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Introduction

1.1 History of Wearable Technology

Earlier in history, it would take hundreds of years between breakthroughs such as eyeglasses being developed in 1286 and the abacus ring being manufactured in 1600. Today, new wearable tech innovations happen on a monthly basis, if not weekly. In the last 10 years, we have had the Google Glass, Fitbit, Oculus Rift, and countless others.

The Nuremberg egg manufactured in 1510 by Peter Henlein was one of the early portable mechanical timekeeping devices (like a watch) which had a chain to hang over the neck. An air-conditioned top hat was a wearable designed by a Victorian in the nineteenth century. In 1890, a lighting company in New York used to send girls with wearable lights onto the performance stage and to light up houses during ceremonies. In the 1960s, the wearers of roulette shoes, created by Edward Thorp and Claude Shannon, used to observe the rotations of the roulette ball, tap the shoe accordingly, and then receive a vibration telling them which number to bet on. In 1963, a small portable TV screen was worn as a glass. The aviator Alberto Santos-Dumont pioneered the use of the wristwatch in 1904 as it allowed him to have his hands free while flying. This also led people to start using wristwatches. Calculator watches came onto market in 1975 and the first low-cost Walkman stereo was offered by Sony in 1979. In the 1990s, interest in the Internet of Things (IoT) started to rise. In December 1994, Steve Mann, a Canadian researcher, developed the wearable wireless Webcam. Despite its bulk, it paved the way for future IoT technologies. This required advances in artificial intelligence, which started to flourish in the 2000s.

The Sony Walkman was a clear commercial success. The Walkman and subsequent Sony Discman helped the company become an entertainment powerhouse. Over 400 million Walkman portable music players have been sold with about 200 million of those being cassette players.

However, not all products launched with a fanfare are destined for success. The commercial potential of many wearable technologies introduced in recent years are not always predictable or even achieved.

Fitbit filed for a \$100 million initial public offering, but it now has to compete against a plethora of other fitness trackers on the market. The Apple Watch was been launched amidst a great deal of publicity, but it comes with no guarantees for Apple – a company that needs a lot of new revenues on a product to move the needle. Finally, the creation of the Oculus Rift virtual reality (VR) headsets could finally bring VR to the masses. The company

has already been bought by Facebook for over \$2 billion. Garmin, as a global positioning system (GPS), and Samsung Galaxy Gear, as a smart watch, are other popular wearables.

What is clear is that, based on the history of wearable technology, devices that move the masses are far and between. The successes that do make it, however, can change the world and generate chart-topping returns. Meanwhile, people's needs change over time, and include entertainment, activity, sport, and now most importantly health. This brings wearables such as Quell to the market. When strapped on the body Quell predicts and detects the onset of chronic pain and stimulates nerves to block pain signals to the brain. Other wearables to measure blood alcohol content, athletic performance, blood sugar, heart rate, and many other bioindicators rapidly came to the market as the desire for health monitoring grew. This may become more demanding as the interest in personal medicine grows.

1.2 Introduction to BSN Technology

Wearable technology including sensors, sensor networks, and the associated devices has opened its space in a variety of applications. Long-term, noninvasive, and nonintrusive monitoring of the human body through collecting as much biometric data and state indicators as possible is the major goal of healthcare wearable technology developers. Patients suffering from diabetes need a simple noninvasive tool to monitor their blood sugar on an hourly basis. Those suffering from seizure require the necessary instrumentation to alarm them before any seizure onset to prevent them from fall injury. The stroke patients need their heart rate recorded constantly. These are only a small number of examples which show how crucial and necessary wearable healthcare systems can be.

At the Wearable Technology Conference in 2018, the winners of seven wearable device producers were introduced. These winners include the best ones in Lifestyle with the objective of 'play stress away'; Sports and Fitness for making a football performance device, healthcare for developing a smart eyewear with assistive artificial intelligence capabilities for the blind and visually impaired; Industrial for designing a unique smart and connected industry 4.0 safety shoe; Smart Clothing Challenge for the nonintrusive acquisition of heart signals that will enable pervasive health monitoring, emotional state assessment, drowsiness detection, and identity recognition; Smart Lamp, which allows you to move the light in any direction without moving the lamp; and Connected Living Challenge, for creating accessories linking braintech with fashion design. Headpieces and earrings use electroencephalography (EEG) technology, capturing and providing users with brain data, allowing them to be conscious of their mental state in real time, for example for reducing anxiety and depression or increasing focus or relaxation of the user [1]. This simple example together with the above examples clearly show the diversity in applications of wearable technology. The aim of this book is therefore to familiarise readers with sensors, connections, signal processing tools and algorithms, electronics, communication systems, and networking protocols as well as many applications of wearable devices for the monitoring of mental, metabolic, physical, and physiological states of the human body.

Disease prevention, patient monitoring, and disable and elderly homecare have become the major objectives for investment in social health and public wellbeing. According to the World Health Organization (WHO), an ageing population is becoming a significant problem

and degenerative brain diseases, such as dementia and depression, are increasingly seen in people while a bad lifestyle is causing millions of people to suffer from obesity or chronic diseases. It is thus reasonable to expect that this circumstance will only contribute to an ongoing decline in the quality of services (QoSs) provided by an already overloaded healthcare system [2]. A remote low-cost monitoring strategy, therefore, would significantly promote social and clinical wellbeing. This can only be achieved if sufficient reliably recorded information from the human body is available. Such information may be metabolic, biological, physiological, behavioural, psychological, functional, or motion-related.

On the other hand, the development of mobile telephone systems since the early 1990s and its improvement till now together with the availability of large size archiving and wide-band communication channels significantly increase the chance of achieving the above objectives without hospitalising the caretakers in hospitals and care units for a long time. This may be considered a revolution in human welfare. More effective and efficient data collection from the human body has therefore a tremendous impact and influence on healthcare and the technology involved. The state of a patient during rest, walking, working, and sleeping can be well recognised if all the biomarkers of the physiological, biological, and behavioural changes of human body can be measured and processed. This requirement sparks the need for deployment of a multisensor and multimodal data collection system on the body. A body sensor network (BSN) therefore is central to a complete solution for patient monitoring and healthcare. Several key applications benefit from the advanced integration of BSNs, often called body area networks (BANs), with the new mobile communication technology [3, 4].

The main applications of BSNs are expected to appear in the healthcare domain, especially for the continuous monitoring and logging of vital parameters of elderly people or patients suffering from degenerative diseases such as dementia or chronic diseases such as diabetes, asthma, and heart attacks. As an example, a BAN network on a patient can alert the hospital, even before they have a heart attack, through measuring changes in their vital signs, or placing it on a diabetic patient could auto-inject insulin through a pump as soon as their insulin level declines.

The IEEE 802.15 Task Group 6 (BAN) is developing a communication standard optimised for reliable 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 security [5]. This was approved on 22 July 2011 and the first meeting of IEEE 802.15 wireless personal area network (WPAN) was held on 3 March 2017.

The BSN technology benefits from developments in various areas of sensors, automation, communications, and more closely the vast advances in wired and wireless sensor networks (WSNs) for short- and long-range communications and industrial control. For interconnecting multiple appliances, for example, some developed their own personal area network (PAN). One was by Massachusetts Institute of Technology (MIT) which was later expanded by Thomas G. Zimmerman to interconnect different body sensors and actuators to locate the human through the measures performed by electric field sensors. He introduced the PAN technology by exploiting the body as a conductor. Neil Gershenfeld, a physician at MIT, did the major work on near-field coupling of the field and human body tissue for localisation [6]. By fixing pairs of antennas on the body, for example around the elbow and hand, and

applying an electric current through them, they showed that the system is capable of tracking the person. They learnt that as one moves a capacitance in their circuit is charged. So, they can locate the antennas in places where there is maximum change in the movement between them.

BSNs have their root within WSNs. Like many advanced technologies, the origin of WSNs can be seen in military and heavy industrial applications. The first wireless network which had some similarity with a modern WSN is the sound surveillance system (SOSUS), developed by the United States military in the 1950s to detect and track Soviet submarines. This network used submerged acoustic sensors – hydrophones – distributed in the Atlantic and Pacific oceans. This sensing technology is still in service, though for many different objectives, from monitoring undersea wildlife to volcanic activity [7]. Echoing the investments made in the 1960s and 1970s to develop the hardware for today's Internet, the United States Defense Advanced Research Projects Agency (DARPA) started the Distributed Sensor Network (DSN) programme in 1980 to formally explore the challenges in implementing distributed WSNs. With the birth of DSN and its progression into academia through partnering universities such as Carnegie Mellon University and the MIT Lincoln Laboratory, WSN technology soon found its place in academia and civilian scientific research.

Governments and universities eventually began using WSNs in applications such as air quality monitoring, forest fire detection, natural disaster prevention, weather stations, and structural monitoring. Then as engineering students made their way into the corporate world of the technology giants of the day, such as IBM and Bell Labs, they began promoting the use of WSNs in heavy industrial applications such as power distribution, wastewater treatment, and specialised factory automation.

Although BSNs' objective and technology have their own requirements, they owe their birth and early development, particularly with regards to data communication, to the WSN technologies, which enable fruitful use of permitted wireless communication features and frequency range.

BSNs are also called wireless body area networks (WBANs) as often the transmission is through wireless systems. In their current form, BSNs are wireless networks of wearable devices with recording and some processing capabilities [4, 7–9]. Such devices may be embedded inside the body, implants, surface-mounted on the body in fixed positions, or carried in one way or another [10]. From its start of development, there have been tremendous attempts in reducing the size and cost, and increasing the flexibility, of such devices—particularly those with direct contact with the human body [11, 12]. The development of BSN technology started in 1995 around the idea of using WPAN technologies to implement communications on, near, and around the human body. Later in early 2000, the term 'BAN' came to refer to the systems where communication is entirely within, on, and in the immediate proximity of a human body [13, 14]. A WBAN further expands WPAN wireless technologies as gateways to reach longer ranges. Through gateway devices, it is possible to connect wearable devices on the human body to the Internet. This allows medical professionals to access patient data online using the Internet independent of patient location [15].

BSNs have opened two important fronts in research and technology: one as a measuring tool in health and the other as an integral part of the public network. Such networks have tremendous applications in healthcare [16–18], sports, entertainment [19–21], industry, the military, and surveillance [22], assistive technology [23], and interactive and collaborative

computer games [24] and other social public fields [25–27]. In parallel with introducing and supplying new sensors, embedding electronic circuits as well as mobile applications and gadgets (Google glass, wristband, armband, headband, watch, and mobile with more biological data recording capabilities), which can be conveniently mounted on human body, the research and development in BSN technology continue apace. The key BSN applications, stated above, benefit from the advanced integration of BANs and emerging wireless technologies. For example, in remote health/fitness monitoring, health and motion information are monitored in real-time and delivered to nearby diagnostic or storage devices, through which the data can be forwarded to off-site clinical units for further inspection. In military and sports training the motion sensors can be worn on both hands and elbows for tracking the movement and accurate feature extraction of sports players' movements. In interactive gaming, body sensors enable players to simulate and perform actual body movements, such as boxing and shooting, that can be fed back to the gaming console, thereby enhancing their entertainment experiences. Or for personal information sharing any private or business information can be stored in body sensors for many daily life applications such as shopping, activity monitoring, and information exchange. Finally, in secure authentication both physiological and behavioural biometrics – such as facial patterns, fingerprints, and iris recognition – can be restored and shared with authorities all over the world. In such cases, potential problems, such as forgery and duplicability, have motivated investigations into more and new physical/behavioural characteristics of the human body, by means of other measurements, such as EEG, gait information, and multimodal biometric systems.

BSNs may also be considered a subset of WSN often used in various industrial applications to monitor a large connected system. In many cases, however, each group of sensors, such as those for an EEG, can be wired up to a central recording system, such as the EEG machine, which can then be processed together. For BSNs the sensors often sample the physiological and metabolic variables from human body. Using BSNs for health monitoring, the necessary warning or alarming states for risk prevention can be generated and the diagnostic data for long-term inspection by clinicians can be recorded and archived.

The main components of the BSN technology are sensors, data processing, data fusion, machine learning, and low- and long-range communication systems. Groups of researchers in sensor design, microelectronics, integrated circuit fabrication, data processing, machine learning, short- and long-range communications, security, data science, and computer networking, as well as clinicians, have to work together to design an efficient and usable BSN.

The advances in sensor technology, data analytics for large datasets, distributed systems, new generation of communication systems, mobile technology, and cooperative networks have opened a vast research platform in BSN as an emerging technology and an essential tool for the future development of ubiquitous healthcare monitoring systems [28]. Researchers should (i) enable seamless data transfer through standards such as Bluetooth, ZigBee, or ultrawideband (UWB) Wi-Fi to promote information exchange and the efficiency of migration across networks and uninterrupted connectivity, (ii) the sensors used in an BSN should be of low complexity, small size lightweight, easy to use, reconfigurable, and compatible with the existing tools and software, (iii) the transmission should be secure and reliable, and (iv) the sensors should be convenient to use and ethically approved.

On the other hand, agile solutions for clinical problems require access to multimodal physiological, biological, and metabolic data as well as those related to body motion,

behaviour, mode, etc., which may be captured by cameras. The fusion of multimodal information is itself a fascinating area of research within both computer science and engineering communities.

Looking at the BSN with respect to WSN, WSNs have more general applications. For example, they can be deployed to inaccessible environments, such as forests, sea vessels, swamps, or mountains. In such cases, many redundant or spare nodes may be placed in the environment, making more dense distribution of the sensors to avoid any negative impact of node failures. In BSNs, however, the nodes are located in clinically more informative zones around or even inside the human body. This makes the total number of nodes limited, and generally rarely more than a few dozen. Each node is mounted properly to ensure more robust and accurate results [29]. However, there are cases where the sensors are movable and deployed for short duration recordings. An example of such sensors is endoscopic capsules, also called esophagogastroduodenoscopy (EGD), for monitoring human intestine and internal abdomen tissues.

Also, in terms of functionality attributes, the nodes in WSNs often record data of the same modality (although, in recent applications, different modalities such as sound and video have been taken into account by WSNs), whereas, in BSNs, various sensors collect different physiological and biological data.

Some limitations in sensor design – such as their geometrical dimensions, weight, shape, appearance, and size – may be less important for the WSN nodes than those of BSNs. Different sensor types are used in a BSN for recording various data types from the human body [8]. For a WSN there may be large-size sensors which are very resistive to a rough and hostile environment. In BSNs the nodes are supported by more robust electronic circuits which are less sensitive to noise, such as well-tuned differential amplifiers, to enable the recording of very low amplitude signals such as scalp EEG or surface electromyography (EMG). The sensors are often small and delicate enough to be wearable, less intrusive, easily deployable within the human body, and in many cases biocompatible [30].

There are other considerations and limitations for BSNs, for example in many applications the human body is in motion and the BSN nodes move accordingly. Also, unlike for WSNs, where the nodes are powered by many sources such as the national grid, wind turbine, and solar cells, for conventional BSNs, the consumable energy should be optimised and batteries with limited power (though rechargeable) used [31, 32]. On the other hand, with regards to data transmission, the nodes in a WSN often transfer the data with similar rates as long as the data modality is the same. This is, however, not the case for a BSN, as various sensors sample and transfer the data at rates appropriate to the underlying physiological variables under examination.

Another concern about the data type in BSNs is that the human body is nonhomogeneous and each part is modelled as an entirely nonlinear system. Also, the physiological signals are inherently highly nonstationary, i.e. their statistical properties vary over time. Therefore, accurate analysis of such data is significantly more challenging than for other types of data, and many linear signal processing methods, therefore, are likely to fail to capture and analyse the true features of the data.

Additionally, BSNs are generally meant for monitoring human physiological, biological, and motion data, which are related to user's personal safety and privacy as well as other

ethical issues. Therefore, some means of QoS, privacy protection, integrity, prosperity, and security in archiving and real-time data transmission must be considered [33, 34].

In terms of data communication through conventional wireless systems, WBANs support a variety of real-time health monitoring and consumer electronics applications. The latest standardization of WBANs is the IEEE 802.15.6 standard [35] which aims to provide an international standard for low-power, short-range, and extremely reliable wireless communication within the surrounding area of the human body, supporting a vast range of data rates for different applications. The security association in this standard includes four elliptic curve-based key agreement protocols that are used for generating a master key.

The Federal Communications Commission (FCC) has approved the allocation of 40 MHz of spectrum bandwidth for medical BAN low-power, wide-area radio links at the 2360–2400 MHz band. This allows off-loading WBAN communication from the already saturated standard Wi-Fi spectrum to a standard band [36].

Apart from 2390–2400 MHz band which is not subject to registration or coordination and may be used in all areas including residential, the 2360–2390 MHz frequency range is available on a secondary basis. The FCC will expand the existing Medical Device Radio-communication (MedRadio) Service in Part 95 of its rules. WBAN devices using this band can operate on a ‘licence-by-rule’ basis, which eliminates the need to apply for individual transmitter licences. Usage of the 2360–2390 MHz frequencies is restricted to indoor operation at healthcare facilities and subject to registration and site approval by coordinators to protect aeronautical telemetry primary usage [37].

1.3 BSN Architecture

The general architecture of a BSN is shown in Figure 1.1. Sensor nodes which are placed around and possibly inside the body collect physiological data and perform preliminary processing. The data are then gathered by a sink node and transmitted to a local PC or

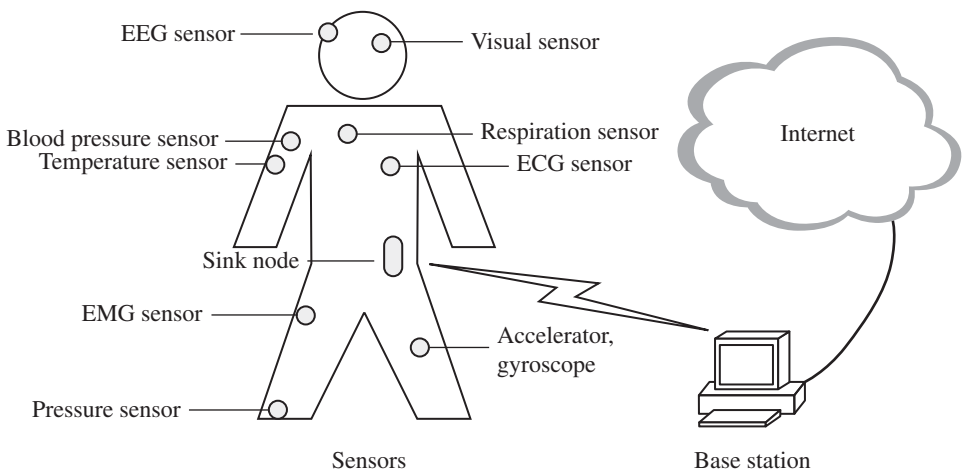


Figure 1.1 Overall architecture of a BSN.

mobile system for personal or local use (such as alarming) or the base station of a public network to share with relevant bodies over the Internet. The recipient of the BSN data can be healthcare units, social welfare, emergency units within hospitals, or other experts in clinical, experimental, and sport departments. For any one of the above cases there are many design and technical challenges to tackle.

A more detail architecture, which are discussed in the corresponding chapter of this book, involves various levels and modes of communications between the body-mounted sensors and the corresponding clinical or social agencies. Such data transfer systems inherently include in-house or short-range media (approximately 2–3 m), often called intra-BAN communication, between personal and public network (inter-BAN communication), and those entirely within public wireless communication system (beyond-BAN communication).

Figure 1.2 summarises the main research areas of BSNs. Some research has been in progress on how to design wearable sensors [38], fault diagnosis of the BSN and how to mitigate the faults and avoid their impacts [39], energy consumption and energy harvesting [40], and sensor deployment [41]. Without doubt, tremendous research in signal processing – particularly on denoising [42], artefact removal, feature detection, data decomposition, estimation, feature extraction [43], and data compression [44] – has been carried out intensively for various applications. Such valuable experiences can be directly exploited and integrated within the design of BSNs.

Data fusion, as another BSN direction of research, has been under vast development as new techniques in multimodal data recording, analysis, and multiagent distributed systems and networks have been introduced.

Moreover, machine learning techniques have powered up BSN research by developing new techniques in clustering, classification [45], anomaly detection, and decision making as well as many other approaches in big data analytics, to suit the corresponding data.

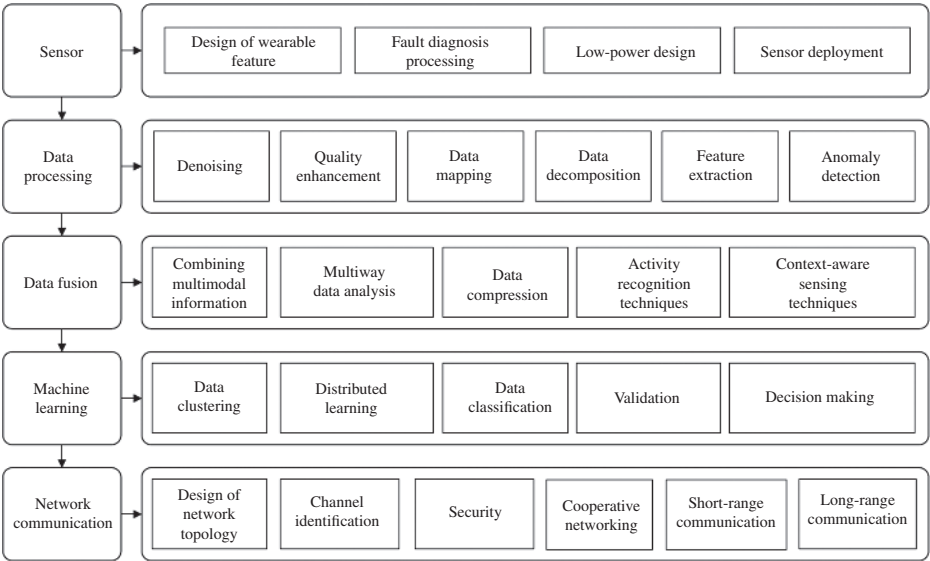


Figure 1.2 Main research areas in a BSN.

BSNs have been looked at through different angles by a growing number of scholars in sensor technology, data processing, and communications. Some researchers have combined situational awareness and data fusion technologies to enable human activity recognition [46, 47]. Others have tried to understand the data by developing sophisticated signal processing algorithms to deal with multichannel biomedical data [48, 49]. Indeed, the design and provision of supercomputers, availability of large memory clusters, and accessibility of the cloud have been crucial to the expansion of sensor networks. Moreover, new data processing and machine learning methods based on tensor factorisation, cooperative learning, graph theory, kernel-based classification, deep learning neural networks, and distributed systems together with pervasive computing have revolutionised the assessment of the information collected from multisensor networks, particularly when the dataset is large. Network communication, on the other hand, involves network topology design [50], channel characterization [51], channel access control [52, 53], routing algorithm design [54], lightweight communication protocols design, energy harvesting in a network, and many other issues related to short- and long-range communications. These key technologies must be considered and further developed for building a complete BSN system.

To enable long-term data collection from the human body, biocompatible sensors and devices need to be designed. This field of research brings new areas of engineering researchers in biotechnology, biomaterials, bioelectronics, and biomechanics together to develop practical sensors.

The demand for a green environment pushes for the optimization of energy harvesting and an effective solution to energy consumption together with enhancing the QoS. For WSNs the plethora of battery technologies available today enables system designers to tailor their energy storage devices to the needs of their applications. The latest lithium battery technologies allow optimization for any operating lifetime or environment. For applications with small temperature variation and short lifetime, lithium manganese dioxide (LiMnO_2) batteries provide solid performance at cost-effective prices, while applications demanding large temperature ranges and multidecade lifetimes are satisfied with batteries based on lithium thionyl chloride (LiSOCl_2) chemistry [7].

While batteries represent the preferred low-cost energy storage technology, energy harvesting/scavenging devices are beginning to emerge as viable battery replacements in some applications. For example, power can be generated from temperature differences through thermoelectric and pyroelectric effects, kinetic motion of piezoelectric materials, photovoltaic cells that capture sunlight, or even the direct conversion of RF (radio frequency) energy through specialised antennas and rectification. Examples of energy scavenging/harvesting devices coming to market today include piezoelectric light, solar batteries, and doorbell switches. Although the above technology can solve BSN problems, further research is needed for designing biologically powered systems and biocompatible batteries which can last longer while being attached to body internal tissues.

Finally, secure connections and data security are vital, particularly when personal information is analysed or communicated. In parallel with increasing complexity in data hacking algorithms, there is great demand for producing more sophisticated data encryption and network security.

In dealing with BSNs, machine-centric and human-centric challenges confront researchers. The machine-centric problems, as mentioned before, include security [55],

compatibility or interoperability; sensor design and sensor validity; data consistency, as the data residing on multiple mobile devices and wireless patient notes need to be collected and analysed in a seamless fashion; interference; and data management [56, 57].

Besides hardware-centric challenges, human-centric challenges include cost, constant monitoring, deployment constraints, and performance limitations [13, 58–61], which need to be taken care of in any BSN design. After all, the wearable system should be acceptable, convenient, and user friendly.

1.4 Layout of the Book

This monograph consists of 15 chapters and has been designed to cover all aspects of BSNs, starting with human body measurable or recordable biomarkers. Chapter 2 is dedicated to understanding these biomarkers, including physical, physiological, and biological measurable quantities. In Chapter 3, sensors, sensor classification, and the quantities measured by different sensors are described. In this chapter, the structures of the sensors for the applications listed in Chapter 2 are detailed. In Chapter 4, more popular and ambulatory sensor systems used in clinical departments and intensive care units are discussed and some examples of their recordings and analysis explained. This discussion continues in Chapter 5, where sleep, as a specific state of human body, is analysed. This chapter includes discussion of various sleep measurement modalities which are more popular and of interest today to researchers. Chapter 6 covers the area of noninvasive, intrusive, and nonintrusive measurement approaches. The objective of this chapter is to introduce the techniques and sensors for nonintrusive or contactless monitoring of major human vital signs, such as breathing, heart rate, and blood oxygen saturation level.

Next, Chapter 7, covers the important concept of gait analysis, recognition, and monitoring. The outcome of this study has a major application in assistive technology, rehabilitation, and assistive robotics. Chapter 8 brings together a wide range of techniques and research approaches in health monitoring. These address the important daily assisted living problems of disabled and older people, and patients with degenerative diseases, and the solutions being currently researched. In Chapter 9 numerous machine learning techniques used for both sensor networks and bioinformatics are explained. This chapter includes most popular, advanced, and very recent machine learning methods for clustering, classification, and feature learning. Support vector machines, reinforcement learning, and different deep neural networks are also included in this chapter. Some examples of machine learning for sensor networks conclude this chapter.

Signal processing techniques and their wide range of applications are covered in Chapter 10. This long chapter explains useful approaches in time, frequency, and multidimensional spaces. Multiresolution analysis, synchro-squeezing wavelet transform, and adaptive cooperative filtering are addressed. At the end of this chapter various signal processing platforms established recently are reviewed. Chapter 11 is devoted to communication systems for BSNs. Short-range communication methods, limitations, and barriers; problems with communication channels and their modelling; linking between body and public networks; and routing methods for BSNs are extensively explained in

this chapter. The important topic of energy harvesting for sensor networks is covered in Chapter 12. Advanced techniques in harvesting kinetic, radiant, thermal, chemical, and biochemical energy are explored. At the end of this chapter, topology control and energy prediction, two hot research topics, are introduced.

Chapter 13 covers a wide range of studies of and practical approaches to solving information and network security problems. In addition to general security and privacy preserving techniques, some problems related to patient and clinical data and their importance are discussed in this chapter. QoS, as the major requirement for BSNs are emphasised in this chapter. In Chapter 14 various hardware and software platforms for developing sensor networks currently employed for BSN design are discussed and some practical examples reviewed. Finally, in Chapter 15, the book is summarised, the main topics highlighted, and some suggestions for future research in BSN proposed.

References

- 1 Lai, X., Liu, Q., Wei, X. et al. (2013). A survey of body sensor networks. *Sensors (Basel)* 13: 5406–5447.
- 2 Younis, M., Akkaya, K., Eltoweissy, M., Wadaa, A. (2004) On handling QoS traffic in wireless sensor networks. *Proceedings of the 37th Annual Hawaii International Conference on System Sciences*, Big Island, HI (5–8 January 2004).
- 3 Liolios, C., Doukas, C., Furlas, G., and Maglogiannis, I. (2010). An overview of body sensor networks in enabling pervasive healthcare and assistive environments. In: *Proceedings of the 3rd International Conference on Pervasive Technologies Related to Assistive Environments*, Samos, Greece (23–25 June 2005). University of Texas at Arlington.
- 4 Ullah, S., Higgins, H., Braem, B. et al. (2010). A comprehensive survey of wireless body area networks: on PHY, MAC, and network layers solutions. *Journal of Medical Systems* 36 (3): 1065–1094.
- 5 IEEE 802.15 WPAN™ Task Group 6 (TG6) 2019 Body area networks. <http://www.ieee802.org/15/pub/TG6.html> (accessed 17 July 2019).
- 6 Gershenfeld, N. (2012). How to make almost anything, the digital fabrication revolution. *Foreign Affairs* 91 (6): 43–57.
- 7 Haver Samara, M., Fournet Michelle, E.H., Dziak Robert, P. et al. (2019). Comparing the Underwater Soundscapes of Four U.S. National Parks and Marine Sanctuaries. *Frontiers in Marine Science* 6 <https://doi.org/10.3389/fmars.2019.00500>.
- 8 Chen, M., Gonzalez, S., Vasilakos, A. et al. (2010). Body area networks: a survey. *Mobile Networks and Applications* 16: 171–193.
- 9 Movassaghi, S., Abolhasan, M., Lipman, J. et al. (2014). Wireless body area networks: a survey. *IEEE Communications Surveys and Tutorials* 16 (3): 1658–1686.
- 10 Poslad, S. (2009). *Ubiquitous Computing Smart Devices, Smart Environments and Smart Interaction*. Wiley.
- 11 Schmidt, R., Norgall, T., Mörsdorf, J. et al. (2002). Body area network BAN: a key infrastructure element for patient-centered medical applications. *Biomedizinische Technik* 47 (1): 365–368.

- 12 O'Donovan, T., O'Donoghue, J., Sreenan, C., O'Reilly, P., Sammon, D. and O'Connor, K. (2009) A context aware wireless body area network (BAN), *Proceedings of the Pervasive Health Conference*, London (1–3 April 2009).
- 13 Yuce, M.R. (2010). Implementation of wireless body area networks for healthcare systems. *Sensors and Actuators A: Physical* 162: 116–129.
- 14 Jones, V.M., Bults, R.G.A., Konstantas, D., and Vierhout, P.A.M. (2001). *Body Area Networks for Healthcare*, 1–6. Faculty of Electrical Engineering, Mathematics & Computer Science Biomedical Signals and Systems.
- 15 Yuce, M.R. and Khan, J.Y. (2011). *Wireless Body Area Networks: Technology, Implementation, and Applications*. Jenny Stanford Publishing.
- 16 Yoo, J., Yan, L., Lee, S. et al. (2009). A wearable ECG acquisition system with compact planar-fashionable circuit board-based shirt. *IEEE Transactions on Information Technology in Biomedicine* 13: 897–902.
- 17 Harrison, B.L., Consolvo, S., and Choudhury, T. (2009). Using multi-modal sensing for human activity modeling in the real world. In: *Handbook of Ambient Intelligence and Smart Environments*, 1e (eds. H. Nakashima, H. Aghajan and J. Carlos Augusto), 463–478. New York: Springer.
- 18 Aziz, O., Lo, B., King, R. et al. (2006). Pervasive body sensor network: an approach to monitoring the post-operative surgical patient. In: *Proceedings of the International Workshop on Wearable and Implantable Body Sensor Networks*, 4–18. Cambridge, MA: IEEE.
- 19 Conroy, L., Ó'Conaire, C., Coyle, S. et al. (2009). TennisSense: a multi-sensory approach to performance analysis in tennis. In: *Proceedings of the 27th International Society of Biomechanics in Sports Conference*, Limerick, Ireland (17–21 August 2009), 17–21. Biomechanics Research Unit, University of Limerick.
- 20 Pansiot, J., Lo, B., and Yang, G.Z. (2010). Swimming stroke kinematic analysis with BSN. In: *Proceedings of the 2010 International Conference on Body Sensor Networks (BSN)*, Biopolis, Singapore (7–9 June 2010), 153–158. IEEE.
- 21 Burchfield, R. and Venkatesan, S.A. (2010). Framework for golf training using low-cost inertial sensors. In: *Proceedings of the 2010 International Conference on Body Sensor Networks (BSN)*, Biopolis, Singapore (7–9 June 2010), 267–272. IEEE.
- 22 Nesime, T., Mark, B., Reed, H. et al. (2004). Confidence-based data management for personal area sensor networks. In: *Proceedings of the First Workshop on Data Management for Sensor Networks (DMSN2004)*, Toronto, Canada (30 August 2004), 24–31. ACM.
- 23 Shi, W. (2015). Recent advances of sensors for assistive technologies. *Journal of Computer and Communications* (3): 80–87.
- 24 Jovanov, E., Milenkovic, A., Otto, C., and de Groen, P.C. (2005). A wireless body area network of intelligent motion sensors for computer assisted physical rehabilitation. *Journal of NeuroEngineering and Rehabilitation* 2: 1–10.
- 25 Li, H.B., Takizawa, K., and Kohno, R. (2008). Trends and standardization of body area network (BAN) for medical healthcare. In: *Proceedings of the 2008 European Conference on Wireless Technology*, 1–4. Amsterdam: IEEE.
- 26 Osmani, V., Balasubramaniam, S., and Botvich, D. (2007). Self-organising object networks using context zones for distributed activity recognition. In: *Proceedings of the*

- ICST 2nd International Conference on Body Area Network*, Florence, Italy (June 2007), 1–9. ICST.
- 27 Wai, A.A.P., Fook, F.S., Jayachandran, M. et al. (2010). Implementation of context-aware distributed sensor network system for managing incontinence among patients with dementia. In: *Proceedings of the 2010 International Conference on Body Sensor Networks (BSN)*, Biopolis, Singapore (7–9 June 2010), 102–105. IEEE.
 - 28 Kong, J.-W. (2011) Research progress and application prospect of BSN. Shanghai Industries Intelligence Services. <http://www.hyqb.sh.cn/publish/portal2/tab227/info4154.htm> (accessed 27 June 2012).
 - 29 Latrè, B., Braem, B., Blondia, G. et al. (2011). A survey on wireless body area networks. *Wireless Networks* 11: 1–18.
 - 30 Garg, M.K., Kim, D.J., Turaga, D.S., and Prabhakaran, B. (2010). Multimodal analysis of body sensor network data streams for real-time healthcare. In: *Proceedings of the 11th ACM SIGMM International Conference on Multimedia Information Retrieval*, <https://doi.org/10.1145/1743384.1743467>. Philadelphia, PA (March 2010), 469–478. ACM.
 - 31 Cooney, M.J., Svoboda, V., Lau, C. et al. (2008). Enzyme catalysed biofuel cells. *Energy & Environmental Science* 1: 320–337.
 - 32 Yoo, J., Yan, L., Lee, S. et al. (2010). A 5.2 mW self-configured wearable body sensor network controller and a 12 μ W wirelessly powered sensor for a continuous health monitoring system. *IEEE Journal of Solid-State Circuits* 45: 178–188.
 - 33 Bui, F.M. and Hatzinakos, D. (2011). Quality of service regulation in secure body area networks: system modeling and adaptation methods. *EURASIP Journal on Wireless Communications and Networking* 2011: 56–69.
 - 34 Kumar, P. and Lee, H.J. (2012). Security issues in healthcare applications using wireless medical sensor networks: a survey. *Sensors (Basel)* 12: 55–91.
 - 35 IEEE P802.15.6-2012, (2012) Standard for wireless body area networks. <http://standards.ieee.org/findstds/standard/802.15.6-2012.html> (accessed 25 November 2019)
 - 36 Mearian, L. 2012 ‘Body area networks’ should free hospital bandwidth, untether patients. <https://www.computerworld.com/article/2503882/-body-area-networks--should-free-hospital-bandwidth--untether-patients.html> (accessed 25 November 2019).
 - 37 B. Butler, 2012 FCC dedicates spectrum enabling medical body area networks. <https://www.fcc.gov/document/fcc-dedicates-spectrum-enabling-medical-body-area-networks> (accessed 25 November 2019).
 - 38 Jafari, R. and Lotfian, R. (2011). A low power wake-up circuitry based on dynamic time warping for body sensor networks. In: *Proceedings of the 2011 International Conference on Body Sensor Network (BSN)*, University of Dallas at Texas, 83–88. Dallas, TX: IEEE.
 - 39 Luo, X., Dong, M., and Huang, Y. (2006). On distributed fault-tolerant detection in wireless sensor networks. *IEEE Transactions on Computers* 55: 58–70.
 - 40 Kwong, J., Ramadass, Y.K., Verma, N., and Chandrakasan, A.P. (2009). A 65 nm sub-V_t microcontroller with integrated SRAM and switched capacitor DC-DC converter. *IEEE Journal of Solid-State Circuits* 44: 115–126.
 - 41 Atallah, L., Lo, B., King, R., and Yang, G.Z. (2010). Sensor placement for activity detection using wearable accelerometers. In: *Proceedings of the 2010 International Conference on Body Sensor Networks (BSN)*, Biopolis, Singapore (7–9 June 2010), 24–29. IEEE.

- 42 Song, K.T., and Wang, Y.Q. (2005) Remote activity monitoring of the elderly using a two-axis accelerometer. *Proceedings of the CACS Automatic Control Conference*, Tainan, Taiwan (18–19 November 2005).
- 43 Preece, S.J., Goulermas, J.Y., Kenney, L.P.J. et al. (2009). Activity identification using body-mounted sensors – a review of classification techniques. *Physiological Measurement* 30: 353–363.
- 44 Akyildiz, I.F., Su, W., Sankarasubramaniam, Y., and Cayirci, E. (2002). Wireless sensor networks: a survey. *Computer Networks* 38: 393–422.
- 45 Akin, A., Stephan, B., Mihai, M.P. et al. (2010). Activity recognition using inertial sensing for healthcare, wellbeing and sports applications: a survey. In: *Proceedings of the 23rd International Conference on Architecture of Computing Systems (ARCS)*, Hannover, Germany (22–25 February 2010), 1–10. IEEE.
- 46 Korel, B.T. and Koo, S.G.M. (2007). Addressing context awareness techniques in body sensor networks. In: *Proceedings of the 21st International Conference on Advanced Information Networking and Applications Workshops*, Niagara Falls, ON (21–23 May 2007), 798–803. IEEE.
- 47 Thiemjarus, S., Lo, B., and Yang, G.Z. (2006). A spatio-temporal architecture for context aware sensing. In: *Proceedings of the International Workshop on Wearable and Implantable Body Sensor Networks*, Cambridge, MA (3–5 April 2006). IEEE <https://doi.org/10.1109/BSN.2006.5>.
- 48 Sanei, S. and Hassani, H. (2015). *Singular Spectrum Analysis of Biomedical Signals*. CRC Press.
- 49 Sanei, S. (2013). *Adaptive Processing of Brain Signals*. Wiley.
- 50 Natarajan, A., Motani, M., de Silva, B. et al. (2007). Investigating network architectures for body sensor networks. In: *Proceedings of the 1st ACM SIGMOBILE International Workshop on Systems and Networking Support For Healthcare and Assisted Living Environments (HealthNet 2007)*, San Juan, Puerto Rico (June 2007), 19–24. ACM.
- 51 Tachtatzis, C., Graham, B., Tracey, D. et al. (2011). On-body to on-body channel characterization. In: *Proceedings of 2011 IEEE Sensors Conference*, Limerick, Ireland (28–31 October 2011), 908–911. IEEE.
- 52 Ullah, S., Shen, B., Riazul, I.S. et al. (2010). A study of MAC protocols for WBANs. *Sensors (Basel)* 10: 128–145.
- 53 Seo, S.H., Gopalan, S.A., Chun, S.M. et al. (2010). An energy-efficient configuration management for multi-hop wireless body area networks. In: *Proceedings of 3rd IEEE International Conference on Broadband Network and Multimedia Technology*, Beijing, China (26–28 October 2010), 1235–1239. IEEE.
- 54 Benoit, L., Eli, D.P., Ingrid, M., and Piet, D. (2007). MOFBAN: a lightweight modular framework for body area networks. *Lecture Notes in Computer Science* 4808: 610–622.
- 55 Toorani, M. (2015). On vulnerabilities of the security association in the IEEE 802.15.6 Standard. In: *Financial Cryptography and Data Security* (eds. M. Brenner, N. Christin, B. Johnson and K. Rohloff). Berlin: Springer.
- 56 O'Donoghue, J., Herbert, J. and Fensli, R., (2006) Sensor validation within a pervasive medical environment, *Proceedings of the 5th IEEE Conference on Sensors*, Daegu, South Korea (22–25 October 2006), 972–975.

- 57 O'Donoghue, J., Herbert, J., and Kennedy, R. (2006). Data consistency within a pervasive medical environment. In: *Proceedings of IEEE Sensors*. IEEE.
- 58 Garcia, P., Virginia Pilloni, V., Franceschelli, F. et al. (2018). Deployment of Applications in Wireless Sensor Networks: A gossip-based lifetime maximization approach. *IEEE Transactions on Control Systems Technology* 24 (5): 1828–1836.
- 59 O'Donoghue, J. and Herbert, J. (2012). Data management within mHealth environments: patient sensors, mobile devices, and databases. *Journal of Data and Information Quality* 4 (1): 5.
- 60 Lai, D., Begg, R.K., and Palaniswami, M. (eds.) (2011). *Healthcare Sensor Networks: Challenges toward Practical Implementation*. CRC Press.
- 61 O'Donovan, T., O'Donoghue, J., Sreenan, C., et al., (2019) A context aware wireless body area network (BAN). <https://www.ucc.ie/en/media/research/misl/2009publications/pervasive09.pdf> (accessed 25 November 2019).

