Guest Editorial
Body Sensor Networks: From Theory to Emerging Applications

***Abstract*—The use of sensor networks for healthcare, well-being, and working in extreme environments has long roots in the engineering sector in medicine and biology community. With the maturity of wireless sensor networks, body area networks (BANs), and wireless BANs (WBANs), recent efforts in promoting the concept of body sensor networks (BSNs) aim to move beyond sensor connectivity to adopt a system-level approach to address issues related to biosensor design, interfacing, and embodiment, as well as ultralow-power processing/communication, power scavenging, autonomic sensing, data mining, inferencing, and integrated wireless sensor microsystems. As a result, the system architecture based on WBAN and BSN is becoming a widely accepted method of organization for ambulatory and ubiquitous monitoring systems. This editorial paper presents a snapshot of the current research and emerging applications and addresses some of the challenges and implementation issues.**

***Index Terms*—Body sensor networks (BSNs), sensors, ubiquitous systems, wireless body area networks (WBANs).**

I. Introduction

THIS SPECIAL issue marks almost ten years from the first implementation of wireless body area networks (WBANs) [1], though at that time, the prototype was named under personal area network (PAN), a term that was originated from Zimmerman [2] and further developed by IEEE P802.15 Working Group [3]. Soon after, the notation of BAN emerged. A group from Philips was among the first to use BAN instead of PAN and has listed distinct features that should be incorporated into the two types of networks [4]. As the applications of PAN or BAN extended from connecting personal electronic consumer goods for the sake of convenience to the user to medical and healthcare applications, BAN has become increasingly popular and is found to be a key element in the infrastructure for patient-centered medical applications [5].

The launch of projects, such as MobiHealth [6], further accelerates the development of BAN and m-Health service platform. IEEE T-ITB published a Special Section on m-Health five years ago [7] and the section turns out to be well recognized, as reflected in the number of citations.

From a system perspective, the concept of body sensor networks (BSNs) [8] moves beyond sensor connectivity, with specific focuses on ultralow-power processing/communication, power scavenging, autonomic sensing, data mining, distributed inferencing, intelligent on-node processing, and integrated wireless sensor microsystems. The primary motivation of BSN research is to provide long-term continuous sensing without activity restriction and behavior modification.

In practice, a collection of sensors on a user can be integrated using wired, wireless, and biochannels or a combination of these approaches. Wired sensor networks are typical for smart clothes that integrate both sensors and sensor interconnections, and achieve ultimate power efficiency. Wireless sensor networks (WSNs) can cover sensors spanning the whole body. They are particularly important for linking with ambient sensors and implantable sensors, such as pacemakers and deep brain stimulators [9]. Biochannels serve as a unique secured means of communication [10], where the human body is used to transmit either exogenous or endogenous information. Since each approach has its pros and cons, a combination of these approaches should be used according to specific applications, i.e., formation of a hybrid network [11].

Recent technological developments have enabled sensor miniaturization, power-efficient design and improved biocompatibility. Issues related to system integration, low-power sensor interface, and optimization of wireless communication channels are active research fields, as presented in this special issue. Other topics related to quality of service, security, multisensor data fusion, decision support, and technological scaling are also important for practical applications of BSNs. The purpose of this special issue is to present recent trends and transition of BSN technology from theoretical concepts to emerging applications.

II. Emerging Technologies and Applications

Earlier prototypes of BSNs tend to use multichip solutions manufactured from off-the-shelf components. Recently, the first system-on-chip (SoC) has been developed specifically for wireless BSNs to monitor vital signs. The SoC integrates a transceiver, hardware media access control (MAC) protocol, microprocessor, IO peripherals, memories, A–D converter, and custom sensor interfaces. The chip can be interfaced with antenna and battery as a single-chip wearable patch [12].

Thus far, long-term and sustainable power supply remains a great challenge to BSNs. New trends in very large-scale integration (VLSI) technology and laboratory prototypes developed by MIT and Texas Instruments promise to decrease processor power consumption 10–20 times and power supply voltage to less than 500 mV in the next five years [13]. While significant effort has been directed to power-efficient processor design and communication protocols, extensive studies have also been carried out in establishing practical techniques for power

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scavenging from the external environment or the human body [14]. One potential direction is the development of biofuel cells, where biocatalysts are used for converting chemical energy of a fuel such as glucose into electrical energy [15].

Parallel to these developments, new materials and technologies have also been developed for innovative sensor embodiment to achieve reliable, pervasive, long-term continuous monitoring of vital signs. This includes, for example, the development of conductive fabric and weaving technologies [16] or planar-fashionable circuit board technique to directly print patterned electrodes and circuits on fabric [17]. Attempts have also been made to model the human body as a communication channel [18], [19]. In addition to the earlier emerging technologies, the widespread use of mobile devices with high-speed Internet connection and GPS location has greatly extended the possible scope of BSNs.

Among the many applications of BSN, healthcare is likely to be an early adopter of the technology for managing both chronic diseases and acute events. This can potentially change the snapshot nature of conventional monitoring approaches, as the current practice is generally limited to the brief time points and often unrepresentative physiological states such as supine and sedated, or artificially introduced exercise tests. Transient abnormalities cannot always be captured reliably. Important and even life-threatening disorders can go undetected because they occur only infrequently, and much time and effort is wasted in trying to capture an "episode" with controlled monitoring. The provision of "ubiquitous" and "pervasive" monitoring of physical, physiological, and biochemical parameters in any environment without activity restriction and behavior modification is the primary motivation of BSN research. Such an approach has already shown promising results in monitoring patients after surgery, during rehabilitation, as well as for assessing activities of daily living for the elderly. Further development of BSN will continue to pave the way for implementing population-wide, multimodality health records such as the Cardiovascular Health Informatics and Multimodal E-record (CHIME) [20].

The intelligence of the system facilitates the use of physiological monitors as "guardian angels" to provide timely warnings and guidance for a variety of medical conditions or wellness management scenarios. In some situations, a feedback loop can be formed within a BSN that integrates wearable and/or implantable devices. For example, the communication network that forms between a cochlear implant and an external wearable unit that processes speech and sound and transmits control signals to the implant can be considered as a BSN. The wearable unit also supplies energy to the implant, where change of battery is inconvenient. Similar ideas have been adopted for visual implant to restore visual sensations in patients with blindness and retinal degenerations [21]. Continuous real-time control of physiological parameters such as blood glucose and blood pressure is another emerging application of BSN. These systems allow adaptive algorithms to be implemented to avoid hypoglycemia or hypotension. Proactive sensors such as automatic inflatable protective airbag for fall protection have also been developed in BSN research.

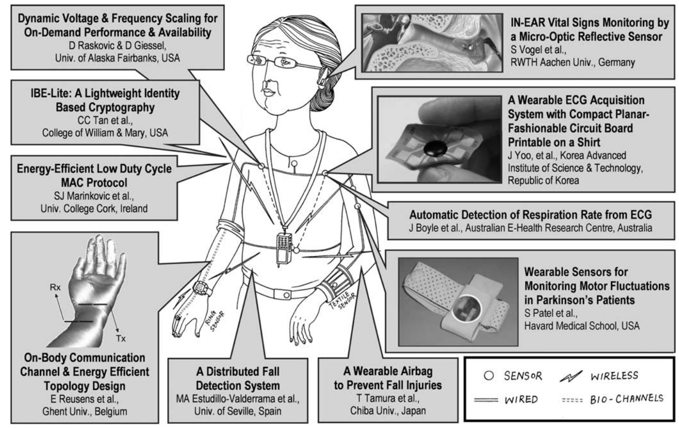

Fig. 1. Illustration of the design space of the special issue on body sensor networks.

III. Current Issues and Obstacles

Thus far, increasing number of research groups around the world have initiated a range of clinical and ambulatory monitoring projects for a number of health conditions. Examples include:

- postoperative monitoring of patients;
- monitoring of patients with chronic diseases;
- social networking of relatives and peers for monitoring of elderly;
- lifestyle and general well-being monitoring (e.g., to deal with obesity);
- wellness and exercise monitoring;
- monitoring vitals and status of soldiers and firefighters;
- emergency medical care and mass casualty events;
- computer-assisted rehabilitation and therapy; and
- development of new emergency services with prolonged monitoring.

Existing deployment of long-term monitoring has revealed a number of issues that may impede the wider acceptance of BSNs. The problems identified include:

- reliability of short range communication;
- intermittent network coverage in rural areas;
- changes of policy and organizational flaw to regulate payments and reimbursements of physicians for monitoring/consultation;
- insufficient battery life;
- motion artifacts and sensitivity to sensor placements;
- lack of seamless integration with infrastructure network and electronic medical records;
- privacy and security considerations; and
- standardization and interoperability.

IV. Special Issue

Papers in this special issue reflect a maturing trend of the BSN technologies. We received 33 papers in response to the call, ten papers were accepted for the special issue. They are illustrated in Fig. 1 and belong to the following general categories:

- development of new applications of BSNs;
- development of new sensors and sensor interfaces;

- development of wearable actuators for prevention of injuries;
- optimization of sensors; and
- characterization and optimization of wireless communication channels and biochannels.

Development of new applications is presented in the papers by Patel *et al.* and Estudillo-Valderrama *et al.* Patel *et al.* present preliminary results of evaluation of possible use of wireless sensors for automated analysis of activity of Parkinson's patients [22]. This research represents a growing trend of applications aimed at quantitative rather than subjective evaluation of the condition of these patients. In this paper, data from wearable inertial sensors are used to determine motor fluctuations as an indication of the effectiveness and timing of typical medications for Parkinson's patients. The second paper by Estudillo-Valderrama *et al.* outlines the use of inertial sensors for in-home monitoring of a distributed fall detection system [23].

New applications require new sensors or optimization of the existing sensors. Vogel *et al.* present the development of a new vital sign monitoring system placed in the ear of the user [24]. The proposed approach allows embedding of physiological sensors in hearing aid devices or wireless headsets.

Monitoring of multiple physiological parameters leads to more cumbersome systems and decreased convenience for the user. Therefore, an emerging trend is minimization of the number of sensors and evaluation of physiological parameters from the reduced set of sensors. Boyle *et al.* present possible use of the existing cardiac sensor for the estimation of respiration rate [25]. The proposed approach reduces the number of sensors required and enhances user's convenience. However, the current generation of cardiac monitors requires the use of clinical "wet" electrodes that may irritate the skin of most users after prolonged use. Therefore, one of the very active research fields is the implementation of "dry" electrodes with minimum skin irritation or embedding of electrodes in the shirt to improve user's convenience. Yoo *et al.* present a cardiac monitoring system with planar-fashionable circuit board shirt [17].

Existing processors could be optimized to provide application specific tradeoff between the required performance on demand and low-power consumption during regular operation. Raskovic and Giessel present a case for dynamic voltage and frequency scaling to provide higher performance of monitoring systems on-demand [26]. This approach can be used to optimize the existing processors before establishing detailed requirements for application specific hardware.

Increased sophistication of sensors and real-time on-node processing can facilitate the development of new applications that will enable proactive system operation to protect the user. As an example, Tamura presents a wearable system with airbags that could be used to prevent fall injuries of elderly or patients with movement disorders [27].

It is widely recognized that wireless communication consumes a significant portion of available power of monitoring systems. Three papers in this special issue reflect current research efforts in the field of low-power and secure wireless communication. Marinkovic *et al.* present an optimized MAC protocol for energy-efficient communication [28]. Power-efficient security is another important issue of wireless BANs. In this issue, Tan *et al.* present a lightweight-identity-based cryptography for resource-constrained platform for BSNs [29]. Power optimization requires optimization of every element of the system, which includes wireless communication channels. Reusens *et al.* present the comparison of simulations and actual measurements of on-body communication channels to determine optimal configuration and operation [19].

Papers published in this special issue represent a snapshot of the current research and implementations of BSN, as they are maturing to become commercially viable systems. We thank all the authors who have submitted their papers to this special issue. Due to space and topical constraints, many of the quality papers submitted are not able to be included in this special issue. We hope TITB will become a regular forum for reporting, as well as discussing, the latest developments in BSNs.

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