A Time-slot Scheduling Algorithm for e-Health Wireless Sensor Networks

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Abstract— **For e-health wireless sensor networks presenting significant traffic loads, MAC protocols based on deterministic scheduling algorithms are consensually considered more adequate than protocols based on random access algorithms. Indeed, TDMA-based MAC protocols are able to control the delay bound and save power by eliminating collisions. However, these protocols always require some expedite scheme to assign the superframe time-slots to the network devices that need to transmit data. Knowing that patients of an e-health wireless network are normally monitored by the same number and types of motes, originating a regular traffic pattern, a simple collaborative time-slot allocation algorithm can be achieved, as introduced in this paper. In the proposed algorithm, the announcement of time-slot allocation by the network coordinator is avoided, which helps to improve the packet delivery ratio and reduce the energy consumption in the e–health wireless network.**

Keywords: Wireless sensor network; e-health; MAC; CSMA; TDMA; superframe; time-slot.

I. Introduction

Wireless sensor networks (WSN) consist of a group of nodes supplied by low energy batteries, and having very limited sensing, signal processing, and wireless communication capabilities. All nodes transmit data to the same collector node, known as base station (BS). Such networks have been deployed in a wide range of monitoring applications, including e-health and e-emergency.

In an e-health WSN containing one or more body sensor networks (BSN), the physiological signals of a patient are captured by a set of sensors placed on the patient´s body and delivered to a BS. With the help of a diagnosis and decision center, the BS keeps informed about the clinical state progress of each patient in the WSN. According to the clinical state of the patients, the BS may modify how motes in the WSN acquire the signal or access the wireless channel to transmit data. In this last case, the medium access control (MAC) protocol plays an important role regarding throughput, latency and energy efficiency. The MAC protocol should be flexible enough to adapt to new communication situations as required by the BS. For example, if the BS requires a higher sampling rate of the electrocardiography (ECG) signal of a patient, the MAC protocol should be able to guarantee bandwidth enough to that signal.

Many MAC protocols have been developed for WSNs using contention or multiplexing-based algorithms. Traditional contention-based protocols assume traffic is distributed stochastically. Still, most of the physiological parameters from a patient are dependent and coupled. For example, when a patient gets a fever, the body temperature rises, the heartbeat rate and the blood pressure rise too, and so does the breath rate. The oxygen saturation level in the blood may change too [1]. Therefore, a single physiological fluctuation may trigger diverse motes simultaneously requiring medium access. As traffic in an e-health WSN tends to be correlated and regular, conventional carrier sense multiple access (CSMA) protocols are not advised for these networks [2]. Contention–based protocols work well under low traffic loads, but they degrade drastically under higher loads because of collisions and retransmissions. For instance, S-MAC [3] and WiseMAC [4] are typical examples of CSMA-based protocols designed for WSNs which help to save energy in applications whose nodes remain idle for long time until an event is detected. Convenient for low traffic, low duty-cycle networks (e.g. surveillance), these protocols are ill-suited for networks requiring high throughput and low latency, as required in e-emergency. Here, multiplexing-based protocols are preferable [5]. Indeed, it was proofed analytically that an unslotted 802.15.4 single-hop WSN containing 10 motes sampling the ECG signals at 250 Hz with a resolution of 16 bits present a packet delivery ratio less than 90%, independently of the packet size [6]. Moreover, computer simulations showed that when the data rates in a WSN are comparable to the available channel bandwidth, traditional randomized access schemes present energy inefficiency, reduced throughput, and unfair data delivery [7].

Amongst multiplexing-based protocols, time division multiple access (TDMA) is a commonly used technique. Time is split into equal intervals known as superframes or timeframes. Each superframe is further divided into time-slots of fixed duration known as time-slots. Dedicated time-slots are used by motes to transmit data without the need to contend for the medium. TDMA protocols can provide bounds on per-hop latency, transmission determinism and medium access fairness [12]. Since nodes only need to turn on the radio during their assigned time-slots, low overhearing and low active-sleep duty-cycle operations can be achieved, resulting in good energy efficiency. However TDMA protocols require frequent synchronization and are less scalable than contention-based protocols.

Fundamental in every TDMA-based protocol is the link scheduling, i.e., the time-slot allocation to the network devices.

In traditional TDMA-based systems, time-slots are assigned to the devices by the central coordinator of the network. However, some schemes do not require any coordinator, and thereby the time-slot assignment and synchronization become distributed. Sensors in a BSN can be considered as generating constant bit rate traffic where traffic requirements do not change quickly over time [8]. Taking advantage of the stable topology and traffic pattern characteristics found in many e-health WSNs, a simple collaborative time-slot allocation algorithm with quality of service (QoS) requirements is herein proposed for one-hop networks. This is the main contribution of this paper. The proposed algorithm can be integrated into any TDMA-based MAC protocols dealing with similar traffic characteristics as found in e-health networks. For example, it has been included in the improved-LPRT (iLPRT) protocol, which is described in section III.

The remaining of this paper is organized as follows: some relevant related works in this area are referred in Section II; iLPRT MAC protocol is described in Section III; the equations sustaining the proposed collaborative time-slot scheduling algorithm are shown in Section IV; experimental results to evaluate strategies required by a MAC protocol using the proposed algorithm are discussed in Section V; and, finally, the conclusions are presented in Section VI.

II. RELATED WORK

Several TDMA scheduling algorithms have been developed taking into account the latency or the energy consumption in one-hop or multi-hop scenarios. In one-hop WSNs the BS is the receiver of all sensor data transmissions, and so only one node can transmit in a time-slot. However, such direct transmission may not be feasible nor energy efficient in some WSNs [9]. This is particularly true in BSNs, as the propagation loss around the human body is high [10]. In multi-hop WSNs, more than one node can transmit at the same time-slot (spatial reuse) if their receivers are not in interfering regions of the network.

Regarding link scheduling in multi-hop networks, Cui *et al.* [11] propose a simple algorithm for an arbitrary loop-free topology with one sink node, to find the minimum-delay schedule given the time-slot lengths for all the links. The tradeoff between the total energy consumption and delay is also studied. Gandham *et al.* [12] state that the time-slot assignment problem is closely related to the edge coloring problem for a graph, i.e. no two edges incident on the same node are assigned the same color. Using this assumption, the authors proposed a distributed algorithm using a minimal number of time-slots to reduce the communication latency. However, the topology of the network must keep unchanged during the time-slot assignment. This condition is hard to find in WSNs, as topology may change due to displacement or failure of nodes. Ergen *et al.* [13] proposed two centralized coloring algorithms based on a conflict graph to determine the smallest length conflict-free assignment of time-slots during which the packets generated at each node reach their destination. The conflict graph, constructed from the original graph, includes all nodes that cannot transmit at the same time. The algorithms are inappropriate for large networks because a lot of communication among the nodes is required. Sridharan *et al.* [6] presented a distributed solution to improve the medium access fairness of flows in a WSN, which outperformed random MAC in terms of fairness and delay. Mao *et al.* [14] present a centralized time-slot assignment algorithm based on genetic algorithms and particle swarm optimization, with a n-hop neighborhood criterion to avoid interferences in the time-slots (only nodes above n hops of distance can reuse time-slots). Scheduling algorithms using the n-hop criterion can only be used in regular network topologies. To overcome this limitation, Nunes *et al.* [15] present a distributed time-slot allocation algorithm based on the interference physically experienced by the WSN nodes through the received signal strength. Capable of coping with irregular node deployments, the algorithm assures that the access to each time-slot is free of interferences. It assigns each time-slot to only one node within the interference vicinity, and allows spatial time-slot reuse outside of that vicinity.

Diverse TDMA-based MAC protocols have been proposed for generic communication traffic patterns in WSNs, such as LMAC [16], TRAMA [17], IEEE 802.15.4/guaranteed time-slots (GTS) [18], and LPRT [19], each one presenting its own time-slot allocation scheme.

LMAC allows a WSN to self-organize in terms of time-slot assignment and synchronization by using a distributed algorithm running in every node. LMAC uses a random time-slot assignment algorithm that ensures that nodes at 2-hops distance do not use the same time-slot number. Nodes wake up at the start of each time-slot to stay synchronized and to listen to a message. If the message is not addressed to the node, it will sleep until the next time-slot. Since each node only has one time-slot assigned and one transmission per superframe (32 time-slots) is allowed, LMAC is inadequate to e-emergency networks.

TRAMA uses a distributed election scheme based on information about the traffic at each node to decide which node can transmit at a particular time-slot. It avoids the assignment of time-slots to nodes without traffic to send, and also allows nodes to decide when they can sleep. It is well suited for applications that require high-delivery guarantee and energy efficiency, without being delay sensitive. The latter characteristic impairs the support of real-time applications.

The IEEE 802.15.4 standard specifies the physical layer and the MAC sublayer, allowing the optional use of GTSs to handle time critical events. A mote transmits to the network coordinator a MAC command requesting some GTSs and, if available, the BS responds granting the number of superframe time-slots requested by the mote. GTSs expire if unused during a few consecutive superframes. The low granularity of the guaranteed time-slots (seven) leads to poor bandwidth efficiency, making it unsuitable to e-emergency scenarios.

Based on LPRT [19], iLPRT was conceived for being robust to channel errors, aiming to provide efficient bandwidth allocation, low energy consumption, and bounded latency, as required by e-emergency WSNs.

III. iLPRT PROTOCOL DESCRIPTION

iLPRT is a simple, beacon-based MAC protocol that uses the available bandwidth dynamically. Its highly-grained superframe (Fig. 1) starts with the transmission of a beacon packet *b* by the BS, followed by the Contention Access Period (CAP). The CAP may be used for sending MAC commands and responses, which are used, for example, to allow motes to associate with or disassociate from a WSN. It is also used to convey low transmission duty-cycle traffic, such as temperature. Data packets sent in the CAP may be confirmed by acknowledgment (ACK) packets emitted by the BS. The Contention Free Period (CFP) follows the CAP. The slotted-CSMA algorithm [18] is used in the CAP, and TDMA is applied in the CFP. The CFP is composed by the Normal Transmission Period (NTP) and the Retransmission Period (RP). NTP is used for motes to transmit new data. Lost data are retransmitted in the RP. The CAP may also be used for packet retransmission in case of lost beacons. Data packets transmitted to the BS during the NTP are acknowledged by the ACK bitmap present in the beacon of the next superframe. Data packets sent in the RP may be acknowledged by ACK packets sent by the BS. Packets are sent in contiguous time-slots. The set of time-slots needed for a mote to send a data packet, and, if required, to receive the ACK packet, is called super time-slot. For example, in Fig. 1 the set of time-slots from *E* to *F* is the super time-slot used to send the data packet *d*.

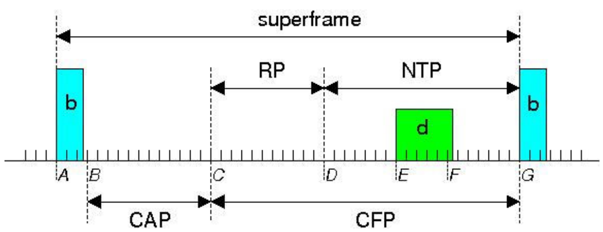

Figure 1. Superframe structure in the iLPRT protocol.

Since patients of an e-health WSN are normally monitored by the same number and types of motes, advantage can be taken from this characteristic to decrease the packet loss ratio and energy consumption in every BSN. For this goal, iLPRT uses short size beacons, i.e. beacons carrying only essential data for the proper operation of the WSN. Such essential data must enable all motes in the WSN to find implicit and unambiguously their time-slot allocation in the superframe.

According to the clinical state of the patients, the BS may need to reconfigure the WSN it belongs to. Hence, an e-health WSN may enter in the reconfiguration state along its operation. However, the reconfiguration state tends to occur sporadically when compared with the steady state. During the reconfiguration state, the BS may announce in the beacon packet the last CAP time-slot, the total number of motes in the WSN, the ACK bitmap, the criticality bitmap, and the activity bitmap, along with other operational parameters of the motes, such as the sampling rate, the sampling resolution, etc. Both the criticality bitmap and the activity bitmap are new concepts introduced by iLPRT protocol. The criticality bitmap informs the WSN about the signals considered critical by the BS, in order to improve the QoS of such signals, like the packet delivery ratio. The activity bitmap serves for the BS to inform about the state of activeness of all motes in the WSN, so that motes are capable of optimizing the time-slots usage without bandwidth waste. The BS considers a mote inactive if it does not receive data from the mote after a number of consecutive superframes. Also, the activity bitmap serves for the BS to inform specific motes for not transmitting data. A mote can only transmit data when the respective activity flag is set.

Once configured the WSN, the BS sends only in the beacon packet the ACK bitmap and the last time-slot of the CAP. According to the received ACK bitmap, each mote must calculate the corresponding superframe time-slots to transmit its data. Using this strategy, the energy consumption in each BSN is improved, since smaller size beacons are received by the motes. If a mote does not receive a beacon or a short sequence of beacons, it may continue to send its new data in the NTP, since a mote clock drift in the order of microseconds should allow the WSN to continue synchronized during a few consecutive beacon intervals. However, a mote cannot retransmit any data in the RP because the ACK bitmap are not available and so it does not know how the RP time-slots are being allocated to the other motes. In this case, the data packet transmitted in the NTP of the last superframe may be retransmitted in the CAP to improve the probability of being delivered to the BS. iLPRT uses also a multiple retransmission procedure to recover lost packets - one retransmission for normal data, two possible retransmissions for critical data.

In a TDMA-based protocol using short size beacons, such as iLPRT, time-slots are not assigned to the devices directly by the BS. In this case, motes must run an algorithm to compute which time-slots should be used to (re)transmit data without interfering to each other, in accordance with a predefined order schema. Next, it is shown how a WSN running a MAC protocol based on short size beacons, such as iLPRT, can be redefined in terms of time-slots allocation from the data broadcasted by the BS, namely the sample rate, the sample resolution, the ACK bitmap, the criticality bitmap, and activity bitmap.

IV. TIME-SLOT ALLOCATION ALGORITHM

In an e-health WSN, parameters may be redefined dynamically along the time in accordance with the patients´ clinical state. For example, a higher monitoring activity of the patients´ vital signals might be required when the clinical situation changes from non-critical to critical, implying the redefinition of the sampling rate parameter.

The setting of an e-health parameter value may be decided and announced to the WSN by the BS. Changing the value of a single parameter value may require a complete time-slot rescheduling of the WSN. If the TDMA-based MAC protocol uses short size beacons, the BS cannot assign the time-slots in the beacon explicitly. In this case, each mote must run an algorithm in the MAC layer to find the time-slots to transmit a frame. As WSNs are collaborative networks working towards a common goal, the time-slot scheduling algorithm running in a mote must operate collaboratively.

In this way, a set of equations will be used to sustain the scheduling algorithm of a MAC protocol using short size beacons operating in one-hop WSNs, and characterized by a stable topology and regular traffic pattern, such as e-health

WSNs. Table I describes the meaning of the symbols used in the equations proposed next.

TABLE I. MEANING OF THE SYMBOLS

Symbol	Description
$A(M_i)$	boolean activity state of mote M_i
B_i	body sensor network B_i
$C(M_i)$	boolean criticality state of mote M_i
H	sampling rate of the sensor, in samples/s
M	number of motes per BSN
MAC_h	MAC header plus trailer size
MAC_d	MAC payload length, in bytes
$MAC_{d\,max}$	MAC payload maximum length, in bytes
M_i	mote M_i
$M_i\,(B_j)$	mote M_i of BSN B_j
$nack_p(M_i)=(nack^i_1\ldots,nack^i_p)$	complement of the ACK bitmap for all motes M_i present in the p BSNs
N	total number of motes in the e-health WSN
P	number of patients, i.e. BSNs
PHY_h	physical header size
R	sampling resolution of the sensor, in bits
$\{r.H\}^n_{max}$	maximum product of sampling resolution and sampling rate found in the n motes of WSN
R	nominal transmission rate, in bps
S	total number of time-slots in the superframe
$S_a(M_i)$	time-slots used by mote M_i to receive the ACK packet
$S_g(M_i)$	safeguard time-slots used by mote M_i
S_r	nr. of reserved final timeslots in the superframe
$S_s(M_i)$	nr. of time-slots used by mote M_i to transmit a packet
$S_t(M_i)$	total nr. of time-slots allocated to mote M_i
S_{NTP}	time-slot where NTP starts
$S_{NTP}(M_{i,}(B_j))$	NTP time-slot for mote M_i of BSN B_j to start data transmission
S_{RP}	time-slot where RP starts
$S_{RP}(M_{i,}(B_j))$	RP time-slot for mote M_i of BSN B_j to start data retransmission
t_D	packet delivery delay, in seconds
$t_{D\,max}$	maximum packet delivery delay, in seconds
t_{TX}	transmission duration, in seconds
t_{SF}	superframe duration, in seconds
$T(M_i)$	maximum number of trials for mote M_i to retransmit one data packet

A. Allocation of Time-slots to a Mote

Let us consider that a TDMA-based MAC protocol using superframes is operating in an e-health WSN containing *n* motes. To guarantee the maximum delay specified for packet delivery, the superframe duration t_{SF} must be less than half of the maximum packet delivery delay $t_{D\ max}$ to assure that retransmitted packets are delivered timely. Also, the superframe duration must be below the time required to fill up the frame payload with sampling data. These conditions can be expressed as:

$$t_{SF} \leq \min(\ \mathrm{int}(t_{D\,max}\,/2),\ \mathrm{int}(MAC_{d\,max}.8/\{r.H\}^n_{max})) \qquad (1)$$

where $MAC_{d\ max}$ is the maximum MAC payload length in bytes, and $\{r.H\}^n_{max} = \max(r_1.H_1, r_2.H_2, \ldots, r_n.H_n)$ is the maximum product between the sampling resolution *r* bits, and the sampling rate *H* samples/s found in the *n* motes of the WSN. This maximum product is normally found in the ECG motes. The function int(x) returns the integer part of the argument, min(x,y) returns the smaller of the arguments, and max(x,…,y) returns the bigger of the arguments.

The total number of time-slots S in the superframe should be large enough to tune accurately the time division allocated to each mote and so minimizing the bandwidth waste, without leading to time-slot duration beyond the motes timer resolution. Since this is typically in order of microseconds, 512 time-slots per superframe is a good compromise.

The number of time-slots S_s that a mote occupies in the superframe to transmit a data packet is:

$$S_s = \mathrm{ceil}(\ S.t_{TX}/t_{SF}\ ) \qquad (2)$$

where S is the total number of time-slots in the superframe, and t_{TX} is the transmission duration. Assuming a fully used superframe, the superframe duration t_{SF} is equal to the beacon interval. The ceiling function ceil(x) returns the integer part of the argument rounded up.

For a packet with a physical header size PHY_h, a MAC header plus trailer size MAC_h, a MAC payload length MAC_d bytes, and a nominal transmission rate R bps:

$$t_{TX} = (PHY_h+MAC_h+MAC_d).8/R \qquad (3)$$

Considering a null overhead for the layers above the MAC layer,

$$MAC_d = t_{SF}.H.r/8 \qquad (4)$$

S_g additional time-slots are included for safeguarding purposes. Furthermore, if a data packet sent by the mote must be acknowledged, then S_a time-slots have to be included to receive the ACK packet. Therefore, a mote may occupy a total number of S_t time-slots:

$$S_t = S_s + S_g + S_a \qquad (5)$$

Consecutive super time-slots may be used for multiple transmission trials. For example, with a maximum of two transmission trials, the second super time-slot is used for retransmission if the packet is not correctly received by the BS during the first transmission. Accordingly, the first transmission must be acknowledged. If a packet is sent with success during the first transmission, then the time-slots reserved for the second retransmission are unused, resulting in bandwidth waste. The last retransmission is not acknowledged. So, the total number of time-slots required by mote M_i can be represented generically as:

$$S_t(M_i) = [(S_s(M_i) + S_g(M_i) + S_a(M_i)).T(M_i) - S_a(M_i)].A(M_i) \quad (6)$$

where the activity flag $A(M_i)$ indicates whether mote M_i is going to transmit data in the current superframe (=1) or not (=0), and $T(M_i)$ (≥ 1) represents the maximum number of trials for mote M_i to transmit one data packet.

B. Transmission in the NTP

Let us consider that a WSN running the iLPRT protocol contains *p* patients (i.e. BSNs), and each patient has *m* motes to monitor distinct physiological signals. To simplify the algorithmic definition, and without losing generality, it is assumed that the time-slots in the superframe are occupied by the sequence defined in Fig. 2. Here, *b* represents the beacon and B_j means the BSN of patient j ($1 \leq j \leq p$). Every mote may transmit only one data packet in the NTP, so the maximum number of trials for mote M_i to transmit one data packet $T(M_i)=1$ ($1 \leq i \leq m$). If $m=5$ and $p=3$ are taken for instance, then $M_1(B_1, B_2, B_3) = (M_1(B_1), M_1(B_2), (M_1(B_3))$ represents the following transmission sequence in the NTP: after mote M_1 of BSN B_1 transmitting a data packet, then mote M_1 of BSN B_2, and mote M_1 of BSN B_3 transmit successively their data packets. The same criterion is applied to the remaining types of motes. M_1 and M_2 may represent, for example, ECG, and arterial pressure motes respectively.

b | CAP | RP | $M_1(B_1 \ldots B_p)$, …, $M_{m-1}(B_1 \ldots B_p)$, $M_m(B_1 \ldots B_p)$ |
-------------------------- NTP -------------------------

Figure 2. Time-slot occupation sequence in the NTP.

As during the reconfiguration state every mote becomes aware of the operating parameters (e.g., sampling rate, resolution, etc.) used by the remaining motes in the WSN, each mote is able to compute the initial transmission time-slot in the NTP using the following expression:

$$S_{NTP}(M_i(B_j)) = S_{NTP} + \sum_{k=1}^{i-1} \left(\sum_{n=1}^{p} S_t(M_k(B_n))\right) + \sum_{n=1}^{j-1} S_t(M_i(B_n)) \quad (7)$$

where $S_{NTP}(M_i(B_j))$ represents the NTP time-slot which mote M_i of BSN B_j must use to start transmitting its data. For example, in Fig. 1, the mote that sent packet *d* used (7) to find the initial transmission time-slot *E*. S_{NTP} represents the time-slot where NTP starts and is given by:

$$S_{NTP} = (S - S_r) - \sum_{i=1}^{m} \sum_{j=1}^{p} S_t(M_i(B_j)) \quad (8)$$

considering the last S_r time-slots of the superframe reserved to allow the motes to enter in listening mode to receive the next beacon. In Fig. 1, S_{NTP} is the time-slot *D*.

These calculations need to be performed only once after the conclusion of every reconfiguration process.

C. Retransmission in the RP

The retransmission order in the RP depends on the ACK bitmap and criticality bitmap received from the BS. Using an increasing time-slot sequence and a predefined order schema, firstly the data packets of all motes having the bit true in the criticality bitmap and the bit false in the ACK bitmap are retransmitted successively. This strategy increases the probability of allocating retransmission time-slots to the packets containing critical data. When the number of available time-slots is insufficient for all required retransmissions, the less important vital signals should not be retransmitted. Since body temperature changes slowly along the time, temperature is a good candidate to be discarded in such situation. The activity bitmap is not required for the retransmission time-slot scheduling, since it is implicit in the ACK bitmap. Indeed, if the BS asks for a mote to retransmit, it is because the BS considers that mote active. An inactive mote should have the respective flag in the ACK bitmap set.

As consecutive super time-slots may be used for multiple retransmission trials, $T(M_i) \geq 1$ ($1 \leq i \leq m$). In iLPRT, one or two retransmissions may only occur during RP, according to the following condition:

$$\text{if } (C(M_i) = 0) \text{ then } T(M_i) = 1 \text{ else } T(M_i) = 2 \quad (9)$$

where the criticality flag $C(M_i)$ indicates whether data from mote M_i is critical (=1) or not (=0).

Let us assume that a WSN contains *p* BSNs, and each BSN is composed of *m* motes to monitor distinct physiological signals. It is assumed that the RP time-slots, comprised between the CAP and the NTP, are occupied in accordance with Fig. 3, considering the same low criticality status for every type of mote in every BSN, i.e. $C(M_i(B_j))=0$, $1 \leq i \leq m$, $1 \leq j \leq p$. $nack_p(M_i) = (nack^i_1, \ldots, nack^i_p)$, represents the complement of the ACK bitmap for all motes M_i present in the *p* BSNs. The meaning of $nack_p(M_1).M_1(B_1 \ldots B_p)$ is equivalent to $M_1(nack^1_1.B_1, \ldots, nack^1_p.B_p)$. M_m must be the type of mote to be discarded firstly in case of truncation. For instance, if $m=5$, $p=6$, and if the complement of the ACK bitmap for motes M_1 and M_2 of all BSNs is $nack_6(M_1) = nack_6(M_2) = (1,0,1,1,0,0)$, and $nack_6(M_i) = (0,0,0,0,0,0)$, $2 \leq i \leq 5$, then $nack_6(M_1).M_1(B_1,B_2,B_3,B_4,B_5,B_6) = M_1(B_1,B_3,B_4)$ represents the following transmission sequence in RP: after mote M_1 of BSN B_1 retransmitting a data packet, then mote M_1 of BSN B_3 and mote M_1 of BSN B_4 retransmit successively their data, followed by the motes M_2 of BSN B_1, BSN B_3, and BSN B_4. Every retransmission occur only once per superframe. But, considering the same ACK bitmap, if the criticality flag is true for motes M_1 of BSN B_1 and BSN B_2, i.e. $C(M_1(B_1))=C(M_1(B_2))=1$, and false for the remaining motes, then motes M_1 of BSN B_1 and BSN B_2 retransmit their packets in this order up to twice. Next, motes M_1 of BSN B_3 and BSN B_4 retransmit successively their data once, followed by the motes M_2 of BSN B_3 and BSN B_4.

b | CAP | $nack_p(M_1).M_1(B_1 \ldots B_p)$,…,$nack_p(M_m).M_m(B_0 \ldots B_p)$) | NTP |
------------------------------- RP ---------------------------

Figure 3. Time-slot occupation sequence in the RP.

As during the reconfiguration state every mote becomes aware of the parameters used by the remaining motes of the

WSN, each mote is able to compute the initial transmission time-slot in the RP using the following expression:

$$S_{RP}(M_i(B_j)) = S_{RP} + \sum_{k=1}^{i-1} \left(\sum_{n=1}^{p} nack_p(M_k).S_t(M_k(B_n)) \right) + \sum_{n=1}^{j-1} nack_p(M_i).S_t(M_i(B_n)) \quad (10)$$

where $S_{RP}(M_i(B_j))$ represents the RP time-slot which mote M_i of BSN B_j must use to start transmitting its data. S_{RP} represents the time-slot number where RP starts, and is the next time-slot after the last time-slot of the CAP announced by the BS. In Fig. 1, S_{RP} is the time-slot *C*. For simplicity of representation, (10) does not consider the premise of motes having the bit true in the criticality bitmap to be retransmitted firstly.

These calculations need to be performed by a mote every time a beacon is received and the respective flag in the ACK bitmap requests for a retransmission in the RP. The critically bitmap is known during the reconfiguration state, and remains unchanged until the next reconfiguration procedure.

D. Proof of Concept

In order to illustrate the operation and simplicity of the proposed scheduling algorithm, an example of its use is given next. Let us consider a hospital room containing a few beds with one patient per bed. Each patient is monitored by a body sensor network, and a BS collects and analyses the vital signals of all patients. The signals being monitored by dedicated motes are ECG, arterial pressure (ART), oximetry (OXI), respiration rate (RR), and temperature (T). The NTP time-slots in the superframe are occupied in the order shown in Fig. 4. ECG(1-6)=ECG(1,2,3,4,5,6) represents the following transmission sequence in NTP: after ECG mote of BSN1 (ECG1) transmitting the data packet, then ECG2, ECG3, ECG4, ECG5, and ECG6 transmit successively their data. The same criterion is applied to the remaining types of motes. During the association phase, every mote must indicate its type to the BS. For example, ECG, ART, OXI, RR, and T motes would correspond to motes M_1, M_2, M_3, M_4, and M_5, respectively, in Fig. 2. Also, each mote must indicate the BSN it belongs to. Whenever a new BSN identification is received, the BS updates the total number of BSNs in the e-health network, and attributes this number to the new BSN. Every time a mote enters or leaves the WSN, the network enters in reconfiguration state to inform the active motes about the fact.

```
b | CAP | RP | ECG(1-6), ART(1-6), OXI(1-6), RR(1-6), T(1-6) |
              --------------------------- NTP --------------------------
```

Figure 4. Slot occupation order in the NTP for the proof of concept example.

Fig. 5 presents the code of the procedure slotNTP that mote M_i at BSN B_j should invoke to find the initial transmission time-slot in the NTP to transmit a new data packet, considering the activity bitmap *A*, and the number of time-slots S_s required by each sensor to transmit data. For instance, mote OXI2 should call slotNTP with $M_i = 3$ and $B_j = 2$ to find its initial transmitting time-slot in the NTP. Fig. 5 shows also the procedure for a mote to find its initial transmission time-slot in the RP (slotRP). In this case, the input arguments of the procedure are the mote M_i, the BSN B_j, the array *Ss*, the ACK bitmap *ack*, and the criticality bitmap *C*. Two possible retransmission trials are allowed for critical data. slotRP returns zero if no more time-slots are available in the RP of the superframe.

```
constants (cf. Table I): m, p, S, Sg, Sr, Sa, T;

S_NTP ← SNTP(A[m][p], Ss[m][p])  // first index of arrays is 1

slotNTP( Mi, Bj, A[m][p], Ss[m][p] )
{
  Sntp[m][p]
  auxiliary variables: b, s, a[m]

  for s=1 to Mi–1   {
     if ( s=1 ) then a[s] ← S_NTP else a[s] ← a[s–1]
     for b=1 to p  {
          a[s] ← a[s] + ( Ss[s][b] + Sg )*A[s][b] }
  }
  if (Mi=1) then Sntp[Mi][Bj] ← S_NTP  else Sntp[Mi][Bj] ← a[s–1]
  for b=1 to Bj–1 {
      Sntp[Mi][Bj] ← Sntp[Mi][Bj] + (Ss[Mi][b]+Sg)*A[Mi][b] }
  return Sntp[Mi][Bj]
}

slotRP( Mi, Bj, Ss[m][p], ack[m][p], C[m][p] )
{
  S_RP, Srp[m][p]
  auxiliary variables: a[m], b, k, q, s, v, z

  S_RP ← 1 + last time-slot of the CAP
  for k=1 to 2    {
   for z=1 to m   {
    for v=1 to p   {
     if( k=2  or  C[Mi][Bj] ) then  z ←Mi, v ←Bj
     for s=1 to z–1   {
        if( s=1 ) a[s] ← S_RP else a[s] ← a[s–1]
        for b=1 to p  {
          if( k=1 ) then q ← C[s][b]*T else q ← 1–C[s][b]
          a[s] ← a[s] + (Ss[s][b]+Sg+Sa)*(1–ack[s][b])*q  }
        }
    if( z=1 ) then Srp[z][v] ← S_RP else Srp[z][v] ← a[s–1]
    for b=1 to v–1 {
       if( k=1 ) then q ← C[z][b]*T  else q ← 1–C[z][b]
       Srp[z][v] ← Srp[z][v]+(Ss[z][b]+Sg+Sa)*(1–ack[z][b])*q  }
   if( k=2  or  C[Mi][Bj] ) {
      if( Srp[z][v] ≥ S_NTP ) then Srp[z][v] ← 0
      return Srp[z][v]  }
   }}
  S_RP ← Srp[m][p]
}}

SNTP( A[m][p], Ss[m][p] )   // procedure to find S_NTP
{
   auxiliary variables: a[m], b, s
    for s=1 to  m  {
    if ( s=1 ) then a[s] ← S–Sr else a[s] ← a[s–1]
       for b=1 to  p  {
           a[s] ← a[s] – (Ss[s][b] + Sg)*A[s][b] }
   }
   return  a[s–1]
}
```

Figure 5. Procedures for a mote to find the initial transmission time-slot in the NTP and RP, and the time-slot where NTP starts.

V. Experimental Results

The proposed time-slot scheduling algorithm is intended for a wireless network that runs a MAC protocol using short size beacons, and multiple retransmissions techniques. In order to evaluate the relevance of these strategies in the improvement of the packet reception ratio, preliminary measurements were carried out using one BS and one mote. The evaluation of the number of retransmission trials proposed in (9) was considered too.

The BS and the mote were implemented with the wireless modules from ZigBit Development Kit [20]. The dual chip antenna of the mote was modified to improve its receiving performance. The mote was around 3.5 meter away from the BS, with line-of-sight. The transmission power was 3 dBm, the superframe duration was 250 ms, the number of superframe time-slots was 500, the payload size of data packets was 100 bytes, the physical plus MAC overhead was 17 bytes. Also, LPRT was used to help studying the performance of the short size beacon technique. It differs from iLPRT, in that LPRT uses relatively large size beacons, a single retransmission procedure, and data is only transmitted in the superframe if the corresponding beacon is received. The beacon size used in LPRT was 70 bytes, and in iLPRT was 6 bytes. Retransmissions in the CAP were not used in iLPRT.

It was noted in all tests that the packet reception error of the BS was always higher (about twice) than that observed in the mote (0.17% on average) for data packets of similar size. This was found to be mainly due to the distinct antenna circuits used by both devices, and not to any bidirectional unbalance of the communication channel. Table II summarizes the results of the measurements.

The moving average undelivered packet ratio ($\overline{\text{UPR}}$) was calculated over a window containing the frames transmitted during the last 15 minutes. This metric reflects the data effectively delivered to the application layer of the BS. It is shown that iLPRT with one retransmission (iLPRT-1r) presented slightly better $\overline{\text{UPR}}$ values than LPRT. Indeed, with iLPRT 85.5% of all calculated $\overline{\text{UPR}}$s had a value not above 0.1%, against 80.7% presented by LPRT. The main reason for these close values is because the beacon loss is similar in both protocols, despite the difference of about one order of magnitude in the beacon size used by both protocols. However, if iLPRT with two retransmissions (iLPRT-2r) is used instead, then the improvement is notorious comparatively to LPRT and iLPRT-1r. In fact, 99.8% of all calculated $\overline{\text{UPR}}$s presented a value not above 0.1%. These results show that to reduce the packet delivery ratio it is more efficient to increase the number of retransmissions than reducing the beacon frame size. Indeed, the packet delivery ratio seems to be not very dependent of the beacon frame size. Nevertheless, short size beacons technique remains valuable regarding energy saving, as smaller packets are received by the motes, as well in reducing the bandwidth usage.

Results show that with two retransmission trials the packet delivery ratio improves significantly when compared with a single retransmission. This confirms that the number of retransmission trials suggested in (9) for a MAC protocol using the proposed scheduling algorithm, such as iLPRT, helps to enhance notably the packet delivery ratio, and consequently the QoS, of the traffic considered critical by the decision center of the e-health WSN.

TABLE II. Experimental results

	% of $\overline{\text{UPR}}$s $\leq$0.1%	**% of $\overline{\text{UPR}}$s >0.1%**	**Total runtime (hours)**	**Beacon loss (%)**
LPRT	80.7	19.3	100	0.17
iLPRT-1r	85.5	14.5	102	0.20
iLPRT-2r	99.8	0.2	102	0.20

VI. Conclusions

Protocols using short size beacons, such as iLPRT, are valuable for the sake of energy saving and packet delivery ratio improvement. As time-slot allocation cannot be announced by a BS transmitting short size beacons, a collaborative link scheduling algorithm may be used by the motes of the WSN. Taking advantage of the regular traffic pattern found in e-health wireless networks, as well of the homogeneity regarding the number and types of motes found in the BSNs of an e-health WSN, a simple collaborative time-slot scheduling algorithm can be achieved to fulfill this goal. As the proposed algorithm is computationally non-intensive, it is adequate for motes with very limited computational resources.

Preliminary experimental tests showed that to reduce the packet delivery ratio it is significantly more efficient to increase the number of retransmissions than reducing the beacon frame size. Two retransmissions revealed a notable improvement in the QoS of the e-health WSN regarding the packet delivery ratio, when compared with a single retransmission.

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