Toward a high-fidelity wireless sensor network for rehabilitation supervision

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***Abstract*—Wireless sensor networks for rehabilitation is becoming a topic of great interest in medical applications generating a large amount of work in biomedical and communication research communities. In this line, several solutions have been proposed to provide unobtrusive, flexible and low cost systems for the supervision of rehabilitation. These solutions have focused on sensor/hardware design, platform/architecture design and signal processing algorithms. However, a little attention has been paid to network communications where there exist challenging problems specific to rehabilitation applications. In this paper, we present the design and the implementation of a new light-weight and easy to use wireless sensor network for high-fidelity rehabilitation supervision. Namely, we propose a fault-tolerant, energy-efficient communication protocol that meets the clinical requirements of rehabilitation supervision in terms of data quality and data rate. Finally, we outline the implementation of this protocol on the top of the IEEE 802.15.4 standard and evaluate its performance through intensive real world experimentations and simulations.**

Keywords: wireless sensor networks, rehabilitation, communication protocols.

I. Introduction

Rehabilitation is an exercises program with the objective of achieving a physical functioning level that allows patients to return to their initial motor capabilities after an accident or a surgery. Studies show an increase in functional recovery of patients with increased amount of exercises during rehabilitation [1]. However, intensive exercises programs require continuous supervision of patients and increase the load for therapists and medical staff. Human motion monitoring techniques, such as optical measurement systems and force plate, attracted significant interest in recent years due to their potential to automate the supervision of rehabilitation therapy. These systems acquire, in real time, data about the changes in body motion/position, and post process the information to characterize the movements. Nevertheless, such systems require a complicated set-up procedure and are too costly to be used in ambulatory or in-home environments.

Advances of Micro Electro Mechanical Systems, wireless technology and inertial sensors such as gyroscopes and accelerometers have boosted wireless sensor networks for rehabilitation supervision. Wireless sensor networks (WSNs) can collect clinically relevant information about individuals' behaviors and provide feedback to the user in real time. They make possible the development of low-cost, light-weight, unobtrusive and easy-to-use monitoring solutions for rehabilitation supervision. There has been a host of research works on wireless sensor networks for rehabilitation supervision. A great deal of theme have focused on sensor/hardware design, platform/architecture design or signal processing algorithms design with little attention paid to network communications.

In this paper, we design and implement a wireless sensor network for high-fidelity rehabilitation supervision using off-the-shelf wireless sensor modules. In addition, we address the challenge of designing a fault-tolerant energy-efficient communication protocol that meets the clinical requirements of our application in terms of data quality and data rate. Our communication protocol minimizes collisions even though several sensor nodes stream their data at high rate. Our contributions, in this work, are many folds: First, we provide a review of existing wireless sensor networks for rehabilitation. Second, we present the design and implementation of a wireless sensor network prototype for high-resolution rehabilitation monitoring. Third, we propose a new fault tolerant communication protocol for rehabilitation supervision built on the top of the IEEE 802.15.4 standard, while meeting the QoS requirements of the rehabilitation monitoring applications.

The rest of this paper is organized as follows. In the next section we review existing wireless sensor networks for rehabilitation supervision. In section 3, we describe the architecture and the hardware of our prototype. In section 4, we outline our communication protocol. Section 5 gives an overview of the IEEE 802.15.4 standard and section 6 details the implementation of our protocol on the top of this standard. We evaluate our solution in section 7 and give some concluding remarks and directions for future works in the section 8.

II. Related Works

There has been a host of research works on wireless sensor networks for rehabilitation. These researches have focused on three main areas:

Sensor node design: To achieve comfortable and non-invasive continuous rehabilitation supervision, wireless sensor nodes should satisfy the following requirements: minimal weight, miniature form factor, wearability and unobtrusiveness. Meeting these requirements is mainly obtained by reducing the size of components in sensor nodes. However, components size reduction puts strong constraints on hardware designers and reduces available resources (memory, battery ...).

In [2], authors design a small sensor unit with gyroscope and accelerometer sensors to build a simplified, low cost and wearable sensor network for gait evaluation. However, this miniature form factor sensors are interconnected by wires which may limit the patient's activity and level of comfort and thus negatively influence the measured results. Lim et al. in [3] present a wireless sensor network used in upper arm rehabilitation for stroke patients. Their work focuses on the design of a wearable, compact and low cost sensing module able to measure the arm movement with accuracy. Although data is wirelessly sent to the base station, sampling frequency is limited to 25 Hz and motion analysis is performed off-line because of wireless transmission challenges. The iNode presented in [4] is a miniaturized sensor node with a Force Sensitive Sensor (FSR) and a Respiratory Inactive Plethysmography (RIP) sensors. iNode measures the locomotive and respiratory signals and analyses the coordination between them. In a separate work [5], authors developed a communication protocol to interconnect the iNode sensors. However, this communication protocol does not support mesh topologies and has a communication range limited to 10 meters.

Signal processing algorithms: The development of efficient signal processing algorithms able to handle a high amount of sensors data is of great importance. These algorithms must process data and provide useful feedback in real time. However, data from a single sensor node may not be sufficient to extract clinically-relevant information. So, more signals have to be combined to produce meaningful information that evolve into medical knowledge.

The previously described iNode[4] implements a step detection algorithm and a respiratory phase detection method, which performs better than other existing methods in terms of efficiency, accuracy and ease of implementation. In [6], authors use a wearable sensor system that measures reaction force and detects eight different gait phases. This system is based on a motion analysis system and a gait phase detection algorithm. To deal with sensor errors and calibration, they implement an intelligent calibration process that fuses accelerometer and gyroscope signals. Zhou et al. in [7] design an arm movement tracking system for rehabilitation of stroke patients. The system is based on a weighted least squares filtering method that eliminates the errors whose Euclidean distance is larger than a threshold. Both works described in [6] and [7] use wired sensor networks which may limit the patient's activity and reduce user's level of comfort.

Framework and architectures: There has been much efforts in designing easily deployable wireless sensor networks for rehabilitation monitoring. These solutions are based on frameworks that support dynamic network construction and configuration, services and resources discovery and sensor node management at runtime. A combination of different technologies like video acquisition, gaming and virtual reality has also been investigated in order to enhance the context awareness and attractiveness of existing solutions.

Mercury [8] is a wearable wireless sensor network platform for motion analysis of patients who suffer from Parkinson's Disease, epilepsy and stroke. It is based on a flexible programming interface allowing clinicians to implement different policies following the application requirements. Kifayat et al. in [9] present a framework that combines wireless sensor network technology and gaming to assist rehabilitation of patients with physical disabilities. While the patient plays the game, data is collected in real-time by the wireless sensor network and feed into a control service allowing the patient to control its virtual representation by physically moving his body. At the end of the game, the framework generates different reports and graphs for doctor and patient. RehabSPOT proposed in [10] is a highly customizable wireless sensor network platform for rehabilitation built on the top of SunSPOT sensors. The system is based on a software architecture which enables dynamic network construction and sensor management at runtime (sensors discovery, adjustable sampling rate). However, RehabSPOT requires a long (a fifteen minutes) and a complex setup procedure and can not be used in home or ambulatory environments.

Discussion: Most of previously surveyed wireless sensor networks had payed a little attention to communication protocols. They supposed that existing communication protocols developed for wireless sensor networks are also suitable to rehabilitation monitoring applications. However, these applications have two specific characteristics that heavily impact the network performance and cannot be ignored. On one hand, the placement of several adjacent sensor nodes on the body may cause serious interference problems. On the other hand, sensor nodes need to continuously stream high volumes of data to a receiver at a determined rate over a long period to be able to extract clinically relevant information.

Some existing works shyly addressed the challenge of designing a communication protocol for rehabilitation supervision. In [11], authors develop a telerehabilitation system that combines a wearable sensor network and a video conferencing system. One objective of this work is to study the impact of the number of sensor nodes and the sampling rate on the reliability of the radio transmission. However, the proposed communication protocol has no fault-tolerance capabilities and the system must be manually restarted at every loss of connection. The HipGuard proposed in [12] is a wireless sensor network for patient recovery from hip surgery. Authors investigate using ANT networking technology [13] to collect data from sensor modules to the base station. However, this technology presents significant drawbacks such as limited communication range and fixed packet size.

III. System Architecture

In this paper, we propose a new low cost, easy to use and unobtrusive WSN for high fidelity rehabilitation supervision. Our system have four major components : a set of motion sensor nodes, a base station, a communication protocol and a system manager software (figure 1). The motion sensor nodes are worn by the patient and measure motion data (acceleration and angular velocity) as the patient moves his limbs. Data collected by motion sensor nodes is wirelessly sent to the base station using our new energy efficient, fault tolerant communication protocol. The base station forms a star topology together with motion sensor nodes and relays received data to the system manager running on a laptop. It is also responsible for a number of functions such as node management, node synchronization and commands dissemination. The system manager processes, saves and displays the received data at real-time. To enhance the ergonomics of our solution, we use elastic adjustable bracelets for easy sensor nodes fixing. These bracelets can be easily fixed with no or minimal help.

In order to improve patient autonomy and comfort, our communication protocol ensures seamless network formation and nodes' discovery. It guarantees that when a sensor node is switched on, it automatically joins the network without any third-party intervention. We describe the communication protocol in more details in the next section. Each motion sensor node has an accelerometer and a gyroscope to measure patient's limb movements. We developed a TinyOS application to sample sensors at high frequency and to send the collected motion data (acceleration and angular velocity in three axis) to the base station. In order to reduce communication overhead and meet high frequency data sampling, we store collected samples in a buffer with a specified capacity and bundles several samples into a single message when sending them to the base station (see figure 2).

The data that we get from sensors sampling represents the voltage value of the sensor output at the moment of measurement. We should transform this value into acceleration or angular velocity before feeding it into a backoffice software (such as a biomechanical model) that helps in patient control by doctors. In order to reduce energy consumption of sensor nodes, we propose that sensor nodes send the raw data to the system manager which processes it into useful information. After processing, the manager stores the data in a clinical database for further signal processing and medical analysis. This data is used by doctors to check the patients' physical performance for the purpose of assessing the best therapies suitable for the patient. Since doctors may have no networking knowledge, we developed a simple user-friendly Java Graphical User Interface for the system manager application. The GUI enables doctors to easily start/stop/resume data collection, plot and filter downloaded data at real-time and access to previously recorded data for offline analysis.

A. Hardware

To make our wireless sensor network suitable for body worn clinical and in-home applications such as rehabilitation supervision, we decided to use the light weight (15g), low power consumption and compact form factor (50mmx25mmx12.5mm) Shimmer platform. Shimmer [14] is an unobtrusive, low power wireless sensor platform which provides Kinematics, physiological and ambient sensing capabilities. In addition, there are several lines of research

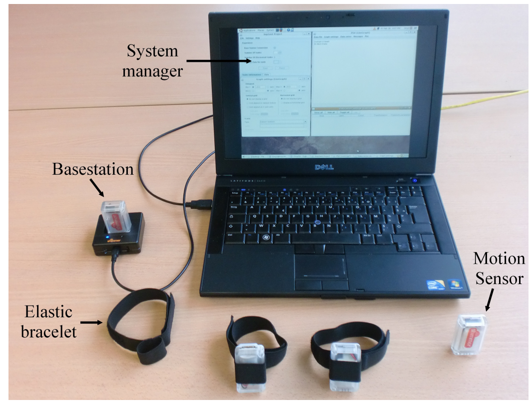

Fig. 1. System components

([15][16][17])that validated Kinematics signals of Shimmer against well-know commercial solutions such as Coda Motion Analysis System [18] and Nexus-10 System [19]. In our prototype, a motion sensor node is a Shimmer platform that comprises a tri-axis accelerometer, a Dual-axis Gyroscope and on-board 2 Gbytes MicroSD flash. The base station is a Shimmer platform without Gyroscope neither MicroSD flash.

The core component of the shimmer platform is the Texas Instrument MSP 430 MCU (8MHz, 10 KByte RAM, 48 KByte flash, 8 ADC channels). We use 6 ADC channels to capture the accelerometer and the gyroscope sensors data (1 channel per axis). Motion sensor nodes have a low-power MMA7260Q accelerometer with a high sensitivity of 800 mv/g[20]. Also, they have an integrated InvenSence Dual-axis Gyroscope IDG300 which offers a 500°/sec full scale range with a sensitivity of 2 mV/°/sec [21]. For wireless communications, Shimmer integrates the widely-used IEEE 802.15.4 compliant CC2420 radio-transceiver.

IV. Communication protocol

A WSN for rehabilitation supervision collects information about patient activity and feeds it into a bio-mechanical model for gesture evaluation. To be able to generate an accurate report and feedback, the bio-mechanical model needs some information (acceleration, angular velocity) from several nodes in real time. Therefore, the sensor sampling and data transmission should be performed at high frequency. Our design objective is to build a WSN that meets those requirements. This challenge is tackled by our new communication protocol that supports multiple high rate data streams.

A. Access To The Medium

Existing WSNs use the contention-based CSMA-CA access method to access to the channel and to send their data. Before sending a packet, a node using CSMA-CA has to listen to the channel to determine whether or not another node is transmitting. If the channel is found to be idle, then the node begins the transmission. Otherwise, the node postpones its transmission for a random period of time (backoff time) before trying to access to the channel again. CSMA-CA

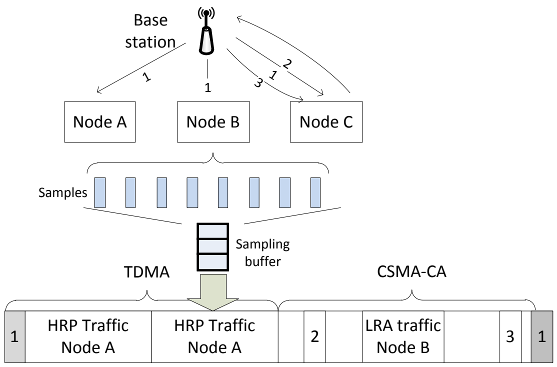

Fig. 2. Communication protocol

shows good performances in small low-rate wireless sensor networks. However, access probability and delivery ratio sharply decrease when the packet size or the network size increase[22][23]. Since sampling frequency and data rate are high in wireless sensor networks for rehabilitation supervision, a novel approach which reduces collisions is definitely needed.

In order to minimize collisions, so improving the channel access efficiency and delivery ratio, we propose a new communication protocol which combines different access methods following data characteristics. Our solution improves also the energy efficiency and implements a fault-tolerance mechanism based on the delay tolerant network (DTN) paradigm. We distinguish two traffic categories in our application. On one hand, we have a high-rate periodic (HRP) traffic which is data generated by motion sensor nodes. On the other hand, we have a low-rate aperiodic (LRA) traffic which includes command/control messages and data generated by non-motion sensors used to enhance the context awareness of the application (eg: temperature). The HRP traffic represents the major part of data and is the main bandwidth consumer.

Our protocol adopts a star network topology where the base station has a major role. It periodically sends a control message to synchronize network's nodes and to advertise the network for new nodes willing to join it. The time between two control messages is organized into a time division multiple access (TDMA) period and a CSMA-CA period (see figure 2). The TDMA period is a contention free period exclusively reserved for the HRP traffic in order to minimize collisions. The CSMA/CA period is used to transmit the LRA traffic. Figure 2 illustrates the different steps that the node C performs to join a network of a base station having two nodes already connected (node A and node B). Upon receiving the control message, the node C sends a join request to the base station and waits for an acknowledgement. If needed, the node C specifies that it needs a timeslot from the TDMA period for its HRP traffic. Messages 1, 2 and 3 in figure 2 represent respectively the control message, the join request and the join acknowledgment messages. The control message also defines the exact moment at which each node is expected to send the data to avoid collisions during the TDMA period. Upon receiving this message, a node that has an allocated timeslot bundles the ready data in its sampling buffer into packets and waits the instant at which it can send these packets. When the node is permitted to begin transmissions, it sends its packets and waits for the next control message. This organization is a practical collision avoidance making more efficient use of medium compared to contention access.

In order to achieve high energy conservation in data transmission, our protocol use low duty-cycle by switching off node radio transceiver all the time except at its time slot. Consequently, it avoids, to the node, continuous listening for synchronization or for access to the channel since the node knows exactly the moment at which it is permitted to transmit its HRP data. Therefore, the device conserves its energy and achieves longer lifetime even though data transmission rate is high.

B. *Fault tolerance*

Designing a fault-tolerant and reliable communication protocol is of a primary importance and is a key challenge in medical wireless sensor networks. Let us consider a patient performing its rehabilitation exercises going beyond the communication range of the base station for a long time. Worst, let us consider a patient working since more than one hour while the base station or the supervision application stopped working. It is not acceptable to lose the data collected by sensors during disconnection or failure periods. To tackle this challenge, we have developed and implemented a fault tolerant mechanism based on the delay tolerant network concept. This mechanism exploits the MicroSD flash memory for local data storage in case device loses connection with the base station. When a device stops receiving control messages from the base station, it enters in the DTN mode and stores collected data on the MicroSD flash memory. If a connection to the base station is available again, the node resumes sending fresh collected data during its TDMA slot. In addition, it benefits from the CSMA-CA period to progressively send the data backed on the flash memory. If no connection to the base station becomes available again before the end of the rehabilitation session, the backed data will be automatically transferred to the clinical database once the device docked for charging. This data is then added to the corresponding rehabilitation session information for further off-line analysis. The two gigabyte MicroSD flash memory of our motion sensor nodes makes possible to store samples for ten days at 100 Hz frequency.

V. The IEEE-802.15.4 standard

We have implemented our protocol described above on the top of the IEEE 802.15.4 standard because it provides several functionalities that we need, namely, CSMA-CA access, Guaranteed Time Slot (GTS) and association/disassociation primitives. The IEEE 802.15.4 is a short range wireless technology specifically designed for monitoring applications with low power consumption and low data rate communications. In this section, we give a brief description of this standard with a focus on the beacon enabled mode to facilitate the understanding of our protocol implementation.

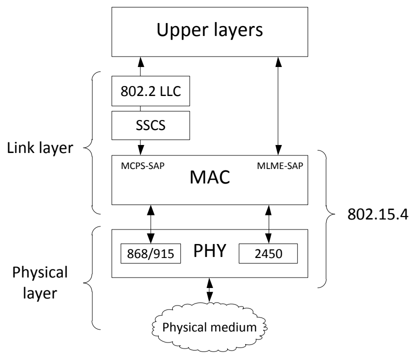

Fig. 3. The IEEE 802.15.4 standard architecture

A. Architecture

The IEEE 802.15.4 standard specifies the physical layer (PHY) and Medium Access Control (MAC) sublayer that are designed for low data-rate, short-range Wireless Personal Area Networks (WPANs). Figure 3 illustrates the global architecture. The physical layer contains the Radio Frequency Transceiver and its hardware control mechanism. The MAC sublayer provides access to the physical channel and supports two operation modes, namely beacon enabled mode and beaconless mode. In both modes, the network shall have one central controller device, commonly referred to as PAN coordinator, responsible for PAN identifier, device address assignment and device synchronization.

The 802.15.4 standard includes a MAC management entity and a MAC data service called respectively MLME (Mac sub-Layer Management Entity) and MCPS (MAC Common Part Sublayer). As shown in figure 3, the higher layer interfaces with these two entities through the Service Access Points (MLME-SAP and MCPS-SAP). The MLME provides several services such as channel access, beacon management, GTS (Guaranteed Time Slot) management, association and disassociation. The MCPS supports the transmission and the reception of frames across the physical layer. Services supported by the MLME and the MCPS provide several primitives that offer to the higher layers (e.g. application layer) the possibility of building new functions on the top of the MAC sublayer. A primitive can be one of four generic types:

- Request: this primitive is passed from application to the MAC-sublayer to request a service initiation.
- Indication: this primitive is passed from the MAC-sublayer to the application to indicate an internal event that is significant to the application.
- Response: this primitive is passed from the application to the MAC-sublayer to complete a procedure previously invoked by an indication primitive.
- Confirm: this primitive is passed from the MAC-sublayer to the application to deliver the results of a request

B. Medium Access Control

IEEE 802.15.4 introduces the concept of beaconing to improve the probability of successful delivery and power consumption. A beacon is a control frame that carries information about the current network configuration. The IEEE 802.15.4 can operate either of two following modes :

1) Beaconless mode: In the beaconless mode, devices communicate without any synchronization and transmit frames according to an unslotted CSMA-CA algorithm. In CSMA-CA, each time a device wishes to transmit data frames, it shall wait for a random number of backoff timeslots and then scan the transmission channel by performing a Clear Channel Assessment (CCA). If the channel is found to be idle the device can transmit its data immediately. Otherwise, the device shall wait for another random period, uniformly drawn from an exponentially increasing backoff interval, before trying to access the channel again.

2) Beacon enabled mode: The PAN coordinator periodically sends a beacon frame to synchronize devices. The time is divided into superframes bounded by beacons frames (figure 4. Each superframe has an active portion and an optional inactive portion. Devices communicate only during the active period and enter a low power mode during the inactive period. The active portion of each superframe is divided into 16 equally sized slots and includes three parts: a beacon, a Contention Access Period (CAP) and an optional Contention-Free Period (CFP). Figure 4 illustrates the structure of two superframes : one without any allocated GTS and the other with two allocated GTSs. The beacon is sent at the start of slot 0 without the use of CSMA-CA. It is used to describe the structure of the current superframes, identify the PAN and synchronize the attached devices. The CAP period shall start right after the beacon and all frames sent during this period shall use slotted CSMA-CA channel access mechanism. Contrary to unslotted CSMA-CA, the backoff slots are aligned with the start of the beacon transmission. When a device wishes to transmit data frames, it shall first locate the boundary of the next backoff slot, then waits for a random number of backoff slots and finally performs two clear channel assessments each starting at the beginning of a backoff period. If the channel is found to be idle during both CCAs, the device can transmit its data at the next backoff period. Otherwise, the device shall wait for another random period as in unslotted CSMA-CA.

The PAN coordinator may dedicate slots from the active superframe to devices that require dedicated bandwidth. These slots are called Guaranteed Time Slots (GTS) and together they constitute the CFP period, as shown in figure 4.a. The PAN coordinator may allocate up to 7 GTSs of one or several slot periods. However, a minimum portion of the superframe shall remain free for the CAP period in case where new devices wish to join the network. The IEEE 802.15.4 standard adopts a TDMA approach in CFP period. When a device wishes to transmit data, it checks the list of the allocated GTSs in the beacon frame. If an allocated GTS for this device is found, it transmits the data during its allocated GTS.

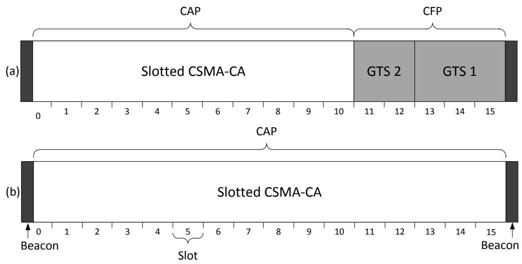

Fig. 4. Superframe structure. a: with two GTS. b: without GTS.

VI. A WSN Communication Architecture for Rehabilitation: Implementation

In order to meet the specific requirements of this application, we have developed an energy efficient, fault tolerant communication protocol which minimizes collisions. We have implemented our protocol on the top of the IEEE 802.15.4 standard running in the beacon enabled mode. Our protocol adopts a star network topology where the base station is the 802.15.4 PAN coordinator. Motion sensor nodes are end point devices which use the CAP period (CSMA-CA) for sending their LRA traffic and the CFP period (GTS) for sending their HRP traffic. In this section, we briefly describe the implementation of different features of our proposed communication protocol.

A. Network joining implementation

In our protocol, the first action that a node does is to join the network by sending a request message to the base station. Upon receiving this join request, the base station allocates a timeslot for this device and acknowledges the success of the operation. We have implemented this mechanism through the association procedure and the GTS allocation procedure of the 802.15.4 standard. The application running on the node initiates an association procedure with the PAN coordinator (i.e. the base station) and waits for the result of the operation. If the association succeeds, and if the node has HRP traffic to send, the application initiates a GTS allocation to reserve a timeslot for this device. The figure 5 details messages sent and action performed during the join mechanism.

B. Data transmission implementation

In the 802.15.4 beacon enabled mode, the network coordinator sends periodically a beacon frame to synchronize devices and describes the structure of the current superframe. Each times a device receives this beacon, the MLME service triggers the MLME-BEACON.indication event. We exploit this event to perform the polling and data transmission mechanism of our protocol. We have implemented a MLME-BEACON.indication event handler in which the device prepares packets to send ready data to the base station. The handler takes available samples in the sampling buffer and creates several packets. Once a packet is ready, the handler forwards it to the MCPS service and requests to send it to the base station during the GTS allocated for this device.

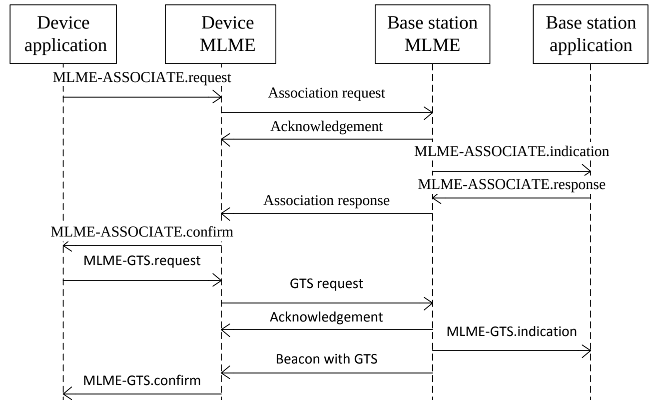

Fig. 5. Message sequence chart for network joining

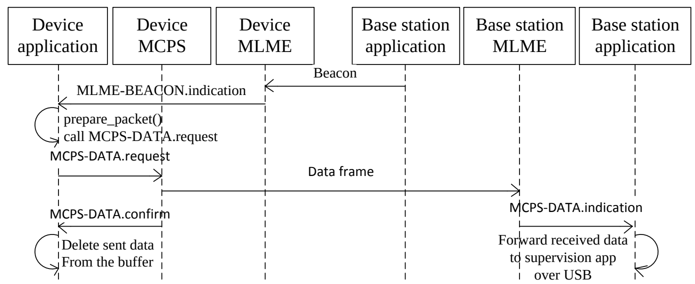

Fig. 6. Message sequence chart for data transmission

The MCPS service handles the timely transmission of this data frame and indicates the result of transmission to the application. The application deletes the sent samples from the sampling buffer just after the frame transmission. The figure 6 describes services and actions involved in data transmission phase. In order to reduce energy and bandwidth consumption, our protocol does not use acknowledgements when sending HRP traffic. This does not decrease transmission reliability since data is sent in GTSs which guarantees exclusive channel access.

C. Fault tolerance implementation

A device has not received the beacon for aMaxLostBeacons consecutive superframes triggers the MLME-SYNC-LOSS.indication event with the LossReason parameter set to BEACON-LOST.In order to implement our fault tolerance mechanism, we have written a handler for the MLME-SYNC-LOSS.indication event. This handler starts the DTN mode in which the application stores all sampled sensor signals on the MicroSD flash memory instead of sending them to the base station. Once the connection established again, the device returns to the online mode and resumes wireless data transmission to the base station.

VII. Performance Evaluation

In order to evaluate our solution, we have conducted intensive real-world experiments and simulations. During real-world experiments, motion sensor nodes were worn by a person while performing different tasks (walking, running,

Fig. 7. Our prototype during lab experiment

~~seating~~, writing, swinging the arm) during several hours. This wide range activity levels and session duration are similar to real rehabilitation conditions. Experiments showed that our system can be used for 5 days with a daily usage of 2 hours and without battery recharging. Figure 7 shows the three motion sensor nodes attached on the arm of the person and the data plotted in the system manager ~~at~~ realtime.

In order to investigate the efficiency of our communication protocol, we have computed the average transmission-error rate while varying the network size from one to five nodes and the sensors sampling frequency from 50 to 100, 200 or 400 Hz. During each experience, transmission-error rate was computed from a set of 100000 samples transmission. ~~Consequently, the simulation time depends on the sampling frequency.~~ We have performed the same experiments using the TinyOS communication protocol defined for the CC2420 chipcon [24] to compare our protocol with.

Figure 8 illustrates the average transmission-error rate of the TinyOS communication protocol depending on the network size and sampling frequency. We notice that the error rate increases when the network size or the sampling frequency increase. This is explained by the high collision probability when using CSMA-CA with high rate data streams. For instance, the transmission-error rate is 55% when only three nodes sample their sensors at 400 Hz. This error rate is not acceptable in medical applications. Figure 9 plots the average transmission-error rate of our protocol. We notice that our protocol performance is not impacted by the sampling frequency neither by the network size contrary to the performance of the TinyOS protocol. We notice also that our protocol shows very small transmission-error rate ($< 5\%$) even when 5 nodes generate data at 400 Hz. These results match our expectations : using a TDMA access method for HRP traffic and CSMA-CA access method for LRA traffic reduces notably the collision probability. This shows the efficiency of our proposed algorithm in avoiding collisions when sensor nodes streams data at high rate.

The Beacon Order (BO) and the Superframe Order (SO) determine the length of the superframe and its active period,

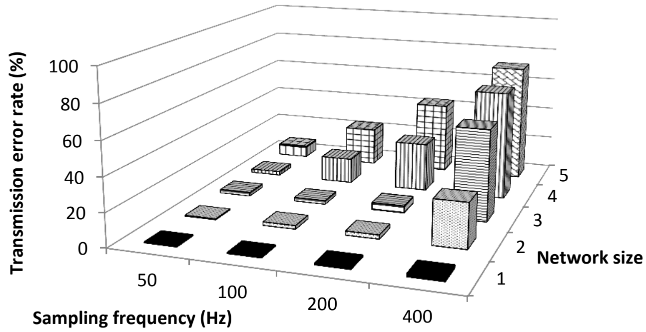

Fig. 8. Transmission-error rate of TinyOS communication protocol

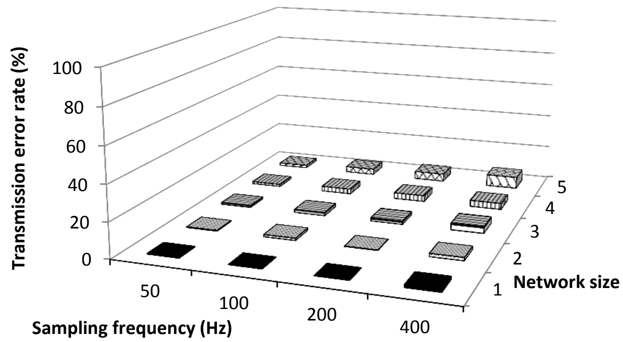

Fig. 9. Transmission-error rate of our communication protocol

respectively. To evaluate the impact of the BO and SO on energy consumption, we have conducted simulations in which we measure the average energy consumption per second for different values of BO. For a given BO, we have considered the case without an inactive period ($SO = BO$) and the case with an inactive period equal to the half of the superframe ($SO = \frac{BO}{2}$). Note that the sampling frequency was set to 200 Hz, the sampling buffer size to 5 Kb and the network size to 5 nodes. It can be easily observed in figure 10 that using an inactive period decreases the energy consumption due to the duty cycle. Figure 10 shows also that when BO gets higher values, the energy consumption decreases. This can be explained by the fact that a large power consumption comes from the need for a node to wake up and to process

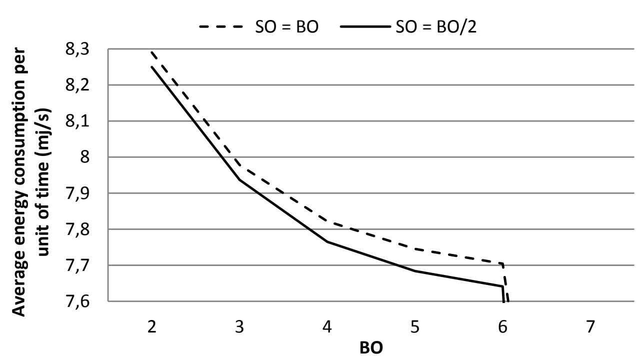

Fig. 10. Energy consumption

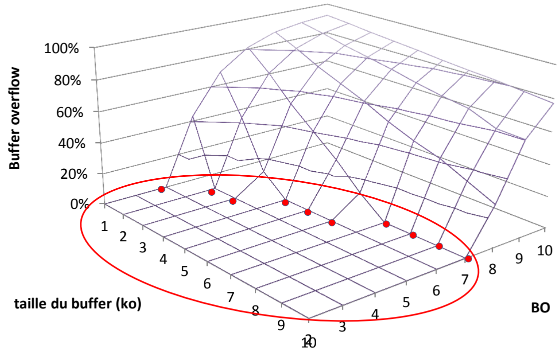

Fig. 11. Buffer overflow

beacon frames. Consequently, increasing the beacon inter-arrival time decreases the number of beacons and hence the energy consumption associated to their processing. It is worth noting that the energy consumption sharply decreases for $BO > 6$. This happens because of the buffer overflow phenomena that we explain in the next paragraph.

Increasing the beacon inter-arrival time (BO) decreases the energy consumption but increases the size of data that a node has to store between two beacons.

Consequently, a node needs a higher buffer capacity to temporary store all generated data without losses. However, WSNs have strong constraints regarding memory resources and can not provide high capacity buffer. In order to chose the optimal BO for a given buffer size, we have conducted intensive simulations in which we compute the buffer overflow rate for each (buffer size, BO) combination. As in previous simulations, the sampling frequency was set to 200 Hz and the network size to 5 nodes. Figure 11 shows that for a given buffer size, the buffer overflow rate increases when BO is greater than a specific value. This means that the size of generated data during one superframe is greater that the buffer size. When the sampling buffer is full, generated data is dropped at the application layer. The ellipse in figure11 shows all acceptable combinations that do not introduce packet loss. Red points shows the optimal BO for a given buffer size. This BO values ensures minimal energy consumption with maximal packet delivery rate.

VIII. CONCLUSION

In this paper we have presented the design and the implementation of a new WSN for high-fidelity rehabilitation supervision. This system is a light-weight easy-to-use monitoring system that can be used in-home or within a hospital. Contrary to existing WSNs for rehabilitation that we surveyed, our solution has a fault-tolerant, energy-efficient communication protocol that meets the clinical requirements of rehabilitation supervision in terms of data quality and data rate. We have conducted several simulation and real world experimentations that showed the high data delivery ratio of our communication protocol with all tested configurations. Our project is a work in progress and much still remains to be done. In particular, we will replace the laptop by a lightweight PDA. This will bring an important added value to our solution and improve the mobility and flexibility. Also, we plan to conduct more comprehensive tests in cooperation with doctors and physical therapists to provide a better evaluation of our solution. Finally, we need to tackle new challenges in order to incorporate our solution into a complete clinical information system.

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