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Wireless Body Sensor Networks for Health-Monitoring Applications

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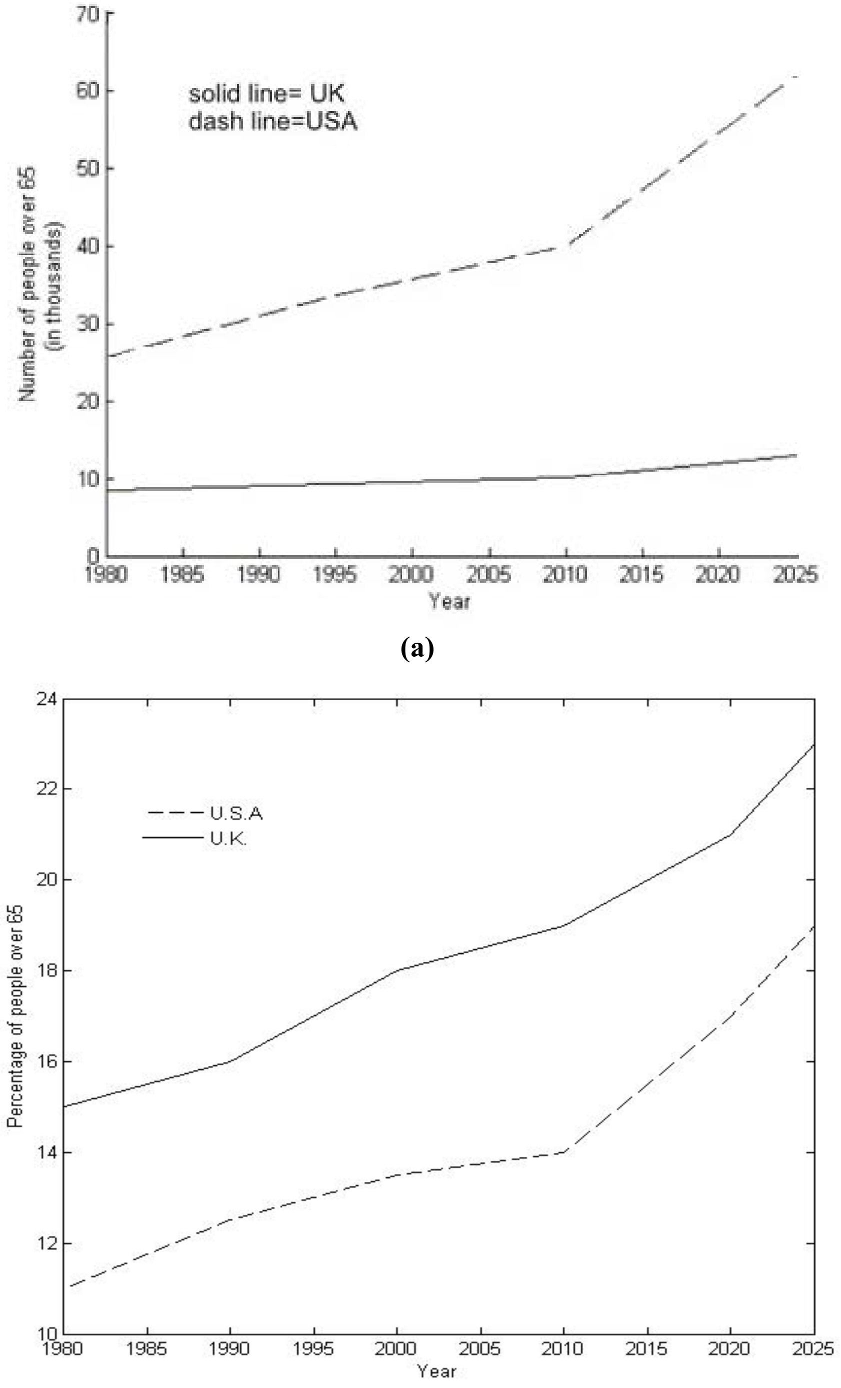
Abstract. Current wireless technologies, such as wireless body area networks (WBANs) and wireless personal area networks (WPANs), provide promising applications in medical monitoring systems to measure specified physiological data and also provide location-based information, if required. With the increasing sophistication of wearable and implantable medical devices and their integration with wireless sensors, an ever-expanding range of therapeutic and diagnostic applications is being pursued by research and commercial organisations. This paper aims to provide a comprehensive review of recent developments in wireless sensor technology for monitoring behaviour related to human physiological responses. It presents background information on the use of wireless technology and sensors to develop a wireless physiological measurement system. A generic miniature platform and other available technologies for wireless sensors have been studied in terms of hardware and software structural requirements for a low cost, low power, non-invasive and unobtrusive system.

Keywords. Wireless sensor networks

1. Introduction

It is recognized that the growing global population is also an aging one. This trend, coupled with the daily developments in new diagnostic techniques and medication discoveries, will place increasing demand on medical and health-care resources. There are currently more than 650 million people over the age of 65, a number that will double over the next 10 years. In the US, about 20% of the population will be over 65 by 2030, compared to 12% today. Similarly, about 20% of the UK population will be over 65 by 2025 [1], as shown in Figure 1. The rapidly growing aging population has resulted in an increase of chronic age-related diseases, such as Type 2 diabetes, cancer, congestive heart failure, chronic obstructive pulmonary disease (COPD), arthritis, osteoporosis, dementia and sleep apnea [2]. In addition, there are more than 1 billion adults worldwide today that are overweight; evidence from several studies indicates that obesity and weight gain are associated with an increased risk of diabetes. Nearly 17.5 million people (29% of the total population in the UK) now live with a long-term medical condition or disease, whilst as much as 80% of healthcare budgets is being spent on the management of chronic diseases [3]. In contrast, the world has just 200,000 hospitals with 18 million beds. There is an ever-increasing shortage of doctors and nurses and skilled ancillary personnel, and an increasing demand by citizens for healthcare services [4].



(a)

(b)

Figure 1. Diagrams illustrating the growth of the section of the population aged over 65 since 1980 in the US and UK, with projections to 2025: (a) number of people; and (b) as a percentage of the population.

Meanwhile, information and communication technology (ICT) has become a central part of our daily life. Many people, including clinical practitioners, are equipped with mobile devices of some kind: pagers; cell phones; personal digital assistants (PDAs); and various mobile computing devices [4]. Today, over 50% of hospitals in the US have wireless local area networks (WLANs) and widely-accessible Wi-Fi and WiMax devices, enabling practitioners to access information, both at the point of care and anywhere else it is needed. Similarly, tablet PCs, PDAs and laptops connected to the WLAN allow clinicians to immediately record medical information in electronic format, as well as order tests and prescribe medication at the patient's bedside, all from their chosen device. Consumers can benefit from advanced home monitoring systems, tele-consultations, personalized care and individualized treatments [4].

The ever-increasing interest in wireless communications has resulted in the development of new technologies and applications for the personal use of radio frequencies. Technological advancement in integrated circuits (ICs), coupled with that of wireless technology and physiological sensors, opens up opportunities for developing small, low power, lightweight and intelligent physiological monitoring devices. These devices can form a Wireless Body Sensor Network (WBSN), launching a new era of using technology to unobtrusively obtain physiological measurements for improved well-being monitoring. This paper aims to give a comprehensive review on the use of wireless sensor technology for monitoring behaviour related to human physiological responses. Section 2 gives a brief introduction to wireless sensor networks and on-going applications for health-care scenarios. Section 3 presents a design approach and related wireless technologies for body-sensor networks (BSN). Current international standards related to wireless sensor technologies are reviewed; in addition, a recent proposal from GE Healthcare (GEHC) to the Federal Communications Commission (FCC) for the allocation of new radio spectrum for healthcare applications is discussed. Section 4 draws some conclusions.

2. Wireless Technology in Healthcare

Medical telemetry systems were originally fixed installations connected to the patient with wires. These installations benefited from the advances in electronics (e.g. reductions in size of the equipment have occurred, allowing in-home use in some cases). However, the main limitations of such wired systems are that the patient is effectively tethered to one location and that the relative costs, including both the equipment and the need for trained staff, are such that patients are only observed for relatively short periods, usually under abnormal circumstances. Wireless systems have been investigated to overcome these issues.

In the past, the use of wireless connectivity in health-care was mostly limited to ambulatory telemetry in hospitals. In the US, the FCC dedicated a part of the spectrum licensed for Wireless Medical Telemetry Service (WMTS) applications. Commercial products include ApexPro™ from GE Healthcare, a leading source of wireless medical telemetry systems. Since the frequency band is specified for low data rate and medical applications, there are hardly any issues of unavailability or interference, or other co-existence issues. Each node (one per patient) communicates with a network controller in a star-type architecture.

Recently, the emergence of 802.11b WLAN technology, operating in the unlicensed 2.4 GHz band, has enabled the movement of patient monitors (e.g. the DASH® 4000 Pro, GEHC) around a hospital or health-care facility. It also allows patient data, such as demographics, medication history and examination results available from portable and bedside monitors, to be transmitted wirelessly to health-care professionals. The data rate to support this service is likely to be less than 1 Mbps. There are other applications that require higher data rates (up to 1 Gbps), including the transfer of X-ray and MRI images and interconnection of medical imaging devices. The WLAN network architecture will normally be star clusters around wireless access points.

2.1. Wireless Physiological Measurement Systems and Their Applications

A wireless physiological measurement system (WPMS) is the use of a wireless medium to carry real-time physiological measurement data from wearable/implantable medical sensors to a central processing unit. The primary purpose of the WPMS is to improve the quality and efficiency of health-care [16]. Wireless physiological measurements hold a number of advantages over wired alternatives, including [17]:

- ease of use;
- reduced risk of infection;
- reduced risk of failure;
- reduced user discomfort;
- enhanced mobility;
- lower cost of care delivery.

Wireless physiological measurements have not only found applications in health-care, but have also been applied in the areas of the military, security, sport and fitness monitoring.

In the improvement of health-care delivery services, the first function of the WPMS is to alert its wearer of the approach or development of a potential medical emergency, so that precautionary action can be taken. Moreover, the use of wireless physiological measurement systems outside the hospital could also help to reduce overall health-care costs, especially among patients with chronic diseases capable of receiving care at home. A good example of this is to alert a patient with chronic cardiac diseases when an increase in blood pressure or abnormal ECG measurement occurs, potentially allowing him to seek assistance before the onset of a cardiac event. Although multi-parameter patient-monitoring systems are available today, they operate in a cost-inefficient way, whereby a high-cost monitoring unit is assigned to each patient. Moreover, existing patient-monitoring solutions typically involve a web of cables connecting the on-body sensors to nearby monitoring equipment. This system can restrict patient mobility and comfort, and can dangerously result in unattached sensors when the tangle of cables causes the patient, either intentionally or accidentally, to become disconnected [16].

The second function of a wireless physiological measurement system is to alert the medical emergency system if vital signs drop below certain threshold. In this scenario, the exact location of the patient needs to be transmitted, along with any useful medical information that could assist the emergency team. For example, the UK's Office for National Statistics (ONS) reported that "*…heart disease (including heart attacks) was the leading cause of death for both sexes in England and Wales in 2005, accounting for one in five male deaths and around one in six female.*" In the United States, "*each year, about 1.1 million Americans suffer a heart attack. About 460,000 of those heart attacks are fatal. About half of those deaths occur within 1 hour of the start of symptoms and before the person reaches the hospital.*" It seems reasonable, therefore, to assume that the use of wireless physiological measurement systems could help save lives, in that they could detect and warn of early symptoms of impending cardiac (or other) problems, enabling the patient to receive potentially life-saving treatments sooner.

The third function of a wireless physiological measurement system is to measure a real-time bio-signal for local processing. A good example is an Automatic Internal Cardiac Defibrillator (AICD, also known as an Implantable Cardioverter Defibrillator, or ICD), which acts to restore the regular heart rhythm by delivering an electrical shock if abnormal behaviour is detected, potentially averting sudden cardiac death. Another example is an implantable drug delivery system: these deliver medication more efficiently for such applications as chemotherapy, pain management, diabetic insulin delivery and AIDS therapy, by locally processing wireless physiological measurements [18]. The wireless physiological measurement system can also provide real bio-signal information for post-processing.

In the military, a WPMS implementation can facilitate remote non-invasive monitoring of vital signs of soldiers during training exercises and combat. For example, it can be used to remotely determine a casualty's condition by medics in a combat situation, without exposing first-responders to increased risks; or to quickly identify the severity of injuries and continuously track the injured condition until they arrive safely at a medical care facility. In safety and emergency, wireless physiological measurement information can also be useful for fire fighters, hazardous material workers, mountain climbers, or emergency first-responders operating in harsh and hazardous environments. It can keep track of an injured person's vital signs, allowing rapid distribution of the information to medical providers and assisting emergency responders in making critical, and often life-saving, decisions in order to expedite rescue operations [19].

Wireless Physiological Measurement Systems can be classified into critical and non-critical applications, as shown in Table 1 below.

Table 1. Applications of wireless physiological measurement systems and their classification.

Critical Monitoring	Non-critical Monitoring
Monitoring chronically ill patients with heart disease, diabetes, epileptic (those that need alarms)	Monitoring of physical conditions and efficiency of sport athlete during exercises.
Monitoring at home and nursing home for elderly and demented people	Control and feedback during athlete training
Monitoring vital signs of soldiers in battle.	Crime investigation with wireless lie detectors
Vehicles such as the ambulance when transporting patients	Monitoring the consciousness of drivers, pilots and operators of heavy machinery
Medical research team can carry out unobtrusive patient study and clinical field trials over an extensive period	In the hospital to reduce discomfort and restriction of wires
Remote telemedicine	Monitoring employees to identify those that are engaging in unlawful activities

2.2. Wireless Body Sensor Networks

The FCC has recently indicated that "*the health care industry has reached the beginning of a wave of breakthroughs in providing care and rehabilitation that will use radio communication technologies in a* *variety of ways*" [16]. With recent advancements in wireless technology, it is possible to use wireless as never before in the delivery of health-care services. One of the most promising concepts on the horizon is that of the wireless body sensor network (WBSN). WBSNs typically consist of multiple sensor nodes worn on the body, each capable of sampling, processing and communicating wirelessly one or more physiological measurements or environmental parameters [20]. These physiological parameters are typically blood glucose and oxygen levels, pulse rate, blood pressure, circadian rhythm and wake-sleep patterns through actigraphy. Antenna components embedded in the sensor nodes make it possible for the data generated to be transmitted wirelessly to a body-worn or closely located hub device, eliminating the need for cables. The hub device, in turn, receives the data generated from the various sensor nodes on the body and may process the data locally, transmit it wirelessly via an appropriate radio link for centralized processing, display and storage, or both [16].

Another benefit of WBSNs is the greater spectrum efficiency that can be achieved. Traditional telemetry systems generally create a separate RF link to the remote monitoring station for each patient sensor. WBSNs utilize network bandwidth more efficiently, by creating a very short-range point-to-point wireless network, thereby enabling greater spectrum reuse. The most common approach to WBSNs is to use a mesh topology. This means that there are typically many links between nodes and each node will choose the best path through the network to the destination. Data transfer thus occurs in multiple "hops" between nodes. Mesh networks are generally self-forming: each node builds up a routing table of the network. This may, however, be calculated by a network controller node in some cases. One advantage of self-forming is that limited configuration is required, a particular need in environmental sensing over relatively wide geographic areas (e.g. in military applications), or if the nodes are mobile, making the network topology dynamic. Mesh networks are also relatively fault-tolerant, as the availability of multiple paths enables the network to handle individual nodes failures gracefully. However, some networks will have a fixed architecture and so may use a star or tree topology.

Currently, there is no specific standard for WBSNs operating among other available wireless consumer technologies. The IEEE 802.15 group has recently initiated a special interest group concentrating on BANs for medical devices and additional specific uses; however, the focus is not broad enough for ultimate deployment. The group's purpose is to tackle the main challenges and constraints, such as power consumption, discovery and quality of service (QoS), in BANs. The main requirements of the initial study are support for very low power devices and sensors (with a target of less than 10% power consumption for communications compared to the total device) and to have a single standard with a broad range of supported data rates – scalability.

The IEEE 802.15 Special Interest Group's first report concluded that (for low data rate applications) WBSNs should operate on, inside or in the vicinity of the body with limited range (<0.01 to 2 metres). The channel model should cover human body effects, including absorption and health effects. Extremely low consumption power (0.1–1mW) is required for each device, which may require them to be capable of energy scavenging/battery-less operation. The WBSN should support a scalable data rate (0.01–1000 kbps, optional 10 Mbps). Deployed devices would provide support for different classes of QoS for high reliability, asymmetric traffic and power-constrained scenarios. Operation of high number of simultaneous piconets (with a maximum of 100 devices per network) using application specific security/privacy is required.

2.2.1. Wireless Sensor Nodes

Wireless sensor nodes, also known as motes, are tiny microcomputers capable of doing small amounts of processing, sensing and using wireless media to communicate with other wireless sensor nodes in the sensor network. The motes combine processing, sensing and wireless networking into a single tiny package. The main components of a wireless sensor node are: a radio transceiver with antenna for wireless communication, microprocessor, memory, analogue or biochemical sensors (e.g. ECG, temperature, glucose) and a battery for electrical power. These motes typically use an operating system with a compact footprint, in terms of memory requirements and system overhead; the most common example is the open-source TinyOS software, coupled with the nesC programming language.

Each wireless sensor node is strategically placed on the human body as a tiny patch or implant, or hidden in users' cloths, allowing ubiquitous physiological measurements in the natural environment over an extended period of time. The following are several kinds of physiological wireless sensor nodes:

1. Swallowed pills (containing a wireless transceiver and sensors that can detect enzymes, nucleic acids, intestinal acidity, pressure, contractions of intestinal muscle and other parameters) allow the WBSN to be involved in gastrointestinal disease monitoring in a non-invasive manner [21];
2. Wired electrode sensors plus a local wireless device, such as a wireless ECG, with several wired electrodes put on the chest to measure the heart parameters;
3. Patch/portable sensors with a wireless transceiver mounted on the surface of human body (e.g. a ring-shaped sensor worn on the finger to monitor heart rate and blood pressure);
4. Implantable physiological sensors, such as an embedded glucose level monitor with an insulin injection system that could be implanted in the patient once to operate within the human body.

The blood glucose monitor automatically sends blood sugar readings to a subcutaneous continuous insulin pump, which takes the glucose readings and other information entered by the user (such as target blood glucose, insulin sensitivity and insulin-to-carbohydrate ratios) and calculates the amount of insulin bolus needed to keep the blood glucose reading in a normal range;

5. Nano-physiological sensors with wireless communication are futuristic and exciting concepts. They use biodegradable nanomachines able to run through the bloodstream, taking physiological measurements and relaying the data wirelessly [21].

To permit prolonged ubiquitous monitoring and seamless integration into a WBSN, wireless sensor nodes must meet requirements for being low profile, lightweight and low cost and having low power consumption and a high degree of integration and packaging with the sensor. Consideration should be given to wireless powering methods, such as inductive, capacitive, ultrasonic and light. Wireless sensors of the future may need energy harvesting methods like vibration (such as piezoelectric) or temperature gradient (such as thermopile), or use an alternative power supply from body fluid, such as glucose [22].

2.2.2. Challenges for Wireless Physiological Measurement Systems

Wireless Physiological Measurement Systems, like other innovations, seek to reduce risk. However, any innovation introduces new risk. The major requirement and challenges for a wireless physiological measurement system are:

- Reliability — the main challenge is to make sure that information reliably gets to its destination. The reliability of a wireless physiological measurement system relies on many aspects, such as reliable wireless communication between nodes, efficient computation in each sensor node and stable software programming [23];
- Biocompatibility — the shape, size and materials are restricted for sensors that directly act on the human body. One of the solutions is to package the sensor nodes in biocompatible materials [23].
- Portability — the size of the sensors used in wireless physiological measurement systems needs to be small and lightweight, whether they are swallowed or worn;
- Privacy and security — there are big security issues to be considered, such as eavesdropping, identity spoofing (i.e. the assumption of a trusted user's security credentials during a communications session) and redirection of private data to unauthorized persons. Security can be improved using data encryption. It is necessary to protected private data from improper access and alteration. "*Consented acquisition of data, proper storage of data, secured transmission, and*

integrity of data and authorized access of data are vital areas for development of hardware or software solutions" [23];

- Lightweight protocols for wireless communication — must support self-organising networks (including security aspects) and able to perform data collection and routing;
- Energy-aware communication — it is desirable for nodes to transmit at low power. An energy-aware protocol is necessary to allow nodes to negotiate their transmission power to a minimum;
- RF radiation safety — the electromagnetic radiation must be within recommended SAR limits. In the United States, the FCC has set the safe exposure limit to a SAR level at or below 1.6 W/kg in 1 g of tissue. In Europe, the European Union Council has adopted the SAR limit of 2 W/kg in 10 g of tissue.

The next task is to design a wireless physiological measurement system with low power consumption (to enable long term monitoring), no unwanted interference with other wireless systems and an efficient protocol due to limited computation capabilities. This system must be both extremely reliable and extremely secure, as it relates to the health and life of the user. Another consequence of this is that it must be robust to changes in the network topology (e.g. if one sensor node fails).

2.2.3. Current Applications

With the increasing sophistication of wearable and implantable medical devices, and their integration with wireless sensors, ever expanding ranges of therapeutic and diagnostic applications are being pursued by research and commercial organisations. Internationally, much of the early work in WBSNs originated at Imperial College, London (ICL); the BSN Workshop series (www.bsn-web.org) initiated by ICL is now regarded as the major international forum for BSN research, attracting top research institutions and industrial organisations each year. The main difficulty is that, for wearable wireless communication devices to be practical and affordable, the antenna must be optimized.

Whilst wireless sensor networks have been around for some time, there has been significant growth in wireless body sensor network research in the last decade or so. For example, a review of wireless telemedicine in 2001 [24] focussed on wireless technologies as used in data transfer to centralised databases (e.g. in hospitals) or for emergency notifications, rather than used in wireless data collection from the sensors. Early research in the field of WBSNs typically saw one or possibly two wirelessly-enabled physiological sensors and a controlling device with a user interface (UI), usually a PDA. The sensors would communicate directly with the controller, thus forming a star network topology. This was soon followed by a growth in the number of sensors in the network, with the application of ad hoc and mesh networking techniques. Examples include Schwiebert et al (2001), who examined power-efficient network topologies under the assumption that the sensor node positions are controlled and fixed [25].

One of the most significant developments was arguably the establishment of TinyOS. This open source operating system for small wireless embedded devices was developed by Jason Hill as part of his PhD [26] and is now used in a significant proportion of academic research in this field and even as the basis for some commercially-produced operating systems (e.g. Crossbow's MoteWorks [27]).

Work in this field may be classified into two areas. The first is fundamental research into WBSNs; the second, applications to specific problems. There are many examples of the latter in conferences, including the eWatch (Maurer et al 2006), a wearable platform sensing light, audio, motion and temperature [28]; the HealthGear system (Oliver and Flores-Mangas 2006), which used a blood oximeter and applied it to the detection of sleep apnea events [29]; and an ECG system based around a mobile phone (Hong et al 2007 [30]). Husemann et al (2004) considered the convergence of health-related wearable devices with personal communications and entertainment devices to create one "personal mobile hub" [31]. More recent examples include Espina et al (2008), who used a WBSN for continuous blood pressure monitoring [32]; the development of an "electronic patch" by Haare et al (2008), which included pulse oximetry and electromyography sensors [33]; and the combination of energy-scavenging, ultra-low power radio and ultra-low power digital signal processors in the Human++ project (Penders et al 2008) [34].

In the former category, there is significant effort invested in higher network functions, including self-configurability, security-related issues and quality of service (QoS). A policy-based approach was undertaken by Zhu et al (2008), where a light-weight policy system called Finger was implemented in TinyOS and its performance evaluated, with benefits in the adaptability and security of sensor nodes [36]. Roman et al (2008) recently discussed the requirement for sensor nodes to be "situation-aware", together with mechanisms for achieving such behaviour [37]. This ability has benefits in self-configuration and security areas. Xiao (2008) has discussed the need for "accountability" in wireless networks, in order to properly determine the source of errors or malicious activity and also act as a mechanism to restore trust [38]. Claveirole et al (2008) discussed the problem of securing wireless sensor networks that include aggregators [39]. Aggregators are intermediate nodes that combine data from sensor nodes in order to minimise bandwidth consumption or to detect meaningful events more quickly. Recent papers tackling QoS issues include a solution to channel impairment that uses a resource-rich aggregator node to handle the majority of the processing (Zhou et al 2008 [40]). Elsewhere, the focus has been on the QoS of the link between WBSN and a wider network, such as WLAN hotspots (Chigan and Oberoi 2006 [41]).

Another broad area of study is power management; recent papers on this subject include Guo et al (2006), who examined the issue of power in implanted biosensor systems. They examined the relationship between the energy cost per bit and the data rate of a given signal type, then proposed the use of UWB communications for the power savings that could be gained based on the proceeding analysis [40]. Park and Lee (2008) presented a comparison of six power-saving algorithms used in IEEE 802.15.4-based networks, showing that there is no single optimum algorithm covering all scenarios [43]. Other research has examined methods of obtaining the energy for the sensor node from its surrounding environment, including Yeatman (2006), who used micro-electro-mechanical systems (MEMS) to scavenge energy from motion and vibration [44]. Other possible sources include RF energy, in a manner similar to RFID tags, thermal energy (e.g. Koplow et al 2008 [45]) and even chemical energy. The performance of energy-harvesting nodes using motion has been modelled with Markov chains by Seyedi and Sikdar (2008), giving insight into their performance and the ability to determine the probability of event loss due to a node running out of energy [46].

The University of Birmingham and Queen Mary, University of London, are collaborating in research on antennas and radio propagation for body-centric wireless communications, supported by companies and the government. The research provides a physical insight of radio propagation around the human body and opens up an opportunity for developing energy and spectrum efficient WBSNs [24]. Some commercial applications of wireless physiological measurement systems available today, and their respective target market areas, are summarized in Table 2. Table 3 summarizes some examples of on-going academic research in relation to the development of wireless physiological measurement systems.

Table 2. Some current commercial applications of wireless physiological measurement systems.

Commercial Applications	Vendor	Description	Market
TeleMuse	Biocontrol Systems	This is a mobile physiological monitor for acquiring ECG, EMG, EOG, EEG, and GSR data from wireless sensors using ZigBee technology.	Medical Care and Research
VitalSense Integrated Physiological Monitoring System	VitalSense	This is a chest-worn wireless physiological monitor that incorporates an ECG-signal processor and offers wireless transmission of Heart Rate and Respiration Rate to a handheld monitor	Fitness and Exercise
The Security Alert Tracking System	Third Eye Inc.	Wrist-mounted surveillance monitors blood oxygen saturation and heart rate fluctuations non-invasively; the information is transmitted wirelessly to a central monitoring system. It can assist in apprehending employees engaged in unlawful activities in casino and banks.	Security and Safety
The Alive Heart and Activity Monitor	Alive	This Bluetooth device monitors heart rate and activity, including ECGs, blood oximeters and blood glucose meters. It communicates with software on your mobile phone to log and upload information to a central internet server	Medical Care, Research, Fitness and Exercise
Polar Heart Rate Monitor/Watch S625X	Polar	This is a watch combined with a heart rate monitor, altimeter and speed/distance monitor. It communicates wirelessly with a chest belt.	Fitness and Exercise
PillCam® capsule endoscopy	Given Imaging	The tiny camera contained in the capsule captures images of gastrointestinal (GI) tract as it travels through the body and transmits the images to a computer, so the physician can view them and make a diagnosis.	Medical Care

Table 3. Examples of on-going academic research on wireless physiological measurement systems.

Research Applications	Vendor	Description	Market
CodeBlue: Wireless Sensor Networks for Medical Care	Harvard University	Exploring applications of wireless sensor network technology to raise alerts when the vital signs of patients fall outside the normal range.	Medical Care and Military
Wireless Physiological Sensors for Ambulatory and Implantable Applications	Tampere University of Technology	The study and development of a new wireless sensor technology for ambulatory and implantable human psychophysiological applications. The goal is to develop commercially mass-produced physiological measurement systems, based on patch-type sensors and implantable smart wireless devices.	Medical Care, Research and Military
Wireless Implantable Sensors with Advanced On-Body Data Processing	Queen Mary College, University of London	The proposed feasibility study aims to deliver a clinically viable strategy that can provide a wireless connected system for implantable electrophysiological and metabolic monitoring sensors, enhancing existing capabilities in both wireless and sensor technology.	Medical Care and Research

3. Method and Design Approach for Wireless Sensors

3.1. Design Goal and Considerations

A number of parameters need to be considered when designing a miniature wireless sensor device. The application sets constraints and requirements for the device. The volume, shape and weight are important factors, particularly for wearable sensors. For a given application, aimed at wireless physiological measurements, operational lifetime, duty cycle, accuracy and stability of sensor output need to be considered. The most challenging scenario is 24-hour, round-the-clock monitoring, where even the incorporation of sensors into clothing may fall short of the goal, making implanted or skin-mounted devices necessary. Implantable devices have a level of invasiveness exceeding current mainstream acceptance. However, the necessity of skin-worn devices or skin-contacting devices is unavoidable in some cases, such as galvanic skin response. Devices embedded into clothing are certainly champions of unobtrusiveness, as long as their weight, shape and volume stay within limits [48]. To meet the design requirements, an investigation into various applicable wireless technologies must be performed.

3.2. Wireless Technologies for WBSN

Wireless communication within a Wireless Body Sensor Network may be based on infrared, light, microwave radio and even near-field coupling through skin conductivity. Microwave radio communication, especially using ZigBee wireless technology, is a popular approach. Wireless Body Sensor Networks may communicate externally with other networks (which may themselves be WBSNs) using one of a range of available wireless technologies. For short, medium and long-range communications, Bluetooth, Ultra-Wide Band, Wireless LAN (Wi-Fi), WiMAX, GSM, GPRS, UMTS and Satellite communication are available, allowing a wide coverage area and offering the possibility of ubiquitous worldwide wireless mobility [16]. Some of these technologies will be discussed in the following subsections, in the context of their applicability to WBSNs.

Communication in networks is a complex task. To simplify the problem, it is broken into a set of layers. Each layer provides a function or service to the layer above; communication is enabled through the building up of the layers. Figure 2 shows the Open Systems Interconnection (OSI) reference model, which partitions "*...the communications process into seven layers...*" and provides "*...a framework for talking about the whole communications process*" [49].

The physical (PHY) layer handles the actual transfer of data on a physical link (wireless or cable). The data link layer (DAT) handles the transfer of "frames" across a transmission link directly connecting two nodes (or where multiple nodes are connected to a broadcast medium). The network (NWK) layer provides the transfer of packets across a network, rather than between nodes. The transfer (TRN) layer deals with end-to-end data transfer; it may perform a variety of tasks, including the segmentation of data into suitably-sized packets and the initiation and release of a connection across a network. Control of the manner in which the data is exchanged (e.g. who sends and who listens, and at what point) can be performed by the session (SES) layer. The presentation (PRE) layer provides a level of abstraction (i.e. independence from how the data is represented) to the application (APP) layer, which is intended to provide commonly-required communications services to applications. In practice, most network protocol "stacks" relate only loosely to the OSI reference model.

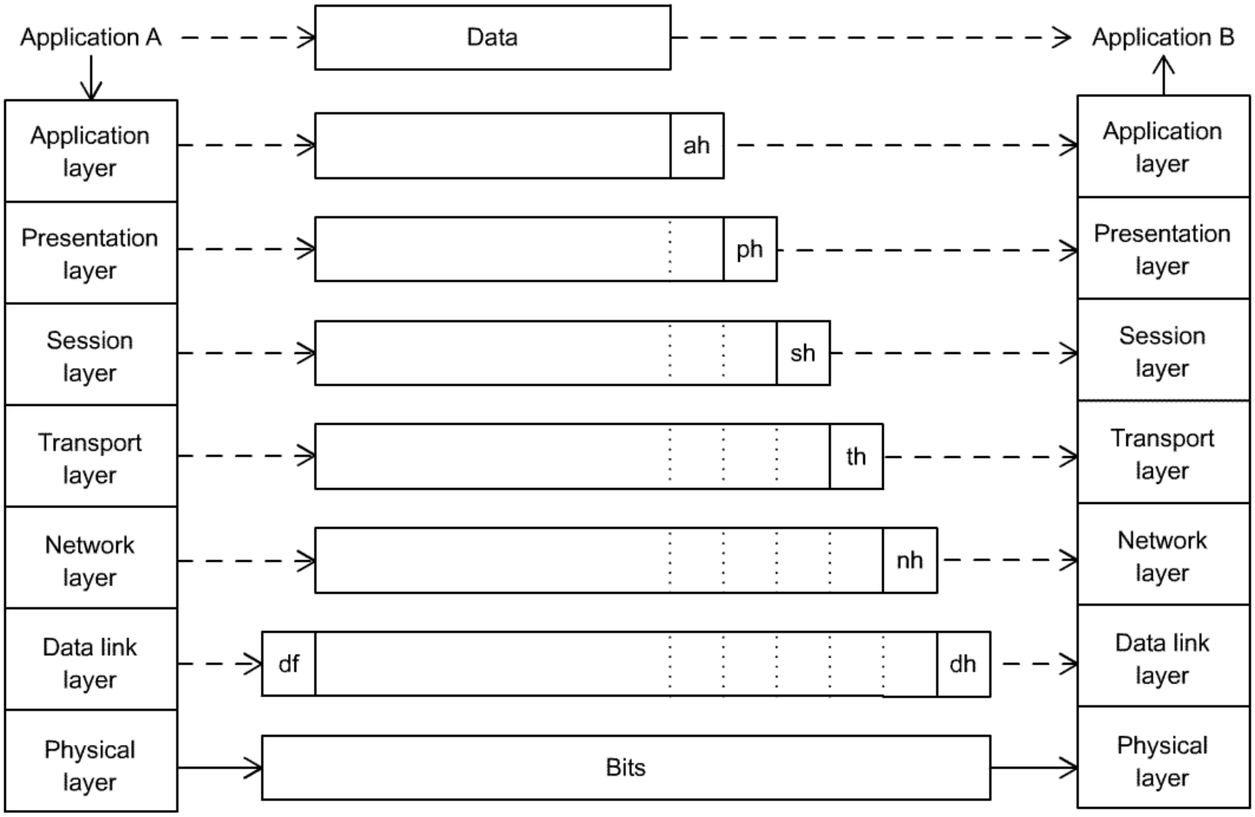


Figure 2. The OSI reference model for data transfer across a network, based on an example given in [49]. The dashed arrows indicate the logical data transfer path; the solid arrows indicate the physical transfer path. Each layer adds additional bits to the "packet", as headers or footers to the data. These headers contain information in a fixed format, enabling the receiving node to recover the data from the received bits.

3.2.1. ZigBee Wireless Technology

ZigBee is an open, global standard providing a low data rate, low power consumption and low cost wireless technology. It is built on top of the IEEE 802.15.4 standard, defined for the PHY and Media Access (MAC) layers. The MAC layer loosely corresponds to the DAT layer in the OSI model. ZigBee specifies network, security, and application layers (see its protocol stack in Figure 3).

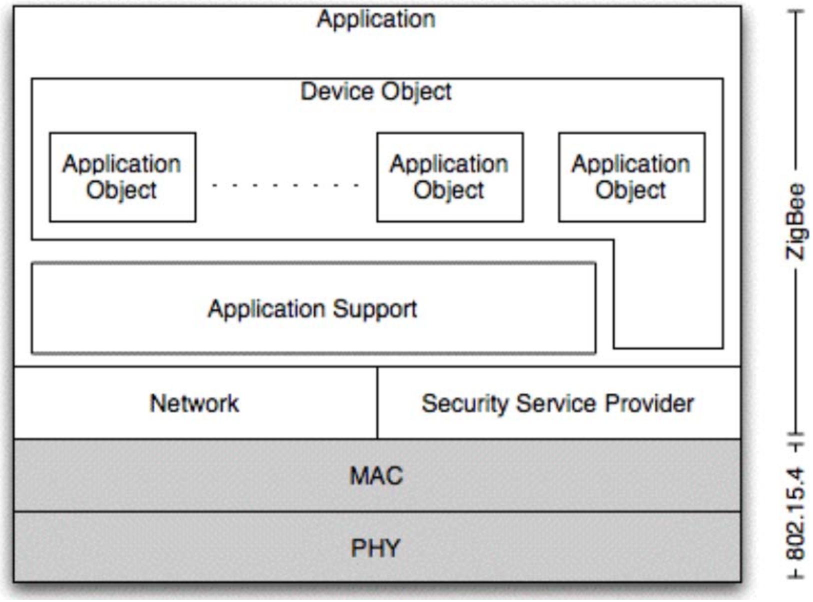


Figure 3. A typical ZigBee protocol stack, built on top of the IEEE 802.15.4 standard [26].

The physical layer operates in unlicensed RF bands at 2.4 GHz (global), 915 MHz (America) and 868 MHz (Europe). The IEEE 802.15.4 physical layer uses direct sequence spread spectrum (DSSS) coding to minimize data loss due to noise and interference. IEEE 802.15.4 supports two PHY layer modulation options. The 868/915 MHz PHY, known as the low band, uses Binary Phase Shift Keying (BPSK) modulation, whereas the 2.4 GHz PHY, called the high band, uses Offset Quadrature Phase Shift Keying (OQPSK) [50]. The data rate is 250 kbps at 2.4 GHz (16 channels), 40 kbps at 915 MHz (10 channels) and 20 kbps at 868 MHz (1 channel).

The MAC layer controls access to the radio channels using the CSMA-CA (Carrier Sense Multiple Access-Collision Avoidance) mechanism, together with an optional time-slot structure and security functionality. The MAC layer supports several network architectures, including the star, tree cluster and mesh topologies, allowing ZigBee to create a scalable, reliable and self-healing network.

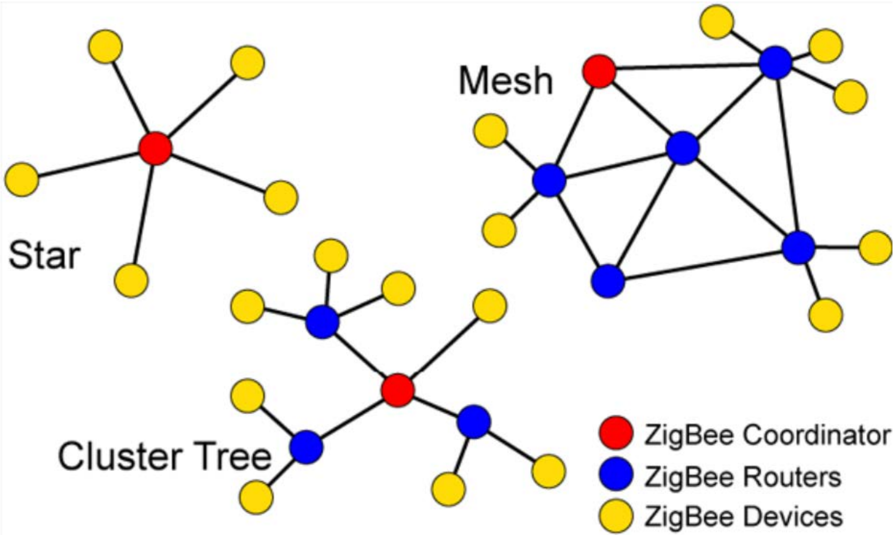


Figure 4. ZigBee network topologies [51].

There are three categories of ZigBee devices, as shown in Figure 4 [51]:

- ZigBee Coordinator (MAC Network Coordinator) — this is a smart node that automatically initiates the formation of the network and maintains overall network knowledge. It is the most sophisticated of the three devices, requiring the most memory and processing power;
- ZigBee Router (MAC Full Function Device) — this is also a smart node that links groups together and provides multi-hoping for messages. It associates with other routers and end-devices;
- ZigBee End Devices (MAC Reduced Function Device) — this node can only communicate with a full function device. It carries limited functionality to control cost and complexity.

ZigBee provide authentication, encryption and integrity services for wireless systems through the security layer, with 128-bit AES encryption and authentication. The transmission range is from 10 to 75 metres, depending on the power output and environmental characteristics. ZigBee devices are expected to have a battery life ranging from months to years.

3.2.2. Bluetooth

Bluetooth, also known as IEEE 802.15.1, is a low cost, low-power wireless radio frequency standard for short distances, aimed at cable replacement between lightweight electronic devices and also building adhoc networks.

The Bluetooth protocol stack, shown in Figure 5, is somewhat unusual compared to other IEEE networking stacks. The Bluetooth stack defines many components above the PHY and MAC layers, some of which are optional, making it complex [50].

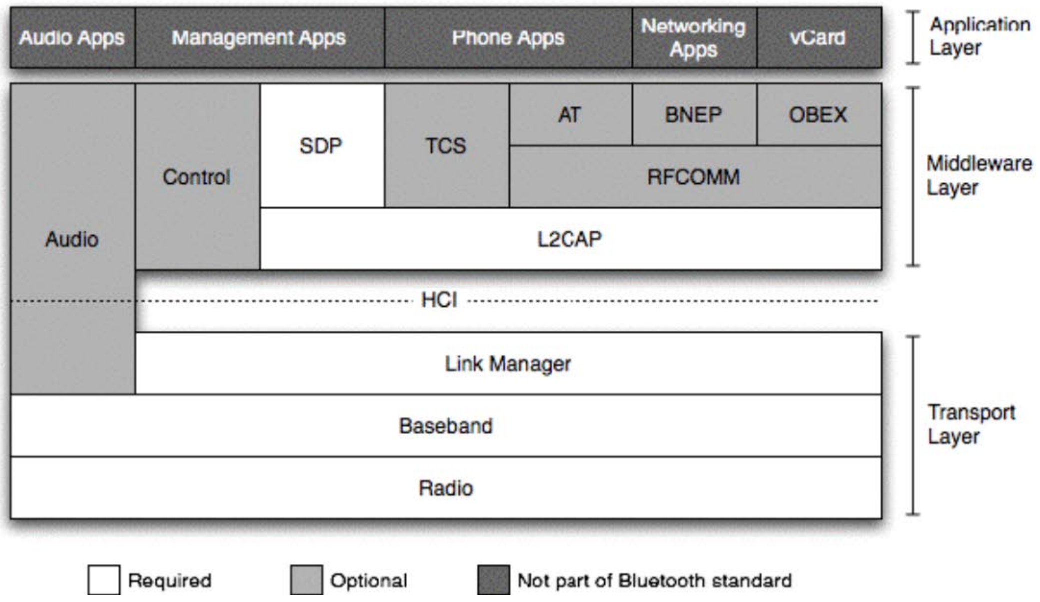


Figure 5. A diagram illustrating the Bluetooth protocol stack [50].

Bluetooth operates in the 2.4 GHz ISM band, occupying 79 channels. The radio layer uses Frequency Hopping Spread Spectrum (FHSS) coding. The primary modulation method is Gaussian-shaped BFSK.

Bluetooth devices are divided into one of three classes, which specify the antenna’s output power:

- Class 1 devices broadcast using 1–100 mW of power;
- Class 2 devices broadcast using 0.25–2.5 mW of power; and
- Class 3 devices broadcast using up to 1 mW of power.

The maximum data rate is 723 kbps at a maximum signal range of 100 m. Bluetooth devices form into piconets and, potentially, scatternets (i.e. groups of inter-connected piconets). Piconets consist of one master device that communicates directly with up to 7 active slave devices. Bluetooth defines three power-saving modes. In hold mode, devices only handle slots reserved for synchronous links, and sleep the rest of the time. In sniff mode, the device stays asleep most of the time, waking up periodically (from every 1.25 ms to every 40.9 s) to communicate. Finally, in parked mode, the device shuts down its links to the master device, excluding the PSB (Parked Slave Broadcast) link. The master device can wake up parked devices by beaconing them over the PSB link [50].

3.2.3. ZigBee versus Bluetooth

ZigBee looks rather similar to Bluetooth but it is much simpler. ZigBee offers a lower data rate and the nodes spend most of the time snoozing [52]. This characteristic means that ZigBee node can run at low power for a period ranging from six months to two years, on just two AA batteries. A Bluetooth node running on same batteries would only last between 1 and 7 days.

Bluetooth supports a higher data rate of 750 kbps compared to the low data rates of ZigBee, the maximum being 250 kbps at 2.4 GHz. The simple architecture of ZigBee allows configuration of static and dynamic star networks, or peer-to-peer network that can support up to 65000 nodes in a network. In contrast, the complex architecture of Bluetooth only allows 8 nodes in a basic master-slave piconet configuration.

ZigBee uses DSSS, which allows nodes to sleep without close synchronisation. When a ZigBee node goes into sleep mode, it can wake up and get data in around 15 ms. Bluetooth, on the other hand, uses FHSS, which does require close synchronisation; therefore, a Bluetooth node that goes into sleep mode would take around 3 s to wake up and respond.

ZigBee is an emerging wireless standard for low data rate, very low-power applications. It has a maximum data rate of 250 kbps, which is still sufficient for intelligent sensors. ZigBee has a simple protocol stack and uses AES 128-bit authentication and security. ZigBee is scalable; it can support a large number of nodes and can respond quickly to topology changes. It is not prone to interference by other devices operating in the same frequency range. It is thus a very good candidate for internal communication by individual sensors in the WBSN. Bluetooth is a mature technology, already integrated in many cell phones and Personal Digital Assistant (PDA) devices. It allows communication bandwidth of up to 720 kbps, which is more than sufficient for most intelligent sensors. However, Bluetooth is too complex, power demanding and prone to interference by other devices operating in the same frequency range. It is better suited as an external communication technology to connect the WBSN to other networks or devices, such as a PDA or cell phone. A comparison of various short-range wireless technologies is shown below in Table 4.

Table 4. Comparison of key features of short-range wireless technology.

Features	IEEE 802.11 (Wi-Fi™)	WiMedia (UWB®)	IEEE 802.15.1 (Bluetooth®)	IEEE 802.15.4 (ZigBee™)
Battery Life	Hours	Days	Days	Years
Cost per Module	$9	$6	$6	$3
Complexity of MAC and Physical layers	Very complex	Simple	Complex	Simple
Radio Spectrum	2.4 GHz	3.1 – 10.6 GHz	2.4 GHz	868 MHz, 915 MHz, 2.4 GHz
PHY Coding	OFDM	OFDM	FHSS	DSSS
Max. Data rate	54 Mbps	480 Mbps	700 kbps	250 kbps
Network Size	32 nodes	Unknown	7 nodes	64000 nodes
Security	WEP keys	128 bits AES	64, 128 bits	128 bits AES
Range	100 m	10 m	10 m	30 m
Applications	High bandwidth applications	High bandwidth cable replacement	Low bandwidth cable replacement	Low-bandwidth sensors and automation

3.2.4. Other Related Wireless Technologies and the MICS and ISM bands

Apart from the aforementioned wireless technologies, there are other wireless communications protocols that may be considered for use in WBSNs. The first, and perhaps most obvious, set of protocols to consider are those based on the IEEE 802.11 family of standards, for use in WLANs. These generally use the 2.4 GHz band, although there is a second band at 5.8 GHz used in 802.11a-based networks. The main motivation for considering the Wi-Fi/WLAN approach is commercial: the rapid growth in mobile computing has lead to low-cost wireless networking in both the home and the workplace and also made "wireless hotspots" a common occurrence in coffee shops and shopping malls. This means that the hardware required is both plentiful and low-cost.

The main drawback to the use of WLAN technology for WBSNs is the power used. WBSN sensor nodes must be ultra-low power devices; this implies there would be a significant risk that the sensor signals would be lost when stronger sources (e.g. notebook computers) were present. Alternatively, they must increase the radiated power, reducing lifetime. A similar objection may be made against the use of

WiMAX (IEEE 802.16), a protocol intended for wireless broadband access across distances of 5-15 km for mobile stations and up to 50 km for fixed stations. IEEE 802.16 specifies a number of different operating bands, including one at 2.5 GHz. WiMAX uses a time-based multiple-access method, whereas Wi-Fi uses a contention-based approach, implying WiMAX should be more power efficient than Wi-Fi.

An active area of research for wireless communications is the so-called Ultra Wideband (UWB) allocation between 3.1 and 10.6 GHz. Strictly speaking, UWB refers to any bandwidth of 500 MHz or more, or of a fractional bandwidth greater than 20% of the centre frequency. However, wealth of activity in this allocation means the term is most often associated with this band. Because of its extremely wide bandwidth and the fact that it spans both licensed and unlicensed frequencies, UWB systems are constrained in their output power, thus having a limited range. UWB comes in two flavours: the first is the Direct-Sequence Spread Spectrum (DSSS) approach; the second utilizes multi-band Orthogonal Frequency Division Multiplexing (OFDM). Both have a maximum range of approximately 10 m. A single standard for UWB is unlikely, which may result in problems when operating in the same location. However, the main objections to UWB, in the context of WBSNs, are the complexity (in hardware and protocol) and the fact that most body-worn or implanted medical sensors will under-utilize the available bandwidth. The next generation of the Bluetooth specification will be based on UWB techniques.

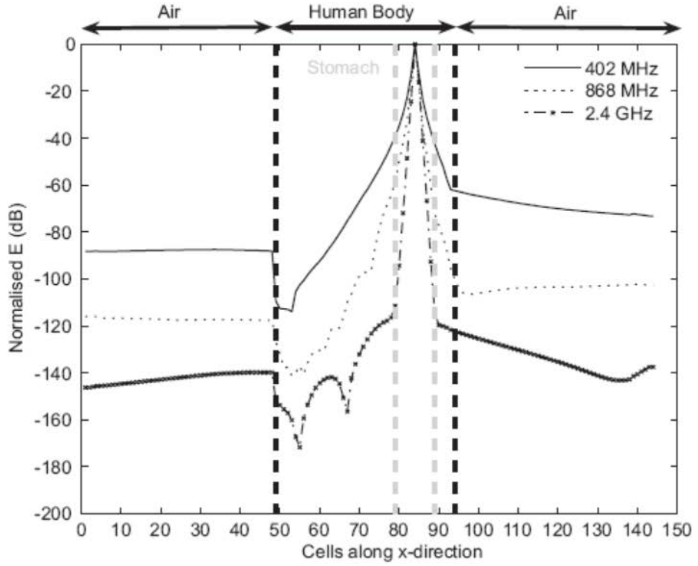
In addition to UWB-based Bluetooth, a new ultra-low-power version has recently been adopted following the merger of the Bluetooth Special Interest Group with the Wibree Forum. Wibree was a variation of the Bluetooth specification developed by Nokia and aimed specifically at low-power applications. In fact, the original Wibree specification was developed as the alternative proposal for the 802.15.4 standard that led to ZigBee. It is envisioned that Bluetooth Low Energy Technology (LET), as it is known, will be available in health-related sensors (e.g. glucose monitors), sports-related sensors (e.g. watches) and entertainment-related sensors (e.g. remote controls), as well as sharing the consumer electronics devices utilising Bluetooth today (mobile phones, PDAs and notebook computers). Its main advantage is the competitive edge granted it by the development of dual-mode Bluetooth hardware, reducing costs and allowing phones, PDAs and notebooks to act as gateways to the Internet for the low power sensors. Its supporters also suggest that it is more suited for ad hoc networks, common in consumer applications, than ZigBee, which is optimised for static networks in industrial environments.

Although Bluetooth LET has some interesting features arising from its integration with Bluetooth-proper, the somewhat proprietary nature of both Bluetooth and ZigBee has led some to push for a completely open standard for use in these low-power networks. In particular, the Internet Engineering Task Force (IETF) has led the development of 6LoWPAN, or Internet Protocol version 6 on Low-power Personal Area Networks. Their approach has been to define modifications to IPv6 that allow it to be used over the 802.15.4 MAC/PHY layers. IPv6 is the future protocol for the Internet and is currently used in parallel with the older IPv4 networks.

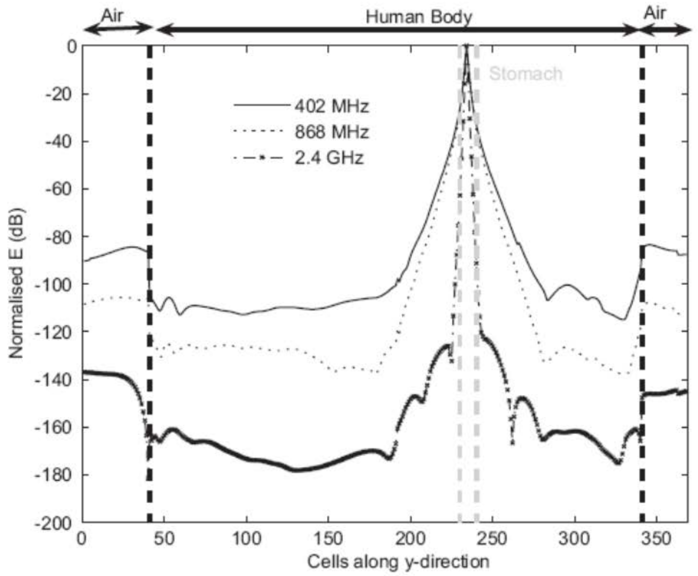
By using IP for the higher networking layers, the sensor network is automatically interoperable with all other IP networks, including the Internet (potentially making gateway devices simpler); the use of 802.15.4 allows the requirements of WBSNs for low power and long lifetimes to be met. In addition, IPv6 has a huge addressing space adequate for all conceivable sensor networks; it also has the advantage that it is an established technology with an extensive set of tools for support, development, design, control and reconfiguration. Security issues are well-known and methods for solving them are identified. In short, 6LoWPAN allows existing standards to be leveraged, rather than needing to build from the beginning. An additional advantage is that TinyOS, the most common operating system on sensor nodes, already supports 6LoWPAN networks.

These protocols all operate in the 2.4 GHz band; there are also other frequencies bands that have been allocated that may, potentially, be used for physiological measurements, such as the 433 MHz and 915 MHz industrial, scientific, and medical (ISM) bands, and the more recently allocated 402–405 MHz Medical Implant Communication Service (MICS) band. The allocation of this band supports the use of longer-range (typically 2 m), high-speed wireless links. The MICS band overcomes the limitations of dated inductive systems and facilitates the development of next-generation wireless implantable medical devices due to the lower level of electromagnetic wave attenuation inside human body at these frequencies. Another band under discussion for wireless personal area networks is the 60 GHz millimetre-wave band, including the unlicensed 57-64 GHz band; this is the focus of the IEEE 802.15 Task Group 3c [54] and would provide both high coexistence (close physical spacing) and high data rates of at least 1 Gbps. Whether or not such rates are of use in medical WBSNs, this band is currently unused and so will not suffer from the congestion experienced at 2.4 GHz.

Implantable devices have promising novel biomedical applications that play vital and important roles in building comprehensive telemedical networks [55]–[57]. Devices, such as pacemakers, the implanted defibrillator and the sacral anterior root stimulator, are required to relay physiological data and control other medical sensors [55]. To provide a clear understanding of the telemetry link between the implanted devices and mobile or base station units located outside the human body, in-depth analysis of the wave attenuation in lossy human tissues and propagation in the vicinity of the human body is essential. As an example, Figure 6 shows a comparison of the normalized electric field distributions in the MICS (402 MHz) and ISM bands (868 MHz and 2.4 GHz), for both the body interior and exterior. The fields were found for a human model with a full stomach, using an in-body wireless sensor. The lossy behaviour of different human tissues for the selected frequency bands is clearly evident, as is the general trend that increasing the operating frequency leads to increased attenuation.



(a) Wave attenuation along horizontal (x-axis) cut of the human model



(b) Wave attenuation along vertical (y-axis) cut of the human model

Figure 6. Electric field distribution inside and outside a human body with a full stomach from an in-body wireless sensor.

3.2.5. New Radio Spectrum for Next Generation Wireless Body Sensor Networks

Based on extensive investigation, GEHC is convinced that the WBSN concept requires the use of protected, or at least special purpose, spectrum. The reasons are manifold [16]: one important issue is that WBSNs must be medical-grade and capable of reliably conveying unprocessed life-critical monitoring data to devices that are responsible for processing and primary generation of alarms. In general, it would be very difficult to ensure adequate QoS for these applications for low power WBSN devices operating in the "free-for-all" ISM and unlicensed bands without any protection from interference. In addition, the traditional WMTS band is already congested for medical telemetry applications.

In order to make WBSNs a viable concept, the cost, size and power consumption of components will have to be kept very low, especially as some WBSN sensors will need to be disposable. Thus, it is important that any band designated for WBSN use be one for which low-cost, commercially available, off-the-shelf technology can be obtained. One way to ensure this is for any WBSN spectrum to be in close proximity to existing bands designated for unlicensed use, such as 400 MHz or 2.4 GHz. It may also be possible to identify one of the existing restricted bands where WBSN devices could operate without causing interference to the existing authorized services in the band. Currently, GEHC proposes the following candidate bands for wireless medical BSNs: 2360–2395 MHz, 2395–2400 MHz, 410–450 MHz, 2300–2305 MHz and 2495–2496 MHz [33].

3.3. Overall System Architecture

The proposed overall system structure of a Wireless Physiological Measurement System is illustrated in Figure 7. The system is comprised of various wireless sensor nodes that use analogue sensors to sample physiological data and wirelessly communicate with the network base unit. The base unit is comprised of the wireless network coordinator connected to either a PDA or tablet PC, where the physiological data is displayed. The processing power of the PDA or tablet PC can provide real time local processing of the physiological data to give feedback to the wireless sensor nodes or give audio or visual alerts (e.g. warnings on the display). The base unit can also function as a gateway to other networks, such as GPRS, WLAN and the Internet, thereby allowing access to the physiological data for remote real-time processing or storage.

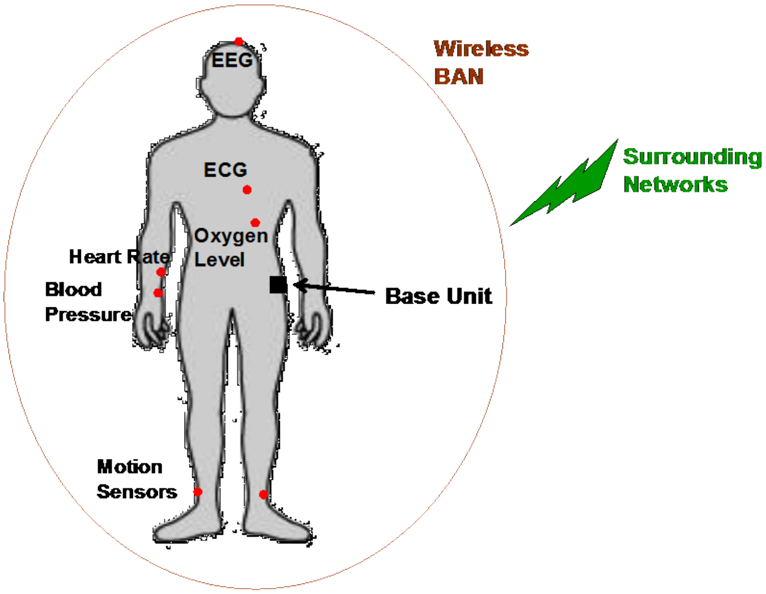


Figure 7. An illustration of the proposed system architecture for wireless physiological measurements.

3.4. *Hardware Architecture*

The system hardware includes a wireless sensor node and a network coordinator (either a PDA or handheld PocketPC, or a Personal Computer). Figure 8 shows the proposed hardware architecture of the wireless sensor node for the design of Wireless Physiological Measurement Systems. It consists of four major components, namely, the microcontroller, flash memory, RF module and medical analogue sensors.

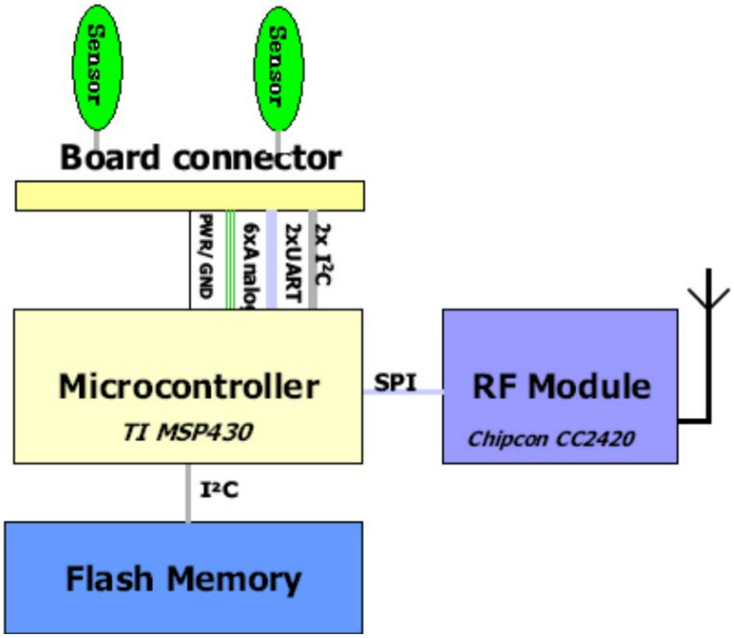


Figure 8. Hardware architecture of a wireless sensor node [14].

3.4.1. Microcontroller

A microcontroller is a special microprocessor emphasizing self-sufficiency and cost-effectiveness, in contrast to a general-purpose one used in a computer. Compared to a design using a separate microprocessor, memory, and input/output devices, microcontrollers make it economical to electronically control many more processes. The ultra low power Texas Instruments MSP430 F1611 microcontroller features 10 kB of RAM, 48 kB of flash, 128 B of information storage, analogue and digital peripherals, and a flexible clock subsystem for time synchronization. The microcontroller is a 16-bit RISC processor and features an extremely low-power active mode. The MSP430 has an internal digitally controlled oscillator (DCO) that may operate up to 8 MHz [15]. The 10-pin expansion connector — with one I2C interface, one UART (Universal Asynchronous Receiver Transmitter) interface, two general purpose I/O interfaces and three analogue input interfaces — allows the microcontroller to control analogue sensors, LCD displays and digital peripherals.

3.4.2. RF Module

The Chipcon CC2420 radio for wireless communications is a 2.4 GHz IEEE 802.15.4 compliant RF transceiver providing the PHY and some MAC functions for low power and low voltage wireless applications. The CC2420 is controlled by the TI MSP430 microcontroller through the SPI port and a series of digital I/O lines and interrupts. The radio may be shut off by the microcontroller for low power duty cycled operation. The CC2420 uses digital direct sequence spread spectrum baseband modulation to provide a spreading gain of 9 dB and an effective data rate of 250 kbps [59]. The CC2420 provides extensive hardware support for packet handling, data buffering, burst transmissions, data encryption, data authentication, clear channel assessment, link quality indication and packet timing information. These features reduce the load on the host controller and allow CC2420 to interface low-cost microcontrollers [59].

Zarlink Semiconductor has a very low power transceiver IC (ZL70101) that supports two-way, half-duplex communication at either the MICS band (around 403 MHz) or the ISM band (433 MHz). The MICS band is used for implanted applications and the ISM band is used where communication is to and from on-body or body-worn devices. The same IC can also be used in the external base-station. The base-station is typically a unit that interfaces with a PC for ease-of-use and has the relevant electronics and antennas to communicate with the implant. A key design consideration for the ZL70101 IC is ultra low-power performance to ensure minimal impact on the battery life of the implanted medical device. Implanted device battery size and capacity are limited. To reduce the average current consumption, the

ZL70101 operates primarily in an ultra low-power sleep mode and only “wakes up” to transmit or receive data. The ZL70101 is woken up with a separate ISM band signal centred on 2.45 GHz, where a much higher transmit power is permitted of up to 100 mW (20 dBm) dependent on country. The wake-up receiver is less sensitive than the 403 or 433 MHz link and so will require less current; this is further reduced by strobing the receiver with typical on time of 200 μs and an off time of 1.1 s. This reduces the sleep mode current to typically 200 nA.

The communication IC requires additional components, such as a crystal, antenna coupling inductors and capacitors and an optional SAW filter, as well as an antenna that will operate at both 403 (or 433) MHz and 2.45 GHz. The layout and assembly of these components is important to the success of the link. Zarlink has produced an Application Development Kit that includes a transceiver module with an antenna, together with a PC-controlled base-station and a wake-up transmitter. An implantable module can be integrated into an existing implant design. The RF module can transfer raw data at up to 800 kbps. Security, error detection and forward error correction are also included in the protocol. Applications include cardiac pacemakers, implanted defibrillators and neurostimulator devices.

The Sensium chip produced by Toumaz Technologies, UK, is a system-on-chip (SoC) device integrating a full custom hardware MAC, digital microprocessor core and I/O peripherals, on-chip memory, micro-power ADC, wireless transceiver, and custom sensor interfaces. This SoC platform device is capable of achieving ubiquitous medical monitoring when interfaced to appropriate body worn sensors, and represents state-of-the art in terms of functionality and ultra low power consumption.

The transceiver is shown in block diagram in Figure 9 [60]; key features are summarized in Table 5. The device operates in the European 862–870 MHz short-range-device (SRD) and North American 902–928 MHz Industrial Scientific and Medical (ISM) bands; these frequencies offer a good compromise between power consumption and small form factor passive components, such as printed antennas.

The receiver uses a two-stage zero-IF architecture based on a sliding IF approach, which provides advantages in filtering and noise profiling and thus allows a lower current consumption than a single-stage direct conversion architecture. The PA stage is designed to deliver –10 dBm into a matched antenna load, giving a typical indoor range of 10 m.

The choice of modulation scheme requires a compromise between data throughput, spectral efficiency and circuit implementation complexity/power consumption. The use of 2-level FSK is chosen, as it reduces demodulation complexity and power consumption, whilst having advantages over on-off-keying/amplitude shift keying (OOK/ASK), in terms of reliability and data rate.

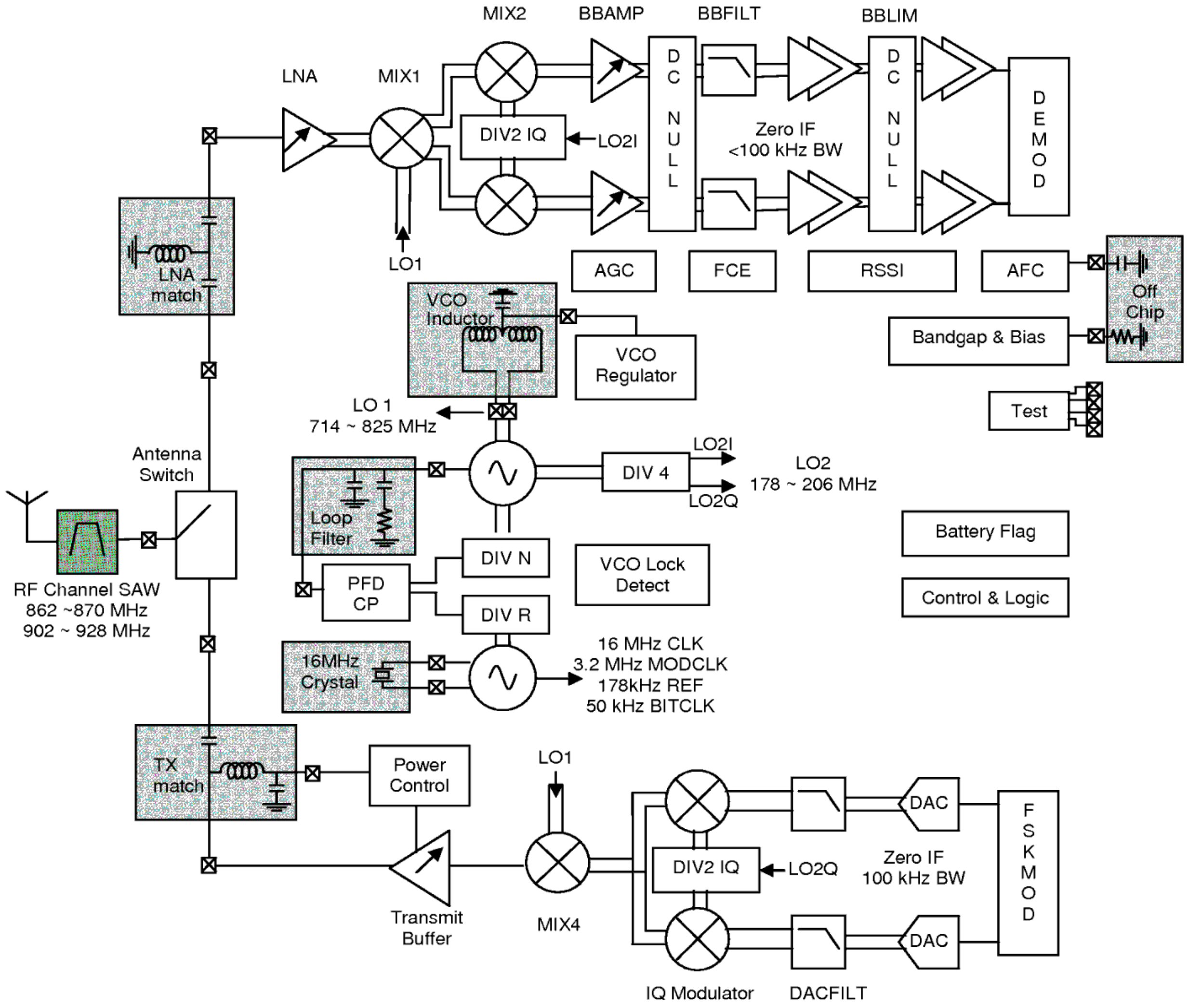


Figure 9. Sensium transceiver architecture [60].

Knowing the sensor interface ADC data streaming rate, MAC protocol duty cycling, time-domain-multiple-access (TDMA) network cluster size management and the overhead of data error correction coding, MAC headers, synchronization words, etc., a raw transceiver data rate of 50 kbps was chosen as sufficient to meet the needs of more demanding vital sign measurements, such as single lead ECG streaming. Choosing a 50 kHz frequency deviation allows for the lowest power transceiver design, whilst meeting regulatory emission and channel bandwidth requirements.

The Sensium chip is fabricated in a 0.13 μm CMOS technology; the transceiver section occupies approximately 7 mm^2 in a total SoC die size of 4 x 4 mm^2. The transceiver consumes 2.1 mA during receive and up to 2.6 mA during transmit from a 1.0 – 1.5 V supply.

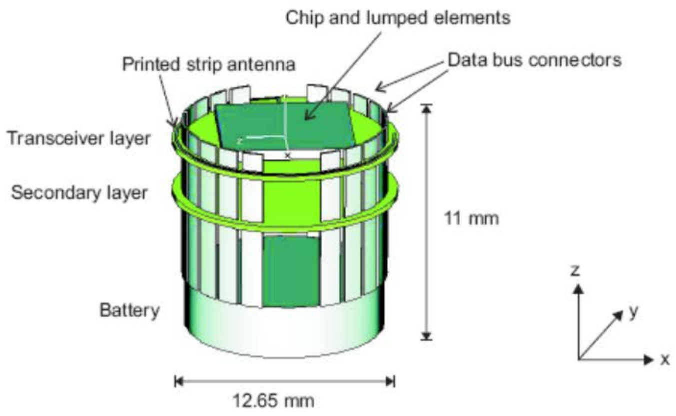
Table 5. Measured performance of the Sensium transceiver [60].

Parameter	**Condition**	**Value**	**Unit**
Operating Frequency	Europe	862–870	MHz
	North America	902–928	MHz
Channel Bandwidth		200	kHz
Channel Spacing		100 / 200	kHz
Data Rate	2FSK, Fdev ±50 kHz	50	kbps
Power Consumption	*Typical Conditions Vbat = 1.2 V*		
Transceiver Receive		2092	μA
Transceiver Transmit	-7 dBm Power	2635	μA
	-10 dBm Power	2368	μA
Transceiver Sleep		1	μA
Hardware MAC	Active RX or TX	30	μA
Performance	*Including match & Antenna Switch*		
RX Sensitivity	For 1E-3 BER	-102	dBm
Maximum RX Signal	For 1E-3 BER	-10	dBm
RX RSSI range	Including AGC	72	dB
RX ACPR	@±200 kHz	9	dB
(wanted @ –99 dBm	@±400 kHz	24	dB
for 1E-3 BER)	@±1 MHz	47	dB
TX Output Power	8 Power settings	-23 to -7	dBm
Synthesizer Phase	@±10 kHz Offset	-60	dBc/Hz
Noise	@±100 kHz Offset	-92	dBc/Hz

3.4.3. Antennas and Radio Propagations for WBSN

The characteristics and behaviour of the antenna need to adhere to certain specifications, determined by the wireless standard or system requirements. This means that the transmitting and receiving frequency bands of the various units need to be justified accordingly. For the wireless BSN to be accepted by the majority of consumers, the radio system components, including the antenna, need to be small in size, lightweight and hidden in some manner. This potentially requires integration of these systems within everyone's daily clothes. Some research projects have been initiated, under the concept of smart clothing/textiles, to integrate antennas and RF systems into clothes with regards to size reduction and cost effectiveness, so the wearer will not even notice that these sub-systems exist [61], [62].

The compact sensor structure introduces many restrictions on the antenna design, including the sensor size, chip placement, lumped element locations and flexibility of the various sensor layers to be shuffled with minimum cost and change in antenna performance. Figure 10a presents a schematic of the sensor model applied in the numerical investigation, with the printed λ/4 monopole antenna around the circumference of the sensor upper layer and all other components included in the module. Photographs of the sensor transceiver layer and the prototype module fabricated are shown in Figures 9b and 9c, respectively.

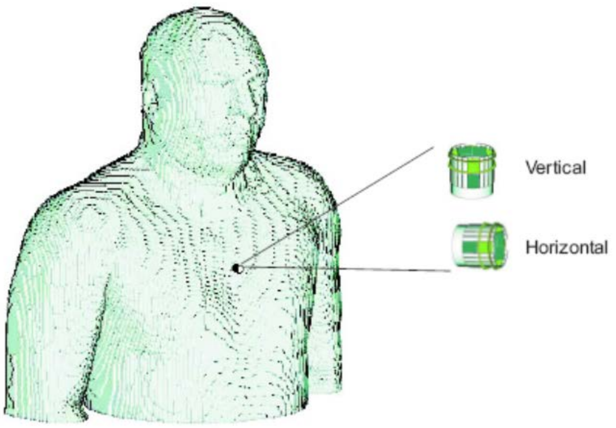


(a) Sensor model applied in numerical analysis

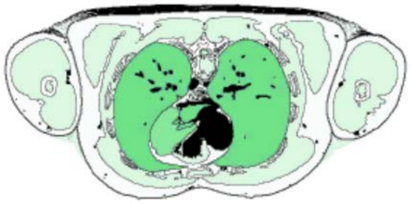
(b) Top view of the fabricated transceiver layer

(c) Photograph of the manufactured prototype sensor

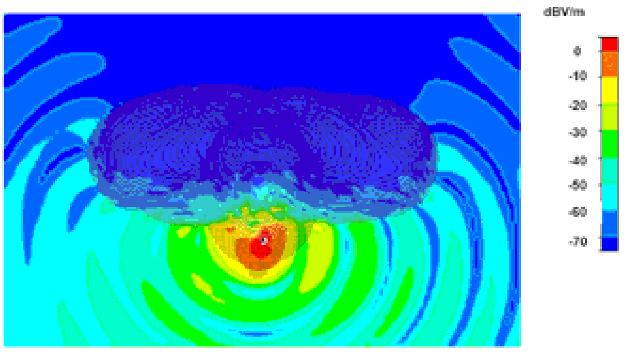
Figure 10. An antenna embedded in the wireless sensor [63].



(a) Sensor placed on the chest of the digital male phantom



(b) Horizontal cut across the digital phantom showing details of the human trunk organs



Normalised electric field distribution around the human body induced by the sensor antenna.

Figure 11. Digital human phantoms used for on-body radio propagation prediction [64].

Figure 11 demonstrates the electric field distribution around the body at 2.4 GHz [64]. The field distribution clearly shows the diffraction of free space waves originating from the antenna caused by the curvature of the human body, introducing creeping waves that follow the human body shape and travel along the body surface. Hence, the received signal at the back contains contributions from creeping waves travelling from the transmitter along the surface at opposite directions, which corresponds to predictions from the General Theory of Diffraction (GTD) along and around cylindrical and elliptical bodies [65].

3.4.4. External Flash

The Tmote Sky platform has a ST M25P80 40 MHz serial code flash for external data and code storage. The flash holds 1024 kB of data and is decomposed into 16 segments, each 64 kB in size [66]. The flash uses the same SPI interface with the CC2420 RF module.

3.4.5. Miniature Wireless Sensor Nodes

The feasibility of miniature wireless sensor devices has been demonstrated for volumes as small as a few cubic millimetres, although mass-market introduction is still lacking. In general, a severe reduction in size leads to a severe limitation in device functionality. In designing miniature wireless devices, requirements — such as fast reaction times, bi-directional wireless connectivity at medium data rates and long operational lifetimes — lead to relatively complex devices and moderate power levels. For instance, most commercialized devices use a wireless standard, such as 802.15.4, with security overhead and other features. Energy scavenging schemes, such as vibration energy scavenging, and thermal energy scavenging, have been shown to have a poor power density and poor miniaturization possibilities, rendering them unsuitable for powering miniature wireless sensor devices, apart from some small exceptional niche applications. Photovoltaic energy scavenging is applicable in a wider range of applications, but miniaturized photovoltaic systems are still far from mature. In order to enable a sufficiently long operational lifetime, the battery volume needs to be sizeable. The energy density of lithium rechargeable batteries thus determines the size of the device. As an example, the energy density of a LiR2430 80 mAh 3.6V battery is 200 Wh/dm^3. Even if the battery volume is allowed to take 50% of the volume of the device, the volume reaches a value close to 3 cubic centimetres, far removed from the desired level of several cubic millimetres [48].

The different devices depicted in Figure 15 are plotted so that the scale puts them in good perspective with each other.

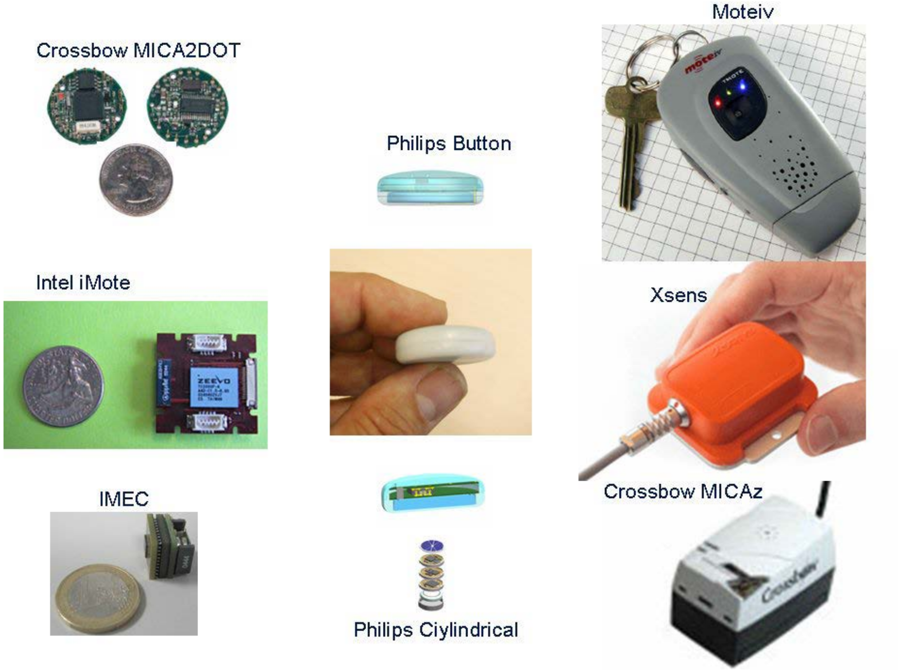


Figure 12. Comparison of the Philips solutions with different devices often cited in the wireless communications community [48].

Table 6. Clarification of the functionality of the shown sensor devices [48].

Philips Button Processor CoolfluxDSP; Wireless 2.4 GHz IEEE802.15.4; 3D accelerometer, 3D magnetometer; antenna, battery, package included; 28mm diameter, 10 mm height	**Philips Cylindrical** Processor CoolfluxDSP/PCH7970; Wireless 2.4 GHz IEEE802.15.4; 3D accelerometer, antenna, battery, package included; 14 mm diameter, 14 mm height
Intel iMote Processor ARM7TDMI; Wireless 2.4 GHz Bluetooth Sensors excluded; Battery excluded; 30 x3 0 mm (W x L)	**IMEC (1st generation)** Processor MSP430F149; Wireless 2.4 GHZ, Nordic; Temperature sensor; Battery included; 14 x 14 x 12 mm
Moteiv Processor MSP430F1611; Wireless 2.4 GHz IEEE802.15.4, ZigBee compliant; 2D accelerometer, temperature sensor, light sensor, microphone, loudspeaker; battery included; 50 x 94 x 22 mm (W x L x H)	**Xsens** Wired system to wireless hub; 3D gyroscope, 3D accelerometer, 3D magnetometer. No battery; 58 x 58 x 22 mm (W x L x H)
Crossbow MICAz Processor Atmel Atmega 128L; Wireless 2.4 GHz IEEE802.15.4, ZigBee compliant; Light, temperature, sound, 2D accelerometer, 2D magnetometer; Battery included	**Crossbow MICA2DOT** Processor Atmel Atmega 128L; Wireless 868/916, 433 MHz or 315 MHz; Temperature sensor; No battery/antenna included; 25 mm diameter, 10 mm height

3.5. Software Architecture

Figure 16 shows the software architecture of the Wireless Physiological Measurement System. The system software is implemented in a TinyOS environment. TinyOS is developed by a consortium, led by the University of California, Berkeley, in co-operation with Intel Research. TinyOS is an open-source operating system designed for wireless embedded sensor networks. It features a component-based architecture, enabling rapid innovation and implementation whilst minimising code size, as required by the severe memory constraints inherent in sensor networks [46].

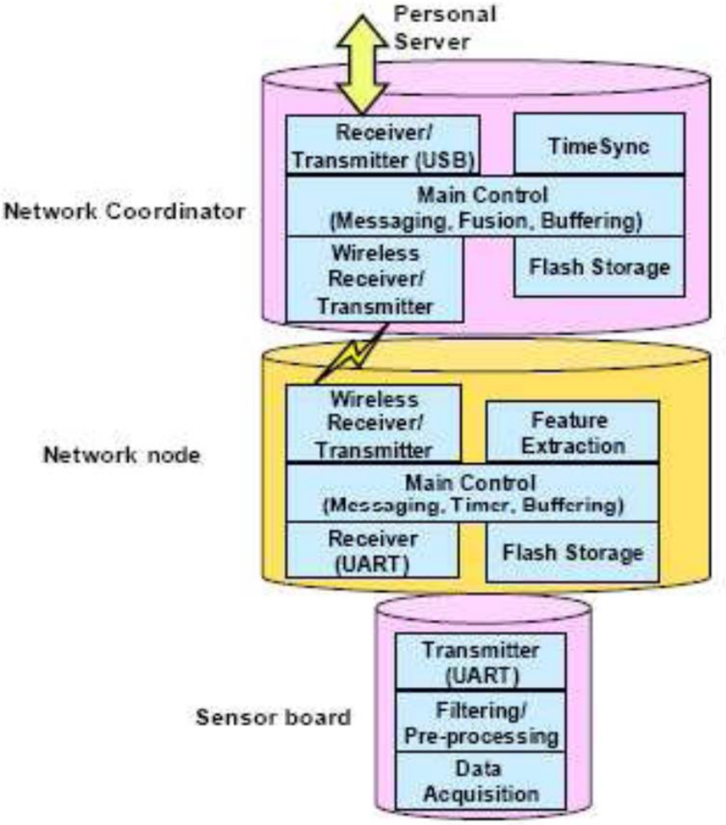


Figure 13. Software architecture of the system [71].

4. Conclusions

Future healthcare will need to manage a large increase in chronic diseases, due, in part, to population aging, with limited resources. In this paper, it has been revealed that human behaviour monitoring via physiological measurement can be achieved efficiently via wireless sensor technology, in the form of wireless body sensor networks (WBANs). This wireless technology will help to shift medical healthcare from hospitals to the community, with patients increasingly responsible for their own health [2].

The paper also identifies the requirements for wireless physiological measurement systems in order to successfully yield the potentials of the market. These requirements include: low cost; low power consumption; small size with a high degree of integration and packaging; the possible use of energy harvesting methods as alternative power supplies; and reliable electrophysiological/physiological sensors.

Wireless sensor technology also faces challenges in producing reliable and robust patient monitoring: network coexistence among Bluetooth, ZigBee, WLAN/Wi-Fi; interference detection/mitigation in high patient density environments; encryption concepts for privacy and security; the realisation of medical-grade wireless connectivity; and centralized spectrum management.

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