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LIPADE's Research Efforts Wireless Body Sensor Networks

Rongrong Zhang, Mohamad Jaafar Ali, and Hassine Moungla
*LIPADE, University of Paris Descartes, Sorbonne Paris Cite, Paris, France Email: {rongrong.zhang, mohamad.ali, hassine.moungla}@parisdescartes.fr

I. Introduction

A Wireless Body Sensor Network (WBSN) typically consists of a collection of low-power, miniaturized and lightweight devices with wireless communication capabilities that operate in the proximity of a human body. Generally speaking, these devices can be distinguished as three types: sensors, actuators and Personal Digital Assistant (PDA). The sensors can be implanted in, on or around the human body to monitor, manage and transmit the real-time physiological parameters such as the heartbeat, body temperature, blood pressure, electrocardiogram (ECG)and electroencephalogram (EEG). The actuators on the other hand act as drug-delivery systems equipped with a built-in reservoir to deliver the medicine on a predetermined moment, triggered by an external source or immediately when sensors notice a problem. The PDA acts as a sink to collect all the information attained by the sensors and transmit it to the users (patient, nurse, physician, etc.) via an external gateway.

As WBSNs can provide interconnection amongst various devices in or around the human body, it can support a large number of potential applications in several areas. The main applications can be roughly categorized into medical and non-medical applications, such as healthcare, sports and entertainment, and military and defense, etc.

- Healthcare: This is the most promising WBSN application at first glance. Using WBSNs in medical applications, the sensor nodes can continuously monitor the vital signals, as well as provide real-time feedback and information. More specifically, the sensor nodes monitor and transmit the one's physiological attributes such as blood pressure, heartbeat and body temperature. In cases where abnormal conditions are detected, the information can be delivered and effectively processed to obtain reliable and accurate physiological estimations and allow scientists, physicians or other medical professionals to have real-time opinions for medical diagnosis and prescription. Therefore, WBSNs can provide interfaces for diagnostics, for remote monitoring of human physiological data, for the administration of drugs in hospitals and aid to rehabilitation. In the future, it will be possible to monitor patients continuously and give the necessary medication whether they are at home, in a hospital or elsewhere. Patients will no longer need to be connected to large machines in order to be monitored. Moreover, WBSNs cannot only detect fatal events and anomalies, but they can also improve the lifestyle of hearing and visually impaired people by methods of earing aid, cochlear implant, and artificial retina, respectively. Recent research has shown the effective realization of human emotions via speech and visual data analysis. Specifically, wearable sensing technologies have enables emotion detection by the introduction of physical appearances throughout the body that leads to the production of signals to be measured by simple bio-sensors. For instance, fear increases respiration rate and heartbeat, which results in palm sweating and more. Therefore, one's emotional status can be monitored anywhere and anytime by monitoring emotion-related physiological signals.
- Sport and Entertainment: In the sporting area, it will be possible to take many different readings from an athlete without having them on a treadmill in a laboratory. WBSNs can provide monitoring parameters, motion capture, and rehabilitation during the athlete's real-life competition, thus the training schedules can easily be tuned based on their strengths and weaknesses. Moreover, the real-time feedback of WBSNs allows the users to prevent injuries related to incorrect training and to plan future training to improve their performance. The entertainment applications consist of gaming applications and social networking. Appliances such as microphones, MP3-players, cameras, head-mounted displays, and advanced computer appliances can be used as devices integrated into WBSNs. They can be used in virtual reality and gaming purposes (game control with a hand gesture, mobile body motion game, and virtual world game), personal item tracking, exchanging digital profile/business card and consumer electronics.
- Military and Defense: The activity of soldiers on the battlefield can be monitored more closely by WBSNs, thus it will enhance the military effect at both individual and squad level. The soldier can avoid threats based on the information about the surrounding environments provided by a set of sensors. And the commander is able to better coordinate the squad actions and tasks. Moreover, inter-WBSN communications play an important role in order to prevent sensitive information from being caught by the enemies. Additionally, WBSNs can also be used by policeman and fire-fighters. The use

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of WBSNs in harsh environments can be instrumental in reducing the probability of injury while providing improved monitoring and care in case of injury.

WBSN applications show great promise in improving the user's quality of life and satisfying many of elderly people by enabling them to live safely, securely and independently. Due to the limitations in the nature of WBSNs, it provides many design requirements which can be summarized as follows:

- Communication range: WBSNs allow the sensors in, on and around the same body to communicate with each other, so 2-5 m operating communication range is enough in a WBSN.
- Network density: With the diversification of WBSN applications, people should be able to have sensor nodes for different applications and different body area networks on them. A typical medical network based on WBSNs is stated to have 6 nodes with a scalable configuration that support up to 256 sensor nodes, while only one sink is allowed to exist in a WBSN. And also only 2-4 WBSNs are stated to coexist on the same person per m2.
- Data rate: The bit rate requirement varies on a very broad range depending on the application and on the type of data to be transmitted. WBSN links should support the bit rate from less than 1 Kb/s (e.g., temperature monitoring) to 10 Mb/s (e.g., video streaming). The bit rate can refer to a single link or to multiple links when several devices transmit/receive information to/from one coordinator at the same time.
- Low power: All nodes in WBSNs should be capable of transmitting at 0.1 mW (- 10dBm) and the maximum radiated transmission power should be less than 1 mW (0dBm). This complies with the Specific Absorption Rate (SAR) of the Federal Communications Commission's 1.6 W/Kg in 1 g of body tissue.
- Latency: The goal of monitoring applications is a collection of information in real time, so the tight delay requirement is necessary. As specified in the IEEE 802.15.6 standard, the latency should be less than 125ms in medical applications and less than 250ms in non-medical applications.
- Coexistence: WBSNs may interact with the internet and other existing wireless technologies like Bluetooth, ZigBee, Wireless Sensor Networks (WSNs), Wireless Local Area Networks (WLAN) and Wireless Personal Area Network (WPAN). Thus, WBSNs should be able to operate in a heterogeneous environment where networks of different standards cooperate amongst each other to transmit and receive information.
- Interference: Since a WBSN is most likely to encounter other WBSNs where the different types of radio interference can be encountered, inter-WBSN interference is of the utmost importance. And collision from external sensors may also lead to interference. Additionally, the unpredictable nature of postural body movement may also introduce additional interference. Therefore, interference should be mitigated as much as possible in WBSNs to satisfy reliable wireless communication.
- Reliability: Nodes should be capable of reliable communication even when the person is on the move. Although it is acceptable for network capacity to be reduced, data should not be lost due to unstable channel conditions. Reliability of WBSNs depends upon transmission delay of packets and packets loss probability. Packet transmission procedure at MAC layer and Bit Error Rate (BER) of channel influence packet loss probability. Appropriate channel access techniques, packet retransmission schemes, packet size, and enhanced scheduling schemes at MAC layer improve reliability.
- Scalability: Scalability is an essential requirement for WBSNs. A number of nodes, to collect life critical and non-critical information, varies according to the patient monitoring requirements. Easily configuration of WBSNs by adding or removing sensor nodes is required to support scalability.

This report provides a summary of the research efforts published by the team of Paris Descartes Computer Science Laboratory (LIPADE) University of Paris Descartes.

II. Interference Mitigation Techniques

Work in [1] devises novel 2-D scheduling specifying the rule of channel hopping and wake-up time slot selection, which achieves the order-minimal worst-case broadcast delay while guaranteeing the full broadcast diversity regardless of clock drifts and asymmetric duty cycles and channel perceptions. Specifically, the authors employ the Chinese remainder theorem to design an effective multichannel broadcast (MCB) algorithm and further propose improved MCB that enhances the granularity of MCB in matching actual duty cycles and a number of channels, reducing the theoretically worst-case broadcast delay of MCB by up to 75%. The authors demonstrate the performance of the proposed algorithms through theoretical analysis and extensive simulations.

Work in [2] presents a novel two-phase receiver-initiated medium access control (MAC) protocol for concurrent traffic based on asynchronous duty cycling, which is called C-MAC. Technically, C-MAC in the first phase employs carrier-sense multiple access with collision avoidance of the IEEE 802.15.6 standard and designs an ordering-based communication algorithm to effectively avoid collisions. Moreover, C-MAC enables sensor nodes to switch to standby mode to avoid idle listening and overhearing in the second phase. Furthermore, theoretically, the authors explicitly formulate the mathematical expressions of the random delay and energy consumption of C-MAC. Finally, they conduct extensive numerical analysis and simulation to demonstrate the correctness of theoretical results and the better effectiveness and efficiency of C-MAC than that of RI-MAC and A-MAC in terms of transmission delay and energy consumption.

Work in [3] proposes a distributed approach that adapts to the size of the network, i.e., the number of coexisting WBANs, and to the density of sensors forming each individual WBAN in order to minimize the impact of co-channel interference through dynamic channel hopping based on Latin rectangles. Furthermore, the proposed approach opts

to reduce the overhead resulting from channel hopping, and lowers the transmission delay, and saves the power resource at both sensors- and WBAN-levels. Specifically, the authors propose two schemes for channel allocation and medium access scheduling to diminish the probability of inter-WBAN interference. The first scheme, namely, Distributed Interference Avoidance using Latin rectangles (DAIL), assigns channel and time-slot combination that reduces the probability of medium access collision. DAIL suits crowded areas, e.g., high density of coexisting WBANs, and involves overhead due to frequent channel hopping at the WBAN coordinator and sensors. The second scheme, namely, CHIM, takes advantage of the relatively lower density of collocated WBANs to save power by hopping among channels only when interference is detected at the level of the individual nodes. The authors present an analytical model that derives the collision probability and network throughput. The performance of DAIL and CHIM is further validated through simulations.

Work in [4] investigates paradigm of radiation awareness in WBAN network environments. The authors incorporate the effect of topology as well as the time domain and environment aspects. Even, if the impact of radiation on human health remains largely unexplored and controversial. They propose a multi-objectives flow model for WBSNs which allows describing a new optimal deployment model for WBAN sensor devices dynamic topology and the relevant possible trade-offs between coverage, connectivity, network lifetime and radiation to human health. They propose oblivious deployment heuristics that are radiation aware. Simulation results show that the algorithm balances the energy consumption of nodes effectively and maximize the network lifetime. It will meet the enhanced WBANs requirements, including better delivery ratio, less reliable routing overhead. The proposed radiation aware deployment heuristics succeed to keep radiation levels low, while not increasing latency.

Work in [5] formulates and studies a broadcast problem arising in multi-channel duty cycling wireless body area networks (WBANs), where the sink needs to broadcast the control message to all sensor nodes. The objective is to design a robust multichannel wake-up schedule with a minimum worst-case broadcast delay while guaranteeing the full broadcast diversity regardless of clock drifts and asymmetric duty cycles. To that end, the authors first derive the lower-bound of worst-case broadcast delay with the full diversity of any broadcast protocol and then design a multichannel broadcast protocol (MCB) that satisfies the performance requirement for the latency and diversity. Finally, the simulation results demonstrate the capability of MCB of ensuring successful broadcast delivery on every channel within the theoretical worst-case broadcast delay, even under asymmetric duty cycles and any amount of clock drifts.

Work in [6] proposes a new protocol to enable WBAN operation within an IoT. Basically, the authors leverage the emerging Bluetooth Low Energy technology (BLE) and promote the integration of a BLE transceiver and a Cognitive Radio module (CR) within the WBAN coordinator. Accordingly, a BLE informs WBANs through announcements about the frequency channels that are being used in their vicinity. To mitigate interference, the superframe's active period is extended to involve not only a Time Division Multiple Access (TDMA) frame, but also a Flexible Channel Selection (FCS) and a Flexible Backup TDMA (FBTDMA) frames. The WBAN sensors that experience interference on the default channel within the TDMA frame will eventually switch to another Interference Mitigation Channel (IMC). With the help of CR, an IMC is selected for a WBAN and each interfering sensor will be allocated a time-slot within the (FBTDMA) frame to retransmit using such IMC.

Work in [7] exploits the 16 channels available in the 2.4 GHz unlicensed international band of ZIGBEE, and propose a distributed scheme that opts to avoid interference through the channel to time-slot hopping based on Latin rectangles, DAIL. In DAIL, each WBAN's coordinator picks a Latin rectangle whose rows are ZIGBEE channels and columns are time-slots of its superframe. Subsequently, it assigns a unique symbol to each sensor; this latter forms a transmission pattern according to distinct positions of its symbol in the rectangle, such that collisions among different transmissions of coexisting WBANs are minimized. The authors further present an analytical model that derives bounds on the collision probability of each sensor's transmission in the network. In addition, the efficiency of DAIL in interference mitigation has been validated by simulations.

Work in [8] addresses the co-channel interference mitigation among coexisting WBANs. First, the authors propose a distributed orthogonal code allocation scheme, namely, OCAIM, where, each WBAN generates sensor interference lists (SILs), and then all sensors belonging to these lists are allocated orthogonal codes. Secondly, they propose a distributed time reference correlation scheme, namely, DTRC, that is used as a building block of OCAIM. DTRC enables each WBAN to generate a virtual time-based pattern to relate the different superframes. Accordingly, DTRC provides each WBAN with the knowledge about, 1) which superframes and, 2) which time-slots of those superframes interfere with the time-slots within its superframe. Thirdly, they further analyze the success and collision probabilities of frames transmissions when the number of coexisting WBANs grows. The simulation results demonstrate that OCAIM outperforms other competing schemes in terms of interference mitigation and power savings.

Work in [9] exploits the 16 channels available in the 2.4 GHz international band of ZIGBEE and proposes a distributed scheme that avoids interference through predictable channel hopping based on Latin rectangles, namely, CHIM. In the proposed CHIM scheme, each WBAN's coordinator picks a Latin rectangle whose rows are ZIGBEE channels and columns are sensor IDs. Based on the Latin rectangle of the individual WBAN, each sensor is allocated a backup time-slot and a channel to use if it experiences interference such that collisions among different transmissions of coexisting WBANs are minimized. The authors further present a mathematical analysis that derives the collision probability of each sensor's transmission in the network. In addition, the efficiency of CHIM in terms of transmission delay and energy consumption minimization is validated by simulations.

Work in [10] employs cognitive radios (CRs) for proactive

interference sensing in such systems. The proposed approach ensures the channel quality evaluation reducing the packet loss rate and mitigate interferences. On one hand, the intra-WBAN interference is managed through FTDMA protocol. On the other hand, if a high intensity of interference is detected, this solution allows switching channel transmission, thereby ensuring the coexistence of WBANs. Moreover, the authors model the functioning of this method using Markov's chains in continuous time. The Transmission error rate is introduced as a measure to quantify the effectiveness of the proposed schemes.

Work in [11] devotes to developing a reliable and energy-efficient leader election (REELE) algorithm for WBANs. To this end, technically, the authors first partition a WBAN into regions and build the reliability and energy consumption models. By the reliability analysis, they then propose a novel communication strategy for nodes and further derive the total energy consumption of a region. With the reliability and residual energy of a node and total energy consumption considered jointly, REELE algorithm can considerably enhance reliability and conserve energy. Extensive simulation results demonstrate the effectiveness and the efficiency of REELE in terms of longer network lifetime, better energy characteristics as well as higher reliability.

Work in [12] proposes a distributed multi-hop interference avoidance algorithm, namely, IAA to avoid co-channel interference inside a wireless body area network (WBAN). The proposal adopts carrier sense multiple access with collision avoidance (CSMA/CA) between sources and relays and a flexible time division multiple access (FTDMA) between relays and coordinator. The proposed scheme enables low interfering nodes to transmit their messages using the base channel. Depending on suitable situations, high interfering nodes double their contention windows (CW) and probably use switched the orthogonal channel. Simulation results show that the proposed scheme has far better minimum SINR (12dB improvement) and longer energy lifetime than other schemes (power control and opportunistic relaying). Additionally, the authors validate our proposal in theoretical analysis and also propose a probabilistic approach to prove the outage probability can be effectively reduced to the minimal.

Work in [13] proposes a dynamic channel allocation scheme (DCAIM) to mitigate node-level interference amongst the coexisting regions of a WBAN. At the time, the sensors are in the radius communication of a relay, they form a relay region (RG) coordinated by that relay using TDMA. In the proposed scheme, each RG creates a table consisting of interfering sensors which it broadcasts to its neighboring sensors. This broadcast allows each pair of RGs to create an interference region or set (IS). Thus, the members of IS are assigned orthogonal subchannels whereas other sensors that do not belong to IS can transmit using the same time slots. Experimental results show that our proposal mitigates node-level interference and improves node and WBAN energy conservation. These results are then compared to the results of other schemes. As a result, the proposed scheme outperforms in all cases. Node-level SINR improved by 11dB whilst, the energy consumption decreased by 20 times. The authors further present a probabilistic method and analytically show the outage probability can be effectively reduced to the minimal.

Work in [14] proposes a distributed Combined carrier sense multiple access with collision avoidance (CSMA/CA) with Flexible time division multiple access (TDMA) scheme for Interference Mitigation in relay-assisted intra-WBAN, namely, CFTIM. In CFTIM scheme, noninterfering sources (transmitters) use CSMA/CA to communicate with relays. Whilst, high interfering sources and best relays use flexible TDMA to communicate with coordinator (C) through using stable channels. Simulation results of the proposed scheme are compared to other schemes and consequently, CFTIM scheme outperforms in all cases. These results prove that the proposed scheme mitigates interference, extends WBAN energy lifetime and improves the throughput. To further reduce the interference level, the authors analytically show that the outage probability can be effectively reduced to the minimal.

Work in [15] considers the problem of intra-interference in a Wireless Body Area Network (WBAN). The problem arises mainly because each bio-sensor collects different parameters with different data rate and alternation. Another source of interference is related to normal patient movement. Proposals in the literature usually assume that the interference can be handled using time multiplexing or by listening before transmission to avoid a collision. However, these adaptive approaches, given the high-occupancy channels, bring with them major problems of collision and extra energy consumption. One solution could be a power control mechanism. Nevertheless, techniques of that kind are challenging in that they require periodic information on the condition of the wireless channels, conditions that are difficult to estimate. To address these concerns, a tree-based WBAN topology using a set of relay nodes with stable communication called a "virtual backbone" is proposed. As bio-sensors report data mainly in uplink traffic, it is assumed that they share a small number of wireless channels using the TDMA technique. Relay nodes, on the other hand, share the most number of channels in order to improve the fluidity of data across the WBAN. To mitigate co-channel interference among relays, two techniques from the literature called the adaptive data rate and the adaptive duty cycle are used. Simulation experiments showed that the proposed architecture when combined with intra-interference mitigation techniques, improves energy efficiency and increases the data rate.

Work in [16] addresses the energy conservation problem in WBANs. the authors develop an Energy-Efficient Leader Election mechanism, called EELE. In EELE, each node competes for the leader following the distributed leader election algorithm in which a utility function is constructed with the consideration of the residual energy and the location of the node. Moreover, a distance-aware hybrid communication mode is proposed such that a node can choose either direct communication or cooperative communication to alleviate the burden of the leader or the far node. Extensive simulation results demonstrate the effectiveness and the efficiency of EELE mechanism in terms of longer network lifetime, better energy characteristics and higher throughput.

Work in [17] tends to improve coexistence between WBAN

based IEEE 802.15.4 protocol and WIFI. The authors adopt multi-hop routing to ensure reliability, connectivity and battery life. Then they investigate different effects of transmit power, transmission frequency, and packet size on WBAN performances under heavy and real interferences circumstances. They propose a well-suited model and simple adaptive algorithm which adjust dynamically its parameters with received performances indicators.

Work in [18] investigates in the heterogeneous communication in WBAN. WBAN should be robust against frequent changes in the network topology; The data mostly consists of medical information. Hence, high reliability and low delay are required; Dynamic communication range management is proposed based multi-commodity flow model which allows to prevent sensor node saturation and take the best action against reliability and the path loss, by imposing an equilibrium use of sensors during the routing process. Experimental results show that the proposition balances the energy consumption of nodes effectively and maximize the network lifetime. It will meet the enhanced WBAN requirements, including better energy management and less reliable routing overhead.

Work in [19] proposes a Min-Max multi-commodity flow model for WBSNs which allows to prevent sensor node saturation and take the best action against reliability and the path loss, by imposing an equilibrium use of sensors during the routing process. Simulation results show that the algorithm balances the energy consumption of nodes effectively and maximize the network lifetime. It will meet the enhanced WBSNs requirements, including better delivery ratio, less reliable routing overhead.

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