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MAC-Network Cross-Layer Energy Optimization model for Wireless Body Area Networks

Laaziz Lahlou*, Amira Meharouech*, Jocelyne Elias* and Ahmed Mehaoua*

Abstract—**In recent years, Wireless Body Area Networks (WBANs) have gained increasing interest in the research community and become an emerging technology, especially in healthcare services. This position paper focuses on the energy optimization issue and the joint routing and MAC protocols in WBANs. We extend upon our previous model on the Energy-Aware Topology Design for WBANs (EAWD), so as to include PHY and MAC-layer WBAN specifications. Indeed, EAWD model considered the topology constraints by minimizing the number of relay nodes, in order to reduce the total energy consumption, as well as the total network installation cost. Yet, EAWD involved quite rough assumptions, omitting overhead considerations, due to MAC routing and physical clear channel assessment problems. Therefore, we first introduce the EAWD model and discuss its limitations. Then, we present our proposal, the Enhanced EAWD (EEAWD), and assess its performance through a synthesis comparison with EAWD and related proposals in the literature.**

***Index Terms*—WBAN, Optimization, Relay Placement, Energy-Efficiency, Routing, Medium Access Control.**

I. INTRODUCTION

Wireless body area networks (WBANs) are sensing networks that present an emerging technology with the potential to transform traditional healthcare services. A WBAN consists of a number of inexpensive and lightweight in-body and on-body sensors that continuously measure and transmit vital signs of a patient without constraining her/his normal activity and without surgical interventions [1].

The medical applications of WBANs can be divided into wearable and implanted categories. Some examples of use of wearable devices are: Pulse Oximetry SpO2, Blood Pressure, Glucose sensor, etc. Implanted devices are inserted inside the human body, such as those used in cardiac arrhythmia monitoring/recording and insulin injection.

The wireless sensor nodes used in a WBAN are tiny and limited power resources. They have different levels of energy and generate different sizes of data. Existing routing and MAC protocols in Wireless Sensor Networks (WSNs) and Ad Hoc networks do not satisfy the specific and challenging requirements of a WBAN.

In this paper, we consider the joint routing and MAC protocols for WBANs, which is our focus of interest in our ongoing and future work. Therefore, we start with a review on some relevant works that will constitute the basis of EAWD improvements. Then, we discuss in detail how to extend the EAWD protocol [2].

This paper is organized as follows: Section II discusses related work. Section III briefly presents the EAWD model and its limitations, then future extensions are discussed in Section IV. Section V presents a summary of our contributions, through a synthesis comparison to related proposals in the literature. Finally, Section VI concludes the paper.

II. RELATED WORK

Authors in [3] studied the performance of unslotted CSMA/CA protocol used in the non-beacon IEEE 802.15.4 standard in WBANs. The study was done considering different traffic rates. They concluded that CSMA/CA is unable to satisfy the WBAN traffic heterogeneity. A recent experimental study was made by Fabio et al. [4], in order to understand and quantify the reliability and energy consumption in both single-hop and two-hop communication patterns. Authors carried out testbed simulations on three human subjects by collecting sensor data, during daily activities, with no predetermined activity scheme.

In each pattern, energy consumption and packet delivery ratio were studied under three power levels: $-20dBm$, $-10dBm$ and $0dBm$. As human movements cause path loss variation, the authors computed the Pearson Correlation Coefficient in order to understand if there exist dependencies between nodes attached to the human body. They discussed the average Packet Delivery Ratio and energy consumption for successful delivered packets in three different power levels. However, the formula used to calculate the energy for Packet Delivery Ratio is very simple in such a way that it does not consider the overhead due to MAC, routing and upper layers design. Indeed, they just consider the packet transmission energy.

Authors in [5] proposed a medium access control protocol for wireless body area networks. First, they proposed a mathematical programming formulation based on Elias et al. [2]. Secondly, they implemented their protocol based on the Time division multiple access (TDMA) approach. A common problem in TDMA is the extra energy cost of the periodic synchronization, since the node synchronization is performed after N number of cycles. In order to avoid collision (packet loss), they introduce what they call Drift Value (DV). The DV is calculated based on expected arrival time and current arrival time. A threshold value is used as an upper bound. The DV value is incorporated in a $SYNC-ACK$ response. They further define the energy of sensing and processing. Thus, in

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the mathematical formulation they include both activity energy and sleep period of sensors.

Same authors in [6] proposed an energy efficient routing protocol for wireless body area networks. The proposed protocol is in the context of handling real-time and on-demand traffic in addition to normal data. They used two communication schemes: the single-hop for real-time and on-demand data and multi-hop for normal data. The main virtue of this protocol is being thermal-aware. The routing path is selected according to the link state if it is a hot-spot or not. In this protocol, TDMA approach is used to schedule the communication of the nodes with the sink. In order to support mobility, nodes are ordered according to their characteristics in terms of data rate. High data-rate nodes are placed in less mobile part of the human body and are considered as the parents. They are connected directly to the sink. The remaining nodes are attached to the parents, so that to form a tree structure. The main drawback of this protocol is when a node is disconnected from its current parent, it will be affected a new parent which induce extra energy consumption for the joint process. Also, the new parent node does not prioritize the disconnected node to send its stored data, delayed by the link failure due to human mobility.

Authors in [7] proposed a TDMA protocol for real-time high data rates for wireless sensor networks (TreeMAC). In this protocol, the used traffic pattern is *many-to-one*. This is the key motivation behind TreeMAC. This protocol was designed for high throughput and energy efficiency. Authors claimed that their protocol regulates the channel access for throughput maximization and energy conservation so that each node gets a number of slots proportional to its bandwidth demand. TreeMAC divides each cycle into frames and each frame into slots. Using a tree structure topology, TreeMAC nodes communicate with their parents, which perform the frame assignment. Time slots are, then, assigned locally. The authors proved that, given any node at any time slot T, there is only one active sender in its 1-hop neighborhood.

A MAC protocol for an EEG remote monitoring application is proposed in [8]. The authors elaborated a TDMA-based protocol in which they considered master-slave architecture and take advantage of the static nature of the body area network. In the master-slave architecture they define what they call Master Node (MN), Monitoring Station (MS) and Sensors (S). The basic idea behind this architecture is to use MN for coordinating the synchronization process and forward the collected data to MS. The authors explained in detail how they calculated each time slot and the entire time frame duration. The synchronization of each sensor is computed by taking into account the guard-time T_g, the total frame duration T_{frame} and the sensor clock accuracy. The computation of the energy consumption and the duty cycle of each sensor is based on various parameters, such as: sensors clock accuracy, sampling data rate, communication data rate, sampled bit during one T_{frame} and other parameters. Please see [8] for further details. The main drawback of this protocol is that a node needs to wait N cycles before resynchronization. Furthermore, the protocol is not generic, it does not consider multiple MNs; it only focuses on one MN.

Authors in [9] proposed a routing protocol with mobility support called $CEMob$. The proposed routing strategy is based on a minimum hop counts metric. They exploited single-hop and multi-hop communications for data differentiation, i.e. normal data and emergency data. The proposed work is an improvement of [6]. However, they do not consider medium access control and physical layer specifications.

The IEEE 802.15.4 is one of the most frequently used wireless technologies in WBANs, by the research community, due to its performance, low power, low data rate and energy efficiency. This standard supports peer-to-peer and star topologies. In [10] authors presented a performance analysis of IEEE 802.15.4 standard in a star topology configuration. They focused their study on the beacon-enabled mode using slotted CSMA/CA. The main motivation of this study is to derive generic equations to model the average power consumption of a sensor. In Beacon mode the Superframe is composed of two parts, the active period and inactive period. The active one contains 16 slots and is divided into Contention Access Period (CAP) and Contention Free Period (CFP). In CAP, the slotted CSMA/CA is used for network formation. The CFP is used to achieve the real-time-constrained traffic, such as video. The beacon is used by coordinator with the aim to synchronize the end devices. The coordinator interacts with end devices during the active period and may sleep in inactive period.

A survey on power-efficient MAC protocols for wireless body area networks is conducted in [11]. Authors gave a synthetic comparison of the most used schemes for medium access control in WBANs.

III. EAWD MODEL

In this section, we give an overview of EAWD [2] and address some of its limitations. EAWD is a mathematical framework based on the integer linear programming. The original work considers the network scenario of Figure 1 and investigates the joint data routing and relay positioning problem in wireless body area networks. The model is very simple and powerful. It includes two well-known mathematical optimization problems: the set covering and multi-commodity flow problems. These problems belong to NP-hard class. Elias et al. stated that it was solved in a very short computing time, with CPLEX 11, a mathematical programming solver [12]. Indeed, the network scenarios are of small size and the total number of sensors and relays are bounded by 13 and 30, respectively. Given a set of biosensors and relay nodes, the framework consists in the design of their interconnection network. As stated in [2], the framework minimizes the total energy consumed and determines the optimal assignment of the relay nodes, based on the following objective function and constraints. For further details please refer to [2]. The basic notation used in the objective function (1) and constraints are referenced in Table I.

$$
\begin{aligned}
Min \quad & \Big\{ \sum_{j\in P} c_j^I z_j + \\
& + \alpha\Big(\sum_{i\in S, j\in P, k\in N} d_{ik} x_{ij} (E_{TXelec} + E_{amp}(n_{ij}) D_{ij}^{n_{ij}}) + && (I) \\
& + \sum_{i\in S, j\in P, k\in N} d_{ik} x_{ij} E_{RXelec} + && (II) \\
& + \sum_{j,l\in P, k\in N} f_{jl}^k (E_{TXelec} + E_{amp}(n_{jl}) D_{jl}^{n_{jl}} + E_{RXelec}) + && (III) \\
& + \sum_{j\in P, k\in N} f_{jk}^t (E_{TXelec} + E_{amp}(n_{jk}) D_{jk}^{n_{jk}} + E_{RXelec}) \Big) \Big\} && (IV)
\end{aligned}
\tag{1}
$$

$$
s.t.
$$

$$\sum_{j\in P} x_{ij} = 1, \ \forall i \in S \tag{2}$$

$$x_{ij} \le z_j a_{ij}, \ \forall i \in S, j \in P \tag{3}$$

$$\sum_{i\in S} d_{ik} x_{ij} + \sum_{l\in P} (f_{lj}^k - f_{jl}^k) - f_{jk}^t = 0, \ \forall j \in P, k \in N \tag{4}$$

$$f_{jl}^k \le \sum_{i\in S} d_{ik} b_{jl} z_j, f_{jl}^k \le \sum_{i\in S} d_{ik} b_{jl} z_l, \ \forall j, l \in P, k \in N \tag{5}$$

$$\sum_{i\in S, k\in N} d_{ik} x_{ij} + \sum_{l\in P, k\in N} f_{lj}^k \le v_j, \ \forall j \in P \tag{6}$$

$$f_{jk}^t \le \sum_{i\in S} d_{ik} e_{jk} z_j, \ \forall j \in P, k \in N \tag{7}$$

$$z_{OR_i(a)} + \sum_{b\in I_i : b>a} x_{iOR_i(b)} \le 1, \ \forall i \in S, a \in I_i \tag{8}$$

$$x_{ij}, z_j \in \{0,1\}, \ \forall i \in S, j \in P \tag{9}$$

The objective function of EAWD model allows it to ensure a tradeoff between the cost installation cost of the relay nodes, represented by the first term, $\sum_{j\in P} c_j^I z_j$, and the total energy consumed by the network which is scaled by the weighting coefficient α. The objective function explicitly specifies the different transmission and reception instances by formulating each energy component such as : (I) sensors transmitting to relays, (II) Relays receiving from sensors, (III) relays forwarding to relays and relays receiving from relays and (IV) relays forwarding to sinks and sinks receiving from relays.

Constraints (2) provide full coverage of all sensors, while constraints (3) are coherence constraints ensuring that a sensor i can be covered by CS j only if a relay is installed in j and if i can be connected to j.

Table I: Basic Notation

S	Set of sensors
P	Set of Candidate Sites (CSs)
N	Set of sinks
c_j^I	Cost for installing a relay in CS j
d_{ik}	Traffic generated by sensor i destined to sink k
v_j	Maximum capacity of a relay installed in CS j
a_{ij}	0-1 connectivity parameter between sensor i and CS j
e_{jk}	0-1 connectivity parameter between CS j and sink k
b_{jl}	0-1 connectivity parameter between CS j and CS l
x_{ij}	0-1 variable that indicates if sensor i is covered by CS j
z_j	0-1 variable that indicates if a relay is installed in CS j
f_{jl}^k	Traffic flow on wireless link (j, l) destined to sink k
f_{jk}^t	Traffic flow between the relay in CS j and the sink k

In this paper we would not revise the whole constraints, we just focus on constraints (5) and (7) since both of them present some weakness aspects. Indeed, constraints (5) considers a binary representation of the relationship between two candidate sites and does not take into account the possibility of a link establishment between successive time epochs. Also, constraints (7) does not consider the multihop paths formed by the relays and just forces to zero the flow between a relay and a sink if they are not connected over a direct link.

Yet, as part of our work in the next section is to revise and enhance these two latter constraints.

IV. ENHANCED EAWD (EEAWD) DESIGN CHALLENGES AND OPEN ISSUES

In this section, we will discuss the EAWD model proposed in [2] and give our insights about the possible extensions of the model, based on syntheses made from previous works and some conclusions that we came to.

Elias et al. made quite strong assumptions and do not take into account the medium access control and physical layer specifications. Indeed, Elias et al. just considered the energy consumption and the total costs of the mesh network formed by biosensors and relay nodes and do not consider the overhead due to MAC, routing and physical clear channel assessment problems. Thus, a cross-layer optimization framework needs to be implemented and tested in real scenarios.

A. Mobility and QoS-aware traffic management for EEAWD

In TDMA medium access control, the network topology is considered static and does not take into account mobility. The main drawback of this approach is the need for synchronization between nodes and then the mobility will cause perturbations that will lead to performance degradation and energy wastage. In the literature, authors do not consider realistic mobility of human body, they just consider different postural positions in a static way, i.e there is no performance evaluation in a timely manner from a body posture A at time T to body posture B at time $T + 1$. Yet, in our approach we propose "pseudo-mobility" support.

It is obvious to see that much of the body area network is static; merely a small part is mobile. This observation is very important as it gives us an idea of the placement of relay nodes in order to take into account the mobile part of the body and even the associated communication pattern (multi-hop). Moreover, in the design of the medium access control protocol, we should also handle a power-level switching mechanism if the mobility is detected for example we can exploit the work done in [14].

This specific design of EEAWD framework is intended for people with low mobility, namely the elderly people. This scenario could constitute a basic model that could be enhanced in order to apply to more general and dynamic scenarios, with more stringent real-time and mobility constraints.

EAWD does not consider different traffic classes as done in [9]. Then, in Enhanced EAWD we will explicitly express the traffic class in the model, by considering both normal and emergency traffic.

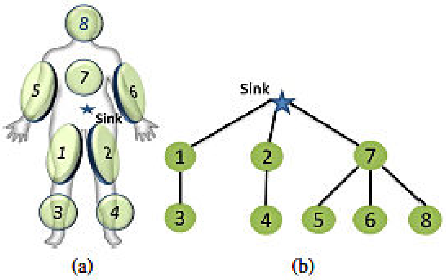

Figure 1: Candidate sites for placing relays and corresponding tree topology [13]

B. MAC and PHY layers for EEAWD

A key feature of EAWD is the hierarchical structure of the mesh network composed by biosensors and relay nodes. Hence, such topological structure lead us to admit a hierarchical synchronization between the nodes that form the network. We propose a combination of two medium access control schemes, which will be interesting if we want to remain in a general case where mobility is handled. We opt for CSMA/CA for network formation and TDMA for network access.

Yet, we need a greater understanding of the physical layer, wireless channel propagation and human bodies' effects (LOS, NLOS, fading...).

C. Energy consumption in EEAWD

In EAWD, there is no energy constraint that guarantees an available amount of energy of the relay node involved in a routing process, to be above a threshold value, denoted hereafter as $E_{threshold}$. We model this constraint as follows, using the energy components of function (1) :

$$\text{(II)} > E_{threshold}$$
$$\text{(III)} > E_{threshold}$$
$$\text{(IV)} > E_{threshold}$$

As we will consider the duty cycle of sensors and relays we need to modify the formulation of the energy in the model. We will consider the active and sleep period in each cycle as E_{cycle}.

$$E_{cycle} = E_{active} + E_{sleep} + E_{switching}$$

such that:

- E_{active} stands for the energy consumed during the activity period.
- E_{sleep} stands for the energy consumed during sleep mode.
- $E_{switching}$ stands for the energy consumed in the switching mode, sleep-to-active, and vice versa.

Yet, in order to provide accurate formulation, the E_{active} can be expressed as :

$$E_{cycle} = \alpha E_{sr} + \beta E_{rr} + \gamma E_{rsk} \tag{10}$$

- E_{sr} stands for the energy consumed by sensors when transmitting to relays.
- E_{rr} stands for the energy consumed by relays when forwarding to relays.
- E_{rsk} stands for the energy consumed by relays when transmitting to the sink.

where α, β and γ values are 0 or 1, respectively depending on the components that are involved in each cycle.

The total energy consumed will be formulated as the sum of the energy amounts consumed during each cycle:

$$E = \sum_{i=1}^{n} E_{cycle_i}$$

We will evaluate the energy consumption for successfully delivered packets and the network lifetime as stated in [4]. For any link (i, j), the energy E_{ij} consumed for transmitting a packet successfully from i to j, during the cycle x is:

$$E_{ij,x} = \frac{E_{TX}^{Z}}{PDR_{ij}}$$

Where PDR_{ij} is the probability of successful delivered packet from i to j and E_{TX}^{Z} is the energy used to transmit packet at $z\ dBm$ as in [4]. This is for the one-hop scenario.

In two-hop scenario, the energy consumed for transmitting a packet successfully from i to j using a node relay k is:

$$E_{ij}^{k} = \frac{2 \times E_{TX}^{k}}{PDR_{ij}^{k}}$$

Where PDR_{ij}^{k} is the number of packets from i delivered successfully to j through relay k [4].

Authors in [4], used the same TX power level for all sensors, but in the case of heterogeneous wireless body area network it will be different.

Other enhancements of the aforementioned framework deal with the original constraints that need to be modified in order to consider further specific cases.

First, we need to modify the constraint (7) of the EAWD. For reminder, this constraint forces the flow between relay j and sink k to zero if node j is not connected to k. This constraint does not take into account the existence of a multi-hop link (a path-relay) formed by relays to reach sink k. In this case, we need to exploit the multi-hop pattern communication and the concept of cooperation among relays.

The constraint (5) is weak because it is a binary interpretation of the existence of a link between CS_j and CS_l and the connectivity parameter b_{jl}, and it does not consider the state of each node in the link they form between two periods of time, T and $T+1$. The idea to improve this constraint and take into account the link availability in EAWD is to use a probabilistic formulation like that presented in [15], considering the Link Availability Estimation.

V. SYNTHESIS TABLE

The table below summarizes our contributions in EEAWD, compared to the surveyed approaches. We mainly focused on the MAC layer, mobility support and time synchronization, which have not been considered, simultaneously, in the aforementioned works.

Approach	MAC	Mobility support	Network config.	Time synchronization
[8]	TDMA	No	Tree	Yes
[2]	Not considered	Not considered	Generic	Not considered
[7]	TDMA	No	Tree	Yes
[6]	TDMA	Pseudo mobility	Star	Yes
[15]	Slotted CSMA/CA	No	Star	Yes
[5]	TDMA	No	Tree	Yes
[9]	Not considered	Pseudo mobility	Star Star	Not considered
EEAWD	TDMA vs CSMA/CA	Yes	Yes	Yes

Table II: Synthesis table of studied protocols

VI. CONCLUSION AND PERSPECTIVES

In this paper we investigated the design of a new framework for wireless body area networks based on the enhancement of EAWD model with TreeMAC [14] and [7]. Our investigations focused on the energy efficiency issue and on the joint routing and MAC-network protocols in wireless body area networks.

The first point of concern was to present EAWD [2]. The second point was to discuss its weaknesses, in order to give our insights about its extensions, based on relevant literature and a possible architecture that we will adopt.

We strongly recommend to add PHY and MAC-layer WBAN specifications to the EAWD model and compare it to the previous work and other related works. Therefore, in a future work, we need to implement and validate our proposal (EEAWD) through simulations or experiments.

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