wireless Body Area Networks for Healthcare: A Survey

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ABSTRACT

Wireless body area networks (WBANs) are emerging as important networks, applicable in various fields. This paper surveys the WBANs that are designed for applications in healthcare. We present a comprehensive survey consisting of stand-alone sections focusing on important aspects of WBANs. We examine the following: monitoring and sensing, power efficient protocols, system architectures, routing and security. We conclude by discussing some open research issues, their potential solutions and future trends.

KEYWORDS

Wireless body area network, body sensor network, healthcare, WBAN survey.

1. INTRODUCTION

The increase in average lifespan and health cost in many developed nations are catalysts to innovation in health care. These factors along with the advances in miniaturization of electronic devices, sensing, battery and wireless communication technologies have led to the development of Wireless Body Area Networks (WBANs). WBANs consist of smart miniaturized devices (motes) that are able to sense, process and communicate. They are designed such that they can be worn or implanted, and monitor physiological signals and transmit these to specialized medical servers without much interference to the daily routine of the patient.

Our purpose is to present a comprehensive survey of WBANs designed for the healthcare industry. By doing this we hope to stimulate more research in the area by identifying open research issues. In section II we survey monitoring and sensing in WBANs. Section III presents an examination of power efficient protocols. In section IV we explore the WBAN system architectures. Approaches to routing in WBAN are presented in section V. In section VI we present various security techniques and protocols. We conclude in section VII with a discussion of open research problems and future trends.

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2. MONITORING AND SENSING

We begin with a review of current examples of wireless sensor technology in the field of mobile healthcare. The examples are organized according to a taxonomy that distinguishes between wearable and implantable sensors. Within these two sensor categories, the examples are organized by the type of signal acquired by the sensor.

2.1 Wearable Sensors

Pulse Oximetry

A pulse oximeter is a medical device that indirectly measures the oxygen saturation levels (SpO_2) in an individual's blood as well as the changes in blood volume in the skin that coincide with the cardiac cycle. Typically, a pulse oximeter is attached to a finger or an earlobe, and it consists of red and infra-red light-emitting diodes (LEDs) and a photodetector. The photodetector measures the amount of red and infra-red light that is transmitted through or reflected by the body part, which is partially dependent on the amount of light absorbed by the blood that perfuses the body part. The relative absorption of red and infra-red light by the blood is related to the ratio oxygenated hemoglobin to deoxygenated hemoglobin, and this serves as the basis of the SpO_2 measurement. The overall amount of light absorption varies as the pulsatile volume of blood within the body part changes with time. This quasi-periodic signal is called a photoplethysmograph (PPG), and can be used to determine heart-rate.

A wearable PPG biosensor in the form of a ring has been developed by Yang and Rhee [1]. As an article of clothing, a ring is more likely to be worn continuously, making it suitable for continuous monitoring applications. Asada *et. al.* have further refined the design of the ring sensor to ensure that the PPG signal output is more resistant to noise components due to motion artifacts and changes in ambient light levels [2]. Also, they have sought to reduce power consumption by using a high frequency, low duty cycle modulation scheme. A picture of the ring sensor is illustrated in Figure 1.

Shnayder, *et al.* have designed a pulse oximeter that integrates a BCI micro power oximeter [3] with a Mica2 [4] or MicaZ [5] wireless sensor platform. This pulse oximeter serves as a node in a medical sensor network platform developed by a research group at Harvard University called *CodeBlue* [6]. Anliker *et. al.* have also designed a pulse oximeter sensor as a part of their wearable multiparameter medical monitoring and alert system called AMON (Advanced care and alert portable telemedical MONitor) [7]. The pulse oximeter sensor is integrated into a single wearable wrist device with the other sensor components of this system (Figure 2).

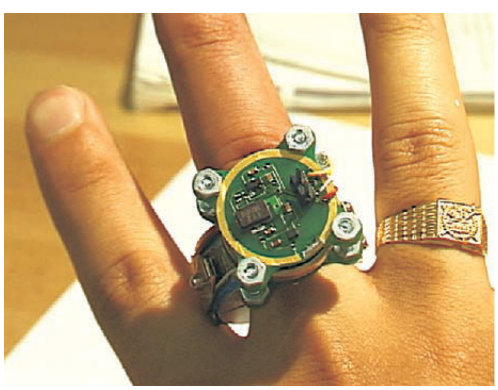

Fig. 1. Photograph of PPG Ring Biosensor Prototype (Courtesy of Asada *et. al* [2])

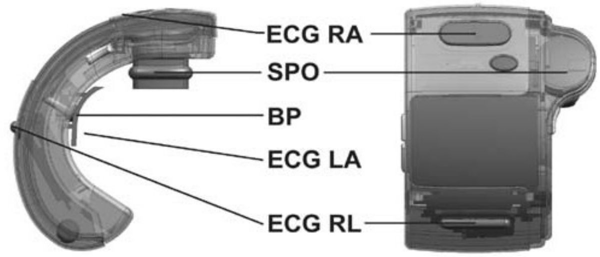

Fig. 2. Photograph of AMON Sensors: ECG, SPO_2, and Blood Pressure (Courtesy of Anliker *et. al* [7])

Wireless PPG devices may be used in applications that require data on the cardiovascular (CV) state of an individual. [2]. A survey of wearable biosensor systems focusing on multi-parameter physiological detection systems is provided in [8] A particular survey that focuses on wearable networks for the visually impaired to avoid obstacles is presented in [9].

Electrocardiography (ECG)

The electrocardiogram (ECG) is a waveform that represents the propagation of electric potentials through the heart muscle with respect to time. The propagation of these potentials results in the quasi-periodic contraction of the heart muscle. Therefore, the ECG waveform provides a non-invasive means for investigating heart function. Standard ECG measurements utilize twelve leads or 'views' of the electrical activity of the heart. However, ECG measurements using wireless sensors are generally for ambulatory applications and will typically utilize a subset of these leads. Figure 3 illustrates the basic features and intervals pertaining to ECG waveforms.

Fulford-Jones *et. al.* designed an ECG sensor that is supported by a Mica2 mote hardware platform [10]. The sensor utilized two electrodes to produce a single ECG signal. This sensor is another node in the *CodeBlue* medical sensor network platform.

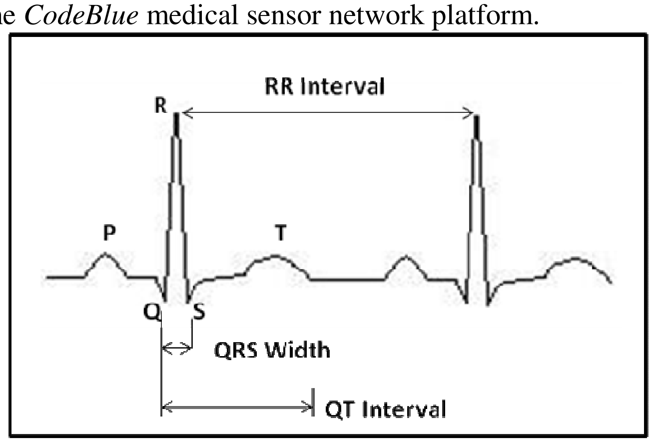

Fig. 3. Basic ECG Features and Intervals

The AMON system also includes an ECG sensor that produces a single-lead ECG signal. The sensor also utilizes an algorithm that calculates QRS pulse width, RR distance and QT interval from the ECG waveform. The Human++ research program has also developed a wireless single-lead ECG patch sensor, where the ECG signal is measured across two Ag/AgCl electrodes [11]. Cao et. al. have created a wireless three-pad ECG system (W3ECG)[12, 13], A pad is a self-contained board with two-three electrodes and front-end analog amplification circuitry. The advantage of this system over the others mentioned is that it enables a user to synthesize conventional 12-lead ECG signals from the three leads being measured.

In addition to the application areas mentioned for pulse-oximeters, the ECG signal can also be used to detect/classify cardiac arrhythmias [14].

Blood Pressure

A blood pressure (BP) reading is a measure of the force exerted by circulating blood on the walls of blood vessels. BP varies between a maximum (systolic) and a minimum (diastolic) pressure during a cardiac cycle. It has been observed that ambulatory BP is more closely related to target organ damage and cardiovascular events than BP readings taken in a clinical environment [15]. This fact provides the motivation for the creation of wireless BP sensors. The AMON system has a BP sensor that uses an inflatable cuff around the wrist and obtains systolic and diastolic readings via the oscillometric method [16]. Though this method can used to obtain ambulatory BP readings, it cannot monitor BP variations continuously and the cuff-based measurement may cause user discomfort. These issues are remedied by Poon et. al. in the creation of a cuff-less BP watch sensor, based on the pulse transit time (PTT) method for measuring BP [17] (Figure 4).

Electromyography (EMG)

Electromyography is the study of muscle function through the monitoring of the electrical signals emitted by the muscle [18]. When a surface electrode is placed on the skin above a superficial muscle while it is contracting, it will receive electrical signals emanating from several muscle fibers associated with different motor units. The spatio-temporal summation of these electrical signals results in what is called an electromyogram (EMG) signal. Therefore, the EMG signal provides an effective means of monitoring muscle activity.

Bonato et. al. describe a data-mining technique (self-organizing maps) that is used to cluster EMG data recorded over a 24-hour period of daily activity [19]. These clustered data are used to determine neuromuscular mechanisms associated with specific biomechanical activities. One possible application of this work is to use EMG signals to investigate mechanisms associated with daily physical activities that induce pain, with the intention of devising treatment regimes.

Activity/Motion Detection

The level of activity or the nature of motion of an individual can be detected by a system that combines an accelerometer with a gyroscope. An accelerometer is a sensor that measures acceleration with respect to gravity, and can be used to determine the orientation of a body part in the absence of movement. A gyroscope is a sensor that measures angular velocity and can be used to determine the orientation of a moving body part as a function of time.

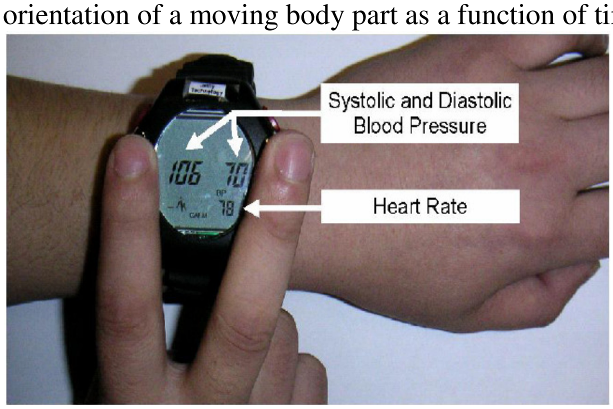

Fig. 4. Cuff-less Blood Pressure Watch Prototype (Courtesy of Poon *et. al.* [17])

Examples of 3-axis accelerometers can be found in [20, 21], and example of an integrated accelerometer/gyroscope in [6]. Kusserow et. al. presented a wireless sensor node design called

BodyANT, which is equipped with an accelerometer[22]. Their investigations revealed the effectiveness of this device in long-term activity monitoring/recognition applications. One potential application of these motion detectors is to monitor the occurrence of uncontrolled body movements, called dyskinesias, experienced by sufferers of Parkinson's disease while undergoing a levodopa (the generic name for a drug used in the treatment of Parkinson's) treatment regime [23]. These investigations may lead to a more effective control of levodopa intake in order to reduce the occurrence of these dyskinesias.

Electroencephalography (EEG)

Electroencephalography (EEG) is a representation of the electrical activity of the brain. Currently, ambulatory EEG (AEEG) recordings have been shown to have great value in the diagnosis of epilepsy and in the monitoring of patient response to therapy [24]. Much of the information obtained from AEEG recordings may not be obtained during a routine, 20-min EEG test. This serves as motivation to develop wireless EEG sensors that will make the recording of AEEG signals during daily activities less obtrusive and less cumbersome.

Jovanov *et. al.* have proposed using their Wireless Intelligent SEnsor (WISE) for EEG signal acquisition applications [25]. This sensor is a microcontroller-based system capable of data acquisition, analog signal conditioning, low-level real-time signal processing, and wireless communication. Farshchi *et. al.* have also introduced a wireless neural interface, using Mica2 and Mica2dot [26] systems as the wireless sensor platforms, which is capable of acquiring two channels of EEG data [27].

2.2 Implantable Sensors

Glucose Monitoring

It has been shown in [28] that real-time continuous blood glucose data will assist in reducing hyperglycemic excursions for individuals with type 1 diabetes, while lowering the risk of episodes of hypoglycemia caused by the administered levels of insulin being too high. Continuous monitoring was enabled by placing an implantable sensor covered with a multilayered membrane in the subcutaneous tissue of the abdomen. Glucose levels were determined every 30 s and radio transmission of the glucose data occurred every 5 minutes. If this sensor were to be combined with a implantable drug delivery system, such as the one in [29] a closed feedback loop would be formed for the control of blood glucose levels via the delivery of variable amounts of insulin.

Implantable Neural Stimulators

Implantable neural stimulators send electrical impulses into the brain or spinal cord for the treatment of Parkinson's disease, intractable epilepsy and chronic pain. An example of such a device is given in [30].

3. POWER EFFICIENT PROTOCOLS

Wireless body area sensor nodes, due to their size, use miniaturized batteries. The battery life of a sensor node is proportional to the battery size. Hence, WBANs must sense, process and communicate data in a power efficient manner. Power efficiency, therefore, is of utmost importance and is a key emphasis of design efforts for WBAN protocols.

The majority of work in this area has been on developing energy-efficient medium access control (MAC) protocols. However, there has been some research in implementing energy-efficient methodologies in the higher layers of the ISO/OSI model. One such work proposed a robust protocol stack for multi-hop WBANs [31]. A multi-hop architecture is utilized because of the possibility of low quality links that may arise due to the movement of on-body nodes.

Link degradation may be large enough to prevent a sensor node from having a direct wireless link to the gateway of the network. The proposed protocol uses a gossiping strategy for data routing between the sensor and the gateway and a time division multiple access (TDMA)-based MAC protocol. Simulation results show that power consumption is reduced compared to a TDMA-based star network.

Another research effort proposed an energy efficient computing model, called wireless device driver for low-duty peripherals for WBANs [32]. The wireless device driver, which is part of the host's operating system, performs the control operations for a wireless peripheral device. Also, the wireless device driver relies on wireless communication protocols for a reliable connection with the peripheral. For energy-efficiency reasons, a wireless peripheral device is not always connectable, but switches its state between connectable and idle continuously. These techniques serve to achieve minimum connection latency without changing power consumption. The experimental results using BlueTooth and ZigBee show that the techniques are effective in reducing energy consumption while meeting connection latency requirements.

Shankar *et. al.* analyzed the energy efficiency of two protocols designed for wireless communication in biosensor networks [33]. TDMA is used for medium access in both protocols. The first protocol is applied to a cluster-based topology, where the network is divided into clusters consisting of sensors and a leader node. Energy saving is accomplished in this protocol by requiring only the leader nodes to make the long distance transmission to the base station. The other protocol is applied to a tree-based topology. In this protocol, a node transmits data to the base station via a tree hierarchy of parents and children with the base station as the root. Energy saving is obtained in this protocol, because no node is required to make a long distance transmission. Simulation results show that the cluster-based approach is more energy efficient that the tree-based approach, because the tree-based approach incurs transmit/receive costs at each level of the tree hierarchy.

The main sources of energy waste in the design of a MAC protocol for a WBAN have been identified as collision, overhearing, control packet overhead, and idle listening [34, 35]. Currently, there are two main schemes used for MAC protocols of sensor networks. Contention-based MAC protocols, such as carrier sense multiple access/collision avoidance (CSMA/CA), have their nodes contend for channel access prior to transmission. The advantages of these protocols are scalability, adaptability to network changes and no time synchronization constraint. In schedule-based MAC protocols, such as TDMA, access to the channel is divided into time slots that are of fixed or variable duration. Each node is assigned a time slot(s) by a controller, and it will only transmit within that time window. TDMA-based protocols eliminate collision, overhearing and idle listening, and are typically utilized in some form in energy-efficient MAC protocols.

In order to streamline the research and implementation efforts in BAN, the IEEE 802.1.4 created a task force in 2007 that would develop the specifications of a radio layer for BAN with emphasis on the allowable radio power levels in the vicinity of the human body. Bluetooth and ZigBee are communication protocols with unique node topologies within the IEEE 802.15.4 wireless networking standards. Bluetooth is a widely used communication protocol for topologies with master-slave architecture in WBANs. Bluetooth has a higher bandwidth and higher data rate for applications compared to ZigBee. ZigBee is used primarily in a star-topology of nodes, provides lower power consumption, lower data rates and longer battery life than Bluetooth. [32] provides a comparative study of ZigBee and Bluetooth used for developing low energy wireless communications. A detailed report on the specification of various communication protocols can be found in [36], where the author presents the requirements of the model for communication in BANs in the context of requirements of the network, communications, physical, data layer and routing layer requirements for low power WBAN applications.

IEEE Standard 802.15.4 defines the physical layer (PHY) and medium access control (MAC) sublayer specifications for low-data-rate WPAN (LR-WPAN), typically operating in the personal operating space (POS) of 10 m [37]. IEEE 802.15.4 has two operational modes: a beacon-enabled mode and a non-beacon enabled mode. In the beacon-enabled mode, the network is controlled by a coordinator, which is responsible for device synchronization. Optionally, the superframe can be subdivided into active and inactive periods. The coordinator may enter sleep mode during the inactive period. The active period contains three components: a beacon, a Contention Access Period (CAP), and a Contention Free Period (CFP). During the CAP period, devices contend for channel access using slotted CSMA-CA. It has been found that IEEE 802.15.4 does not meet all the energy efficiency requirements for WBAN applications [38-40]. It is because of these shortcomings that the IEEE 802.15 Task Group 6 (BAN) has begun developing a communication standard optimized for low power devices and operation on, in or around the human body (but not limited to humans) to serve a variety of applications including medical, consumer electronics / personal entertainment and other [41].

In the absence of a standard, several energy efficient MAC protocols specifically designed for WBAN applications have been presented. An energy-efficient MAC protocol was presented in [42]. This protocol was designed specifically for a star topology that consists of clusters with a central master node plus slave sensor nodes. The network access is obtained using clear channel assessment and collision avoidance with time division multiplexing (CCA/TDMA). This network access scheme significantly reduces the likelihood of collision and idle listening, leading to power savings. The hardware implementation of the MAC incorporates cross-layer optimization by performing some functions from the session layer in the physical layer, reducing the power overhead of software implementations.

Table 1 – Power Efficiency of MAC Protocols for WBAN

Protocol Description	**Power Consumption Measure**	**Measurement Conditions**	**Reference**
CCA/TDMA with cross-layer optimization	P_{AVG} = 3 mW	Protocol implemented on Sensium SOC WBASN ASIC with for temperature sensing and ECG applications.	Omeni *et al.*[42]
Low-duty cycle TDMA	P_{AVG} = 2.04 mW at 3 VDC	Protocol implemented using Analog Devices 70XMBZ2 platform with ADF7020 RF transceivers.	Marinkovic *et al.*[43]
HMAC: TDMA with heartbeat rhythm synchronization	Increased network lifetime 15% - 300% compared to 2 WSN MACs	OMNet++ simulation, cardiac rhythm obtained from MIMIC database, Tmote Sky specification	Li *et al.* [44]
BodyMAC: Energy efficient TDMA-based MAC	P_{AVG} = 3 mW (sleep mode) P_{AVG} = 6 mW (no sleep mode)	Simulation uses single star topology and MICAz mote specification.	Fang *et al.* [45]
MedMAC: Adaptive TDMA-based MAC protocol	$P_{AVG} \approx$ 1 mW (EEG) P_{AVG} = 1.81 mW (Respiration) P_{AVG} = 0.2 mW (Temperature)	Opnet simulation model uses star topology for two applications: EEG (up to 24 nodes at 86.4 kbps/node) and health/fitness (respiration node at 640 bps + pulse at 8 bps + temperature at 16 bps). MICAz mote specification.	Timmons *et al.* [46]

	P_{AVG} = 0.2 mW (Pulse monitor)		
DQBAN (Distributed Queuing Body Area Network): Cross-layer fuzzy logic scheduling mechanism	All sensors transmit at lowest possible level specified in 802.15.4. (i.e. -25 dBm)	Simulation uses a star-based WBAN. Matlab simulations using the CC2420 transmitter-receiver benchmark used two scenarios: • Homogeneous: 5-35 wireless ECG sensors • Heterogeneous: 10-35 wireless ECG sensors along with 4 other sensors for clinical doctor PDA, respiratory rate, blood pressure and endoscope imaging	Otal *et al.* [47]

Marinkovic et. al. [43] present an energy-efficient, low duty cycle MAC protocol based on TDMA. The MAC protocol enables access to the physical layer for a hierarchical topology consisting of nodes communicating with master nodes, which in turn communicate with the monitoring station. The hierarchy removes the need for sensors to expend power by transmitting to the monitoring station. Also, the use of TDMA ensures collision-free transfer and minimization of idle-listening. The protocol is implemented using the Analog Devices 70XMBZ2 platform with ADF7020 RF transceivers. Measurements reveal that the protocol is energy-efficient for streaming and short burst data communications.

A novel TDMA-based protocol for BSNs, called H-MAC, is proposed in [44]. This protocol improves energy-efficiency by using the heartbeat rhythm to perform TDMA synchronization, avoiding energy consumption associated with transmitting time synchronization beacons. Power efficiency is also accomplished in H-MAC as a TDMA-based protocol assigns time slots to each biosensor to guarantee collision-free transmission. Simulations show that H-MAC prolongs the network life of sensors dramatically.

In [45] a TDMA-based MAC protocol called BodyMAC is proposed. Three types of bandwidth allocation schemes are devised to cope with different types of data communications, such as periodic data sensing and important event allocation. In conjunction with bandwidth allocation, a sleep mode mechanism is introduced, which turns off a node's radio during beacon, uplink and downlink periods, as much as possible. Simulations results show superior performance of BodyMAC compared to that of IEEE 802.15.4 MAC.

Timmons et. al. [46] introduce an adaptive TDMA-based MAC protocol called MedMAC. MedMAC incorporates a novel adaptive TDMA synchronization mechanism in which only a multi-superframe beacon has to be listened to by the nodes. An optional contention period is also available for low-grade data, emergency operation and network initialization procedures. Simulations show that MedMAC consumes less power than IEEE 802.15.4 for two classes of medical applications.

In [48] a power efficient MAC protocol is proposed for WBANs. This work presented a traffic based wakeup mechanism that utilizes the three categories of traffic patterns of the body sensor nodes, namely: normal traffic, on-demand traffic and emergency traffic. The wakeup patterns of all body sensor nodes are organized into a table called traffic-based wakeup table. The table is maintained and modified by a network coordinator according to the application requirements. Based on the body sensor node's wakeup patterns, the network coordinator can also calculate its own wakeup pattern. During normal traffic, both the body sensor nodes and the network coordinator send data based on the traffic–based wakeup table. The network coordinator sends a wakeup radio signal to body sensor nodes, which wake up in response to these signals, during on-demand traffic period. During emergency traffic period, the body sensor nodes send a wakeup radio signal to the network coordinator, which responds to the wakeup radio signal.

Otal and Alonso proposed an energy-saving MAC protocol, DQBAN (Distributed Queuing Body Area Network) for WBAN in [47] as an alternative to the 802.15.4 MAC protocol which suffers from low scalability, low reliability and limited QoS in real-time environments. The proposed DQBAN is a combination of a cross-layer fuzzy-logic scheduler and energy-aware radio-activation policies. The queuing of access packets and data packets is determined by fuzzy-logic rules, which permit body sensors to find out '*how favorable*' or '*how critical*' their situation is in a given time-frame. The fuzzy-logic scheduling algorithm is shown to optimize QoS and energy-consumption by considering cross-layer parameters such as residual battery lifetime, physical layer quality and system wait time. The authors tested their proposed protocol on two scenarios: a homogenous scenario of a body sensor network with 5 – 35 homogenous ECG wireless sensors and a heterogeneous scenario of a body sensor network with wireless ECG sensors and four other sensors for clinical doctor PDA, respiratory rate, blood pressure and endoscope imaging. Further specifications are shown in Table 1. The authors showed that the DQBAN protocol has higher reliability, while fulfilling certain battery limits and latency demands and displays energy-saving behavior compared to most MAC implementations.

Another cross-layer protocol, CICADA (Cascading Information retrieval by Controlling Access with Distributed slot Assignment) for low-delay and energy efficiency has been proposed in [49]. The authors used a spanning tree approach to determine presence/absence of next-hop nodes, and hence the data transfer schedule. By leveraging the network topology, CICADA enforces a downward motion of control information and upward information of data along the spanning tree. This allows for simplified routing, lower interference and idle listening; all of which contribute to energy-efficiency for body area networks.

4. SYSTEM ARCHITECTURES

In this section, we survey the architectures of WBANs with respect to network topologies, application-specific network design, and topologies with various physical locations.

4.1 Network Architectures

The network architecture of WBANs can be broadly classified into two major categories: flat architectures and multi-tier architectures. Flat architectures comprise of a single data-gathering unit that sends its data to a personal computer or a personal server application running on a PDA. An example of this is described in [25]. Here the authors describe the use of wireless intelligent breathing telemetry sensor (WIBRATE) to study breathing patterns. A thermistor-based breathing sensor is equipped with on-board data processing mechanisms. This device is connected to a PC using a wireless link. This is an example of a point-to-point network of a single client and server. Data upload to a personal server is facilitated whenever a wireless link is available. A flat architecture of WBAN is illustrated in Figure 5.

Multi-tier architectures, as shown in Figure 6, are widely used to achieve large data gathering of multiple physiological signals using multiple nodes in the base tier, a gateway at the second tier that acts an interface between first tier and a server at the third tier. For example, the architecture described in [50] is a prototypical WBAN. In [50], the authors have studied the performance of a WBAN for remote patient monitoring through an OPNET simulation study. The multi-tier architecture used for the WBAN in [49] is the widely used three-tier architecture. A WBAN is connected through a voice and data gateway to the hospital core-switch, which in turn is connected to the IP phone. The voice and data gateway is also connected to the wireless access point which provides access to the patient's and doctor's PDAs. Finally the core switch is connected to the hospital's ZigBee network which records the data from multiple patient WBANs.

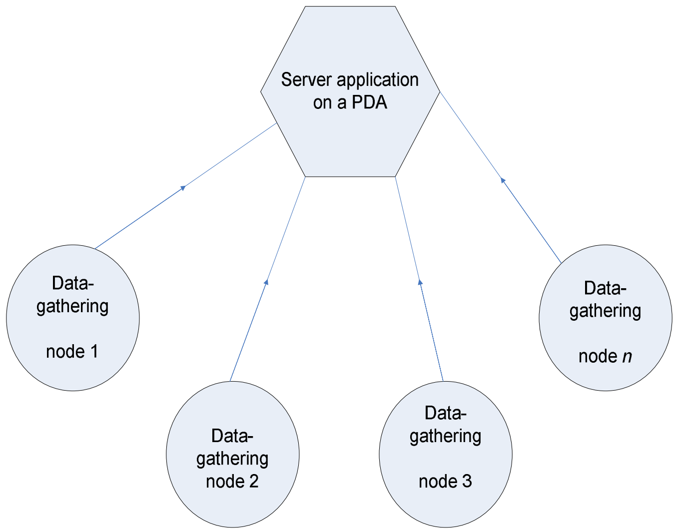

Fig. 5. Flat architectures in WBANs

The rest of this section focuses on various multi-level architectures with an emphasis on specific topologies for parameter optimization of security, energy efficiency, node locations and the emerging use of ultra-wideband transceivers for WBANs.

Security-Centric Architectures

In [51], the authors have studied the design of WBAN architecture with an emphasis on security and cross-layer operation. The paper studies CICADA-S, a secure multi-hop protocol that places stringent security requirements on the existing CICADA (Cascading Information retrieval by Controlling Access with Distributed slot Assignment) protocol. The main components of the WBAN are the network of nodes, external networks and back-end server. Each patient has their own unique gateway that securely processes patient data and sends it to the back-end server. The CICADA protocol addresses both MAC and routing layer by ensuring collision-free medium access, low interference and avoidance of idle listening. Routing is performed along a distributed spanning tree. Security is enforced during node initialization using a secure key which is generated by back-end servers uniquely for each node in each session. When a node leaves or rejoins the WBAN, it triggers a network topology update which generates a new key for each node. This ensures that nodes which leave the network cannot read/modify the patient data. In addition, node membership in WBAN networks is mutually unique and location privacy has been enforced through anonymity in messages shared between the back-end server and the WBAN.

Energy Efficient Architectures

In [52], the authors described an energy efficient TDMA-based MAC protocol for a multi-tier architecture of a WBAN. The multi-tier architecture is that of the widely used sensor nodes at the first tier, a set of master nodes that collect data from first tier nodes and a monitoring station in the highest (third) tier that encompasses the monitoring and data access functionalities at the user level.

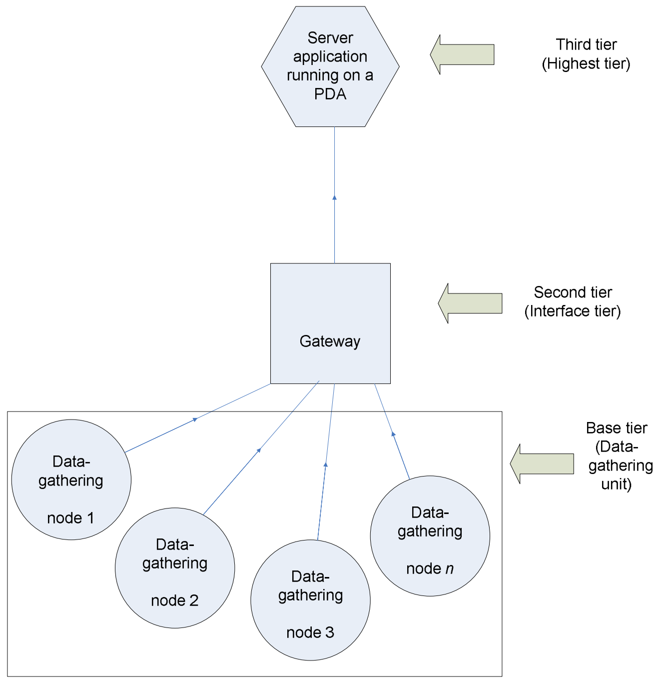

Fig. 6. Multi-tier architectures in WBANs

By exploiting the features of a fairly stationary network of first tier nodes with fixed data collecting functions (as opposed to dynamic ad-hoc networks or mesh networks with dynamic topologies of wireless sensor networks (WSNs)), and smaller distances between the first tier nodes and second tier master nodes, the authors develop a MAC protocol that is energy efficient and uses concise synchronization messages to co-ordinate data transfer on the network.

In [53], the authors presented a WBAN that measures stress through the heart-rate variability parameter. The BAN is organized as a network of (**W**ireless **I**ntelligent **Se**nsor) WISE sensors (clients) that connect to a personal server (PS). In addition to data processing, the PS also facilitates synchronization of clients. In order to reduce the power consumption of the wireless transceiver on the PS the authors introduce the concept of a mobile gateway (MOGUL) that establishes wireless communication with the PS and downloads data. Energy efficiency is implemented using energy efficient communication protocols and low-energy radio layer 900 MHz RF modules. Increased on-board data processing at sensor nodes reduces the size of the transmitted packets to the PS. The system architecture is a master-slave architecture, where the MOGUL acts as the master and downloads data from WISE sensors when it is in within its communication range. The architecture allows for multiple sessions of communication with WISE sensors. All data obtained from these sensors is aggregated in a central device that is connected to the multiple mobile gateways generating these sessions.

In [25] , the authors present the prototype implementation of a network of WISE sensors. To minimize power consumption in communications, the communication range of a sensor is limited. The architecture features sensors that perform data collection and on-board signal processing. The multiple WISE clients communicate with a single server. A remote intelligent control system determines when a new measurement is needed and signals the sensor to do so or requests that the patient do it. The collected data is transmitted to the databases on the personal server.

Ultra-wideband (UWB) transceiver design

In [54], the authors proposed the use of a UWB transmitter for energy-efficient operation of WBANs. Due to the high interference generated by the human body and its environment, one solution to develop low power-output transceivers for radios in the sensor nodes is to optimize the air interface of the network. By creating architectures that exploit the features of robust nodes and energy-constrained nodes, low latency and simple network topologies, the authors show that an UWB based architecture is advantageous over narrowband radio communication.

The use of UWB has been further explored in [55]. Here the authors described the use of UWB for an in-body WBAN application of capsule endoscopy. Within the 402-405 MHz frequency band, allowed by the FCC for in-body communication systems, UWB communication has shown to be most effective for integrating in-body and on-body medical sensors into a single system. With the help of radio channel simulation results, the authors presented the link capacity, signal power spectral density and interference mitigation. Finally a WBAN coordinator acts as an interface between the network of sensors and a medical server. The current state of this work is documented under the MELODY Project [56, 57].

Application-Specific Network Design

WBANs can have unique architectures to tailor them for various applications. In [57], the authors described the implementation of a WBAN for bio-telemetry for elderly people. Although ZigBee and Bluetooth are widely used in WBANs due to their low-power simple topology operation, they can be inefficient due to the high data volume sensing and communication operations required in monitoring physiological parameters. The network architecture is a scalable architecture of bio-sensors and motion sensors at the first tier, a gateway at the second tier that interfaces between the first tier nodes and the monitoring station and medical station at the third tier.

In [58], the authors described the implementation of a WBAN for hip rehabilitation called HipGuard. This implementation uses the ANT WSN technology since it enables repetitive measurements with low latency requirements. The ANT architecture uses a master-slave framework, where a central unity is connected with sensor units. The focus of this paper is on network issues with the HipGuard implementation and the authors study various performance parameters such as human body interference, throughput and latency in this context.

In [59], the authors presented general system architecture for WBANs. They propose a system for activity sensing (Actis) that is a multi-tier system architecture of intelligent physiological sensors at the lowest level, a personal server running on a PDA in the second tier, which is connected to a medical server or the Internet in the third tier.

A re-configurable sensor architecture for enabling a range of detection of physiological signals is presented in [60]. The authors develop this architecture for the application of pulse oximetry and use a reconfigurable platform that can be self-initiated or request-triggered. The advantages of such architecture include reusability of hardware and code, precise time synchronization and cost efficiency. Run-time configuration adapts readily to change in patient environments and supports updation of software parameters for data processing, thus customizing the medical application.

In [61], the authors described the architecture and implementation for two types of tier -1 sensors- Actis and eActis, where eActis is the ECG and tilt sensor enabled framework for Actis. The architecture uses the ZigBee star network topology to minimize power consumption, a Flooding Time Synchronization Protocol (FTSP) for accurate synchronization of WBAN nodes, and power-saving sleep modes for the sensor nodes. The architecture allows for scenarios where raw data can be sent over a link to a personal server. This approach allows for precise localization of events leading to a specific occurrence in the patient's health, as opposed to transmission of processed data that loses some information in the data aggregation process.

Node Locations

WBAN architectures can also be classified based on their location in the human vicinity. In particular, these architectures can be wearable or implanted on/within the human body. Capsule endoscopy discussed in [55] is an example of implantable WBAN architecture. In [62], the author reports various implementations of body area networking. One such implementation is that of a pill camera which the patient ingests. The camera takes pictures and transmits them to a recorder. The camera is scheduled for an operational time of up to eight hours. Another application is that of using signals from implants to stimulate muscles to allow limb movements.

Most of the WBAN architectures and applications discussed in this section are wearable architectures. An additional example is [63]. Here, the authors described wearable WBAN (WWBAN) for health monitoring. The proposed WWBAN architecture is a multi-tier architecture, where first tier comprises of sensors, second tier is an application-specific layer and third tier includes data accessibility through servers connected to the Internet. Specifically, the sensors in first tier monitor physiological signals such as ECG and blood pressure. In second tier, a personal server (PS) running on a PDA acts as an interface between the user, medical server connected to the Internet (third tier) and the sensors in first tier. Hence the server application in second tier is responsible for network configuration of the sensors, secure communications and data processing for data obtained from first tier sensors. In the event that the second tier server is unable to connect a third tier server, the proposed architecture enables local data storage. Finally third tier enables data access by healthcare providers. The proposed WWBAN architecture can be configured for use at home, work or in a medical setting, where the architecture ties in seamlessly by virtue of the connectivity between second tier and third tier servers. The authors developed a WWBAN prototype for monitoring ECG, trunk and ankle motion. The network coordinator manages synchronization, ensures secure links for data transmission and data aggregation before forwarding it to the second tier PS application. Using a star topology of the ZigBee architecture, a master node (network coordinator) periodically transmits beacons to its slave nodes and allows for energy conservation through the use of power-saving sleep modes.

In the area of on-body communications, Sensium [64] is an application for monitoring physiological signals. It comprises of a '*digital plaster*' worn on the body to measure parameters such as heart rate. Multiple Sensium devices report to a base station Sensium plugged into a PDA or a smartphone. This is a multi-tier architecture with the base-tier of Sensium devices that collect data, a base station (second tier) that collects data from (first tier) nodes, and the highest tier is a server that acts as a local database and can also be connected to the Internet.

In [65], the authors described a specific routing architecture for the MAC protocol for body sensor networks. The authors propose the *data-pulling* paradigm for body sensor networks (BSNs) as opposed to the *data-pushing* model adopted by nodes in current WSN architectures. The advantages of using a *data-pulling* model in a BSN with resource constrained nodes and a robust base station (BS) are that it allows for sensors that support high throughput over the single hop to the base station while eliminating collisions and overhead due to synchronization and timing. The BS is a robust data processing unit that has a larger battery and larger processing power that enables it to carry on data processing and network configuration. The data collection is achieved through a *data-pulling* model, where the BS requests (pulls) data from a set of nodes with the help of simple commands, thus eliminating packet collision and channel contention issues. It uses the same model to manage the nodes in power-saving models and for network configuration. The sensor nodes are however configured as a thin server architecture where nodes collect data about the physiological signals and store them locally. Since the nodes are lighter, smaller and more resource-constrained than the BS, they have lower processing power which also enables wearability. These characteristics call for *thin servers* that are smaller data collection entities in the BSN network. The authors use this architecture and the resulting MAC protocol for a wearable ECG monitoring system and show that this architecture achieves high channel utilization by eliminating power consumed in the time synchronization and avoids the use of complex MAC protocols.

5. ROUTING

Routing and related issues have not been sufficiently addressed, while a lot of attention has been paid on designing MAC layer, energy and power constraints, and related Physical layer characteristics.

The principal characteristics of a Wireless Body Area Network (WBAN) that necessitate the design of a routing protocol are frequent network partitioning due to postural mobility of the on-body sensors, high propagation loss across the human body, low transmission power of the sensors, and low reliability of end-to-end path from source to sink. Link layer behavior of WBANs at 2.4 GHz have been studied in [66], where the authors observed the following:

(i) Average packet delivery ratio (PDR) increases with increase in transmission power.

(ii) Increasing transmission power at regions with low multipath increases PDR even more.

(iii) Environments do have an impact on PDR. In a lab setting more than 70% of links have PDR 90% or more; while in an open setting (on the roof) about 50% of links have 90% or more PDR.

The authors in [66] also found that channel symmetry is better in environments having more reflective surfaces (more multipath). Average channel symmetry in a lab environment was found to be 3.9% as compared to 7.3% on a roof. Sensor placements on the body also have an impact on the network performance. While average PDR was found to be 94.9% between nodes on the left hand side and 94.4% between nodes on the right hand side, significant drop in PDR was observed between the left-hand side and right-hand side nodes.

A fundamental question arises on whether there is a need to design a routing protocol on top of the link layer protocol already in place. Some preliminary studies [67] have shown that there are clear tangible benefits of multihop communication between on-body sensors. In an open environment with low transmission power, there has been significant improvement in PDR with multihop communications. Moreover, as the propagation loss around the human body is high with high signal attenuation, direct communication between the sensors is energy-expensive. Multihop communication is therefore a more viable alternative among on-body sensors.

Traditionally, there have been two approaches to routing in BANs. One approach is to integrate the routing functions with the MAC layer, with a fundamentally cross-layer approach. The other is to design a routing layer on top of the MAC layer, where link qualities are measured based on selected parameters, and taken into path computation.

The first approach has been studied and proposed in [68-70]. The authors in [69] have proposed a cross-layer CICADA protocol that sets up a spanning tree and uses time slots for controlling each node's transmission and reception cycles. Each node informs its children about their turns for sending data. Data transfer takes place as a sequence of cycles: a control cycle and a data cycle. In the control cycle all nodes are informed about the order in which they can transmit. When all nodes receive their control schemes, that data cycle starts. In the data cycle each data scheme has two parts: a data period (α), and a waiting period (β). The data period also provides a contention slot to allow nodes to join the tree. This also provides mobility support for the network where nodes may get disconnected due to postural mobility. The authors have also discussed the energy efficiency of the algorithm, which depends on the network topology. As the nodes have to spend time on idle listening and overhearing during the control cycle, depth of the tree plays a significant role in controlling the energy efficiency of the protocol. However, the efficiency of the protocol needs to be evaluated based on frequent node disconnection and network partitioning due to postural mobility. The protocol also lacks an approach to define link metrics and use those metrics for finding effective multihop routes. This can be a compelling argument for necessitating a separate routing layer on top of MAC that would provide the basis for computing efficient multihop paths based on link quality metrics.

The second approach has been investigated in [71], where the authors have proposed a probabilistic packet routing protocol, Probabilistic Routing with Postural Link Cost (PRPLC), using a stochastic link cost. The experimental topology is being built in the laboratory with on-body sensor nodes using 900 MHz Mica2Dot Motes running TinyOS. The motes have Chipcon's SmartRF CC1000 radio chips and MTS 510 sensor cards from CrossBow Technologies. The radio chips' transmission powers are reduced to set the transmission range between 0.3 to 0.6 meters. The proposed protocol, based on postural link cost formulation, uses time-varying costs formulated for each link based on the locality in the connectivity patterns of the links. The protocol uses postural link costs to compute probabilistic forwarding of data packets. The authors have reported a significantly low end-to-end packet delay using PRPLC, as the protocol can successfully capture the locality in postural movements. The worst case scenario in the number of transmissions per packet for PRPLC is comparable to other store and forward protocols. While most of the packets are transmitted in two hops, some also take three and four hops to reach the destination. Packet delivery ratio for PRPLC is also comparable to other store and forward protocols.

However, the proposed protocol computes links cost based only on the connectivity pattern of the links, and lacks consideration of transmission power and residual energy of the nodes in the link cost computation. An alternative approach would be to consider transmission power of forwarding packets from node i to node j at time t. Another approach would be to consider the residual energy at each node, along with the link cost, in making the forwarding decision. All nodes would send their residual energy at that time instant to all their neighbors by piggybacking with the Hello messages.

Another approach is to design a routing protocol is based on the mobility pattern of the nodes. This approach has been investigated in [72], although not in context of WBANs, where a generic algorithm has been presented based on the use of high-dimensional Euclidian space. This is somewhat difficult to accomplish in WBANs, where the only mobility of the nodes is postural mobility. A possible approach can be using temporal mobility patterns of nodes based on historical data of link disconnections. A temporal pattern of link disconnection data can be used to select links for computing a probabilistic end-to-end path. However, extensive evaluations of these protocols need to be conducted based on prototype implementation in laboratories.

6. SECURITY

6.1 Security Requirements of WBAN

The WBAN and supporting infrastructure must implement security operations that guarantee the security, data integrity, privacy and confidentiality of the patients' medical records. In addressing privacy issues it must be ensured that the Health Insurance Portability and

Accountability Act of 1996 [73] is observed. The following security requirements must be attained:

Authentication: This is necessary to enable the WBAN to validate network nodes and thus prevent network compromise and/or node impersonation.

Data Integrity: this is needed to prevent the altering of data traversing the communication paths between nodes, and to prevent replay attacks.

Confidentiality: the network should be able to guarantee the secrecy of message exchange among nodes.

Availability: Since this network carries highly sensitive, important and potentially life-saving information, it is of utmost importance that the network resources are available at all times.

Privacy: The patients' data should not be disclosed to unauthorized entities (persons). Medical information is one of the most sensitive forms of personal data. The system must employ mechanisms that are able to adequately address current and potential laws in the future, governing the privacy of medical data.

6.2 Proposed Security Solutions

We now turn our attention to emerging security approaches in WBANs.

TinySec

TinySec is proposed in [74] as a security solution in biomedical sensor network to achieve link-layer encryption and data authentication. TinySec [75] is a software based security architecture that implements link-layer encryption. It is a component of the official TinyOS release. TinySec is very popular in the wireless sensor community and has even been implemented on a variety of custom hardware.

TinySec encrypts the data packet with a group key common to the sensor nodes and computes a message authentication code (MAC) for the entire packet including the header. This group key is shared network-wide and manually programmed into the nodes prior to deployment. This network-wide key presents a single point of vulnerability. TinySec does not protect against node capture. If a node is compromised and keying material revealed the entire network can be compromised.

IEEE 802.15.4 Security

Several security suites can be implemented under the IEEE 802.15.4. The IEEE 802.15.4 security suite modes can be classified into two basic modes: unsecured mode and the secured mode. The unsecure mode simply means no security suite has been selected. The standard defines 8 distinct security suites (see Table II). The first of these is the Null suite that provides no security. The others can be further classified based on the security properties they provide. There is encryption only AES-CTR (counter mode of cryptographic operation with AES), authentication only (AES-CBC-MAC), and encryption & authentication (AES-CCM). Encryption is performed using AES encryption [76], which consumes comparatively less energy than other algorithms. Authentication is achieved using the cipher block chaining with message authentication code (CBC-MAC). A detailed description can be found in [37].

TABLE II

IEEE 802.15.4 Security Suites

Name	**Description**
Null	No security
AES-CTR	Encryption only. This provides access control, data encryption, and

	optional sequential freshness.
AES-CBC-MAC-128 AES-CBC-MAC-64 AES-CBC-MAC-32	Authentication only allowing flexibility by the selection of different MAC lengths: 32, 64, 128 bits.
AES-CCM-128 AES-CCM-64 AES-CCM-32	This provides authentication and encryption allowing flexibility by the selection of different MAC lengths: 32, 64, 128 bits

ZigBee Security Services

ZigBee is a consortium of industry players which came together to define a new standard for ultra-low power wireless communication [77]. The ZigBee network layer (NWK) is designed to operate on top of the IEEE 802.15.4 defined PHY and MAC layers. The ZigBee standard defines extra security services including processes for key exchange and authentication, in addition to the security services of IEEE 802.15.4, upon which it is built.

The ZigBee standard specifies a "Trust Center". Usually the function of the Trust Center is performed by the ZigBee coordinator. The Zigbee coordinator is responsible for allowing nodes to join the network and for the distribution of keys. The roles specified for the Trust Center are: (1) trust manager- responsible for authenticating nodes requesting to join the network, (2) network manager- responsible for key maintenance and distribution, (3) configuration manager-responsible for ensuring end-to-end security[78]. More information can be found in [77].

Hardware Encryption

Instead of using software encryption as done in TinySec, hardware encryption can be implemented utilizing the ChipCon 2420 ZigBee compliant RF Transceiver. The CC2420 is able to execute IEEE 802.15.4 security operations with AES encryption using 128-bit keys. These operations include the counter (CTR) mode encryption and decryption, CBC-MAC authentication and CCM encryption plus authentication.

Hardware encryption has been implemented in a WBAN project with off-the-shelf ZigBee platform [79]. In this project it was determined that the hardware encryption does not significantly increase power consumption on the sensor platform. This was attributed to the efficient on-chip hardware support for encryption on the wireless controller and the dominant power consumption of the radio frequency (RF) unit when compared to the processing circuitry. However, the drawback of this method is that it is dependent on the specific sensor platform. Not all sensor node hardware offers hardware encryption support.

Elliptic Curve Cryptography

Elliptic curve cryptography (ECC) has emerged as a viable option for public key cryptography in wireless sensor networks. The main reason for this is its comparatively fast computation, small key size and compact signatures. There have been several noteworthy contributions in the past few years. One of the earliest works utilizing ECC in sensor networks was done by Malan *et al.* [80]. In this work, a public key infrastructure, using ECC, was implemented and evaluated on a Mica2 sensor mote platform supported by TinyOS. Uhsadel *et al.* [64] proposed an efficient implementation of ECC. Liu *et al.* [81] proposed TinyECC, which is another variation of ECC designed for TinyOS environment. As stated by the developers, "TinyECC is a configurable library for ECC operations in wireless sensor networks. The primary objective of TinyECC is to provide a ready-to-use, publicly available software package for ECC-based PKC operations that can be flexibly configured and integrated into sensor network applications"[81]. Recently, Szczechowiak *et al.* proposed NanoECC[82], which executes comparatively faster than existing ECC implementations but typically requires significant amount of ROM and RAM.

Although ECC has been successfully implemented in several variations it is still not a top choice for WBAN. This is because its energy requirements are still significantly higher than symmetric systems. This being the case, others have proposed that ECC be implemented only for infrequent and security-sensitive operations such as key establishment during the initial setup of the network or code updates. In line with this thinking, Malasri *et al*. [83] proposed a solution for medical sensor networks that uses: (i) an ECC-based secure key exchange protocol to set up shared keys between sensor nodes and base stations, (ii) symmetric encryption and decryption for protecting data confidentiality and integrity, and (iii) an authentication scheme for verifying data source.

Identity-Based Encryption

Oliveira *et al.*[84] proposed TinyTate, a lightweight Identity-Based Encryption (IBE) security solution for traditional wireless sensor networks. Tan *et al* [85] proposed an Identity-Based cryptographic security solution for WBAN. In their work, the sensor nodes compute public keys by applying a hash function on an arbitrary number of application dependent self-generated keys. These keys are stored on their flash memory and are used to execute elliptic curve encryption/decryption using Elliptic Curve Digital Signature Algorithm (ECDSA). This approach has several drawbacks: higher execution time, greater energy consumption due to increased computational overhead, and higher storage requirement for flash ROM as a result of the public key storage. Sankaran *et al.* [86] proposed IDKEYMAN, an identity-based key management scheme for wireless body area networks. IDKEYMAN is designed for a publisher-subscriber architecture like that of CodeBlue[87]. It uses IBE to set up pair-wise symmetric keys to preserve data confidentiality and integrity. IBE is only used to exchange pair-wise symmetric keys between publishers and subscribers. To reduce the computational overhead on the publisher, the symmetric keys are used in all communications subsequent to setup. IDKEYMAN takes advantage of the superior security strength of public key cryptography while minimizing energy consumption by only utilizing IBE in the bootstrapping phase.

Biometrics

Biometrics has emerged as a useful mechanism to use in the key establishment and authentication of body sensor nodes [88-91]. This method uses measurement of physiological characteristics of the body itself as an important parameter in a symmetric key management system. While the measurement of several physiological signals can be used for biometrics, the ECG (electrocardiogram)[91], and the timing information of heart beats, that is, interpulse interval (IPI)[88], are among the most appropriate since they exhibit proper time variance and randomness. The following are necessary characteristics for a useful biometric physiological value [88, 92]:

- Universal: possessed by most patients
- Distinctive: sufficiently different in any two patients
- Collectable: easily measured and collected
- Effective: able to implement a relatively secure biometric system within the constraints of processing, computing and power of the body sensor nodes

- Acceptable: adoption by the public
- Invulnerable: difficult to compromise
- Random: difficult to guess
- Time variance: changes over time

Currently there exist low cost sensor devices for medical applications that can record suitable biometric physiological signals [88, 89, 93, 94]. This could mean that in some current and future WBANs the additional system requirement for implementing a biometric based system would be almost negligible.

7. DISCUSSION: OPEN RESEARCH PROBLEMS AND FUTURE TRENDS

In this section, we provide an overview of open research problems in WBANs and suggest some potential solutions. We also discuss future trends in the area of WBANs especially as it relates to healthcare applications.

Extended Power Supply Lifetimes

Fuel cell technology provides a potential alternative to conventional batteries [95]. Micro-fuel cells provide high energy efficiency and density and refueling simply requires a cartridge replacement. These characteristics make fuel cells attractive for portable applications such as WBANs. Energy scavenging of solar, heat or vibration from the ambient environment also has the potential to extend the life of the power supply. Leonov et. al. have designed a self-powered wireless sensor node that is powered solely by human body heat [96]. The thermoelectric generator (TEG) converts temperature difference into electrical energy by the Seebeck effect [97], and the power generated is used to support the acquisition and transmission of battery voltage, temperature and light intensity data.

Low Power Consumption

The majority of the power consumption budget is dedicated to wireless communication. Possibilities for reducing communication-based power consumption are the use of ultra wideband (UWB) transceivers, because of the high data rates and low power consumption they provide [98]. Use of energy-efficient data compression algorithms to the data obtained from the A/D [99] would reduce the number of bits that would need to be transmitted by the transceiver. Power consumption may also be reduced by organizing the sensor data into packets and transmitting the data in short communication bursts. In between bursts, the transceiver is off. This is called data-level duty cycling and can be combined with signal duty cycling to reduce power consumption [11].

Biocompatibility

Biocompatibility refers to "the ability of a biomaterial to perform its desired function with respect to a medical therapy, without eliciting any undesirable local or systemic effects in the recipient or beneficiary of that therapy, but generating the most appropriate beneficial cellular or tissue response in that specific situation, and optimizing the clinically relevant performance of that therapy [100]." In the context of implantable sensors, biocompatibility encompasses the reactions the sensor undergoes once being placed within the body (sensocompatibility) and the reaction the body experiences in response to the sensor. One aspect of a sensor's reaction to being placed within the body is called biofouling, which refers to the accumulation of proteins, cells and other unwanted biomaterials on a surface. If biofouling occurs on the active surface of an implantable sensor, it will result in a fall in the sensor current and may eventually result in sensor failure. Wisniewski et al. present nine sensor modifications to mitigate the effects of biofouling [101]. The body's reaction to an implantable sensor involves two factors: mechanical and chemical disruption. Mechanical disruption may involve tissue distortion and occlusion of blood vessels. To minimize tissue damage it is recommended that the sensor should be blunt and rounded instead of sharp. This reduces the probability that tissue will be sliced.

Unobtrusiveness

A key factor in making wearable sensors less noticeable is the size of the individual sensor. The largest component of a sensor in terms of size and weight is usually the battery. Therefore, methods that may result in the reduction in battery size, such as the adoption of fuel cell technology, have the potential to make wireless sensors less obtrusive. Also, the utilization of ASIC technology will produce greater levels of integration than would be obtained by adapting commercial off-the-shelf (COTS) motes to a specific sensor application, and this would result in a reduction in sensor size.

Optimization of network resources

Since WBANs are either wearable or implanted and are developed primarily for the study of physiological parameters, a key concern is the development of network protocols that use ultra-low radio power levels for transmission and reception that are safe for human use. With increasing number of WBANs, the radio layers used by the 802.15.4 networking standard need to be optimized to increase the throughput and minimize interference between multiple networks and users of the frequency bands.

Security

As computing and technology inches closer to the human body (WBANs being the latest forefront), it is important to protect the privacy of the data collected and disseminated by these networks. Complex security mechanisms require more computational and power resources, and optimizing the tradeoff between these is crucial for the widespread use of WBANs.

As mentioned earlier, there exists a number of emerging security approaches to WBAN. Novel methods of achieving security to satisfy low resource consumption should be explored. There is currently no standard designed specifically for WBAN. However, the IEEE 802.15 Task group 6 has been recently formed to facilitate standardization. This will no doubt outline a path for further research in the security operations of WBAN and hopefully define a security suite.

Preventative Healthcare

Present WBAN technology is mostly developed on-demand; WBANs are developed in response to specific physiological requirements. Using dynamic programming environments and cognitive interfaces, we should be able to measure multiple parameters in the human body and use this data to aid in preventive medicine and diagnosis.

Computational and Economic Perspective

Since WBANs comprise of networks of sensors performing specialized detection of physiological data, the cost and size of these devices impose limitations on their use. Creating networks that seamlessly interface with the human environment will be an interesting area of research.

Routing

The main challenges in designing any efficient routing protocol would be to address network partitioning with postural mobility, design an energy-constrained protocol, and ensure end-to-end path reliability. Some research questions that need to be addressed are:

- Can an effective multihop communication protocol be designed taking into consideration constraints of wireless channels and power constraints of on-body sensor nodes?
- Can the mobility pattern of on-body sensor nodes be effectively designed to assist in designing a mobility pattern-based communication protocol?

Emerging Markets and Future Applications

Although WBANs have been developed for medical applications, they can be easily tailored for smart environments that combine sectors such as business, entertainment and education for a heightened seamless experience. The recent explosion of personal computing devices into the consumer market that combine social networking applications can be boosted with the introduction of WBANs without active involvement of the individual at the center of the networks. This kind of passive involvement in data transfer can ease the cognitive burden on the individual and result in more unobtrusive computing applications. It also has the potential for breakthroughs in the study of medicine, ecology and other civilian and military applications. A major concern underlining these advances will be that of privacy and security of data and the applications running on them, since this kind of passive involvement by the individual might result in the use of default settings for data privacy and might be vulnerable to malice by unintended users of the data. WBANs will also need evolving standards for co-existence and data transfer with other ad hoc networks, mobile networks and the Internet. The success of WBANs and their eventual widespread acceptance will be accelerated by merging it with existing technologies and creating frameworks with ease of data transfer and data access.

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