A Robust Protocol Stack for Multi-hop Wireless Body Area Networks with Transmit Power Adaptation*

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ABSTRACT

Wireless Body Area Networks (WBANs) have characteristic properties that should be considered for designing a proper network architecture. Movement of on-body sensors, low quality and time-variant wireless links, and the demand for a reliable and fast data transmission at low energy cost are some challenging issues in WBANs. Using ultra low power wireless transceivers to reduce power consumption causes a limited transmission range. This implies that a multi-hop protocol is a promising design choice. This paper proposes a multi-hop protocol for human body health monitoring. The protocol is robust against frequent changes of the network topology due to posture changes, and variation of wireless link quality. A technique for adapting the transmit power of sensor nodes at run-time allows to optimize power consumption while ensuring a reliable outgoing link for every node in the network and avoiding network disconnection.

Categories and Subject Descriptors

C.2 [**Computer Communication Networks**]: Network Architecture and Design; Network Protocols; C.4 [**Performance of Systems**]: Performance attributes; Reliability, availability, and serviceability

General Terms

Algorithms, Performance, Theory.

Keywords

Wireless sensor network, Body area network, Medium access control, Gossiping, Dynamic adaptation, Quality of service.

1. INTRODUCTION

Health monitoring is an interesting application for wireless sensor networks (WSNs). A Wireless Body Area Network (WBAN) consists of several tiny bio-sensor devices that measure the vital biological signals of the body, such as blood pressure, fever, heart beat rate, and movement activities. The information is relayed to a gateway node on the body and then to a base station for further analysis. The condition of the body can also be forwarded to a medical center to be observed by care workers. Elderly care, health care of patients with specific chronic diseases such as COPD, and post-surgery monitoring are some relevant applications for WBANs.

There has been a lot of recent activity to provide appropriate body sensor devices. Specific sensors have been developed in the CodeBlue [19] project at Harvard University to measure several body signals (heart rate, EKG, and oxygen saturation). The Ubimon group at Imperial College has developed custom wireless nodes with the feature of interfacing to wearable and implantable sensors [20].

WBANs have specific characteristics creating opportunities and challenges. Some important issues should be considered when designing a network architecture and protocol stack for this kind of wireless networks.

- **Power constraint and short RF transmission range:** The power and size constraints of body sensors are tighter than in other wireless sensor applications. A short transmission range is a common limitation of low-power RF transceivers. The literature describes several low-power body sensors with a transmission range below one meter ([3],[16],[17]). In some applications, ultra-low power RF devices have been used to enlarge the lifetime of sensors. There also exist devices that generate power from body resources. Thus, the amount of consumable energy is strictly limited.
- **Mobility:** In a WBAN, several sensor nodes are placed on different locations on a body. The human body can be in several postures, and the nodes are basically mobile with respect to each other. Therefore, no assumptions can be made for relative node positions. The network protocol should be robust against frequent movements of the sensor nodes.
- **Low and time-variant quality of wireless links:** Several investigations using simulations and experiments show that the propagation loss around and in a human body is considerably high ([5],[6],[15],[21]). The path-loss coefficient value lies between 4 and 7, whereas its value is less in normal circumstances. This makes the wireless links between on-body sensor nodes unreliable and further limits the transmission range. In [6], the effect of body size and posture on the radiation pattern has been studied. The authors of [11] and [12] have done a complete measurement of Packet Delivery Ratio (PDR) of wireless links in a body sensor network using CrossBow TelosB [20] sensor nodes. Their results show that the PDR between some nodes are lower than 60% for 46% of the experiments. In addition, experiments in [14] show that the link status varies in different postures. Furthermore, it is shown that even within a given posture, the links may vary and have intermittent disconnections. The general conclusion is that wireless links in WBANs are more unreliable and time-variant than in other WSNs.

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• **Network size:** Among the above challenging properties of WBANs, one relaxing property of WBANs is that the number of sensor nodes on a body is limited. In [12], the largest on-body sensor network known in the literature has been deployed including twelve TelosB sensor nodes on a body. So the problem of scalability of protocols does not exist in WBANs.

The first choice for designing a WBAN has been a star or multipoint-to-point architecture. In such networks, because of short distances, the sensor nodes are supposed to send information directly to a gateway node placed on the body. In [13], hardware and software system architecture has been designed for health monitoring. In that architecture, a collision-free slotted mechanism is used for sending data from on-body sensors directly to a gateway node. An adapted version of IEEE 802.15.4/ZigBee was used in [7]. A Medium Access Control (MAC) protocol has been developed in [10] in which a TDMA strategy is used to reduce power consumption of sensor nodes. In a star network in general the power consumption is higher, but the overall latency is low because of direct links to the gateway.

In contrast, the power constraint and short transmission range of on-body sensor nodes, and the severe transmission loss through the body suggest the use of a multi-hop network for WBANs. Taking energy consumption into account, it is shown in [15] that multi-hop routing can be beneficial, and even in some cases it is the only possible option. A recent experimental investigation in [12] explores the trade-off between using a star and a multi-hop architecture, highlighting their respective performance characteristics. It has been pointed out that there is no solution that is optimal for all applications of WBANs because of different constraints and requirements. Multi-hop protocols are shown to have a high end-to-end PDR and have better network lifetime and energy consumption, but may suffer from longer latencies. More details about using star and multi-hop architectures for WBANs and their respective advantages and weaknesses can be found in [11] and [12].

In this paper, we develop a multi-hop WBAN protocol stack using a data dissemination strategy based on epidemic principles. The design addresses the typical WBAN challenges and exploits the small size of a typical WBAN. A transmit power adaptation strategy allows for energy saving and provides robustness.

The paper is organized as follows. The next section explains two multi-hop protocols for WBANs existing in the literature. Our protocol stack is presented in Section 3. In Section 4, a method for dynamically adapting the transmit power of sensor nodes is proposed. The protocol evaluation results are shown in Section 5. Section 6 concludes.

2. RELATED WORK

In this section, we explain two multi-hop protocols for WBANs in some detail. A periodic slotted multi-hop approach to MAC and routing is presented in [2], aiming to reduce packet delivery delay. The wireless autonomous spanning tree protocol (WASP) is proposed, where the spanning tree is set up autonomously to route data from the sensor node to the gateway. In each cycle, time slots are allocated to different nodes using a tree structure by transmitting a WASP-scheme from each parent to its children starting from the gateway node. Every node receives its assigned slot in each cycle from its parent. The node then sends the appropriate scheme to its children. In [9], the authors present an extension (CICADA) by dividing the cycles into separate control and data subcycles to reduce the data delivery delay to the gateway node to one cycle.

A native problem of every tree structure in wireless sensor networks is that in the case of a node failure or node movement, the tree has to be reconstructed. Although [9] has a method for tree reconstruction using a join procedure, it is explicitly 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. Furthermore, the sensor nodes close to the gateway node have to forward more information than others, so the power consumption of sensor nodes is not evenly distributed. Another issue is that the protocol strongly relies on the wireless link for sending the vital control information for scheduling data transmission of nodes. But, as mentioned, link quality in WBANs is typically low and time-variant.

A probabilistic packet routing mechanism is proposed in [14]. A stochastic metric called link likelihood factor (LLF) is calculated in every node using the history of the link quality between the node and other nodes in the network. This metric reflects the postural trend of the human body and is used for decision making about routing the packets to the neighbors. In fact, the routing goal is to reduce end-to-end delay by choosing high likelihood links. Each node calculates its own LLF and receives the metric calculated in other nodes. In each round, a node compares its LLF to the gateway node with the LLF of its neighbors and sends the packets to the neighbors that have the best values.

Although the paper states a method for routing data items, MAC issues are not discussed. Moreover, the wireless links are supposed to be symmetric for calculating the quality metric of links. This assumption is typically unrealistic. There is also no evaluation of energy consumption needed for doing such a routing mechanism. Every node has to calculate its link quality to all other nodes via propagating *Hello* messages periodically. The same overhead results from distributing the LLF values.

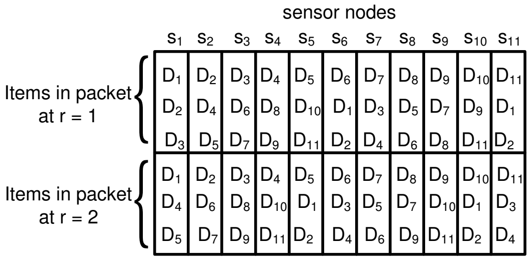
In summary, none of the existing multi-hop WBAN protocols truly addresses the typical WBAN challenges. In this paper, we present a protocol stack that uses a multi-hop data propagation strategy while no specific routing structure, such as a tree, is used. The protocol does not make any assumption about the relative position of nodes or link properties (such as PDR, symmetry). Therefore, the protocol stack is robust against such WBAN challenges as high node mobility (posture changes) and low quality time-variant wireless links. We use a TDMA-based MAC layer and a gossiping data routing strategy that match with each other to realize a reliable, robust and quite fast data propagation with little overhead.

3. PROTOCOL STACK DESIGN FOR WBAN

The challenges in WBANs demand particular attention while designing an appropriate protocol stack. On the other hand, the limited network size provides opportunities to relax some constraints on the protocol. To realize an appropriate protocol stack, we use an epidemic inspired mechanism for data routing on top of a TDMA-based MAC layer.

3.1 Body Area Network Architecture

Assume that $\{s_1, s_2, ..., s_N\}$ is the set of N sensor nodes deployed on a body each with a unique *ID*, say its subscript. One of these nodes, which one is not relevant, is the gateway and is supposed to have more powerful characteristics than other sensor nodes. These characteristics can include more battery capacity and a higher transmission range that



	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}
Items in packet at r = 1	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	D_9	D_{10}	D_{11}
	D_2	D_4	D_6	D_8	D_{10}	D_1	D_3	D_5	D_7	D_9	D_1
	D_3	D_5	D_7	D_9	D_{11}	D_2	D_4	D_6	D_8	D_{11}	D_2
Items in packet at r = 2	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	D_9	D_{10}	D_{11}
	D_4	D_6	D_8	D_{10}	D_1	D_3	D_5	D_7	D_{10}	D_1	D_3
	D_5	D_7	D_9	D_{11}	D_2	D_4	D_6	D_9	D_{11}	D_2	D_4

Figure 1: Data items in transmission packets in a WBAN with $N = 11$ and $\lambda = 3$ for two consecutive rounds

is sufficient to reach all other nodes. All nodes send their last sampled data to the gateway in one or more hops. The gateway node then sends the collected data items from all nodes to a base station. Depending on the specific application scenario, the gateway may receive control information from the base station and inform body sensor nodes. Note that the protocol for communicating with the base station is not addressed in this paper and can for instance be a star architecture with the base station as its center or a multi-hop ambient network.

In our architecture, the gateway node uses a high enough transmit power to include all body sensor nodes in its transmission range. The sensor nodes use the packets received from the gateway as beacon for synchronizing themselves. The gateway's packet can also include control information which might be needed in the running application.

Other body sensor nodes are supposed to have several distinct transmit power levels. The nodes need to use a low power level to reduce power consumption. On the other hand, each sensor node should create a reliable connection to some others by adjusting its transmit power level.

3.2 Data Routing Using a Gossiping Strategy

A gossiping strategy for data dissemination in large scale ad hoc wireless networks is proposed in [4]. The protocol has a probabilistic replication and storage scheme with random data item selection from a local cache. The selected data items are broadcast in each round (MAC frames). We apply an adapted version of this algorithm for WBANs.

We assume that every sensor node has an adequate space of cache to store one data item of each sensor node in the network (N). This assumption is reasonable because WBANs consist of limited numbers of sensor nodes. In every round, a sensor node may receive one packet from each neighbor. Every data packet includes several data items from different nodes. The node then stores received items in its cache if the version (time stamp) of the arrived items is newer than existing ones currently in the cache. So every node keeps the latest data item of every node that it has received.

A data item (D_i^t) consists of sampled data, corresponding sampling time stamp t and the source node $ID\ i$. A radio packet then is the information that every node broadcasts in each round and includes λ data items of different sensor nodes. In every round, a node broadcasts its own data item plus at least one other item from the cache ($\lambda \geq 2$). The value of λ depends on the packet size which is fixed for some radio chips or is adjustable for others. In the case of an adjustable packet size, we consider λ as a design time parameter which can be optimized based on Quality-of-Services (QoS) requirements.

Different from the method in [4], item selection from the cache is not performed randomly. Instead, a predefined part of the cache is selected. Every node includes its own latest sampled data into its packet. Thus, there are $\lambda-1$ remaining items that the node will select from its cache. A node divides its cache into $M = \lfloor (N-1)/(\lambda-1) \rfloor$ parts, and at each round it selects one part in a round robin fashion. Care has to be taken in the selection of parts to be broadcast. If all nodes select the same part of their cache in a round, data items from some nodes will be received multiple times by a receiving node; such duplicates will be ignored by the receiving nodes. On the other hand, items that are not included in the packets will be delayed. Therefore, we want the nodes to select different parts in a round. By considering the ID of the node and the round number (r), we achieve efficient data dissemination. In round r, node s_i selects the $(r+i\ mod\ M)^{th}$ part of its cache for transmission. Doing so, one data item of each sensor node will be transmitted several times in every round (besides the newly sampled item sent by the node itself). Fig. 1 shows the data items included in the packets of the nodes for two consecutive rounds.

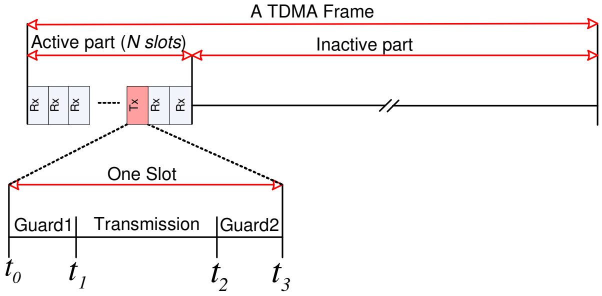


Figure 2: A TDMA frame of medium access control

3.3 TDMA-based Medium Access Control

For running the gossiping mechanism, we need an appropriate MAC layer which is also efficient from the energy consumption point of view. Contention-free, schedule-based MAC protocols such as a TDMA-based MAC are a common option for WBANs in the literature ([2],[9],[10],[12],[13]). The limited network size, the small deployment area, and the presence of a more powerful node as gateway make the synchronization between nodes quite reliable.

Each TDMA frame is divided into equal sections called slots. Nodes are active in the active part of frames and are in sleep mode in other slots to reduce power consumption. A node transmits its packet in exactly one slot and listens in other slots in the active part of the frame. Fig. 2 illustrates a TDMA frame. As every node has a unique Tx slot, the protocol is contention free. Notice that no destination address is set in packets. Thus, every node broadcasts its packet and any other node in the range will receive it.

Each frame consists of N slots which are assigned to the sensor nodes arbitrarily at design time. The only exception here is for the gateway node to which the last slot in the frame is assigned. Doing so, the item delivery time to the gateway node will be considerably decreased. Data items from a node multiple hops away from the gateway can sometimes even reach the gateway node in a time less than the active part of the frame. It may seem to be a reasonable choice here to assign the last slots in the frame to the nodes closer to the gateway. Because of high relative node mobility, we do not have this knowledge, and so the slot distribution is done randomly for other nodes than the gateway node.

Synchronization of sensor nodes is an important aspect in a TDMA protocol. In every frame, nodes that receive the packet from the gateway node use that packet also as a beacon to synchronize their clock. Although the gateway has a long transmission range, there is always a chance that a node does not receive the gateway's packet in a round. In this case, such nodes synchronize themselves with their neighbors in that round. Moreover, as is common, a guard time is inserted at the start and the end of every transmission slot to resolve small phase differences. Every receiving node starts to listen to the slot from t_0 until it receives the whole packet or reaches the end of the slot time (t_3). The transmitter sends its packet between t_1 and t_2.

4. TRANSMIT POWER ADAPTATION

Due to the high mobility and frequent topology changes in WBANs, dynamic adaptation of transmit (Tx) power plays an important role in the optimization and QoS of the running application scenario. The general concern is to minimize the power consumption of sensor nodes by adjusting the Tx power. At the same time, we take two important issues into consideration namely *outlink quality* of sensor nodes and the *network connectedness*. The adaptation mechanism should ensure an adequate number of receiving nodes for each sensor node. Every node should also be able to reach the gateway in one or more hops. The adaptation mechanism is supposed to react reasonably fast to a posture change and avoid fluctuating Tx power due to the incidental disconnections of the wireless link. The overhead of performing the mechanism should be as low as possible.

To deal with the first concern, outlink quality, every node uses some local information to keep an adequate number of receiving neighbors. Every node can directly measure its *inlink* status by considering the received packets in every round. However, the information that a node needs is indeed its *outlink* status. This cannot be calculated directly and needs some kind of feedback. Furthermore, the asymmetric and time-variant link quality complicate the problem. We define a metric to estimate the outlink quality of every node. Each node tries to keep this metric within predefined thresholds by adjusting its Tx power.

In [14], a link quality metric is defined which is used for making decisions about data routing. In that work, all links are supposed to be symmetric and so it simplifies measuring link quality. Because of different Tx power and different propagation shape of radios, links are normally asymmetric. Here we suppose that the links are indeed asymmetric, and based on that, define the link quality metrics.

The sensor node s_i knows the set of nodes from which it receives packets at round t, which we call its inlink set (I_i^t). Moreover, assume that O_i^t is the outlink set of node s_i which is actually the set of all sensor nodes that receive the packet from node s_i in round t.

IO_i^t can be defined as the subset of O_i^t from which node s_i receives a packet ($IO_i^t = O_i^t \bigcap I_i^t$). To calculate this subset, every node s_k will include its inlink set (I_k^{t-1}) into its broadcast packet. Thus every receiving node s_i can extract the *inlink* set of all nodes existing in its own inlink set. The receiver node s_i can then approximate its own IO_i^t by considering two consecutive rounds.

$$IO_i^t = \{s_k : k \in I_i^t \ \& \ i \in I_k^{t-1}\} \tag{1}$$

To implement the mechanism, every node includes $N-1$ bits into its transmission packet (the so-called *inlink bitmap*). The k^{th} bit shows whether node s_k is part of the inlink set of the node in the last TDMA frame. As the number of sensor nodes is low in a WBAN, the overhead of propagating such a bitmap is not considerable.

Although IO_i^t is not the same as O_i^t, it can be used for estimating a metric for setting the Tx power. To deal with the temporal changes in link quality, we take a limited history of each link into consideration. Node s_i calculates the average of the membership of every node s_j in its I_i^t and IO_i^t over the last h rounds.

$$\varphi_{i,j}^t = \frac{1}{h}\sum_{k=0}^{h-1}(j \in I_i^{t-k}) \quad 1 \le j \le N \ \& \ i \neq j \tag{2}$$

$$\omega_{i,j}^t = \frac{1}{h}\sum_{k=0}^{h-1}(j \in IO_i^{t-k}) \quad 1 \le j \le N \ \& \ i \neq j \tag{3}$$

$\varphi_{i,j}^t$ represents the average reception ratio of s_i from s_j. $\omega_{i,j}^t$ gives an approximation of the ratio of successfully acknowledged messages over the last h rounds. It is obvious that $\varphi_{i,j}^t \ge \omega_{i,j}^t$ for any i and j and at any time t. To have a sense of the behavior of a link, we calculate the *outlink quality metric* ($0 \le q_{i,j} \le 1$) in every round based on the history of the link and the link status in the last frame.

$$q_{i,j}^t = \begin{cases} q_{i,j}^{t-1} + (1 - q_{i,j}^{t-1})\omega_{i,j}^t & j \in I_i^t \ \& \ i \in I_j^{t-1} \\ q_{i,j}^{t-1}.\omega_{i,j}^t & j \in I_i^t \ \& \ i \notin I_j^{t-1} \\ q_{i,j}^{t-1}.\mu_{i,j}^t & j \notin I_i^t \end{cases} \tag{4}$$

In the first two cases, node s_i has received the packet from node s_j. In such cases, s_i updates the $q_{i,j}$ according to the inlink bitmap extracted from the received packet. If s_i is in the inlink set of node s_j, the metric will be increased with a rate determined by the history of this link ($\omega_{i,j}^t$) and the distance of the previous $q_{i,j}$ to its maximum value, which is 1. Notice that if the outlink has shown a good connection in the history, $\omega_{i,j}$ is relatively high. Consequently, $q_{i,j}$ will converge to its maximum value very fast. On the other hand, if s_j does not have a good history of receiving from s_i, $\omega_{i,j}$ is low and so $q_{i,j}$ will increase with a lower rate. In the second case, in which s_i is not in the inlink set of node s_j, the metric will be decreased, again with a rate proportional to the history of the link. The main idea behind this is that if the outlink has shown a good record, one incidental disconnection does not decrease the metric too much and vice versa.

The last case is challenging because s_i has not received a packet from s_j and no conclusion can be made about the inlink of s_j. In such a case, the historical behavior of the link form s_i to s_j is considered to update the $q_{i,j}$. We define a *confidence factor* $\mu_{i,j}^t$ for every link that represents the ratio of rounds that node s_j has received packets from node s_i over all times that the link from s_j to s_i existed ($\mu_{i,j}^t = \omega_{i,j}^t/\varphi_{i,j}^t$). However, when the inlink is completely broken ($\varphi_{i,j}^t = 0$), we cannot make any conclusion about the outlink and assume that the outlink does not exist (by setting $\mu_{i,j}^t = 0$). Doing so, we underestimate the true outlink quality in this situation.

To evaluate the basic behavior of the proposed adaptation mechanism, Fig. 3 shows the calculated value of outlink quality metric for a link under different circumstances. In the first 30 rounds, both directions of the link are almost perfect. The outlink quality is 1 and incidental link failure does not have a strong effect on the metric. At round 30, e.g. because of a posture change, the link goes to a bad status. The packet reception of the inlink is around 30%, but the outlink

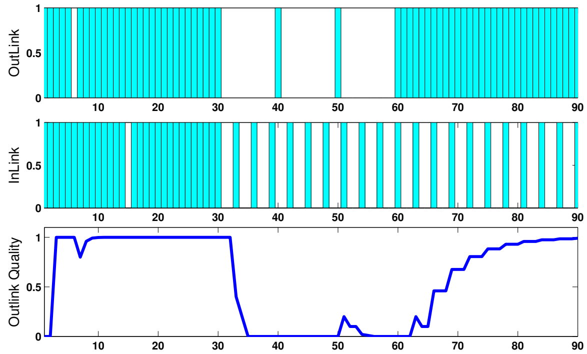


Figure 3: outlink quality metric ($q_{i,j}^t$) for a link

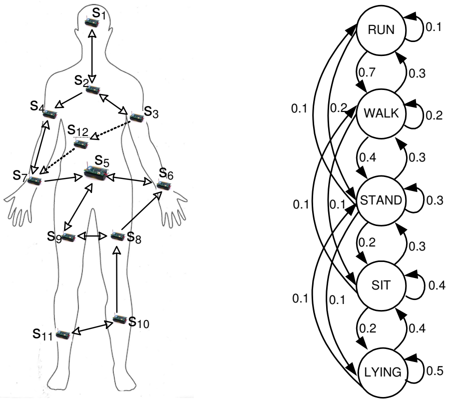
has a very low quality. The metric sharply decreases which is expected and desired. Again, at round 60, because of for example increasing the Tx power, the outlink becomes perfect and the metric gradually increases. The metric would increase faster if the inlink quality were better.

Computing the outlink quality metric with respect to all nodes in the WBAN gives the node an estimate of its outlink status in the current posture. Using the above method, with a postural change, the metric will be appropriately updated and the update is sufficiently fast. Note that the link status is not just a factor of the distance; if the link is through the body, the propagation loss will be much higher. After calculating the outlink quality metric in s_i for any other node s_j, the overall outlink quality metric of s_i will be calculated as the sum of $q_{i,j}^t$ over all its neighbors.

$$Q_i^t = \sum_{j=1,\ldots,N,\ j\neq i} q_{i,j}^t \tag{5}$$

Q_i^t can intuitively be interpreted as the expected number of neighbors reached in every round. The goal is to maintain this metric in a predefined range ($lb \leq Q_i^t \leq ub$) by setting the proper Tx power. Notice that a value of 1 for Q_i^t can have very different meanings. It is possible that node s_i has just one perfect outlink. It is also possible that there are three outlinks, each with 33% reception ratio and so on. The important issue is that by providing a proper value, we obtain confidence about the ability of the node to reliably propagate data items with an acceptable delay.

The second concern is to maintain the network connectedness which means that there should be a path for every node to the gateway. Note that it is not enough for every node to have a $Q_i > lb$, because of local clusters. To maintain connectedness, nodes need to have more global information. Here we measure a simple weighted hopcount to the gateway node and every node tries to keep this metric above zero. Every node calculates a metric by which the node estimates its connection quality to the gateway ($\mathcal{C}_i$). Each node puts its calculated $\mathcal{C}_i$ into its packet. The value is one for the gateway node. For other nodes, it is calculated as $\mathcal{C}_i = \max\{\mathcal{C}_j \times q_{i,j}\}$ for every node s_j from which s_i has received its packet in the last round. The multiplication with $q_{i,j}$ makes sure that the outlink quality to node s_j is properly taken into account. A zero value means there is no connection to the gateway node. Assume that in a specific posture, the network splits into two separate parts. In such a situation, the value of $\mathcal{C}$ for sensor nodes in the part which does not include the gateway node gradually becomes zero. Thus, those nodes decide to increase their Tx power to reach a node in the other part.



(a) (b)

Figure 4: a) WBAN used for simulation. s_5 is the gateway node. b) Markov model for posture change.

5. EXPERIMENTS

5.1 Simulation Setup and Mobility Model

To observe the behavior of the protocol stack and evaluate its performance, we implemented the stack in the MiXiM [8] framework of the OMNeT++ 4 [1] network simulator.

An essential aspect for accurately simulating a WBAN is a mobility model to mimic the behavior of a human body. We implemented an appropriate model as an add-on to the mobility framework of MiXiM. The model includes five different postures (RUN, WALK, STAND, SIT, and LYING). In each posture, the initial position of every sensor node is given, which is called its reference point. Each node may move individually in an area around its reference point with a given range and velocity. The random walk mobility model is used for their individual movement. The reference point, movement freedom range, and velocity are defined individually for each node in each posture. So the parameters are set based on the position of the node and the current posture.

The effect of the human body on propagation loss and link quality in various postures is taken into account. For every pair of nodes in each posture, the mean (μ_α) and deviation (σ_α) of the path loss coefficient α is set. The mean value is specified (in the range from 3 to 7) according to the ratio of the distance between the pair of nodes in which radio waves should be propagated around or through the body. The deviation is set based on the relative mobility of the pair in the specific posture. Whenever a node receives a message, it selects the value of α according to the normal distribution $\mathcal{N}(\mu_\alpha, \sigma_\alpha)$. The corresponding parameters of the distribution are taken from the mobility model. Finally, each link can be disconnected at each round with a probability of 10% to model instantaneous disconnections or interferences.

We created a WBAN consisting of twelve sensor nodes depicted in Fig. 4(a) for posture STAND. The shown links are just for the time of the snap shot and can change in the next round. Notice that node s_{12} has been positioned on the back. The time distance between two consecutive posture changes is set to 50 seconds. A *Markov* model is used for changing posture based on which the same or a different posture will be selected at every posture change. The Markov model is shown in Fig. 4(b) in which the probability of every transition is also specified. To have a consistent posture pattern for various simulation runs, the Markov model is executed once and all simulation runs use the same pattern.

Since we are planning future experiments with *MyriaNed* sensor nodes [18], we used the specification of those nodes for

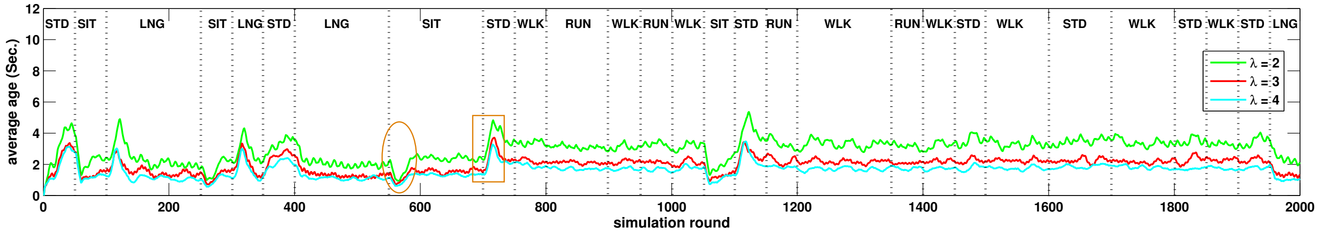


Figure 5: Average age of data items in the gateway node for different number of items per packet (λ).

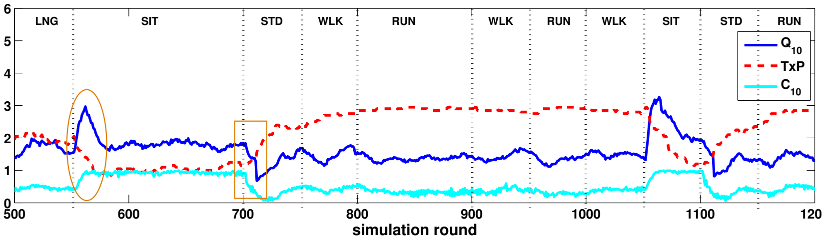


Figure 6: Outlink quality metric (Q_{10}), connectedness to the gateway ($\mathcal{C}_{10}$), and transmit power trend of sensor node s_{10}.

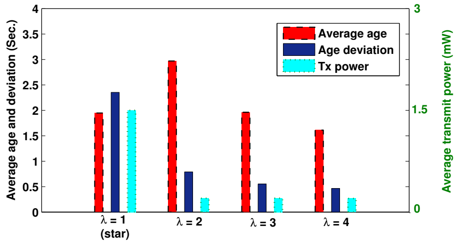


Figure 7: Average age, its deviation, and average *Tx* power over all rounds.

the physical layer characteristics in our simulations. *MyriaNed* uses a *Nordic* chip (nRF24L01) as transceiver which broadcasts radio packets of 32 bytes with a 2.4GHz ISM-band frequency and data rate up to 2Mbps. The transceiver has four adjustable transmit power levels (-18, -12, -6, 0dBm).

Each TDMA slot lasts $500\mu s$ while real transmission of a packet takes $200\mu s$. Two guards are inserted at the beginning and the end of transmit slots each with a length of $150\mu s$. The TDMA frame length is set to one second so that one frame has 2000 slots from which 0.6% are active (12 slots). Frame length is indeed a design time parameter that allows a trade-off between power consumption and latency, and has to be decided according to the QoS requirements and constraints of the target application.

Every simulation run has been performed for 2000 rounds. Moreover, we run every simulation configuration for 32 different seeds for the random number generator to achieve statistically more reliable results. Consequently, the presented results are the average over all runs of the corresponding set up with different seeds. As said before, the same posture pattern is used for all runs.

5.2 Evaluation Result

Based on the network architecture, the gateway node forwards the last received data items from every sensor node in the WBAN to a central station. We define *item age* (L_i^t) as the time distance between the current round and the sampling time stamp attached to the considered data item of sensor node s_i at the gateway. It reveals the latency of the WBAN for each node. Fig. 5 presents the average age over all nodes at any time during simulation for three different values of parameter λ (number of data items per packet). The active posture is also shown which gives the opportunity to investigate the behavior of the protocol during the posture changes. Specifically note the changes from the closed posture (SIT) to an open posture (e.g., STAND) and vice versa. Transition from a closed posture to an open one (illustrated in the rectangle in the figure) increases the age. But due to the reaction of the transmit power adaptation mechanism, it quickly improves. Changing from an open to the closed posture (e.g., shown in the ellipse) lowers the age. Since we set an upper bound for the outlink quality of nodes, some nodes decrease their transmit power to save energy, and consecutively age becomes higher again. The impact of the parameter λ on the performance of the WBAN is also visible in Fig. 5. As expected, more data items in one packet improves performance.

To have a closer observation, Fig. 6 shows the estimated outlink quality metric (Q_{10}), and the connectedness to the gateway metric ($\mathcal{C}_{10}$) of node s_{10} for a selected part of the simulation runs. The trend of the transmit power is also shown. Sensor node s_{10} is selected because it has a different neighborhood in various postures so that the behavior of the adaptation mechanism can be seen well. The two posture changes between closed and open postures are again highlighted in the figure. In the area specified by the ellipse, the posture changes from LYING to SIT and the outlink quality becomes very good. Thus, the adaptation mechanism decides to decrease transmit power. The corresponding effect of this reaction on the age is visible in the ellipse in Fig. 5. The opposite story applies for the transition from the SIT to the STAND posture highlighted by the rectangle. In summary, the results in Fig. 5 and 6 confirm that network connectedness is maintained, which is crucial for robustness, and that the adaptation mechanism responds as expected.

In our protocol stack, the minimum number of data items per packet is 2 ($\lambda \geq 2$). However, if we set $\lambda = 1$, the network is converted to a TDMA-based (contention-free) star network when every node has enough transmit power to reach the gateway. We use this case as a reference for evaluation of our protocol. With existing maximum transmit power levels of our sensor nodes, some nodes in the WBAN are not able to reach the gateway. So we use a higher transmit power (3dBm) to make the reference star network. For our protocol, sensor nodes just use the existing transmit power levels of nodes (0dBm at most). Fig. 7 depicts the average age and the deviation from the average age of the data items in the gateway node over all simulation rounds for various values of parameter λ including the star network ($\lambda = 1$). The figure also shows the average transmit power. The results confirm the energy efficiency of our protocol stack. Performance is robust, in the sense that the age of data items shows little variation. The average age is less than the age in the star network for $\lambda \geq 3$.

The key advantage of our protocol stack compared to other existing multi-hop WBAN protocols such as WASP [2], already discussed in Section 2, is the robustness against the real challenges in a WBAN. The first aspect that makes the protocol stack robust is the data routing mechanism (based on gossiping) that does not rely on any specific routing structure. The WASP protocol uses a tree routing structure that may need to be reconstructed with a posture change. This can be done by a join procedure of the protocol. As the authors of [2] already acknowledge, this procedure takes time. The WBAN will be unreliable until the routing tree gets reconstructed. In contrast, in our protocol, nodes propagate information to any node in range without any assumption about relative node positions. Simulation results show that the age (latency) of packets shows indeed little variation over time, despite posture changes. A second important aspect is the power adaptation mechanism, that prevents network disconnection or isolated nodes by setting appropriate transmit powers. Simulation results confirm that all nodes stay connected to the gateway, while using as little transmit power as possible given a quality threshold.

Several parameters in our protocol stack provide flexibility, allowing the protocol to be used for various applications with different QoS requirements. The length of TDMA frames, the length of each data item, the number of data items per packet (λ), and the upper and lower bounds (lb & ub) for our outlink quality metric are some design time parameters that should be set based on the target application. Methods to configure a network for a given application is a topic for future work.

6. CONCLUSIONS AND FUTURE WORK

We reviewed some characteristic issues in Wireless Body Area Networks (WBANs), showing the need for an appropriate communication protocol. Taking these issues into consideration, this paper proposes a simple and well-matched multi-hop protocol stack which is robust against the high mobility, and the low-quality and time-variant links in WBANs. A transmit power adaptation mechanism is introduced for optimizing the transmit power consumption of sensor nodes while maintaining a desired level of outgoing link quality for every node and the network connectedness. An appropriate WBAN mobility model is developed for simulating the network which includes many issues existing in WBAN in real life. Evaluation results show that the protocol behaves as expected in several circumstances including posture changes. It performs well in comparison to a star network and it is the first multi-hop protocol stack that addresses all the challenges in a WBAN.

As future work, we plan to work on optimizations for the listening activity of sensor nodes to reduce the power consumption overhead due to idle listening. A node may predict the slots in which it should listen. The protocol also is not yet optimized for different sensing intervals. All sensed data is currently forwarded with equal probability. The forwarding strategy may be tuned to take differences in sensing interval into account. We also plan to investigate methods to configure the parameters in our protocol stack given a specific application and specific QoS requirements.

Although several experiments with large scale *MyriaNed* sensor networks [18] have been performed to investigate the behavior of the MAC layer and epidemic routing mechanism in real deployments, we are setting up a WBAN using those nodes to check the performance of our mechanisms in real situations on a human body with real mobility patterns.

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