Collaborative Body Sensor Networks: Taxonomy and Open Challenges

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***Abstract*—Single Body Sensor Networks (BSNs) have gained a lot of interest during the past few years. However, the need to monitor the activity of many individuals to assess the group status and take action accordingly has created a new research domain called Collaborative Body Sensor Network (CBSN). In such a new field, understanding CBSN's concept and challenges over the roots requires investigation to allow the development of suitable algorithms and protocols. Although there are many research studies in BSN, CBSN is still in its early phases and studies around it are very few. In this paper, we define and taxonomize CBSN, describe its architecture, and discuss its applications. The differences between CBSN and other sensor networks are highlighted to justify the need to develop new protocols and schemes appropriate for this type of networks. The major challenges are discussed, and open research issues are outlined to help in identifying new research directions in CBSN. To the best of our knowledge, this article is the first to define CBSN as a standalone domain that is distinct from other sensor networks and to develop its taxonomy.**

Keywords: BSN; CBSN; WSN; Taxonomy.

I. Introduction

The advancements in the medical sensors field allowed the development of Body Sensor Networks (BSNs) in which sensor nodes implanted in or placed on the human body can capture physiological data, and send them wirelessly through a central data collection unit, i.e. sink node, to medical personnel who will be able to identify the current state of the person, predict his future evolution, and make proper decisions [1]. BSN has gained a lot of research interest during the past few years since it has a direct influence on improving peoples' lives, and can be applied to various medical and non-medical fields including healthcare, sport, military, entertainment, etc. However, the emergence of applications where multiple individuals' monitoring is required has created a new type of BSN called Collaborative BSN (CBSN), in which data should be gathered and analyzed from multiple bodies rather than a single body to take action accordingly. Examples of such collaborative applications include monitoring employees status in hostile environment industries, supervising rescue teams condition and sports team performance, interactive games etc. Even though there are several researches about single BSNs, little studies were found to cover CBSNs. In fact, CBSN is still in its early phases and strong understanding of its architecture and techniques are still lacking [2]. This paper taxonomizes CBSN and provides a clear definition of its concept, architecture, and applications. It identifies the different challenges facing this type of networks and outlines the corresponding open research issues. The aim of this study is to show the unique features that distinguish CBSN from other sensor networks to help in directing researches toward developing new protocols and algorithms appropriate for this field. As far as we know, this article is the first to define CBSN as an independent field different than other sensor networks and to establish its taxonomy. The paper is organized as follows: CBSN concept and architecture is presented in Section II. CBSN applications are listed in Section III, while the difference between Wireless Sensor Network (WSN), BSN and CBSN is presented in Section IV. The major challenges in CBSN to provide appropriate QoS are drawn in Section V, and the open research issues in CBSN are summarized in Section VI, to conclude in Section VII.

II. CBSN Concept and Architecture

CBSN is a network formed of multiple BSNs able to collaborate and synchronize among each other to reach a common objective. This interaction between BSNs allows the development of collaborative applications like interactive games, sport, emergency and factory, where instead of single individual monitoring, exchanging data and cooperative processing between many BSNs is a must to detect the activity of a group, identify the events perceived by many persons, and monitor the health of many individuals at the same time [3, 4]. There are three types of collaboration in CBSN depending on the way different sensors collaborate between each other [5]:

- Cooperation-based collaboration: Where different nodes

cooperate between each other based on their level of contribution to the objective, such as collaborative sensing.
- Competition-based collaboration: Where nodes participate in the collaboration process based on their competitive potentials such as scheduling resources.
- Self-organization collaboration: Where the cooperation process is induced and controlled by on the spot sensing in special conditions.

CBSN follows a Multiple Body-Multiple Base Station (MB-MBS) architecture, where many BSNs can communicate with many BSs. In every BSN, wireless nodes can communicate with the corresponding BS or sink placed on the body, and the BSs of all BSNs can collaborate, share and exchange data to reach a common objective such as monitoring the heath of a rescue team.

The basic architecture of CBSNs is presented in Fig. 1 [4].

As stated earlier, CBSN is formed of many BSNs interacting between each other. Every BSN is formed of many wireless sensors that communicate with one Body Control Unit (*i.e.*, sink node or BS) through BSN intra-communication Over-The-Air (OTA) protocol, and different BSNs communicate between each other via BSN inter-communication OTA protocol. Intra-BSN communication includes discovering and configuring the wireless sensors that belong to each BSN along with the corresponding services, as well as transmitting data between different sensors or between the WSs and the BS of the same BSN. Inter-BSN communication includes detecting neighbor BSNs, discovering and activating the services among them, as well as sending data between each other.

III. CBSN Applications

In general, CBSN applications can be classified into two categories [5]:

- Collaboration-based WSN: Where the collaboration techniques are used to find solutions to WSN issues like finding ways to minimize energy consumption, increase security, enhance coverage and develop new localization schemes.

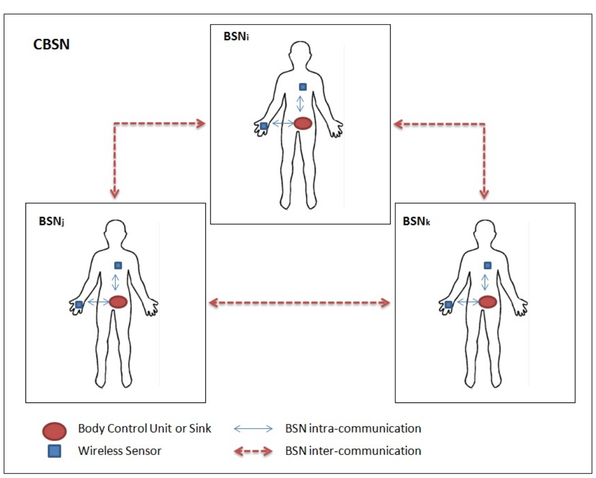

Fig. 1: CBSN General Architecture

- WSN-based collaboration: Where the wireless sensor network cooperate in order to provide services like locating and following mobile objects and monitoring specific targets.

Concerning CBSN, there is a variety of applications where monitoring single body is no longer enough to reach the objective. Such applications include [3]:

- Emergency: Monitoring the status of the rescue team and of the environment in emergencies like fire, earthquakes and landslides.
- Industries: Monitoring the status of the employees working in hostile environments like nuclear plants, blast furnaces, etc.
- Sports: Monitoring the status of every team member to assess the team's performance and activity, like submarines divers, football players, etc.
- Social interaction: Studying the behavior and interaction between multiple persons through emotion and stress detection.
- Entertainment: Developing interactive human/computer games involving real time activity between multiple individuals.
- Healthcare: Monitoring the vital signs of many individuals simultaneously, like patients in emergency rooms, elders in hospital /care facility, etc. and assist them remotely.
- Military: Monitoring the status of the army in war zones, and providing them with directions remotely to reduce the risk of injuries.

IV. Comparison between WSN, WBAN, and CBSN

In order to illustrate the differences between CBSN and other types of sensor networks, a comparison between WSN, BSN, and CBSN is summarized in Table 1 [6–13]. The comparison is performed with respect to different network requirements including scale and operating space, network coverage, network size, nodes' lifetime, nodes' size, network topology, result accuracy, data rates, nodes and battery replacement, mobility, latency, energy scavenging source, security level, target frequency bands, sensor type, wireless technology, network architecture, scalability, and finally environment conditions. It shows that CBSN shares some common characteristics with WSN; it also shares other common features with single BSN while maintaining some unique characteristics. Thus, The table proves that there is a need to investigate and develop new algorithms and techniques in different research areas to satisfy CBSN requirements.

V. Major Challenges in CBSN

To guarantee a robust and reliable network able to gather and deliver data with high QoS measures, CBSN needs to address the following challenges:

- High mobility. CBSN consists of monitoring multiple bodies that can move constantly. One of the challenges in CBSN is to send data reliably, with the lowest delay, highest throughput and energy efficiency, in a network where not only nodes placed on one body change location as the person moves, but also different bodies move in different directions, creating unpredictable mobility patterns and leading to highly dynamic network topology.

TABLE I: COMPARISON BETWEEN WSN, BSN AND CBSN

Requirements	**WSN**	**BSN**	**CBSN**
Scale/operating range	Meters vs. kilometers	Few centimeters to 2 m. standard and 5 m. special use	Meters vs. kilometers
Coverage	Monitored environment	Placed in, on, and around the body	Placed in, on, around many human bodies and covering the monitored environment
Network size/node number	Can reach thousands of devices/network	Maximum 100 devices per network [6]	Can reach thousands of devices per network
Lifetime/battery life	Many years/months	Many years/months with smaller battery capacity	Many years/months with smaller battery capacity
Node size	Small is better but not mandatory	Small and light in weight is essential	Small and light in weight is essential
Network topology	Mostly static: star, P2P, tree or mesh	Dynamic due to single body movement	Very dynamic due to mobility of multiple persons
Received Data accuracy	Through node redundancy	Through node accuracy and robustness, as well as QoS systems	Through node accuracy and robustness along with more complex QoS systems
Data rates	Mostly homogeneous	Heterogeneous: Varies from sub Kbps up to 10 Mbps in one network	Heterogeneous: Varies from sub Kbps up to 10 Mbps in one network
Nodes and battery replacement	Easy: accessible or disposable nodes	Difficult, specially for implanted nodes	Difficult, specially for implanted nodes
Mobility	Low: nodes considered stationary	High mobility of nodes as person moves. Nodes follow the same mobility pattern [6]	Very high mobility: different bodies are moving in different directions. Also, nodes within one body change location when the body moves, and nodes placed in different bodies have different mobility patterns
Latency	Application dependent (can be much higher than 10ms)	10ms [6]	10ms [6]
Energy scavenging source	Mainly wind and solar energy sources	Additional sources like vibration, thermoelectric, sound, RF energy sources	Additional sources like vibration, thermoelectric, sound, RF energy sources
Security level	Lower	Higher to protect people's information	Higher to protect people's information. More complex due to presence of multiple bodies
Target frequency bands	Europe: 315 MHz, 433 MHz and 868 MHz; North America: 915 MHz; ISM band [14]: 2.45-GHz	Unlicensed and medical approved bands: MICS [15], MEDS [15], WMTS [14], ISM, UWB [14]	Unlicensed and medical approved bands: MICS, MEDS, WMTS, ISM, UWB
Sensor type	Terrestrial WSNs, underground WSNs, underwater WSNs, multimedia WSNs, mobile WSNs	Wearable and implantable medical sensors, mechanical sensors (position and motion sensors)	Wearable and implantable medical sensors, mechanical sensors (position and motion sensors)
Wireless technology	Bluetooth, Zigbee, GPRS, WLAN, etc.	For intra-BSN communication: low power technologies like IEEE 802.15.1 (Bluetooth), IEEE 802.15.4 (Zigbee), Bluetooth Low Energy (BLE), and low power WiFi. For inter-BSN Communication: IEEE 802.11 (WiFi), GPRS, 3G/4G (LTE), IEEE 802.15.4 (Zigbee)	For intra-BSN communication: low power technologies like IEEE 802.15.1 (Bluetooth), IEEE 802.15.4 (Zigbee), Bluetooth Low Energy (BLE), and low power WiFi. For inter-BSN Communication: IEEE 802.11 (WiFi), GPRS, 3G/4G (LTE), IEEE 802.15.4 (Zigbee)

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Requirements	**WSN**	**BSN** efficient,	**CBSN**
Architecture	Wires nodes communicate via WiFi in ad-hoc mode fashion	Single Body-Single Base Station (SB-SBS) architecture: sensor, actuator, and central unit communicate through PDA	MB-MBS architecture: each BSN is composed of a BS and a set of WSs. The BS communicates with its WSs through an intra-BSN OTA protocol and with the BSs of other BSNs through a set of inter-BSN OTA protocols
Scalability	High: nodes can be added to the network as needed	Limited number of nodes can be added to single body	High: limited number of nodes can be added to single body but multiple bodies can join the network
Environment conditions	Dynamic	More stable	Dynamic and possible extreme or hostile environment conditions

- High scalability requirements [16]. Unlike single BSN, the number of nodes in CBSN is not limited and can reach thousands of devices, as more bodies, each holding many sensors, can join the network. Therefore, the QoS measures are highly affected in the design of a high scalable CBSN.
- Coverage and connectivity issues [17]. The coverage area for CBSN is very large; and many CBSNs applications occur in hostile and extreme environments, like in war zones, wildfires, underwater, etc. This harsh and dynamic environment strongly affects the connectivity between the nodes. Signal might be scattered, defused and weakened before reaching its destination. Thus ensuring the reception of the correct information with minimal delay becomes a challenge in CBSN.Different network architectures, protocols, routing algorithms, data processing, and sensing methods should be presented to guarantee that data reaches its destination, without compromising important QoS metrics like delay and energy consumption.
- Complex security requirements. Security is one of the most important QoS metrics in CBSN. It encloses both data protection and data privacy. Challenges in CBSN security arise from the presence of large number of wireless sensors, each carrying data that should be protected from malicious attacks to prevent tempering with the information, and to keep the information private and confidential. This requires the development of complex security algorithms, without overcrowding the network or consuming too much energy.
- Limited power of nodes [17]. Sensors in CBSN have limited power; therefore energy constraints should be always kept in mind when choosing MAC protocols, routing and localization algorithms, security systems, etc.
- Heterogeneous traffic and irregular traffic pattern [16]. Traffic sent by nodes in CBSN varies from few Kbps up to 10 Mbps in one network. Also, traffic pattern is unpredictable; the network can encounter burst of data at one time, and a decrease in the data frequency at other times. Therefore, CBSN system designs should be highly flexible to accommodate traffic heterogeneity and to send data reliably regardless to traffic fluctuation.

VI. Open Research Issues in CBSN

The challenges faced by CBSN and listed in Section IV open the door to many research areas. The following presents a summary on the major research issues to achieve robust and reliable CBSN.

A. Sensor Nodes

Research issues related to sensors in CBSN include [18]:

- Energy control schemes: Low power designs of sensors are needed to increase their lifetime. This includes designing low-power architecture, low-power processor, and low-power transceiver. This is in addition to the development of appropriate energy harvesting methods.
- Fault diagnosis methods: Includes developing new fault detection algorithms to identify and isolate any node failure that would affect the QoS of the system.
- Node placement schemes: Node placement optimization is needed to reduce the number of sensor nodes, thus reducing the cost, saving energy, and reducing data redundancy.
- Wearability improvement designs: Aims to decrease the size of sensor nodes in order not to affect everyday life and remove any possibility of harming the human body as a result of long-time use.
- New sensors design: Design of new types of sensors to cope with new discovery of physical parameters.
- Improved measurement accuracy methods: Though studying the factors that affect the wireless communication like the person's weight and age, sensors position and their ability of reduce noise.
- Sensor antennas designs: Includes designing low cost antennas, made of safe and biologically compatible materials, and with good wireless communication capabilities that can communicate over longer distances since CBSN spans a large area.
- Identification of nodes: Since CBSN can enclose a large number of sensors, a long ID is needed to identify the nodes to avoid ID conflicts between IDs. However new ways to identify nodes should be proposed since long IDs may induce a big overhead that cannot be afforded by CBSN.

B. Data Fusion

Collaborative data fusion is an essential research topic in CBSN. Developing architectures that allow gathering, merging and analyzing raw or preprocessed data coming from different BSNs is required to provide and accelerate the delivery of joint services between multiple BSNs [3]. There is a need to develop collaborative data fusion schemes that allow processing and analyzing real-time collaborative data between BSNs, coordinate feature sharing and exchange between several BSNs and support the coordination of joint decisions agreed by the involved BSNs. Also, sensors have limited computational capability and are unable to carry complex computations [19].

Therefore developing collaborative energy efficient and lightweight data gathering schemes is necessary to reduce the load of processors [18]. In addition, CBSNs span large coverage areas and may operate in dynamic and sometimes extreme environmental conditions. Therefore the design of reliable and robust data fusion schemes is mandatory.

C. MAC Protocols

Designing of MAC protocols that guarantee adequate QoS in CBSN is essential. MAC protocols should offer low delay, high scalability, high throughput, low probability of collision, low processing and hardware complexity, low energy consumption, and low time synchronization requirements. Thus, there is a need to select or develop MAC protocols that are:

- Able to control sources of delay and energy consumption, like collisions, overhearing, overheads, idle listening, and over-emitting, high processing and extensive computational requirements.
- Able to maintain high reliability and good QoS in high traffic environments present in CBSNs.
- Show high level of flexibility to adding more nodes and more single BSNs to the system.
- Simple and easy to implement. Choosing a MAC protocol with low hardware complexity and synchronization requirements is important specially that CBSN is a sizable network.

D. Routing

In a dynamic network where nodes move with the interveners, their number is not fixed, each node only has a local view of the network and can only perform small tasks due to energy constraints, there is a need to develop QoS aware routing schemes to guarantee a reliable and efficient data delivery. In general, routing schemes should satisfy the following QoS characteristics: low path latency/delay, high routing reliability, high energy efficiency, low congestion probability, low routing control overhead, and minimum cost forwarding. Thus, developed routing algorithms in CBSN should [2, 6]:

- Adapt to the dynamic network.
- Account local interactions, noise and collisions.
- Tolerate network failures when the area of intervention is extended.
- Guarantee data delivery even when the network changes in space and time.
- Achieve the load balancing of the network to prevent a node from becoming too central and thus too stressed in order to increase the nodes' lifetime.
- Guarantee temperature and heat control.

In addition, there is a need to explore which routing structure provides the best QoS for CBSN: single hop or multi hop; flat, hierarchical (cluster based), or location based. Also, new routing operation schemes should be developed, including cluster head selection criteria, and path discovery and selection within the chosen structure.

E. Inter-BSN communication

Since CBSN involves multiple bodies, new inter-communication models should be proposed to allow every BSN to detect its neighbors and the services provided by them efficiently and dynamically, especially that bodies in CBSN are in motion and neighbors might frequently change.

F. Coverage and connectivity

CBSN are large networks, however studies on the maximum practical network capacity, path cost, ways to increase connectivity reliability and robustness, and ways to provide and maintain good coverage are still lacking.

G. Localization and tracking

The environment around CBSN is dynamic, and can become hostile and extreme like in war zone and wildfire. Therefore developing collaborative localization and tracking algorithms is important to locate injured persons, or track important objects. Signals in CBSN can be scattered, reflected, and diffracted due to environment's alteration and nodes' mobility [20], introducing a challenge to estimate the correct distances and to compute the position of nodes. Developing cooperative and distributed localization schemes can actually be the solution of many localization problems and lead to reliable node's tracking [5].

H. Power Supply and Energy Concern (Collaborative harvesting, and Energy-Aware QoS)

The energy constraints of sensors in CBSN introduce two main concerns: ways to supply power to the nodes, and ways to minimize energy consumption of these nodes to increase their lifetime. Supplying power to nodes can be achieved through developing new collaborative energy harvesting models, where cooperating nodes can exchange and balance the harvested energy information between each other. Whereas minimizing energy consumption of nodes requires the development of energy-aware schemes in all research areas of CBSN, such as CBSN architecture design, the choice of protocols and algorithms, data sensing and processing, nodes' tracking and localization, security methods, etc.

I. Security

Protecting different types of networks from intrusions and attacks is usually a challenging task [21]. So how about ensuring reliable security for CBSNs that are large and very dynamic. Complex security algorithms will be needed to ensure that data is sent safely and people's privacy is maintained. Developing cooperative security algorithms is one of the most important research areas in CBSN. Example of cooperative security includes sending different parts of the message over different paths in a way that no node along the path will receive the complete message. Collaborative security schemes can be used to protect data efficiently, without costing the network too much energy [2].

VII. Conclusion

In this paper, CBSN was investigated. To the best of our knowledge, this paper is the first to provide an exhaustive study about CBSNs, and to compare it to other types of sensor networks. The corresponding concept, architecture and applications were discussed, and a comparison between CBSN, WSN, and single BSN was presented. The comparison showed that CBSN has some common grounds with WSN like the network scale, coverage area, environment condition and scalability; it has other common features with single BSN like heterogeneity, sensor types and capabilities, wireless technologies; and at the same time, it has some unique features like system architecture and dynamic topology. This proves that different protocols and algorithms should be developed to comply with CBSNs characteristics. The main challenges and some open research issues were also discussed in order to highlight on the wide areas that still need to be studied in CBSN.

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