On-Demand Data Forwarding for Automatic Adaptation of Data Propagation in WBANs

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Abstract—**Practical experience reveals the characteristic properties of Wireless Body Area Networks (WBANs), signifying the need for a well-designed communication protocol. High mobility, stringent resource constraints, and low and time-variant quality of wireless links are some of the challenging issues in WBANs. Typical applications further have varying Quality-of-Service requirements and demand reliable and fast data transmission at low energy cost. This paper proposes a simple, robust, and optimized protocol for data propagation in WBANs. A hybrid design approach is proposed that automatically adapts the network topology according to the connectivity status of the network. An on-demand data forwarding mechanism combined with an epidemic data propagation strategy realize a proper data delivery and robustness while minimizing the idle listening and unnecessary data forwarding. Several experiments using wireless sensor nodes deployed on a body reveal how this protocol can automatically adapt the network in different situations. The results confirm the robustness and improved behavior of this protocol in comparison with existing fixed protocol architectures.**

I. Introduction

In the last decade, there has been lots of interest in exploiting wireless sensor devices in health applications. More specifically, deploying bio-sensors on a human body to measure various biological signals of the body, to form a Wireless Body Area Network (WBAN). Very small devices make it more convenient and feasible to wear a WBAN during normal daily life. In a typical WBAN, information from sensors deployed on different positions on the body is relayed to a gateway node on the body and then to a base station for further analysis, and storage. This information can also be sent to a medical center, for instance, to be observed by care workers. Important applications for WBANs are elderly care, healthcare of patients with specific chronic diseases such as COPD (chronic obstructive pulmonary disease), post-surgery monitoring, and sports training.

There has been a lot of recent activity to provide body sensor devices. For instance, specific sensors have been developed in the CodeBlue [1] project at Harvard University to measure several body signals (heart rate, EKG, and oxygen saturation). The Ubimon group at Imperical College has developed custom wireless nodes [2] with an interface to wearable and implantable sensors. However, several experimental studies including our own experiments using wireless nodes show that WBANs have specific characteristics that differentiate them from the typical Wireless Sensor Networks (WSNs). Thus special attention is required for designing appropriate communication protocols for such networks. In particular, we point out three special characteristics of WBANs as follows.

Stringent power constraints and short transmission range: The power and size constraints of body sensors are tighter than in other wireless sensor applications. To enlarge the lifetime of sensors, ultra-low power RF devices are used which leads to a very short RF transmission range. The literature describes several low-power body sensors with a transmission range below one meter ([3], [4], [5]). In some applications, sensor devices generate power from body resources. Consequently, the total amount of consumable energy for wireless communication and computation is strictly limited.

Low and time-variant quality of links: Several empirical investigations show that the propagation loss around and in a human body is considerably high ([6], [7], [8], [9], [10]). The path-loss coefficient value lies between 4 and 7, whereas its value is much less in air. This makes the links between body nodes unreliable and further limits the transmission range. Practical experiments using CrossBow TelosB [2] sensor nodes presented in [11] and [12] show that the Packet Reception Ratio (PRR) between some nodes is lower than 60% for 46% of the experiments. In addition, experiments in [13] show that the link status varies in different postures and even within a given posture, the links may vary and have intermittent disconnections [14]. The general conclusion is that wireless links in WBANs are quite unreliable and time-variant.

Mobility: The human body is basically mobile and can be in several postures. It causes frequent changes in network topology over time. Thus no assumptions can be made for relative node positions and the network protocol should be robust against such frequent movements of the sensor nodes.

We performed several experiments using MyriaNed [15] nodes deployed on a body in different postures to get insight into the links behavior in the network. These experiments confirm the mentioned challenges in WBANs. To address these challenges and considering typical requirements in the target applications, we developed a protocol for intra-WBAN communication with the main objectives of robustness, power efficiency, and simplicity. An on-demand data forwarding strategy using gossiping is exploited that does not rely on any specific routing structure. Using the proposed mechanism, the data propagation strategy is automatically changed from a star strategy to a multi-hop architecture and vice versa according to the network condition. Experiments show that this protocol gives a good trade-off in terms of performance metrics and energy consumption and can be a generic solution for communication in WBANs.

The paper is organized as follows. The next section gives a review of related work, comparing two general approaches used in protocol design for WBANs. Section III presents the

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underlying network architecture of our hybrid approach. The proposed on-demand data forwarding mechanism is presented in Section IV. The experiments, comparing several protocol approaches, are explained in Section V. Section VI concludes.

II. WBAN Protocol Design Approaches

The first choice for designing a WBAN has been a *star architecture* (Fig. 1(a)). In such a network, the sensor nodes are supposed to send information directly to a gateway node placed on the body. In [16], [17], and [18], for instance, MAC protocols are proposed for WBANS assuming an underlying star architecture. Considering the short distances between nodes in a typical WBAN, a star architecture seems to be a reasonable option that in general is simple to implement with an overall low latency because of direct links to the gateway. Moreover, nodes in a star architecture are independent. For instance, in the case of a node failure, other nodes continue to work as normal. However, this architecture suffers from low Packet Delivery Ratio (PDR) and insufficient reliability caused by low and time-variant quality of wireless links. Further, the power constraint and short transmission range of typical on-body sensor nodes, and the severe transmission loss through the body limit the effectiveness of such architectures for many applications. Our experiments using MyriaNed wireless nodes [15] show that in certain postures of the body, some nodes are disconnected from the gateway node, even if they use their highest transmission power. This shows that a star architecture cannot be sufficiently reliable in all applications.

The alternative approach for WBANs is multi-hop communication (Fig. 1(b)). In such networks, nodes are not required to send their data directly to the gateway node. Instead, they send their data to some neighbors in range according to the underlying routing structure to reach the gateway in one or more hops. A tree-based multi-hop protocol is proposed in [19] in which the routing spanning tree is set up autonomously to route data from the node to the gateway. A common problem of every tree structure in WSNs is that in the case of a node failure or node movement, the tree has to be reconstructed. Although a method for tree reconstruction using a join procedure is presented in [19], it is mentioned that only low mobility is supported. A posture change in a human body will likely change the body network topology. Moreover, frequent posture changes demand a frequent tree reconstruction which is challenging and costly. A probabilistic packet routing mechanism is proposed in [13]. A stochastic metric called link likelihood factor (LLF) is calculated and is broadcast by all nodes. Each node tries to send its data to a neighbor with the best link to the gateway. The drawbacks of this protocol are, first, the reliance on symmetric links for measuring the quality of outgoing links which is typically unrealistic for WBANs; second, the data exchange overhead imposed for detecting the best connection path.

Multi-hop protocols are shown to have in general a high end-to-end PDR and nodes can be equipped with lower power radios. Considering low transmission range, a multi-hop architecture can be beneficial, and in some cases it is the only possible option. On the other hand, multi-hop protocols are more complicated and the network may suffer from longer latencies. Experiments in [11] and [12] explore the trade-off between using a star and a multi-hop architecture, highlighting

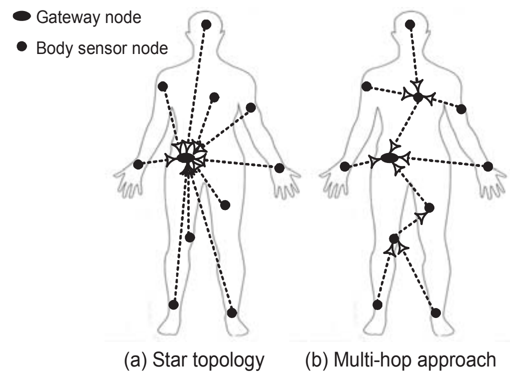


Fig. 1. Common approaches for intra-WBAN communication.

their respective performance characteristics. There is no solution that is optimal for all applications of WBANs because of different constraints and requirements.

To deal with the link unreliability issue and overhead of routing structure reconstruction in the existing multi-hop protocols, we presented a multi-hop protocol stack [20] in which a gossiping strategy is exploited for data dissemination. It does not use any specific routing structure and does not make any assumption about the relative position of nodes or link properties (such as PDR, symmetry). This makes the protocol robust against such WBAN challenges as high node mobility (posture changes) and low quality wireless links. However, it is not optimized from the power consumption point of view, as the nodes always listen to other nodes and always forward information both of which might not always be necessary.

In this paper, we propose a hybrid approach to develop a *simple*, *robust*, and *power-efficient* protocol for intra-WBAN communication taking the special characteristics of typical WBANs into consideration. As is common, we assume one more powerful node (gateway) in the WBAN. The body sensor nodes try to send their data directly to the gateway node (as in a star topology); they further utilize a mechanism to detect nodes that cannot properly reach the gateway and then start forwarding their data. Doing so, the network will have a star topology when all nodes have a good connection to the gateway. However, if some nodes do not have a proper link to the gateway, the topology will autonomously change to a required level of multi-hop communication. A gossiping strategy, like the one we used in [20], is used for data forwarding. Therefore, even for on-demand multi-hop data dissemination, no specific routing structure is required to be established and maintained. This keeps the network protocol simple and robust.

III. Network Architecture

Assume that $S = \{s_1, s_2, ..., s_N\}$ is the set of N sensor nodes deployed on a body. One of these nodes, say s_N, is the gateway and is supposed to have more powerful features than other nodes. This can include more battery capacity, more computation capability, and a higher transmission range. The gateway gathers information from all nodes in the WBAN and then sends the collected (or aggregated) data to a base station. Depending on the application scenario, the gateway may receive some information from the base station and forward this to the body sensor nodes. Note that the protocol for communicating with the base station is not addressed in

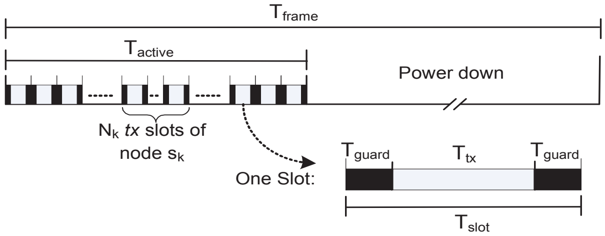


Fig. 2. The structure of a TDMA frame of the MAC protocol

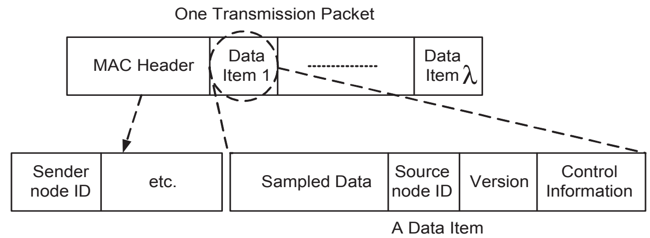


Fig. 3. A transmission packets in the data propagation protocol

this paper and can for instance be a multi-hop ambient network [21] or star architecture with the base station as its center.

TDMA-based protocols are widely used for WBANs ([16], [17], [18], [19], [20]) as a suitable MAC layer which outperforms other mechanisms such as CSMA-based protocols in many aspects. Long sleep periods and contention-free behavior of the TDMA strategy make the protocol energy efficient with maximal bandwidth utilization. Thanks to the small deployment area and the presence of a more powerful node (the gateway) playing a coordinating role, the synchronization between nodes in a WBAN is quite reliable. Moreover, the limited network size allows a very small duty cycle and limits scheduling efforts. Thus we exploit a TDMA-based MAC layer in our protocol stack for intra-WBAN communication.

In the TDMA strategy, time is divided into frames with length T_{frame} consisting of active and inactive parts. Nodes are in sleep mode in the inactive part. The active part of the frames is divided into equal length time slots. Every node s_i in the WBAN is assigned $M_i \geq 1$ fixed, subsequent, and unique transmit (tx) slots in which the node transmits its packets. The value of M_i depends on the amount of information that s_i has to transmit in each frame and the slot size (T_{slot}). Since the slots are unique, the protocol is contention free (provided that a proper synchronization mechanism is in place). The total length of the active part is then $T_{active} = T_{slot} \times \sum_{1 \leq i \leq N} M_i$. Fig. 2 depicts the structure of a TDMA frame. To resolve small clock differences between different nodes, as is common, a guard time with length T_{guard} is inserted at the start and the end of every transmission slot. Every listening node starts to listen to the slot from the beginning of the slot until it receives the whole packet or reaches the end of the slot time. The transmitter sends its packet in the T_{tx} time duration.

The gateway node listens to all nodes in every frame. Other nodes always listen to the gateway slot as well as the slots of any node that is requested by the protocol. Therefore, the minimum radio activity of a node in a frame consists of the transmission of its packets in its dedicated slots and listening to the gateway slot. More listening activity occurs only when invoked by the data routing mechanism.

Listening to the gateway slot in each round is crucial for the protocol. The gateway packets are also used as a beacon for synchronization purposes. Any node in each frame aligns its time frame with the gateway. If a node does not receive a packet from the gateway in some exceptional cases, to prevent loosing synchronization, it starts to listen to other nodes. However, this does not occur in normal circumstances, as the gateway transmission range is supposed to be high enough to cover all nodes in all postures.

We use the term *packet* to refer to what a node broadcasts in one tx slot. A packet consists of λ data items, shown in Fig. 3. A *data item* is a piece of data which includes the sampled data, its version, and the ID of the source node of the data. As s_i is given M_i tx slots, the number of data items that s_i can transmit in a frame is $M_i \times \lambda$ from which a part is reserved for its own data items. If T_i denotes the sampling period of node s_i, T_{frame}/T_i data items are generated per frame on average and should be included in the packet. Actually, at design time, the value of M_i is properly set so that $\frac{T_{frame}}{T_i} < M_i \times \lambda$. Note that if $T_i > T_{frame}$, one data item from the node itself is still inserted to the packet in each round. So each item generated by s_i may have the opportunity to be retransmitted in several rounds which provides a better data delivery ratio. The remaining part of the available data items in each frame is used for data forwarding.

IV. On-demand Listening and Forwarding

All nodes are supposed to have a direct connection to the gateway (star network) unless the opposite is stated by the gateway. We propose a mechanism which dynamically recognizes the nodes that do not have proper connection to the gateway. The gateway computes a quality factor for all its incoming links and then distributes a short summary. Nodes receive this information, start listening to the nodes in need and then forward their data. An epidemic strategy is exploited for data forwarding in such cases.

A. Outage Characteristics in WBANs

We experience two kinds of disconnection in WBANs. The first kind of outages are rather short term and caused by fading due to movement of the nodes or a temporary interference. This frequently happens in mobile postures such as walking. An empirical measurement for outdoor setting in [18] reveals the periodic fluctuation of RSSI of several links while walking. It is shown that the RSSI fluctuation frequency matches the walking step frequency (i.e., 1.2 steps per second in [18]). Moreover, the IEEE 802.15.6 working group [14] has reported the results of extensive indoor experiments, proposing a two-state channel model for walking in a WBAN. The transmission of a node may happen while the RSSI has its own high peak and succeeds. On the other hand, the packet may be transmitted while the link is in its weak state and so fails. Therefore, we always see some transient failure or success in packet transmission of a node. If a node has a good link to the gateway, this kind of short outages can be combated using retransmission of the packets by the source node itself.

The second kind of outages which are specially the target for our on-demand forwarding mechanism are longer term outages. Shadowing caused by posture changes and also movements can bring a link to a situation in which the node cannot reach the gateway for a long period of time. We observed many cases during our experiments in which some nodes cannot send any packet to the gateway for the whole posture duration. This kind of outage is especially very problematic since there will be no data reception from a node for minutes or even longer. This may lead to a serious failure of the application.

As the core of the on-demand data forwarding, the gateway measures a metric based on which it reports the nodes with a poor link to the gateway. There are two points in such measurement. First, the metric should differentiate short and long term outages so that the forwarding mechanism is initiated only when a node is in a long term outage state. Second, it is important to detect this situation quickly to minimize the amount of data loss of the node with a poor link.

B. Gateway Measurements and Feedback

The gateway calculates a metric $\rho^t_{i\to N}$, defined below in Eqn. 2, for each node s_i in the network, during TDMA frame t, that is compared to a threshold to evaluate the quality of the link from s_i to the gateway. This metric is derived from the link Packet Reception Ratio (PRR). Let $L^t_{i\to N}$ be a logical value (0 or 1) that shows the connection status of node s_i to the gateway node (s_N) in round (TDMA frame) t. The value of PRR for s_i at round t, denoted by $P^t_{i\to N}$, over the last h rounds is then estimated as follows.

$$P^t_{i\to N} = \frac{1}{h}\sum_{k=0}^{h-1} L^{t-k}_{i\to N} \qquad 1 \leq i < N \tag{1}$$

A proper choice for parameter h depends on the characteristics of the human movement and postural changes. Considering 10 seconds for a posture change to take place seems to be reasonable and so a value of $h = 10/T_{frame}$ is set. As the value of $P^t_{i\to N}$ gives the average status of the link $L_{i\to N}$ in a time window, it adheres the same importance to all previous samples. To adapt accurately to new circumstances, the link history should be taken into account and the metric should react quickly to dynamics influencing network topology such as mobility and posture changes. If the metric value is increased late, information from the corresponding node may be lost for a while because other nodes have not been informed about listening to that node. Decreasing it late does not lead to information loss, but causes unnecessary listening for nodes that were participating in forwarding the packets of that node. On the other hand, the metric should be stable against short term outages.

We use a metric derived from $P^t_{i\to N}$, similar to the metric proposed in [13], by considering the history of the link, to detect if a link failure is due to a real change in the network status (long term outage).

$$\rho^t_{i\to N} = \begin{cases} \rho^{t-1}_{i\to N} + (1-\rho^{t-1}_{i\to N}).P^t_{i\to N} & L^t_{i\to N} = 1 \\ \rho^{t-1}_{i\to N}.P^t_{i\to N} & L^t_{i\to N} = 0 \end{cases} \tag{2}$$

If the gateway received a packet directly from node s_i in the last frame, the metric is increased towards 1 with a rate determined by the history of this link ($P^t_{i\to N}$) and the deviation of the previous value $\rho^{t-1}_{i\to N}$ from its maximum value. Notice that if the link from s_i to the gateway ($L_{i\to N}$) has shown a good connection in the history, $P^t_{i\to N}$ is relatively high. Consequently, $\rho_{i\to N}$ will converge to its maximum value very fast. On the other hand, if the gateway does not have a good history of receiving from s_i, the value of $P^t_{i\to N}$ is low. Thus, the last successful reception is considered as a likely temporary connection and so $\rho_{i\to N}$ will increase with a lower rate. In the second case, in which s_i has not succeeded to reach the gateway in the last round, the metric is decreased, again with a rate proportional to the history of the link. If $P^t_{i\to N}$ is high, the last link failure is supposed to be an incidental disconnection and the metric $\rho_{i\to N}$ decreases with a low rate. The main idea behind this is that if the link has shown a good record, incidental disconnections do not decrease the metric too much and vice versa. Fig. 4 illustrates the reaction of the PRR and the derived quality metric $\rho_{i\to N}$ for a sample link.

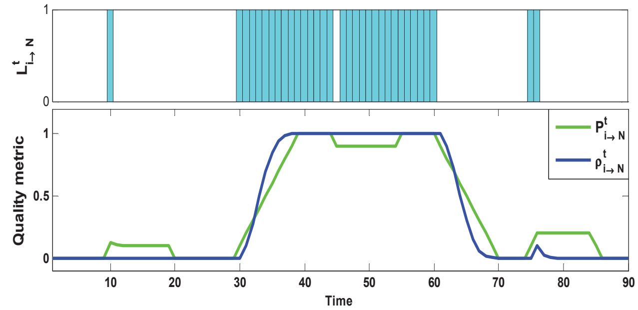


Fig. 4. Packet Reception Ratio (PRR) and the derived link quality metric for a sample link $L_{i\to N}$.

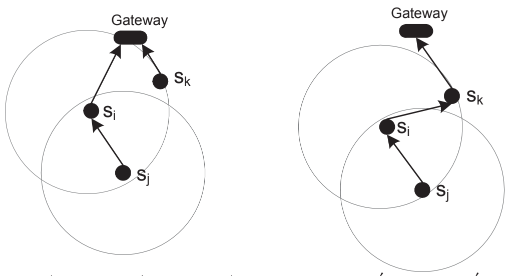
Based on the metric $\rho_{i\to N}$, the gateway decides whether node s_i needs data forwarding help, by comparing its link quality with a given threshold ℓ_i. The value of the threshold is given individually for each node in the WBAN according to the nature of the signal being sampled by node s_i, and its required level of Quality-of-Service (QoS) such as reliability. Later, we discuss how to decide about these thresholds.

Let $\Psi^t \subset S$ be the set of nodes without a sufficiently good link to the gateway at round t, called the *requested set* ($\Psi^t = \{s_i \in S \mid \rho^t_{i\to N} < \ell_i\}$). To activate on-demand forwarding, the gateway includes a bitmap consisting of $N-1$ bits in its packets in which the i^{th} bit reflects whether $s_i \in \Psi^t$. This bitmap activates the data forwarding mechanism, as explained in the next subsection. Note that in the implementation of the mechanism, some hysteresis is applied to prevent too frequent switches when the value of the quality factor is around the threshold. We add s_i to the requested set when $\rho_{i\to N}$ drops below threshold ℓ_i. In contrast, for excluding s_i from Ψ^t, the quality factor should go higher than $\ell_i + \Delta\ell$. We used value $\Delta\ell = 0.2$ in the implementation. Using such a hysteresis, the node is kept in the requested set while its link quality to the gateway is around the threshold.

C. Listening Schedule

Each node transmits its information in the assigned tx slots hoping that the gateway receives the packets. On the other hand, nodes receive a bitmap, stating the requested set Ψ^t at each round which represents the nodes that do not have a good link to the gateway. Then, each node starts listening to the slots dedicated to the nodes in Ψ^t. Subsequently, if they receive any data from those nodes, they participate in forwarding that data.

Note that a node s_i tries to participate in data forwarding for the nodes in the requested set regardless of whether node



$s_j \in \Psi^t, s_i \notin \Psi^t, s_k \notin \Psi^t$ $\quad$ $s_j \in \Psi^{t'}, s_i \in \Psi^{t'}, s_k \notin \Psi^{t'}$

Fig. 5. An illustrative example of the on-demand forwarding mechanism.

s_i itself has a direct link to the gateway. This provides a multi-hop structure for data propagation within the WBAN. For example, suppose that node s_j cannot reach the gateway due to large distance or low transmission range while node s_i is in its radio range. So if s_i listens to s_j, it receives and forwards the data of node s_j. If node s_i itself has a direct link to the gateway, then the packets of s_j reach the gateway in two hops (Fig. 5, left side). Otherwise, the same procedure happens for all propagated information from node s_i by another node, say s_k (Fig. 5, right side). Note that considering the typically rather small network size and deployment area, the multi-hop paths will not be long (at most three hops in any of our experiments).

With such listening mechanism, the number of listening slots in each frame is determined by the number of nodes in the requested set. When all nodes have good connection to the gateway, the requested set is empty and nodes do not listen to any other nodes in the WBAN (but the gateway). If some nodes do not have good enough links to the gateway, other nodes listen to them to forward their data to the gateway.

Listening to the entire requested set can be thought of as a conservative strategy to provide as little as possible data loss in the case that some nodes have no proper link to the gateway. However, more aggressive schemes can also be exploited here to further reduce power consumption of the nodes. The point is that when the quality of link $L_{j\to i}$ is very poor, it may make no sense that node s_i consumes energy for listening to s_j with only a low chance of success. So s_i can maintain a *listening subset* of the requested set at any point of time from which it can hear well. Such a subset should be carefully updated to include nodes that are still in the requested set and whose link to s_i becomes good, because of a movement for instance.

Adding such an extension to the protocol imposes an additional level of complexity in the implementation. So the obtained gain should be convincing, specifically when the requested set is small in a WBAN. We investigated such a mechanism in real WBAN deployments in our experiments. The results are discussed in Section V-D.

D. Data Propagation

If all nodes have a good connection to the gateway ($\Psi^t = \emptyset$), every node only transmits its own data. Otherwise, a routing mechanism should be exploited for multi-hop data propagation. As the network topology of the WBAN is always prone to change, any assumption about the position of the nodes and their connectivity is not reliable. We use a gossip-based strategy [20] which does not rely on any routing structure and so is robust against frequent changes in the WBAN topology.

The node s_i may receive several packets in each round from the nodes that it is listening to, each including several data items. The node then maintains a pool of the data items that it has received and has to forward. At any time, a buffer of the last $\lceil T_{frame}/T_j \rceil$ received data items originated from the node s_j is stored in the data pool. The older data items from s_j will be removed from the pool once the newer data items arrive. Doing so, the maximum number of data items in the pool of node s_i is $\sum_{1\le j<N, j\ne i} \lceil T_{frame}/T_j \rceil$. In a typical WBAN, the actual number of data items in the data pool is much less than the maximum, as only a few nodes might be in the requested set and able to reach s_i. Once the node s_j is taken out of the requested set Ψ^t, all its data items are deleted from the data pool of any node in the network, as it no longer needs data forwarding help. This provides a better chance for other data items in the data pool to be forwarded.

Every sensor node is primarily responsible for propagation of its own sampled data. In addition, other data items that it may have received from other nodes should be forwarded. At every round, the node s_i can include $\lambda \times M_i$ data items in its packets. A part of this amount ($\lceil T_{frame}/T_i \rceil$) is dedicated to the node's own data items and the rest is used for transmitting the data items in its data pool. As the number of data items in the data pool waiting for transmission may be more than the available room in the packets, a subset is selected in each round. This is done by a uniformly random item selection from the data pool to give statistically equal chance to all items. Algorithm 1 presents the behavior of body sensor nodes in each TDMA frame to implement the on-demand listening and gossip-based data forwarding mechanism.

E. Link Quality Thresholds

The basic concept of our on-demand data forwarding mechanism is that a node receives data forwarding help when it does not have a good enough link to the gateway. Different nodes may have different PDR requirements. In this subsection, we give a guideline for setting values for these thresholds according to the individual QoS requirements of the nodes.

Note that higher thresholds impose more power consumption overhead to the nodes as they have to listen to more nodes. It also affects the efficiency of the data forwarding mechanism. When nodes have to listen to more nodes, they will have more items in their data pool waiting for transmission. So the probability of being selected from the data pool decreases. It means that we may be sacrificing some really demanding items for propagating items that might already have reached the gateway. On the other hand, a very low value for the thresholds boils down to a dived data delivery to the gateway. Thus, setting the right thresholds is crucial for an optimum working condition for the WBAN.

Initially, nodes may use a retransmission schemes to have better PDR against short term outages. The node s_i is generating samples every T_i seconds. So a data item generated by node s_i has $\frac{T_i}{T_{frame}}$ rounds of opportunity to be transmitted directly by s_i itself. Let X_i be the probability distribution of the number of required transmissions of a single data item of s_i to be received by the gateway. We assume that X_i has a geometrically distributed behavior. This assumption is confirmed to be reasonably accurate by the result of experiments that we have performed using wireless nodes. To statistically

Algorithm 1: Behavior of body sensor node s_i at time frame t.

```
foreach active slot k do
    if Owner(k) = s_i then                        /* own tx slot */
        TransmitPacket(TxPacket);
    else if Owner(k) ∈ Ψ^{t-1} then          /* in requested set */
        RxPacket=ListenToSlot();
        if RxPacket ≠ Nil then
            foreach RxItem ∈ RxPacket do
                StoreInDataPool(RxItem);
            end
        end
    else if Owner(k) = s_N then              /* the gateway slot */
        RxPacket=ListenToSlot();
        if RxPacket ≠ Nil then
            Ψ^t ⟵ RxPacket.Ψ − {s_i};
        else
            Ψ^t ⟵ Ψ^{t-1};
        end
    end
end
forall node s_l ∈ S − {s_N} do
    if s_l ∉ Ψ^t then
        FlushDataPool(s_l);
    end
end
TxPacket ⟵ {OwnDataItems} ∪ SelectFromDataPool();
```

satisfy the packet delivery requirements of node s_i denoted by $0 < R_i \leq 1$, the probability of X_i being less than the number of available transmission rounds should be less than the reliability requirement R_i, stated in Eqn. 3.

$$\mathbf{P}(X_i < \frac{T_i}{T_{frame}}) > R_i \tag{3}$$

The probability of a successful transmission from s_i directly to the gateway is approximated by the PRR of the link ($P_{i \to N}$). Considering the cumulative distribution function of the geometric distribution, we come to Eqn. 4.

$$1 - (1 - P^t_{i \to N})^{\frac{T_i}{T_{frame}}} > R_i \tag{4}$$

Solving that, we obtain the threshold ℓ_i for the quality of the link from node s_i to the gateway, as follows.

$$P^t_{i \to N} > \underbrace{1 - (1 - R_i)^{\frac{T_{frame}}{T_i}}}_{\ell_i} \tag{5}$$

At run time, a link with a PRR less than this threshold does not statistically satisfy the reliability requirement. This is the point that the on-demand listening and forwarding mechanism is triggered to help the node with insufficient link quality to the gateway. In our protocol, we compare the derived quality metric from PRR (Eqn. 2) with this threshold. As explained, this metric is based on the PRR, with a faster reaction for constant changes in the link quality and less variation in the case of transient link fluctuations.

V. Experiments

We performed several experiments using wireless nodes deployed on a body to verify the functionality of the proposed mechanism and to compare it with other approaches. In this section, the experimental setup is explained and the analysis of the obtained result is presented.

A. Experimental Setup

We use the *MyriaNed* [15] wireless nodes for our experiments which feature an ATMEGA128 microcontroller and a *Nordic* nRF24L01 radio chip [22] as transceiver. The radio chip works in the 2.4GHz ISM band which is one of the proposed carrier frequency bands by IEEE 802.15.6 for WBANs, using a data rate of 2Mbps and a 32 bytes fixed packet size. Taking the packet preambles into account, the transmission time of a packet is around $T_{tx} = 200\mu s$. The radio can be set in RX, TX, or Standby modes. Current supply of the radio chip in RX mode is 12.3mA. In TX mode, four transmit power levels (-18, -12, -6, 0dBm) can be adopted for the radio with the radio current of 7, 7.5, 9, and 11.3mA, respectively. It allows us to test the protocol in various network conditions. The radio consumes very low power (22μA) in standby mode.

Each TDMA slot of the MAC layer consists of a time for transition to the desired radio mode (T_{trans}), two guards (T_{guard}), and the transmission time (T_{tx}). In the MAC implementation and considering the specification of the radio chip, the slot length is approximately $T_{slot} = 900\mu s$. The TDMA frame length is set to one second ($T_{frame} = 1$ sec.). Therefore, having 11 active slots in each frame, we come to a duty cycle of around 0.99%. Considering a 32 bytes packet length, three data items ($\lambda = 3$) can be included in each packet. Each node is equipped with a 4MByte Flash memory which is used to log data such as the radio activities, content of the data pool and other useful information at each round during the experiments. After finishing each experiment, the logged data is downloaded from the nodes and is analyzed to extract efficiency metrics.

We deployed 11 nodes (including the gateway) on different positions of the body, shown in Fig. 6. Node s_{10} is deployed on the back. Several experiments of in total 30 hours have been done each lasting one hour with a particular configuration. This is done to observe the behavior of the protocol in various circumstances. The configurations include different transmit power levels, different sampling periods ($T_s = 1$, 3, or 5 sec.), and different posture patterns. To simplify the process of data analysis and presentation, we assume the same settings for all nodes during each setup. A combination of *walking*, *standing*, *sitting*, and *lying down* postures is set as the posture pattern for each experiment. An experiment is repeated three times, with exactly the same settings and MAC protocols, exploiting different data propagation mechanisms. The tested protocols are the star approach, full gossip data forwarding as presented in [20] (FG), and the proposed on-demand listening and forwarding strategy (ODLF). Although the same posture patterns and similar movement behaviors are used for three experiments of a setup, the actual connectivity and link quality cannot be guaranteed to be exactly the same. However, according to our measurements, the average size of the requested set is very similar for the three experiments in each setup, which indicates a similar average connectivity to the gateway. All experiments were done in an indoor environment.

B. Performance Metrics

We calculate several metrics from the logged information in the Flash memory of nodes, especially the gateway node. The Packet Delivery Ratio (PDR) is the fraction of items received by the gateway over all generated items. It reveals

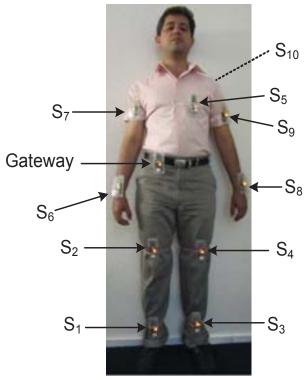


Fig. 6. Position of the nodes deployed on the body in the experiments.

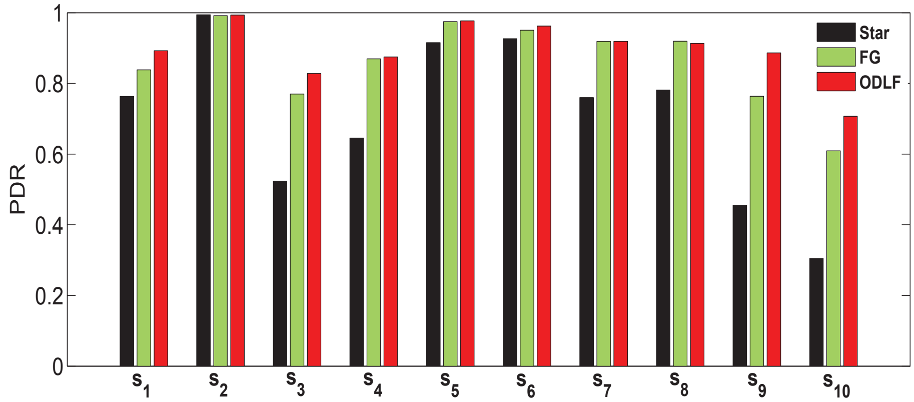


Fig. 7. Average PDR of nodes to the gateway over all experiments exploiting different protocols.

the reliability of each protocol. In a star strategy, the data originating from node s_i will be lost if the link $L_{i \to N}$ fails for T_i/T_{frame} subsequent rounds. There is also a chance of data loss in the multi-hop protocols. Having no connection to any node can be a source of data loss, because none of the nodes in the WBAN can help in this situation.

The next metric that is worth considering here is the length of burst data loss. Long outages of a node can be a strong drawback of an approach. Note that even if the PDR values of two experiments are the same, the distribution of the data losses may be a distinguishing factor. We calculate the average length of burst data losses for each node as well as the maximum length of burst loss as two metrics for evaluation of the protocols.

The last metric is the energy consumption of sensor nodes whose value in a tx and rx slot is calculated as follows.

$$E_{tx} = (I_{tx} \cdot T_{tx} + I_{trans} \cdot T_{trans}) \times V_{bat} \tag{6}$$

$$E_{rx} = (I_{rx} \cdot (T_{tx} + 2 \cdot T_{guard}) + I_{trans} \cdot T_{trans}) \times V_{bat} \tag{7}$$

I_{rx} and I_{tx} are receiver and transmitter current, respectively. I_{trans} and T_{trans} are the radio current during the transition between modes and the time length of the transition which for nRF24L01 have the values of 8mA and 130μs, respectively. V_{bat} is the voltage level of the battery, which is 2.4V for these nodes. Provided that the radio current during the standby mode is $I_{pd}(= 22\mu A)$, the energy consumption of a node in each frame in standby mode is calculated by Eqn. 8. Finally, the total radio energy consumption of a node per TDMA frame is computed by Eqn. 9.

$$E_{pd} = I_{pd} \times (T_{frame} - T_{slot} \times (L+1)) \times V_{bat} \tag{8}$$

$$E_{radio} = E_{tx} + L \times E_{rx} + E_{pd} \tag{9}$$

Parameter L stands for the number of listening slots in a frame and its value is 1, $1 + |\Psi^t|$, and N for the Star, ODLF, and FG mechanisms, respectively.

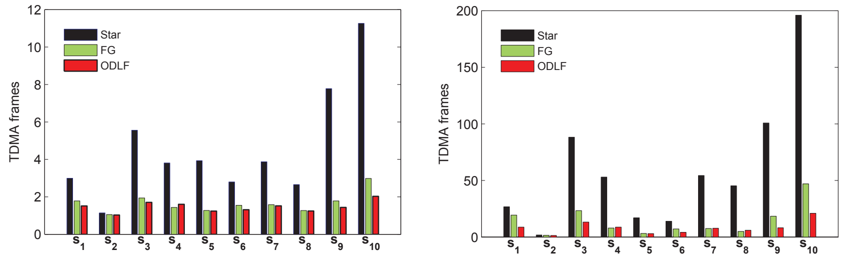
C. Data Analysis and Results

Observations from our experiments confirm the challenges about the quality of wireless links in WBANs. The transmission range of nodes on the body strongly decreases in comparison with transmission through the air. Quality of links is observed to be very time-variant. Posture changes and even minor movements of the body change the quality of links. These have been our main motivations for developing the on-demand data forwarding mechanism.

To get a general impression of the behavior of different protocols, the average results obtained from all performed experiments are presented. Fig. 7 shows the PDR values over all experiments, individually shown for each node and each protocol stack. This result shows that, taking all experiments with different setups into account, our ODLF protocol provides much better PDR than the Star approach, and almost the same or slightly better values than the FG protocol. The latter may seem counterintuitive. Below, we clarify this result. Considering the average result for all nodes, the ODLF mechanism gives a 27% improvement for PDR in comparison with the Star network. Note that for some nodes, like s_2, the PDR is always very good, as it can always reach the gateway. So there is a minor improvement achieved by exploiting ODLF. In contrast, for some nodes with lower link quality to the gateway, the improvement is considerable. In an experiment, for instance, the PDR value in the Star network is less than 20% for four nodes, whereas values more than 75% are achieved for those nodes by using the ODLF protocol.

Fig. 8 depicts the average and maximum length of burst data loss during all experiments using different protocols. The main observation here is that in many cases during the experiments, continuous outage has happened for some nodes in the network. This could happen because of the node position in specific postures for a sustained period. Of course, some nodes do not have such a problem because they have a good link to the gateway. Nodes s_3, s_4, s_9, and s_{10} showed to be the most risky nodes in the performed experiments. Again, the obtained result using the ODLF approach is much better than the result for the Star network and slightly better than for the FG approach. If we take an average of the results over all nodes into consideration, ODLF gives a 68% and 85% improvement compared to the Star strategy for average and maximum length of the burst data loss over all experiments, respectively.

With respect to FG, the ODLF protocol gives an average improvement of 4%, 12% and 41%, for PDR, average and maximum burst loss, respectively. The reason of such improvement is that in the FG mechanism, the nodes always listen to all other nodes to avoid data loss. Doing so, many packets may be received which should be stored in the data pool and



(a) Average length of burst data loss over all experiments (b) Average of the maximum length of burst data loss in each experiment

Fig. 8. Average and maximum length of burst data loss.

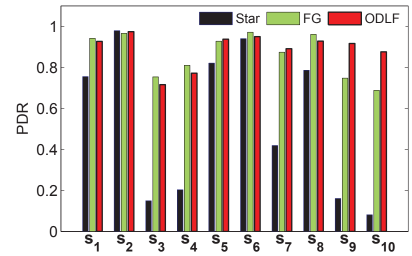


Fig. 9. PDR of different body sensor nodes to the gateway in an experiment with low quality links.

forwarded. Because of more data items in the data pool, each data item has less chance to be selected from the data pool for transmission in a round. So there is a higher probability that a data item is overwritten by the next version before being transmitted. In contrast, in ODLF, a node only listens to the nodes in the requested set. This means less data items in the pool and a bigger chance for the data items from the nodes in the requested set to be forwarded.

Our ODLF mechanism achieves improvements at the expense of more energy consumption than the Star strategy whenever data forwarding is necessary. The average energy consumption of nodes per frame over all experiments is 53μJ, 278μJ, and 137μJ for Star, FG, and ODLF protocols, respectively. Comparing ODLF with FG, we observe a big gain in the energy saving with the same or better QoS. Comparing our protocol with the Star network shows that we may spend more energy to make WBAN application feasible and achieve much better QoS. As the amount of radio activity in a frame is always fixed in Star and FG approaches, the energy consumption is almost the same in all experiments (minor variation is caused by having different tx power levels). In contrast, the connectivity to the gateway plays a major role in energy consumption using the ODLF mechanism. In a network with poor links, the requested set is bigger and nodes should listen in more slots. In a WBAN where nodes can always reach the gateway, the requested set is almost empty and so the energy consumption is as low as in the Star network.

To further investigate the behavior of the protocol in different network situations, we present more details about the result of two experimental setups, one with the best connectivity (all nodes use the highest tx power level) and another with the worst connectivity (lowest tx power level). In the former network, the requested set is almost empty. The average energy consumption per frame is 57μJ which is quite close to the one of the star network (i.e. 54μJ for this experiment). The minor energy consumption overhead is for some rare cases during the experiment that some nodes (in particular s_{10}) cannot reach the gateway for short periods in some postures such as lying down. On average, an almost full packet delivery (99.8%) was provided in this experiment by using ODLF whereas there is slightly more data loss in the Star network (PDR of 97.8% on average). The achieved PDR for node s_{10}, for instance, is 99.4% and 85.7% using the ODLF and Star mechanisms, respectively. This means that in a WBAN with proper links to the gateway, our ODLF mechanism spends almost the same energy as the Star strategy. However, ODLF guarantees data forwarding if the gateway dropped out of reach of a node during network operation, giving a better PDR. Note that such a good connectivity to the gateway is not feasible in many applications of WBANs. Specifically designed wireless body sensor nodes with very small size (short antenna) and nodes using energy scavenging may have very limited transmit range.

For the experiment with low network connectivity, the achieved PDR using ODLF is almost three times better than in the Star network for four of the nodes. Fig. 9 depicts the PDR values in this experiment using different protocols. The average length of burst data loss over all nodes is around 9 frames in the Star network whereas its value is around 1.3 frames using ODLF. Of course this result has been achieved by spending more energy. However, the energy consumption using ODLF (95.4mJ) is around half of the energy consumption in the FG approach. This is because the average size of the requested set was around 5 in this experiment. This experiment confirms that for a network of which the nodes have limited radio range, for instance because of ultra-low power RF radio, ODLF allows the WBAN to work with a sufficient QoS level.

As we expected, it is shown by the experiments that our hybrid protocol automatically changes the data propagation strategy. According to the current connectivity status of the WBAN, it turn to a Star topology or to multi-hop gossip-based data forwarding. Fig. 10 shows the average energy consumption of the ODLF protocol in several experiments of different levels of connectivity together with the one in the Star and FG protocols as two extremes. The average size of the requested set ($|\Psi|$) is also shown as an indication of the connectivity to the gateway in each experiment.

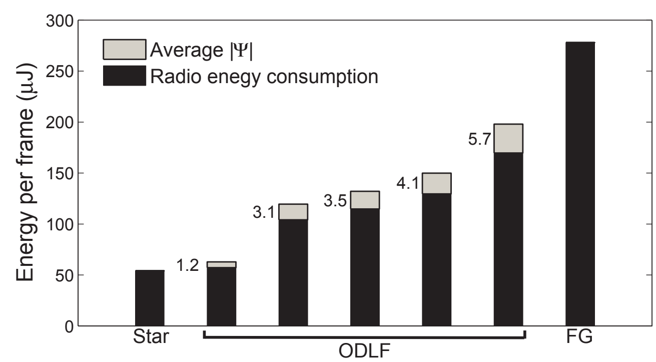


Fig. 10. Average energy consumption using ODLF protocol in experiments with different link quality, and the consumption in Star and FG protocols.

D. Further Power Saving

As discussed in Section IV-C, it might be possible to further reduce energy consumption of nodes by maintaining a subset of the requested set from which the node can hear well. Thus, node s_i only listens to such a subset in each round instead of listening to all the nodes in the requested set. Such a subset should be carefully updated. We performed an experiment to investigate the functionality and performance gain of such an extension. To implement it, we use time intervals for listening to the nodes in the requested set. So s_i listens to s_j once per interval. When node s_i detects that it has not received anything from s_j in the past three frames, it starts to increase its interval for s_j by one up to a given maximum point (10 in our experiment). If a packet is received from s_j in a round, the size of the interval drops to one to allow a maximal listening to s_j. Note that this is done while s_j is in the requested set. Such conservative strategy (additive increase and sudden drop) is exploited to minimize the amount of data loss.

We conducted two experiments with the same posture patterns and node settings, one running the base protocol and another using this extension. Table I presents the result obtained from these two experiments. The average energy consumption saving is 24.5% at the expense of 10% decrease of the PDR in comparison with the base protocol. It means that during some periods of the experiment, not providing forwarding help for some nodes in the requested set leads to data loss. High mobility in the WBAN and time-variant links have an important role here. The result shows a trade-off between achieved QoS and energy consumption. The exact method for updating the listening subset and its parameters are also important. A complexity overhead should also be taken into account for implementing this method. To make the final decision about using such an extension, the objectives of the target application should be taken into consideration.

TABLE I
RESULT OF SUBSETTING THE REQUESTED SET.

metric	*base protocol*	*extension*
PDR	94%	86.4%
Avg. burst loss	1.3 sec.	1.7 sec.
Max. burst loss	6 sec.	8.4 sec.
Energy per frame	129 μJ	97.3 μJ

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VI. CONCLUSIONS

In this paper, a mechanism is proposed for data propagation in Wireless Body Area Networks (WBANs) addressing real challenges of these networks such as high mobility, and low and time-variant quality of links. The proposed on-demand listening and data forwarding mechanism adapts the data propagation strategy according to the quality of the links to the gateway. Nodes with a poor link receive data forwarding help through multi-hop gossiping. In a network with sufficiently good connectivity to the gateway, the protocol works like a star network. Several experiments are done to observe the behavior of the protocol in a real deployment. The results show a big gain in Packet Delivery Ratio (PDR) in comparison with star networks, especially for networks with low quality links. Moreover, a considerable gain is observed in energy consumption in comparison with a full gossip strategy. Experiments with various configurations of nodes show that the protocol adapts itself according to the connectivity of the body sensor nodes to the gateway.

As future work, we plan to perform extensive simulations to explore the trade-offs made by different parameters in the protocol. Adapting the protocol for specific healthcare applications and connecting WBANs to a multi-hop ambient network are also considered as future work.

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