Energy-aware Topology Design for Wireless Body Area Networks

Jocelyne Elias* and Ahmed Mehaoua†

Abstract—**Wireless Body Area Networks (WBANs) represent one of the most promising approaches for improving the quality of life, allowing remote patient monitoring and other healthcare applications. In such networks, *traffic routing* plays an important role together with the positioning of *relay nodes*, which collect the information from biosensors and send it towards the sinks.**

This work investigates the optimal design of wireless body area networks by studying the joint data routing and relay positioning problem in a WBAN, in order to increase the network lifetime. To this end, we propose an integer linear programming model which optimizes the number and location of relays to be deployed and the data routing towards the sinks, minimizing both the network installation cost and the energy consumed by wireless sensors and relays. We solve the proposed model in realistic WBAN scenarios, and discuss the effect of different parameters on the characteristics of the planned networks.

Numerical results demonstrate that our model can design energy-efficient and cost-effective wireless body area networks in a very short computing time, thus representing an interesting framework for the WBAN planning problem.

***Index Terms*: - WBAN, Network Planning, Relay placement, Routing, Optimization, Energy-efficiency.**

I. INTRODUCTION

Wireless Body Area Networks (WBANs) have recently emerged as an effective means to provide many promising applications in different domains, such as healthcare, medicine, patient monitoring, sport and multimedia, to cite a few.

In WBANs, nodes are usually placed in the clothes, on the body or under the skin. In general, a WBAN topology comprises a set of sensor nodes, which have to be very simple, cheap and energy efficient, and a sink node. Sensors collect information about the person and send it through multi-hop wireless paths to the sink, in order to be processed or relayed to other networks. Although a lot of research has been done toward energy-efficient routing in ad hoc and wireless sensor networks [1], [2], the proposed solutions are inadequate for WBANs, and they need to be significantly improved. Recent surveys on wireless sensor networks for healthcare are provided in [1], [3], where the authors evaluate the state-of-the-art research activities, and present issues that need to be addressed to enhance the quality of life for the elderly, children and chronically ill people. Special devices, called *relay nodes* or relays, can be added to the WBAN to collect all the information from sensors and send it to the sink, thus improving the WBAN lifetime [4], [5]. In fact, relay nodes play an important role in reducing the transmission power of biosensors, which therefore has the double advantage of (1) protecting human tissue and (2) decreasing the energy consumption of such sensors. On the other hand, the introduction of relay nodes permits a much easier maintenance of the WBAN, limiting the number of periodical (medical or surgical) interventions for the replacement of *in-vivo* biosensors with exhausted batteries.

Obviously, the deployment of the WBAN is an important issue that impacts the network lifetime. In general, (bio)sensors have pre-determined positions; therefore, it is imperative to optimize the number and positions of relay nodes, along with the traffic routing, to improve the network lifetime while minimizing at the same time the WBAN installation cost, which includes the sensors and relay nodes installation cost.

Very few works consider the topology design problem for Wireless Body Area Networks [4], [5]. All these works, though, assume that the number and/or location of relay nodes are pre-determined, while the relay node placement is a critical issue in the deployment of the WBAN architecture. Furthermore, these works do not impose bounds on the number of relays, and as a consequence on the total network installation cost, since they focus only on the network lifetime issue.

Therefore, as a key innovative feature, in this work we investigate the joint problem of positioning the relay nodes and designing the wireless mesh network that interconnects them. More specifically, we propose a novel and effective integer linear programming formulation of the WBAN topology design problem, which minimizes the network installation cost while taking accurate account of energetic issues. Our model determines (1) the optimal number and placement of relay nodes, (2) the optimal assignment of sensors to relays, as well as (3) the optimal traffic routing.

We solve the proposed model in realistic WBAN scenarios, and investigate the impact of different parameters on the WBAN design problem. Numerical results demonstrate that our model plans very efficient and cheap WBANs, and can be solved to the optimum in a very short computing time in all the considered scenarios; thus representing a promising framework for the design of wireless body area networks.

The paper is structured as follows: Section II discusses related work. Section III introduces our WBAN design model, while Section IV presents numerical results that show both the efficiency of the proposed model and the effect of different parameters on the characteristics of the planned WBANs. Finally, Section V concludes this paper.

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II. RELATED WORK

Very few works have appeared in the literature with the purpose of increasing network lifetime of Wireless Body Area Networks using additional devices called *relay nodes* [4], [5].

In [5], two mechanisms are considered to improve the network lifetime: relaying and cooperation. The first solution introduces relay nodes, which only handle traffic relaying and do not do any sensing themselves, so that more energy is available for communication purposes. In the second solution, relays cooperate in forwarding the data from one node towards the central device. However, it is assumed that relay nodes are placed next to existing nodes, hence their positions are fixed and are not optimized.

Relaying for improving the network lifetime in a WBAN is also considered in [4], where an upper bound on the number of relay nodes is determined based on the path loss coefficient of the body, the number of sensor nodes and their distance to the sink. The authors, though, do not take into account the problem of minimizing the number of relay nodes (and hence the total network *cost*), but instead assume that relay nodes will be added to the network until all the sensor and relay nodes have at least one relay node in line of sight.

However, none of the above reviewed works has introduced an optimization framework for designing the topology of WBANs. The problem of determining the optimal number and positions of relays to be installed in a WBAN is not taken into account and will be the main focus of this paper.

To our knowledge, we are the first to provide an optimization framework that minimizes installation costs and maximizes the energy efficiency, while considering both multi-hop coverage and connectivity constraints in a WBAN scenario.

III. WIRELESS BODY AREA NETWORK DESIGN MODEL

This section illustrates our proposed wireless body area network optimization framework.

A. Network Model

We consider a WBAN scenario where biosensors for data collection are connected to sink nodes through a set of special nodes, called *relays*. Such relays form a wireless backbone network which transports the data collected by biosensors to sinks. Hence, the wireless body area network is composed of three types of nodes: the biosensors, the sink nodes (which collect and process data from all sensors) and the relays.

A common approach to the network design problem is to consider feasible positions where relays can be installed (Candidate Sites, CSs) [6]. On the other hand, the biosensors and sinks' positions (e.g., arms, legs, breast, ...) are usually pre-determined and fixed, according to the medical application for which they are deployed.

Let S denote the set of sensors, P the set of CSs, and N the set of sinks. Each relay can establish a wireless link with any other relay located within its communication range, R_c, as well as with any sensor at a distance lower than R_s (the sensor radio range), where $R_c > R_s$, in general. For each sensor i, we define the ordered vector OR_i of the reachable wireless relays. These relays are ordered from the closest to the farthest with respect to sensor i. The j-th and k-th element of OR_i are given by $OR_i(j)$ and $OR_i(k)$, respectively, and they indicate the relays at the j-th and k-th place in the vector. So, if $j < k$, then $OR_i(j)$ is closer to sensor i than relay $OR_i(k)$. Let us denote by I_i the index set of the ordered vector OR_i.

The cost associated with installing a relay in CS j is denoted by c_j^I, and its capacity is denoted by $v_j, \forall j \in P$. Furthermore, the traffic generated by sensor i towards the sink k is given by the parameter d_{ik}, $i \in S, k \in N$.

According to sensors, sinks and CSs location, the following connectivity parameters can be calculated. Let a_{ij}, $i \in S$, $j \in P$ denote the sensor coverage parameters:

$$a_{ij} = \begin{cases} 1 & \text{if sensor } i \text{ can establish a link with} \\ & \text{a relay installed in CS } j \\ 0 & \text{otherwise} \end{cases}$$

and e_{jk}, $j \in P, k \in N$ the sink coverage parameters:

$$e_{jk} = \begin{cases} 1 & \text{if a relay node installed in CS } j \text{ can establish} \\ & \text{a link with sink } k \\ 0 & \text{otherwise} \end{cases}$$

Obviously, a_{ij} depends on the proximity of sensor i to CS j, as well as on the propagation conditions between such nodes. Similarly, e_{jk} is related to the distance between CS j and sink k.

Finally, let b_{jl}, $j, l \in P$ denote the connectivity parameters between two different CSs, which may depend on the proximity of the relays j and l in the network:

$$b_{jl} = \begin{cases} 1 & \text{if CS } j \text{ and } l \text{ can be connected with a wireless link} \\ 0 & \text{otherwise} \end{cases}$$

Decision variables of the problem include sensor assignment variables x_{ij}, $i \in S, j \in P$:

$$x_{ij} = \begin{cases} 1 & \text{if sensor } i \text{ is assigned to CS } j \\ 0 & \text{otherwise} \end{cases}$$

relays' installation variables z_j, $j \in P$:

$$z_j = \begin{cases} 1 & \text{if a relay is installed in CS } j \\ 0 & \text{otherwise} \end{cases}$$

and finally flow variables f_{jl}^k which denote the traffic flow routed on link (j, l) destined to the sink $k \in N$. The special variables f_{jk}^t denote the total traffic flow between the relay installed in CS j and the sink k.

B. Propagation and Energy Model

In the following, we adopt the propagation and radio models used in [5], [7]. The path loss coefficient on the wireless link between nodes i and j is denoted by n_{ij}, and is equal to 3.38 along the human body for line of sight propagation and to 5.9 for the non line of sight case.

To calculate the energy consumption in wireless nodes (sensors, relays and sinks), we assume that the sensing and processing energy are negligible with respect to communication energy. Therefore, the total energy consumption is represented by the total transmission and reception energy of all wireless nodes. The energy the radio dissipates to run the circuitry for the transmitter and receiver are denoted by E_{TXelec} and E_{RXelec}, respectively. $E_{amp}(n_{ij})$ represents the energy for the transmit amplifier, and D_{ij} is the distance between nodes i and j. The transmission energy can therefore be computed as $w[E_{TXelec} + E_{amp}(n_{ij})D_{ij}^{n_{ij}}]$, while the reception energy is wE_{RXelec}, where w is the total number of transmitted/received bits.

C. Energy-Aware WBAN Design Model

Given the above notations, parameters and variables, we now illustrate our proposed Energy-Aware WBAN Design model (EAWD), which minimizes at the same time the total network installation cost and the overall energy consumed by the network, while ensuring full coverage of all sensors and effective routing of medical data towards sink nodes.

The EAWD model is defined as follows:

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

$s.t.$

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

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

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

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

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

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

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

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

The objective function (1) accounts for the total installation cost and the total energy consumption. The first term, $\sum_{j\in P} c_j^I z_j$, takes into account the relay nodes installation cost, while the second term represents the total energy consumed by the network (relays and sensors), including the transmission and reception energy, α being a parameter that permits to give more weight to one component with respect to the other. For big α values, the first component becomes negligible and the model minimizes only the energy consumed by the network. On the other hand, for small α values the model minimizes the relays' installation costs.

More in detail, the second term of objective function (1) is composed of the following elements: $\sum_{i\in S, j\in P, k\in N} d_{ik} x_{ij} (E_{TXelec} + E_{amp}(n_{ij}) D_{ij}^{n_{ij}})$ is the total energy consumed by all sensors to transmit data to relays, while $\sum_{i\in S, j\in P, k\in N} d_{ik} x_{ij} E_{RXelec}$ is the total energy consumed by relays to receive data from all sensors. The terms $\sum_{j,l\in P, k\in N} f_{jl}^k (E_{TXelec} + E_{amp}(n_{jl}) D_{jl}^{n_{jl}})$ and $\sum_{j\in P, k\in N} f_{jk}^t (E_{TXelec} + E_{amp}(n_{jk}) D_{jk}^{n_{jk}})$ are the total energy consumed by relays to forward data to other relays and to sinks, respectively. Finally, $\sum_{j,l\in P, k\in N} f_{jl}^k E_{RXelec}$ is the total energy that relays dissipate for receiving data from other relays, while $\sum_{j\in P, k\in N} f_{jk}^t E_{RXelec}$ is the total energy consumed by sinks to receive the corresponding data collected by all sensors 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.

Constraints (4) define the flow balance in relay node j for all the traffic destined towards sink node k. These constraints are similar to those adopted for classical multicommodity flow problems: the term $\sum_{i\in S} d_{ik} x_{ij}$ is the total traffic generated by the covered sensors destined towards sink node k, $\sum_{l\in P} f_{lj}^k$ is the total traffic received by relay j from neighboring nodes, $\sum_{l\in P} f_{jl}^k$ is the total traffic transmitted by j to neighboring nodes, and f_{jk}^t is the traffic transmitted towards the sink node k. Note that these constraints define the multi-hop paths (i.e., the routing) for all the traffic that is transmitted in the WBAN.

Constraints (5) define the existence of a link between CS j and CS l, depending on the installation of relays in j and l and the connectivity parameters b_{jl}.

Constraints (6) impose, for each relay node j, that the ingress traffic (from all covered sensors and neighbors) serviced by such network device does not exceed its capacity v_j, whilst constraints (7) force the flow between relay j and sink k to zero if node j is not connected to k.

Constraints (8) force each sensor to be assigned to the closest installed relay, and constraints (9) are the integrality constraints for the binary decision variables.

Finally, it is easy to observe that the above model is NP-hard since it includes the set covering and the multicommodity flow problems as special cases. However, we will demonstrate in the next section that it can be solved to the optimum in a very short computing time (only fractions of a second), thus representing a very effective tool to plan both energy-efficient and cheap wireless body area networks.

IV. NUMERICAL RESULTS

In this section, we test the sensitivity of the proposed Energy-Aware WBAN Design (EAWD) model to different parameters like the number of candidate sites and sensors, as well as the α value in objective function (1), which permits to express a trade-off between planning cost-effective and energy-efficient networks.

To this end, we consider realistic WBAN scenarios, and we compare the performance of our model to the *single-hop* and *multi-hop* approaches in terms of both the total energy consumed by the network and by each sensor to route all data collected by sensors towards sink nodes. The single-hop approach consists in transmitting all data directly from each sensor to the sink node. In the multi-hop approach, the traffic is relayed by intermediate sensor nodes towards the sink.

Since extremely low transmission power in non-invasive WBAN is required to protect human tissue [1], in the following we limit WBAN devices' transmission range (and as a consequence, the power) assuming that each sensor and sink can be connected to a CS only if the CS is at a distance not greater than 30 cm from the sensor or the sink (i.e., $R_s = 30$ cm).

As for the connectivity parameters between different CSs, we assume that each CS can be directly connected with a wireless link to any other CS (i.e., $b_{jl} = 1, \forall j, l \in P$); this allows our model to investigate all possible link configurations to find the optimal WBAN topology. We further assume that the maximum capacity of each relay is equal to 250 kb/s.

If not specified differently, the relay installation cost is equal to 10 monetary units. The radio dissipates $E_{TXelec} = 16.7$ and $E_{RXelec} = 36.1$ nJ/bit to run the transmitter and receiver circuitry, respectively. The energy for the transmit amplifier $E_{amp}(n_{ij})$ depends on the path loss coefficient (n_{ij}), which assumes either the value 3.38 (line of sight case) or 5.9 (non line of sight case), as discussed before, and it is equal to 1.97 nJ/bit for $n_{ij} = 3.38$ and 7.99 μJ/bit for $n_{ij} = 5.9$. These specific parameters' values correspond to the Nordic nRF2401 transceiver which is frequently used in sensor networks [5], [7].

We underline that none of the above assumptions affects the proposed model, which is general and can be applied to any problem instance and network topology.

All the results reported hereafter are the optimal solutions of the considered instances obtained by formalizing the proposed model in AMPL and solving them with CPLEX 11. The workstations used were equipped with an Intel Pentium 4 (TM) processor with CPUs operating at 3 GHz, and with 1024 Mbyte of RAM.

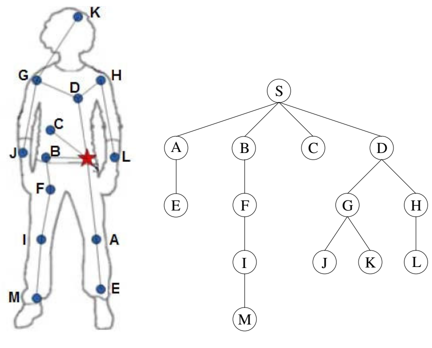
Wireless Body Area Network Scenarios

To evaluate the performance of the EAWD model, we consider the wireless body area network topology depicted in Figure 1(a) [4]. This scenario includes 13 bio-sensors that are placed on the human body to capture electrical signals, like electrocardiograms (sensors D, E, J, L and M), electroencephalograms (sensor K), and electromyograms (sensors A and I) thus providing useful information on the physiological state of the patient.

For the multi-hop approach, we assume that the routes from the sensors to the sink are those illustrated by straight lines in Figure 1(a), and hence the corresponding tree topology is the one shown in Figure 1(b).

The distances (in meters) between sensors and the sink for the single-hop case, and between sensors and the nearest node for the multi-hop case are given in Table I.

We further assume that candidate sites for placing relays are chosen uniformly at random along the wearable suite/short of the patient.



(a) (b)

Fig. 1. (a) WBAN topology and (b) the corresponding tree.

We first solve the EAWD model minimizing the total energy, neglecting the installation cost component in objective function (1), i.e., we choose a very large value for the weighting parameter α.

Table II reports the average value of both the total energy consumed by the network (E_{tot}), which includes the energy consumed by both relays and sensors, and by each sensor (E_s) under the single-hop and multi-hop approaches. The number of relays chosen by our model is equal to 12, in average, and the computing time necessary to obtain the optimal solutions is very small (below 0.2 s). Numerical results demonstrate that the installation of relays is extremely effective for reducing the energy consumption: in fact, the total energy consumed by the network without deploying relays is in average 127.74 and 4.202 μJ/bit for single-hop and multi-hop approaches, respectively, while the installation of relays permits to decrease such value by a factor of 62 w.r.t. single-hop and by 2 w.r.t. multi-hop approach (as reported in Table II). On the other hand, if we focus on the energy consumed by each sensor to send one data unit to the sink, we can observe that, with our EAWD model, such energy is significantly lower (0.017 μJ) than the one obtained with the single-hop (9.826 μJ) and multi-hop (0.323 μJ) approaches.

Furthermore, it is interesting to notice that the energy consumed (per data unit) by sensor B is equal to 175.235 nJ with the multi-hop approach, while such energy is 16.734 nJ with both the single-hop and our approach. This is due to the fact that, in the multi-hop approach, all sensors in the proximity of the sink (like sensor B) forward the physiological

TABLE I

Distances (in meters) between sensors and the sink for the single-hop case, and between sensors and the nearest node for the multi-hop case.

sensor	A	B	C	D	E	F	G	H	I	J	K	L	M
single-hop	0.6	0.3	0.2	0.5	1.2	0.6	0.7	0.6	0.8	1.0	0.8	0.8	1.5
multi-hop	0.6	0.3	0.2	0.5	0.6	0.3	0.2	0.1	0.3	0.6	0.4	0.6	0.6

TABLE II

Total energy per data unit consumed by the network and by each sensor, in average, in the single-hop, multi-hop approaches and with our EAWD model.

model	E_{tot} (μJ/bit)	E_s (μJ/bit)
single-hop	127.740	9.826
multi-hop	4.202	0.323
EAWD	**2.059**	**0.017**

data received from other sensors situated far away from the sink; our model, on the other hand, plans WBANs where all sensors (nearby and far away from the sink) transmit their data to relays, which in turn, forward such data to the sink.

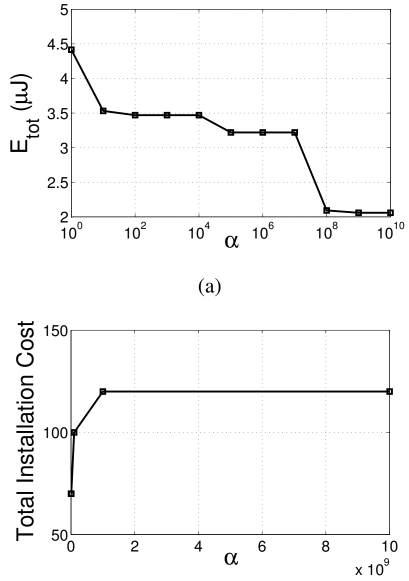
Effect of the weighting parameter (α): We now evaluate the effect of the α parameter on the EAWD model considering the same WBAN scenario illustrated in Figure 1(a). We assume that α ranges from 0 to ∞, where $\alpha = 0$ means that the EAWD model minimizes the network installation cost, neglecting the energy consumption, while with $\alpha \to \infty$ the model minimizes the total energy consumed by the WBAN.

Figures 2(a) and 2(b) show, respectively, the total energy consumed by the network and the total installation cost as a function of α. For small α values, the EAWD model plans cheap WBANs with a small number of relays (below 7), but at the cost of quite a high energy consumption. On the other hand, when $\alpha \to \infty$ the model plans an energy-efficient WBAN, reducing the energy by a factor of 750.4 and 2.2 w.r.t. the case of $\alpha = 0$ and $\alpha = 1$, respectively; the number of installed relays is 12 in this case.

Finally, we underline that in all the considered WBAN scenarios, the computing time necessary to obtain the optimal solutions was always very small (only fractions of a second). As a consequence, our optimization framework is perfectly tailored also for possible network reconfigurations (due to patient movement) that can be performed during the network functioning in a very short time.

V. CONCLUSION

In this paper we addressed the topology design problem for Wireless Body Area Networks, proposing a novel and effective model based on mathematical programming that determines (1) the optimal number and placement of relay nodes, (2) the optimal assignment of sensors to relays, as well as (3) the optimal traffic routing, taking accurate account of both the total network cost and energy consumption. The model can be used to minimize both the total energy consumption and the network installation cost, while ensuring full coverage of all sensors.



(a)

(b)

Fig. 2. (a) Total energy consumed by the network and (b) total installation cost as a function of the weighting parameter α.

The numerical results we gathered illustrate the sensitiveness of the optimal solution to the main parameters considered in our optimization (number of sensors and candidate sites, weighting parameter), and show that our optimization framework is very promising for the design of wireless body area networks.

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