Peak Transmission Rate Resilient Crosslayer Broadcast for Body Area Networks

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Abstract

Wireless Body Area Networks (WBAN) open an interdisciplinary area within Wireless Sensor Networks (WSN) research, with a tremendous impact in healthcare area where sensors are used to monitor, collect and transmit biological parameters of the human body. We propose the first network-MAC cross-layer broadcast protocol in WBAN. Our protocol, evaluated with the OMNET++ simulator enriched with realistic human body mobility model and channel model issued from the recent research on biomedical and health informatics, outperforms existing flat broadcast strategies in terms of percentage of covered nodes and correct reception of FIFO-ordered packets. We investigate the resilience of both existing flat broadcast strategies and our new protocol face to various transmission rates and human body mobility. Existing flat broadcast strategies without exception have a drastic drop of performances for transmission rates above 11Kb/s while our cross-layer protocol performances maintains its good performance for transmission rates up to 190Kb/s.

Keywords: **Wireless Body Area Networks; Broadcast; Mobility; Cross-layer**

I. Introduction

In healthcare area, WBAN emerged as a viable solution in response to various disadvantages associated with wired sensors commonly used to monitor patients in hospitals and emergency rooms. Recent medical reports predict that the number of people using home health technologies will enormously increase from 14.3 to 78 million consumers from 2014 to 2020, respectively.

In WBAN tiny devices with low computing power and limited battery life, deployed in/on or around human body, are able to detect and collect physiological phenomena of the human body (such as: EEG (Electroencephalography), ECG (Electrocardiography), SpO2, lactic acid, etc.), and transmit this information to a collector point (i.e *Sink*) that will process it, take decisions, alert or record. Note that the current needs in surgery rooms [13] are as follows: for ECG, the frequency ranges from $1000Hz$ to $15000Hz$ and it is measured every mili second, body temperature is measured each minute, blood pressure is measured every mili second, CO2 is measured every $200ms$ and aspirator every $10ms$.

WBANs differ from typical large-scale wireless sensor networks in many aspects: the size of the network is limited to a dozen of nodes, in-network mobility follows the body movements and the wireless channel has its specificities. Links have a very short range and a quality that varies with the wearer's posture. The transmission power is kept low, which improves devices autonomy and reduces wearers electromagnetic exposition. Consequently, the effects of body absorption, reflections and interference cannot be neglected and it is difficult to maintain a direct link (one-hop) between a data collection point and all WBAN nodes. Although, recent research [11] advocates for using *multi-hop* communication in WBAN, very few multi-hop communication protocols have been proposed so far and even fewer are optimized for the human body mobility.

The current work extends in several ways the results published in [4, 5], where we evaluate in multi-hop WBAN several broadcast strategies.

We propose a *network-MAC cross-layer broadcast protocol*, called *CLPB: Cross Layer Protocol for Broadcast*, designed for multi-hop topologies and resilient to realistic human body mobility. Layer cooperation in cross-layer based schemes enhances the overall WBAN performance.

CLPB is optimized to exploit the human body mobility by carefully choosing the most reliable communication paths. Moreover, our protocol includes a slot assignment mechanism that reduces the energy consumption, collisions, idle listening and overhearing. Additionally, *CLPB* includes a light synchronization scheme that helps nodes to resynchronize with the *Sink* node on the fly.

Our protocol outperforms existing flat broadcast strategies in terms of network coverage, latency, traffic load and correct reception of FIFO-ordered packets (i.e. packets are received in the order of their sending). Furthermore, our protocol maintains its good performances up to 190Kb/s transmission rates.

This paper is organized as follow: section II. presents relevant works on cross layer approaches in WBAN. In section A., we detail *CLPB*, our new cross-layer broadcast protocol, functioning. In section D., we extensively evaluate protocols in [4, 5] and our new cross layer protocol. Section B. concludes the paper.

II. Related Work

Several works have discussed cross layer principle in different networks: WSN [3, 14], DTN [20], adhoc [2, 17].

In [14], authors present a framework for cross-layer design towards energy-efficient communication characterized by a synergy between the physical and the medium access control (MAC) layers. In [3], a unified cross-layer protocol is developed, which replaces the entire traditional layered protocol architecture that has been used so far in WSN.

In order to address the trade-off between link utilization and energy efficiency, authors in [20] develop a cross-layer data delivery protocol for Delay/Fault Tolerant-Mobile Sensor Network (DFT-MSN). Due to the characteristics of DFT-MSN, the communication links exist only with certain probabilities due to sparse network density, sensor node mobility and limited battery power. First, the sender contacts its neighbors to identify a set of appropriate receivers. Then, the sender gains channel control and multicasts its data message to the receivers.

A. Cross-layer in WBAN

There are very few cross-layer protocols specifically designed for WBAN [18, 8].

In the following we will discuss mainly multi-hop cross-layer protocols that involve MAC and Network layers and take advantages of the characteristics and parameters of the medium access layer to implement efficient routing protocols.

Adaptive Multi-hop tree-based routing (AMR), proposed in [16] is a distributed spanning-tree based approach which considers battery level, Received Signal Strength Indicator (RSSI) and number of hops. AMR balances energy consumption amongst nodes by which it provides extended network lifetime and an efficient number of transmissions per delivered packet. However, it does not take into account the mobility of the human-body.

In [9], Elhadj *et al.* present a Node Management Entity (NME) and a Hub Management Entity (HME) architectures based on IEEE 802.15.6 standard. The two architectures combine cross and modular design architecture to ensure network reliability and enhance the WBAN Quality of Service (QoS). Although authors have treated data heterogeneity, their proposals suffer from high energy consumption due to idle listening.

Lahlou *et al.* present EEAWD [15], a MAC-Network cross layer energy optimization model for WBAN. Authors introduce two traffic classes (normal and emergency) and consider a pseudo mobility model. Authors only focused on energy efficiency parameter despite others.

In [6], Braem *et al.* propose WASP: Wireless Autonomous Spanning tree Protocol, a converge-cast cross-layer protocol for multi-hop WBAN. WASP is a slotted protocol that uses a spanning tree for medium access coordination and traffic routing. Each node will tell its children in which slot they can send their data using a special packet called WASP-scheme. Each node has a unique WASP-scheme constructed based on its parent scheme. WASP-scheme is also used as acknowledgement to each node's parent and as resources request. However, for some parent nodes sleep period is shorter because they have to handle more children than other parent nodes. In addition, latency is correlated to the number of levels of the spanning tree. WASP is not resilient to realistic human body mobility due to parent-child definition. Scalability is also an issue since each node has only one packet to send per cycle and increasing number of nodes decreases throughput.

In [1] authors present a Cross-layer Opportunistic MAC/Routing (COMR) protocol for multi-hop WBAN but the evaluation was made using a static network topology. As an extension, in this work the performance of COMR protocol is investigated taking into account node's mobility with different speeds depending on body positions. The impacts of varying payload sizes are evaluated for both COMR and Simple Opportunistic Routing (SOR) protocols using a mobility model in two scenarios: standing and walking.

Proposed protocols, discussed earlier, focus only *converge-cast* (multiple source nodes send packets to a unique destination *Sink*). To the best of our knowledge, no paper has discussed broadcast in WBAN exploiting a cross-layer approach. In addition, these proposals handle body mobility by reconstructing and updating the tree topology used for packet routing.

III. *CLPB*: Cross Layer Protocol for Broadcast in WBAN

In this section, we introduce our new cross layer broadcast protocol *CLPB*.

CLPB handles both the control medium access and the broadcast process. *CLPB* is a slotted protocol that builds on top of a pruned communication graphs constructed based on the channel model [11].

In order to include the channel model specificities in the broadcast process, *CLPB* needs a *preprocessing* phase. The preprocessing phase is only handled at the beginning and only at the *Sink* node level.

After this preprocessing phase, *Sink* broadcasts packets that will carry both data and control information (e.g. slots assignment, synchronization information, etc).

We settled on a centralized preprocessing phase conducted on the *Sink* node. It is more efficient to handle the preprocessing phase centralized in one unique node since our work addresses small scale networks (up to 10 nodes). A distributed preprocessing phase using for example control message exchange would have heavy costs especially given human body mobility. In addition, a distributed preprocessing phase would be more interesting in a large scale network. Also, we target medical critical applications where WBAN network is precisely inspected by medical staff, nodes position is carefully selected according to the desired application.

A. Preprocessing phase

The aim of preprocessing phase is to identify, for each posture and for each node, one or more reliable paths from *Sink*, i.e paths with the highest success transmission probability. This phase is executed only by *Sink* node before starting the broadcast process.

The mobility model, we are using, gives us signal attenuation between each couple of nodes for different postures as the average attenuation (in dB) and the standard deviation (in dBm). We involve these channel characteristics in our protocol design.

First, *Sink* node computes, based on the mean attenuation and the standard deviation of each link between a couple of nodes, the Cumulative Distribution Function (CDF) of the random attenuation x : $F(X) = P[x < X]$ where X is a threshold. X represents the maximum acceptable attenuation referring to the transmission power $-55\,dBm$ and the reception sensibility $-100\,dBm$. X is equal (-55 - (-100))=45 dBm and $F(45)$ represents the probability of a successful transmission at this link. A similar approach is used by the authors of [7].

Then *Sink* computes a pruned communication graph. Nodes in this graph are the nodes in the network, the edges correspond to the links with success transmission probability greater than 0.5.

Figure 1 shows three pruned communication graphs, for walk, run and sleep postures, obtained by applying the procedure described above.

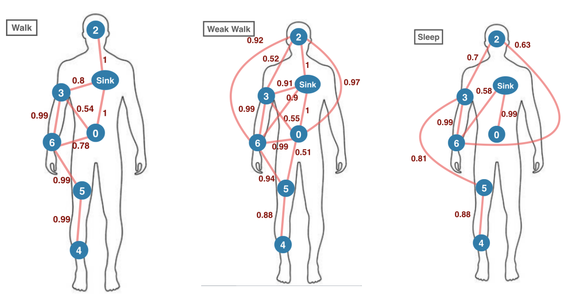


Figure 1: The resulting communication graphs on which CLPB is based

Then, *Sink* selects a set of *senders*, for each posture, starting from top to down (from node at the head to node at the ankle). A sender is a node that presents a link with a high transmission success probability with a node other than the *Sink*.

For each node, in the communication graph, *Sink* computes the paths between *Sink* and N_i with maximal reliability.

We suppose that *Sink* node knows in advance the postures of the body. Postures detection is out of the scope of our study. Note that several works [21, 10] addressed the posture detection.

B. CLPB Protocol Overview

After the preprocessing phase, *Sink* assigns a slot to each sender outputted by the preprocessing phase (see section A.).

Then, *Sink* node broadcasts packets which include data and a *medium access and synchronization scheme*. The broadcasted packets will carry both data and control information (e.g. slots assignment, synchronization information, etc).

Our new cross layer approach minimizes coordination overhead. No exchange of control packets is needed because informations added to data packets are used as control informations and thus nodes are aware of communication and traffic characteristics.

Our protocol assumes that nodes execute in synchronized time-slots. Furthermore, it is assumed that the boundaries of slots are also synchronized. We also show that nodes are able to resynchronize even though some packets are lost.

C. Medium access and synchronization scheme

Nodes synchronize with *Sink* node via the scheduling and synchronization scheme described in details in the sequel.

Sink node divides time into *cycles*. A cycle corresponds to a fixed number of time slots i.e. a sequence of time slots equals to the number of senders, in other words, equals to the number of nodes allowed to broadcast including *Sink* node.

In a cycle, during its corresponding time slot, each sender node is allowed to forward data received in the previous time slot or previous cycle.

Cycle duration is given by the following equation eq.1:

$$CycleDuration = NumberOfSenders * SlotDuration \quad (1)$$

Figure 2 presents the synchronization and scheduling parameters detailed below.

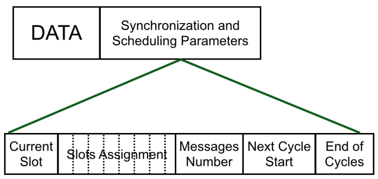


Figure 2: CLPB packet description (data & synchronization and scheduling parameters)

Current slot: is a reference slot that allows nodes to position in time.

Slots Assignment: is the result of the preprocessing phase. It describes what time slot did the *Sink* node assigns to each sender. Slot number 0 is always assigned to *Sink* node.

Messages Number: represents the total number of packets to be sent by *Sink* node and that should be received by all nodes. This parameter enable nodes to recognize missing packets.

Next Cycle Start: Depends on the transmission rate of *Sink* node. This transmission rate allows to compute the time between two consecutive cycles: the *CyclesInterleave* parameter presented below.

$$CyclesInterleave = \tag{2}$$

$$\begin{cases} 0, \\ \text{if } \textit{Sink} \text{ Transmission rate} < \text{Cycle Duration} \\ \\ (\lceil Transmissionrate/SlotDuration \rceil) \\ *SlotDuration] - CycleDuration(eq.1), \\ \text{otherwise.} \end{cases} \tag{3}$$

If the transmission rate is such that *Sink* node receives an application packet while previous packet is still in broadcast (the current cycle is not finished), then *CyclesInterleave* is null.

If *Sink* node receives an application packet much later. Hence, packets are queued at MAC layer if the total input rate exceeds the packet forwarding rate at the MAC layer. In this case, nodes enter in a sleep mode waiting for the next cycle.

Next Cycle Start is a key parameter that optimizes nodes duty cycle. In fact, instead of alternating between reception and sleep mode each time slot, nodes will go back to sleep and schedule wake up when more packets are available.

End of Cycles: Nodes sleep definitely based on *End of Cycles* value.

Nodes have to wake up each cycle in order to receive data packets. However, in case of packet loss, nodes will keep waiting for lost packets. To avoid such scenario, *Sink* node computes, based on traffic parameter, an end of communication time that we call *End of Cycles*. Then, when a node reaches the estimated time, it decides to sleep definitely (an another alternative could be chosen regarding the application requirements specified by the concerned entity: a come back to the initial state i.e half of the slot awake the other half sleep, or a wakeup after x seconds, etc.)

Nodes recognize missing packets scenario by comparing the number of received packets with the number of messages defined in the synchronization parameter (Figure 2).

To avoid that nodes miss data packet, it is important to over estimate *End of Cycles* parameter by supposing the worst case given by the Equation 4 below. We suppose that, in worst case, a sender has to delay broadcast to its time slot at the next cycle to send each packet. This gives as:

$$EndOfCycles = MessagesNumber * CycleDuration(eq.1). \tag{4}$$

D. Protocol Details Description

Upon reception of an application packet, *Sink* node schedules the broadcast of the packet plus the medium access control scheme information (see section C.) at the next time slot.

Each *sender* node wakes up on each slot on reception mode, RX, for a period of time that equals to a half time slot. During this period, there are two possible cases:

- no packet is received: The node goes back to sleep mode and wakes up (on reception mode RX) next time slot.
- a packet is received:
  - if it is allowed to transmit (based on time slots schedule), then it schedules a transmission.
  - if more packets are expected, based on *Sink* node transmission rate, then it computes the next cycle and goes back to sleep at the end of the current cycle. Otherwise, it sleeps definitely.

When a node wakes up on its assigned time slot to transmit previously received data, it transmits until the end of its slot. After this point, it delays the remaining packets to be broadcasted in the next cycle.

Nodes alternate between: reception, sleep and transmission modes. However, differently from other similar techniques, we strive to reduce the number of state switches and the duty cycle duration.

IV. Performance analysis

In this section, we compare flat broadcast strategies published in [4] (and its companion technical report [5]) and the new cross layer protocol *CLPB*.

We adapted, implemented and compared 9 multihop broadcast strategies [4, 5] with different levels of knowledge and extensively evaluate them against realistic human body mobility in a scenario that is representative of a real WBAN.

Our evaluation targets the parameters below:

- **Reliability: Percentage of covered nodes** Note that *Sink* node is our unique source of packets. We therefore compute the number of nodes that have received the message and present results as the percentage of covered nodes.
- **FIFO Order: Percentage of de-sequencing** The percentage of packets received in a different order than the sending order. This parameter is evaluated only in the case when *Sink* transmission rate is greater than $1 packet/s$.

Section B. presents simulation results when strategies are stressed with a *Sink* node transmission rates from 2 to 1000 packets/s.

The goal of studying strategies performance with various transmission rates and different MAC buffer sizes is to highlight the hidden impact of some parameters like MAC buffer size on strategies performances. Our simulation confirms that a cross-layer approach offers the best performance.

A. Simulation Settings

We use the discrete event simulator Omnet++ [19] and the Mixim framework [12] enriched with a specific channel and mobility model.

Above the channel model, we used standard protocol implementations provided by the Mixim framework [12]. In particular, we used, for the medium access control layer, the IEEE 802.15.4 implementation (2006 version, non-beacon mode). Sensitivity levels, packets header length and other basic information and parameters are based on IEEE 802.15.4 standard.

Each data point is the average of 50 simulations run with different seeds. We used Omnet++ default internal random number generator, i.e. the Mersenne Twister implementation (cMersenneTwister ; MT19937) for the uniform distribution, with different initialization seeds for each run, and the normal distribution generator (cNormal) for the signal attenuation.

The transmission power is set at the minimum limit level $-55\,dBm$ that ensures a limited energy consumption, reduces wearers electromagnetic exposition and allows an intermittent communication given the channel attenuation and the receiver sensitivity $-100\,dBm$.

For *CLPB* protocol, slot duration is set to $5ms$ with a bitrate equal to $1Mb/s$.

B. Increasing transmission rate

In this section, we stress the different strategies with *Sink* node transmission rate up to 1000 packets/s and a MAC buffer size equals to 100 which is the default value in the IEEE 802.15.4 standard.

In all body postures, *CLPB* strategy outperforms the flat strategies. Moreover, *CLPB* good performance is maintained up to 200 packets/s while the other strategies percentage drops starting from 10 packets/s.

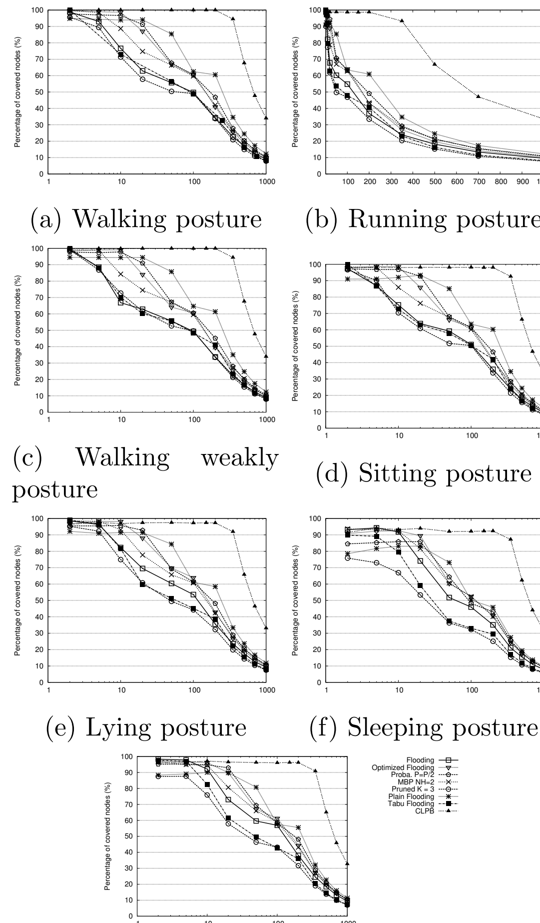
Network coverage Figure 3 presents the percentage of covered nodes in function of *Sink* transmission rate. This rate is presented as the number of broadcasted packets per second.

All flat broadcast strategies behave similarly: Going to 1000 packets/s, the percentage of covered nodes almost linearly decreases to reach 10%. At 100 packets/s, only 50% of the network is covered.

With *Flooding* strategy, the percentage decreases starting from 5 packets/s. With this strategy, nodes broadcast each received packet without restrictions. In the network the important amount of packets overloads the network and creates collisions.

For *Pruned Flooding* and *MBP*, the percentage decreases starting from 5 packets/s too. With *Pruned Flooding*, even if nodes are restricted to broadcast to only K nodes, still, with $K = 3$ many packets copies are generated and the network is overloaded. Also, because of the random choice of the next hops, some nodes are not qualified for forwarding. With *MBP*, broadcast is only delayed to give time for the other nodes to receive and acknowledge correct reception. This delay allows *MBP* to avoid network overloading and hence limits collisions and ensures a better percentage of covered nodes than *Flooding* and *Pruned Flooding* strategies.

In sleeping posture, *Flooding* and *MBP* strategies are able to maintain a good percentage of covered nodes equal to 91% up to 10 packets/s. Due to low mobility and less available links, network is less overloaded so less collisions and less packets loss. However, in more mobile and dense postures, performance decreases, for example, in running posture, *Flooding*



(a) Walking posture (b) Running posture

(c) Walking weakly posture (d) Sitting posture

(e) Lying posture (f) Sleeping posture

(g) Wearing a jacket posture

Figure 3: Percentage of covered nodes per posture for flat broadcast strategies and CLPB

strategy shows 82% of covered nodes for 10 packets/s and 75% in sitting posture.

CLPB maintains a good percentage, greater than 90%, up to 350 packets/s. Indeed, with 350 packets/s, *Sink* has one packet to send each 0.00285s. In our settings, a cycle lasts 5 time slots with a time slot duration equals to 5ms. At the end of the cycle, *Sink* node has 8 packets waiting in buffer for broadcast. Or, with a bit rate equals to $1Mbs$, *Sink* node can send up to 5Kbs during its time slot. A packet size is equal to 544 bits then *Sink* node can send up to (5Kbs/544 bits) packets i.e 9 packets per time slot. Beyond the rate 350 packets/s, performance falls to 30% of covered nodes by 1000 packets/s. Nodes are no more able to broadcast all waiting packets, then new received packets are dropped because buffer is saturated at MAC level.

MAC buffer size impacts strategies performance. For this reason, we extend our analysis by varying MAC buffer size to pinpoint this impact. Simulation results are presented in [5].

Percentage of De-sequencing Figure 4 presents the percentage of de-sequencing in function of *Sink* node transmission rate. We evaluate the FIFO order consistency of the different strategies.

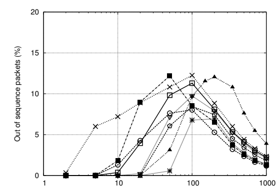
Three phases can be observed:

- At the beginning, all strategies present 0% of de-sequencing. At this point, strategies are able to handle more than one packet in the network.
- Then, from a given rate (depending on the strategy), the percentage increases. Here, based on Figure 3, the percentage of covered nodes decreases due to collisions. Therefore, sequencing is no longer ensured.
- Finally, the percentage decreases to converge to 0% again due to the fact that few packets are received.

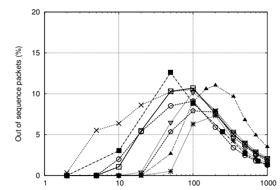
We observe that, for flat broadcast strategies, the inflection points of different curves have the same abscissa. This abscissa corresponds to a transmission rate equal to 100 packets/s. Looking deeper to different set parameters, 100 is the default value of the buffer size at the MAC level.

MBP strategy presents the highest percentage of de-sequencing for all postures, starting from 2 packets/s. In this strategy, nodes can whether broadcast immediately received packet or put it in the buffer and delay broadcast depending on threshold values.Thus, de-sequencing is more feasible.

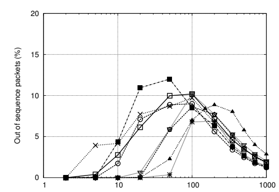
Percentage of de-sequencing increases starting from 5 packets/s for *Flooding* and *Pruned Flooding*



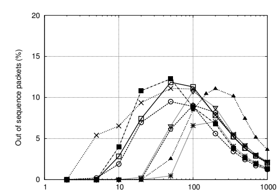
(a) Walking posture



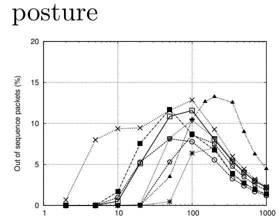
(b) Running posture



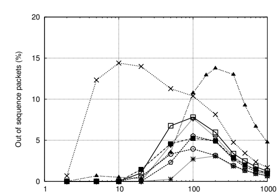
(c) Walking weakly posture



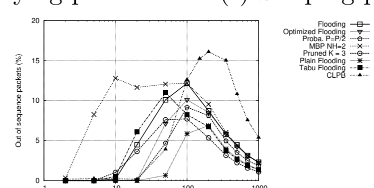
(d) Sitting posture



(e) Lying posture



(f) Sleeping posture



(g) Wearing a jacket posture

Figure 4: Percentage of de-sequencing per posture for flat broadcast strategies and CLPB

and from 20 packets/s for *Optimized Flooding*, *Plain-Flooding* and *Probabilistic Flooding*, for most postures. *Flooding* and *Pruned Flooding* have difficulties to handle transmission rate increase due to collisions and packets loss. An exception with sleeping posture, where the percentage of de-sequencing is observed starting from 10 packets/s due to the characteristics of this posture.

CLPB reacts as the other strategies and we observe de-sequencing in the received sequence. This is due to the mobility model. That is, unreliable links may occur, thus allowing reception of one of several packets from the broadcasted sequence. The links then disappear and the complete sequence will be received through a more reliable link.

V. Conclusion and future works

This work is, to the best of our knowledge, the first that proposes a MAC-network cross-layer protocol for broadcast in WBAN. Our work was motivated by results obtained after an extensive set of simulations where we stressed the existing network layer broadcast strategies [4] against realistic human body mobility and various transmission rates.

With no exception, the existing flat broadcast strategies (detailed in chapter register a dramatic drop of performances in terms of percentage of covered nodes, end-to-end delay and energy consumption when the transmission rates are superior to 11Kb/s.

We therefore, propose a new MAC-network cross-layer broadcast protocol that exploits communication graph defined by the body postures in order to optimize medium access and nodes synchronization. Our protocol maintains its good performances up to 190Kb/s transmission rates.

Our work opens several research directions. We plan to investigate the slot synchronization in WBAN.The cross-layer protocols designed so far for WBAN assume a strong slot synchronization. Efficiently synchronizing slots in WBAN with realistic human body postures and mobility is an open issue.

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