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Optimal design of energy-efficient and cost-effective wireless body area networks ☆

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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. The deployment of a WBAN is a critical issue that impacts both the network lifetime and the total energy consumed by the network. This work investigates the optimal design of wireless body area networks by studying the joint data routing and relay positioning problem, in order to increase the network lifetime. To this end, we propose a mixed integer linear programming model, the Energy-Aware WBAN Design model, which optimizes the number and location of relays to be deployed and the data routing towards the sink, minimizing both the network *installation cost* and the *energy* consumed by wireless sensors and relays. We solve the proposed model in both realistic WBAN scenarios and general topologies, and compare the model performance to the most notable approaches proposed in the literature. Numerical results demonstrate that our model (1) provides a good tradeoff between the energy consumption and the number of installed relays, and (2) designs energy-efficient and cost-effective WBANs in a short computation time, thus representing an interesting framework for the dynamic WBAN design problem.

1. Introduction

Wireless Body Area Networks (WBANs) have recently emerged as an effective means to provide several promising applications in different domains, such as remote healthcare [2–4], athletic performance monitoring [5,6], military and multimedia [7,8], to cite a few. In WBANs, nodes are usually placed in the clothes, on the body or under the skin [9–11]. 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. 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 and reliability [12–15]. In fact, relay nodes play an important role in reducing the transmission power of biosensors, and therefore have the double advantage of (1) protecting human tissue from radiation and heating effects, and (2) decreasing the energy consumption of such devices. On the other hand, the introduction of relays (embedded in the clothes or in disposable coveralls) 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[1] have predetermined positions; therefore, it is imperative to optimize the *number* and *positions* of relay nodes, along with the traffic routing, to improve the network

☆ Preliminary results of this work have been presented in [1].

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[1] *Biosensor* and *sensor* will be used as synonyms throughout the paper.

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lifetime while minimizing at the same time the WBAN installation cost, which includes the sensors and relay nodes cost.

Few works have considered the topology design problem for wireless body area networks [12,13]. These works, though, assume that the number and/or location of relay nodes are predetermined, while the relay nodes placement is a critical issue in the deployment of the WBAN architecture. Furthermore, these works do not impose bounds on the number of relay nodes (and as a consequence, on the total network installation cost), and do not take into consideration the comfort of the patient, 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 mixed 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, named Energy-Aware WBAN Design (EAWD) 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 EAWD model in realistic WBAN scenarios as well as in more general topologies, and investigate the impact of different parameters on the WBAN design problem, such as the number and installation cost of relay nodes as well as traffic demands. We further compare our model's performance to the most notable approaches in the literature, especially in terms of the total energy consumed by the whole network and by each sensor, as well as the number of relays installed in the network to forward data to the sink. Numerical results demonstrate that our model (1) provides a very good compromise between planning energy-efficient WBANs and minimizing the number of relays deployed on the patient in all the considered scenarios, and (2) can be solved to the optimum in a very short computation time, thus representing a promising framework for the dynamic design (and, possibly, on-the-fly reconfiguration) of wireless body area networks.

The rest of this paper is structured as follows: Section 2 discusses related work. Section 3 introduces our Energy-Aware WBAN Design model, and Section 4 presents the assumptions and parameters' setting for performance evaluation results. Sections 5 and 6 evaluate the performance of the proposed model considering real WBAN scenarios as well as general network topologies, comparing it to a set of approaches in terms of energy consumption, number of installed relays and network cost. Finally, Section 7 concludes this paper.

2. Related work

In this section, we first review the most notable surveys on wireless body area networks, along with several works related to the network architecture and the peculiar communication channel of WBANs. Then, we discuss relevant works that deal with the WBAN topology design problem, which is the main focus of this paper.

Recent surveys on wireless body area networks are provided in [9–11], where the authors evaluate the state-of-the-art research activities, and present challenging issues that need to be addressed to enhance the quality of life for the elderly, children and chronically ill people. A comprehensive review and outlook of pioneer WBAN research projects and enabling technologies is provided in [10], including application scenarios, sensor/actuator devices, radio technologies, and interconnection of WBANs to the outside world. Several open research issues for enabling ubiquitous communications in WBANs are discussed, such as propagation and channel models, networking and resource management schemes, security, authentication and privacy, as well as power supply issues. In [11], a survey is provided of the recent research on intelligent monitoring applications from a smart home perspective, and in particular from a healthcare related perspective. Such survey discusses a number of benefits that will be achieved, and challenges that will be faced while designing future healthcare applications. Furthermore, it presents a list of prototypes and commercial applications for pervasive healthcare monitoring. The work in [16] describes the design, implementation and optimization of a lightweight system based on wireless sensor networks for the automatic supervision of fragile people with a broad range of pathologies (including cognitive and/or perceptual disorders, Down's syndrome, epilepsy), within nursing institutes.

The choice of the network architecture for body sensor networks is an important issue since it significantly affects the overall system design and performance. This problem is tackled in [17,18], where the authors try to define the correct network architecture for body sensor networks. The main contributions can be summarized as follows: (1) identifying the design goals and comparing the star and multi-hop network topologies, (2) conducting experiments to investigate the nature of transmission through and around the body in a high interference environment, (3) developing a visualization tool to discern patterns in large data sets, and (4) analyzing channel symmetry and packet delivery ratio to provide insights about the channel. Finally, by performing a simple optimization on the obtained results, it is observed that in rich scattering environments with significant multipath, the star architecture will suffice. However, large gains can be reaped by switching to a multi-hop architecture in low-multipath environments.

The problem of characterizing the communication channel on the human body and designing energy-efficient topologies for wireless body area networks is addressed in [12,19,20]. The work in [12] discusses the propagation channel between two half-wavelength dipoles at 2.45 GHz placed near a human body, and presents an application for cross-layer design to optimize the energy consumption of different topologies (single-hop and multi-hop network topologies). In [19], it is shown that for on-body communications, diversity reception is most effective when the on-body path between transmitter and diversity receiver crosses from the front to the back of the human body and the user is mobile in a multipath environment.

Energy-efficient MAC protocols for WBANs are proposed in [21–23], where the authors tried to improve energy-efficiency by reducing packet collisions, transmission times, idle listening, etc. However, the main drawback of these works is that they assumed that a WBAN is not a dynamic network structure and therefore they cannot adapt to changes in network topology due to the movement of the person at home or in hospital (e.g., real-time patient monitoring), while our optimization framework can straightforwardly take into account person mobility improving simultaneously energy-efficiency and data reliability.

Topology design in wireless body area networks

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* [12,13].

In [12], 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, wireless devices 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, and the total energy consumed by each biosensor (and by the whole network) is therefore considerably higher than the one obtained with our model.

Relaying for improving the network lifetime in a WBAN is also considered in [13]. This relaying approach is quite similar to the multi-hop approach, in the sense that each relay at one *level* forwards the traffic of at most one node at a previous level, and the number of relays to be deployed at a given level depends directly on the number of nodes (relays and sensors) at the previous level. The total number of relays is determined based on the path loss coefficient of the body, the number of sensor nodes and their distance to the sink. The authors of [13], though, do not take into account the problem of minimizing the number of relays (and hence the total network *cost*), but instead assume that relays will be added to the network until all sensors and relays have at least one relay node in line of sight. Note that, with this relaying approach, the number of relays is dramatically high and has a great impact on the comfort and mobility of the patient.

In summary, none of the above reviewed works has introduced an optimization framework for designing the topology of WBANs. The joint problem of determining the optimal number and positions of relays to be installed and the optimal traffic routing 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 (the number of relays), and maximizes the energy efficiency, while considering both multi-hop coverage and connectivity constraints in a WBAN scenario.

3. Wireless Body Area Network Design model

This section illustrates our proposed wireless body area network optimization framework. We first introduce the network model, along with all parameters and optimization variables; then, we illustrate the radio propagation model as well as the energy model used to compute the total energy consumed by the WBAN. Finally, we discuss in detail the mixed integer linear programming (MILP) model for designing energy-efficient and cost-effective wireless body area networks. This model allows us to (i) solve to optimality realistic WBAN scenarios in a very short computation time, and (ii) evaluate the impact of system parameters on the obtained solutions.

3.1. Network model

In this work, we consider a WBAN scenario, where the body is in a standing position with arms hanging along the side. Biosensors are placed on the body for data collection, and they 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.

We assume that biosensors can share the same radio spectrum in a time division multiple access manner, and therefore, there is no interference between such wireless devices within a single WBAN [22,24–26]. Our optimization framework is a key building block for wireless body area networks, and is complementary to TDMA-based protocols, like those proposed in [22,24–26]. On the other hand, the proposed optimization framework for the stand scenario represents a starting point for understanding the impact of the WBAN topology on energy-efficiency and network lifetime, and it can be easily extended to dynamic scenarios, like those investigated in [14,15,27–30].

We adopt a practical approach to the network design problem, by considering feasible positions where relays can be installed (Candidate Sites, CSs) [31–33]. On the other hand, the biosensors and sinks' positions (e.g., arms, legs, breast,...) are usually predetermined and fixed, according to the medical application for which they are deployed.

Let $S = \{1, \ldots, s\}$ denote the set of sensors, $P = \{1, \ldots, p\}$ the set of CSs, and $N = \{1, \ldots, n\}$ the set of sinks. The basic notation used in this paper is summarized in Table 1.

Each relay can establish a wireless link with any other relay/sensor located within its communication range, R_c. The sensor communication range is denoted by R_s, where $R_c \geqslant R_s$, in general. In fact, we are assuming that biosensors and relays may have different transmission power. Biosensors can reduce their transmission powers to the minimum level necessary to maintain network connectivity, thus protecting human tissue from radiation and heating effects, and decreasing their energy consumption. Instead, relay nodes (embedded in disposable coveralls) may have less restrictive power constraints, hence ($R_c \geqslant R_s$).

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 jth and kth element of OR_i are given by $OR_i(j)$ and $OR_i(k)$, respectively, and they indicate the relays at the jth

Table 1
Basic notation.

S	Set of sensors, $s = \|S\|$
P	Set of Candidate Sites (CSs), $p = \|P\|$
N	Set of sinks, $n = \|N\|$
c_j^l	Cost for installing a relay in CS j
w_{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

and kth 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^l, 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 w_{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:

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

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

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

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}, $i \in S$, $j \in P$:

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

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.

3.2. Propagation and energy models

For an accurate characterization of the In/On-Body channel model, different key issues should be considered: power absorption (specific absorption rate, SAR), human body tissue, fading (small/large scale), path loss and shadowing, to cite the most important. This aspect deserves further investigation, but is out of the scope of this paper. Before presenting the propagation and energy models we adopt in this work, we first provide a brief survey on in-body and on-body channel models for wireless body area networks.

3.2.1. Survey on In/On-Body channel models

As stated in [20], the human body is not an ideal medium for Radio Frequency (RF) wave transmission: it is partially conductive, and consists of materials of different dielectric constants, thickness, and characteristic impedance. Therefore, depending on the frequency of operation, the human body can lead to high losses caused by power absorption, central frequency shift, and radiation pattern destruction. The absorption effects vary in magnitude with both the frequency of the applied field and the characteristics of the tissue [34,35]. Based on the location of the communicating nodes *in*, *on* and *around* the human body, a set of scenarios have been described in [20], along with a set of channel models for WBANs.

3.2.1.1. In-Body channel models. In [36], the authors present a propagation loss model (PMBA) for homogeneous tissue bodies, and verify such model for the 900 MHz to 3 GHz frequency range using a 3D Electromagnetic simulator, as well as through experimental measurements using saturated salt water. The PMBA model is compared with the free space propagation model, and it is observed that there is an additional 30–35 dB of attenuation at small distances in the far field; this loss increases further with the distance and frequency. It is also noted from the simulation results that a major amount of power is absorbed in the near-field region of the antenna, and this cannot be ignored as in the case of other applications. In [37], a 3D virtual reality simulation platform is used to study electromagnetic propagation from/to medical implants. The platform is then used to extract a simple statistical path loss model for medical implant communication channels. The in-body path loss model is also investigated in [38] for homogeneous human tissues at 2.45 GHz. The model is based on 3D electromagnetic simulations and validated through measurements, and takes into account permittivity, conductivity, and separation between antennas. Finally, such model is evaluated in both homogeneous and heterogeneous mediums. Other previous works by the same authors [39,40] study the in-body path loss model in human muscle, brain, fat and skin.

On the other hand, to address the limitations of RF propagation in the human body, the authors in [41] propose to use ultrasonic waves to wirelessly interconnect in-body devices. To do so, they first assess the feasibility of using ultrasonic communications in intra-body BANs, and then discuss the fundamentals of ultrasonic propagation in tissues, and explore important tradeoffs, including the choice of a transmission frequency, transmission power, bandwidth, and transducer size. Next, they present a system architecture and discuss future research challenges for ultrasonic networking of in-body devices at the physical, medium access and network layers of the protocol stack.

3.2.1.2. On-Body channel models. Since in this work we are interested in the *on-body communications*, we review hereafter the most relevant works on on-body channel modeling and characterization [12,42–48]. Ultra-wideband channel models for communication around the human body are studied in [47] and in [48], when the user is stationary and in the case of limited movements of the arms, respectively. In [47], the authors use a vector network analyzer and small antennas to obtain several channel responses around a human torso in an office. Based on the extracted responses, the estimated channel statistics are incorporated into a model. Finally, the model is implemented and compared with experimental measurements, focusing on the 3–6-GHz band which is commonly used for UWB systems. An experimental investigation into the influence of user state and environment on small-scale fading characteristics in WBANs at 2.45 GHz has been performed in [42]. The work in [12] characterizes the physical layer in terms of path loss, delay spread, and mean excess delay for narrow band communication at 2.45 GHz between two half wavelength dipoles near a realistic human body. A total of 583 measurements are performed in a multipath environment on real humans considering different parts of the human body: arms, leg, torso, and back. The authors derive a channel model which only accounts for Line of Sight (LOS) propagation and does not consider, for example, the communication between the back and torso, nor does it take into account the curvature effects of the body, while in [47] the path loss is modeled in Non-Line of Sight (NLOS) situations around the human body.[2] It has been observed a higher path loss and path loss exponent along the NLOS than along the LOS channel due to diffraction around the human body and absorption of a large amount of radiation by the body.

3.2.2. Used propagation and energy models

In this work, we will focus on the *on-body* propagation model and we will exploit the path loss results presented in the previous section (especially those obtained in [12,47,48]), including both LOS (i.e., along the front of the body) and NLOS (i.e., around the torso) situations.

When two biosensors (placed on the body) communicate with each other, transmitted signals can arrive at the receiver in three ways: (i) propagation through the body, (ii) diffraction around the body and (iii) reflections off of nearby scatterers then back at the body. However, propagation through the body is negligible in the gigahertz frequency range and can be ignored [12,47,48].

In general, the path loss in dB between the transmitting and the receiving wireless device, P^{ij}_{dB}, can be modeled as a function of the distance D_{ij} using the following equation [12,37,47]:

$$P^{ij}_{dB}(D_{ij}) = P^{ij}_{0,dB} + 10 n_{ij} log_{10}(D_{ij}/D_{0,ij}) + S,$$

where $P^{ij}_{0,dB}$ is the path loss in dB at a reference distance $D_{0,ij}$, n_{ij} is the path loss coefficient[3] and $S \sim N(0, \sigma_S)$ is a normal variable which represents the deviation in dB caused by different materials (i.e., body tissues and organs) and antenna gain in different directions.

To calculate the energy consumption in wireless nodes (sensors and relays), we assume, as in [12,13], 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 $w\, E_{RXelec}$, where w is the total number of transmitted/received bits.

3.3. Energy-Aware WBAN Design model

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

The EAWD model is defined as follows:

$$\begin{aligned} Min \Bigg\{ & \sum_{j \in P} c^I_j z_j + \alpha \Bigg(\sum_{i \in S, j \in P, k \in N} w_{ik} x_{ij} (E_{TXelec} + E_{amp}(n_{ij}) D_{ij}^{n_{ij}}) \\ & + \sum_{i \in S, j \in P, k \in N} w_{ik} x_{ij} E_{RXelec} + \sum_{j,l \in P, k \in N} f^k_{jl} (E_{TXelec} + E_{amp}(n_{jl}) D_{jl}^{n_{jl}}) \\ & + \sum_{j \in P, k \in N} f^t_{jk} (E_{TXelec} + E_{amp}(n_{jk}) D_{jk}^{n_{jk}}) + \sum_{j,l \in P, k \in N} f^k_{jl} E_{RXelec} \Bigg) \Bigg\} \end{aligned} \quad (1)$$

s.t.

$$\sum_{j \in P} x_{ij} = 1, \qquad \forall i \in S \quad (2)$$

$$x_{ij} \leqslant z_j a_{ij}, \qquad \forall i \in S, j \in P \quad (3)$$

$$\sum_{i \in S} w_{ik} x_{ij} + \sum_{l \in P} (f^k_{lj} - f^k_{jl}) - f^t_{jk} = 0, \qquad \forall j \in P, k \in N \quad (4)$$

$$f^k_{jl} \leqslant \sum_{i \in S} w_{ik} b_{jl} z_j, f^k_{jl} \leqslant \sum_{i \in S} w_{ik} b_{jl} z_l, \qquad \forall j, l \in P, k \in N \quad (5)$$

$$\sum_{i \in S, k \in N} w_{ik} x_{ij} + \sum_{l \in P, k \in N} f^k_{lj} \leqslant v_j, \qquad \forall j \in P \quad (6)$$

$$f^t_{jk} \leqslant \sum_{i \in S} w_{ik} e_{jk} z_j, \qquad \forall j \in P, k \in N \quad (7)$$

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

$$x_{ij}, z_j \in \{0, 1\}, \qquad \forall i \in S, j \in P. \quad (9)$$

[2] The transmitter is placed on the front of the body, and the receiver is placed at various positions on the torso at distances of 10–45 cm.

[3] *Path loss coefficient* and *path loss exponent* will be used as synonyms throughout the paper.

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. Hence, the α value should be set carefully in order to guarantee both low energy consumption and small number of installed relays. This is discussed in detail in the Performance Evaluation sections.

More in detail, the second term of objective function (1) is composed of the following elements: $\sum_{i \in S, j \in P, k \in N} w_{ik} x_{ij} (E_{TXelec} + E_{amp}(n_{ij}) D_{ij}^{n_{ij}})$ is the total energy consumed by all sensors to transmit data to relays, while $\sum_{i \in S, j \in P, k \in N} w_{ik} x_{ij} E_{RXelec}$ 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.

In this second term, we do not consider the total energy consumed by the sink to receive the data, collected by all sensors, from relays, since (i) we focus mainly on the energy consumed by critical nodes (sensors and relays), and (ii) the energy dissipated by the sink for receiving data does not affect in any way the optimal solution. However, it is straightforward to take into account the energy dissipated by the sink; it suffices to add to the objective function the expression $\sum_{j \in P, k \in N} f_{jk}^t E_{RXelec}$, where f_{jk}^t is the total traffic flow between the relay installed in CS j and the sink k, and E_{RXelec} is the energy required to run the circuitry of the receiver.

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 multi-commodity flow problems: the term $\sum_{i \in S} w_{ik} x_{ij}$ 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. Finally, constraints (9) are the integrality constraints for the binary decision variables.

Note that we can consider alternative formulations to this model. For example, we might want sensors to be connected to more than one relay, for redundancy. This is easily accomplished by modifying constraints (2) as: $\sum_{j \in P} x_{ij} = \eta, \forall i \in S$, where η is the number of relays that receive the packets from sensor i.

We further observe that our model can be easily extended taking into account sensor positioning. In fact, if there exist also several candidate sites where to place sensors, the extended model can decide at the same time the optimal number and positions of sensors and relays, as well as the traffic routing, in order to minimize further the energy consumed by the network.

Note that EAWD is a MILP[4] model since some decision variables are integers (more specifically, they are binary: $x_{ij} \in \{0,1\}$ and $z_j \in \{0,1\}$), and other variables are continuous ($f_{lj}^k \geqslant 0, f_{jk}^t \geqslant 0$). In addition, the objective function (1) as well as all constraints are linear in x_{ij}, z_j, f_{lj}^k and $f_{jk}^t, \forall i \in S, j, l \in P, k \in N$. The EAWD optimization problem can be solved by employing for example a combination of branch-and-bound and cutting-plane techniques that are commonly used by MILP solvers, such as the CPLEX software which we chose to compute the optimal solutions in the numerical analysis provided in the next sections. Roughly speaking, branch-and-bound [49] is a technique that permits us to solve a discrete variable problem by solving a sequence of simpler problems derived from the original one. The search is organized via a branch-and-bound tree. On the other hand, the cutting-plane [50,51] is an optimization method that iteratively refines a feasible set or objective function by means of linear inequalities, named *cuts*. For more details, the reader is referred to the work by Lawler and Wood, Kelley and Gomory [49–51].

The Energy-Aware Wireless Body Area Network Design problem is NP-Hard. In fact, it can be demonstrated that the Minimum-Cost Set Cover problem is a subproblem of our EAWD problem.

Let $X = \{x_1, \ldots, x_m\}$ denote a finite set of elements to cover and $S = \{1, \ldots, m\}$ the set of indices. Let $\mathscr{F} = \{X_1, \ldots, X_n\}$ denote a family of subsets of X (i.e., $X_j \subseteq X, \forall j \in P$), where $P = \{1, \ldots, n\}$. We assume that each subset X_j has a *cost* c_j, and we define the parameter a_{ij}, $i \in S, j \in P$ as follows:

$$a_{ij} = \begin{cases} 1, & \text{if element} x_i \text{is in the set} S_j \\ 0, & \text{otherwise} \end{cases}$$

The Minimum-Cost Set Cover (MCSC) problem is to find $P^* \subseteq P$ such that each element x_i, $\forall i \in S$, is covered and the total cost is minimum. Hence, the MCSC problem can be formulated as follows:

[4] A mixed integer linear program (MILP) is a mathematical program with linear constraints, in which a subset of the variables are required to take integer values.

$$Min \quad \sum_{j \in P} c_j z_j \tag{10}$$

s.t.

$$\sum_{j \in P} a_{ij} z_j \geqslant 1, \quad \forall i \in S \tag{11}$$

$$z_j \in \{0, 1\} \quad \forall j \in P. \tag{12}$$

It can be observed straightforwardly that:

- The objective function (10) of the MCSC problem is very similar to the first term ($\sum_{j \in P} c_j^I z_j$) of our EAWD problem's objective function.
- Constraints (11) of the MCSC problem are equivalent to constraints (2) and (3) of the EAWD problem. In fact, it suffices to first sum over all $j \in P$ constraints (3) thus obtaining $\sum_{j \in P} a_{ij} z_j \geqslant \sum_{j \in P} x_{ij}$, and then replace the right hand side of this inequality, $\sum_{j \in P} x_{ij}$, by 1 according to constraints (2).
- Constraints (12) are the same as our problem integrality constraints (9).

Since the (Minimum-Cost) Set Cover problem is a sub-problem of our EAWD problem, and it was demonstrated to be NP-hard by Karp [52], the Energy-Aware Wireless Body Area Network Design problem is indeed NP-hard.

It is worth noting that the structure of our model is quite different from classical flow models usually adopted for the design of physical networks [53], since it includes the traffic routing and the placement of wireless relays.

4. Assumptions and parameters' setting for performance evaluation results

In this section, we detail the assumptions and parameters' setting used to evaluate the performance of our model.

Since extremely low transmission power in non-invasive WBAN is required to protect human tissue in practice [11,21,54], 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). If not specified differently, we assume that a CS j can be directly connected with a wireless link to a CS l ($b_{jl} = 1$), if l is at a distance not greater than 30 cm from j (i.e., R_c = 30 cm).

We further assume that the relay installation cost is equal to 10 monetary units, and its maximum capacity is equal to 250 kb/s.

According to [12,47,48], compared with free space ($n_{ij} = 2$), the (average) path loss exponent near the body in the gigahertz range is much higher ($n_{ij} \approx 5.9$). This exponent is consistent with previous gigahertz range studies around the human torso, where it is estimated between 5 and 7.4. However, lower exponents ($n_{ij} \approx 3.38$) are reported when propagation is along the front rather than around the torso [55]. These latter values (5.9 and 3.38) correspond to NLOS and LOS conditions, respectively, and are adopted in our simulation setup. Therefore, when two nodes (sensor or relay nodes) are placed along the front of the body, in such a way that they are close to each other and in *line of sight*, the path loss coefficient is equal to 3.38. Conversely, when the two nodes are in *non-line of sight* (for example, one node is on the front of the body and the other on the back), the path loss coefficient is 5.9.

The sensors we consider in our study use the Nordic nRF2401 transceiver [56], which is commonly employed in body sensor networks [12,57]. Hence, 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 n_{ij}, and it is equal to 1.97 nJ/bit for n_{ij} = 3.38 (LOS) and 7.99 μJ/bit for n_{ij} = 5.9 (NLOS). The Nordic nRF2401 transceiver parameters' values are also reported in Table 2, for sake of clarity.

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, a modeling language for mathematical programming [58], and solving them with CPLEX 11, a mathematical programming solver [59]. The workstations used were equipped with an Intel Pentium 4 (TM) processor with CPUs operating at 3 GHz, and with 1024 Mbyte of RAM. For each network scenario, the results are obtained averaging each point on 10 instances.

In the next two sections, we evaluate the EAWD model performance considering real wireless body area network scenarios and full binary tree topologies, respectively. More specifically, we compare our model performance to a set of approaches, in terms of the total energy consumed by the whole network, the total energy consumed by each relay and by each sensor, as well as the number of relays installed in the network, to route all data collected by sensors towards the sink. We further show, in particular in Section 5, that realistic WBAN instances (with 13 biosensors on the human body, 30–80 candidate sites for placing relays, and one sink) can be solved to the optimum in a short computation time (less than 10 s on the commodity hardware we employed in our numerical analysis). Hence, our EAWD model represents a very effective tool to plan both energy-efficient and cheap wireless body area networks.

5. Performance evaluation: wireless body area network scenarios

We first evaluate the performance of the EAWD model considering the wireless body area network topology depicted in Fig. 1 [13]. More in detail, we test the sensitivity of our model to different parameters like the number of candidate sites and biosensors, the traffic demands, as well

Table 2
Energy consumption values for the Nordic nRF2401 transceiver.

Parameter	Value (nJ/bit)
E_{TXelec}	16.7
E_{RXelec}	36.1
$E_{amp}(3.38)$	1.97
$E_{amp}(5.9)$	7990

as the α value in objective function (1), which permits to express a trade-off between planning cost-effective and energy-efficient networks. Furthermore, we compare our model to the single-hop, multi-hop and Relay Network approaches [12,13], in terms of energy consumption and number of relays installed in the WBAN. 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. Recall from Section 2 that the *Relay Network* approach installs relays in the WBAN until each sensor and relay have at least one relay node in line of sight.

The considered WBAN scenario includes 13 biosensors that are placed on the human body to capture electrical signals, like electrocardiogram (sensor D), electroencephalogram (sensor K), and electromyogram (sensors A and I), thus providing useful information on the physiological state of the patient. In fact, we consider hereafter a complete (worst-case) WBAN scenario with quite a high number of biosensors (up to 13), since our goal is to evaluate the proposed optimization framework in a general case, where we can capture at the same time Heart condition, Temperature, Blood pressure, Pulse, Glucose and Motion (as illustrated in Fig. 1). It is worth noting that our approach can be also applied to specific scenarios, to measure special electrical signals, like electrocardiograms or electroencephalograms or electromyograms.

For the multi-hop approach, we assume that the routes from the sensors to the sink are those illustrated by straight lines on the left-hand side of Fig. 1, and hence the corresponding tree topology is the one shown on the right-hand side of the figure. 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 3.

We further assume that candidate sites for placing relays are chosen uniformly at random on the surface of ellipsoidal areas, along the clothes of the patient, as illustrated in Fig. 2. However, it is noteworthy that relays, besides biosensors, should be placed on the human body in an intelligent manner without causing any discomfort for the person, with reduced disturbance to her/his daily activities. For example, in the case of e-health applications seeking continuous monitoring of chronically ill patients, it would be impractical to place a sensor/relay on the stomach or on the back, thus limiting significantly their daily activities, like sitting and sleeping. Hence, these physical constraints are accurately considered in the choice of candidate areas while designing our wireless body area network.

Furthermore, our proposed model can be straightforwardly extended to choose at time epoch t a set of feasible relay nodes which are different from those determined at epoch $t-1$, when the operating time of the whole system is divided in time epochs $t \in \mathcal{T}$. In this way, we can guarantee that the positions of used relay nodes change during system operating time, thus reducing consistently over-absorption and temperature increase of skin tissue and organs due to data relaying nodes. Of course, deciding the number and positions of relays to be installed depends directly on both the number and positions of sensors and the sink; in fact, when sensors are farther away from the sink (e.g., sensors E, M and K in Fig. 1), more relays are needed to collect the physiological data.

We first solve the EAWD model minimizing the total energy, neglecting the installation cost component in objective function (1), by choosing a very large value for the weighting parameter α. Then, we investigate the impact of the α parameter on the EAWD model, letting α vary from 0 to ∞, thus ranging from one extreme (minimizing only the WBAN installation cost) to another, where the model minimizes exclusively the total energy consumed by the network.

5.1. Effect of the number of candidate sites

We first evaluate the effect of the number of CSs on the EAWD model, varying p from 40 to 200. This allows us to compare the characteristics of the optimal solution in two opposite scenarios: only a limited set of CSs is available for installing relays ($p = 40$), and several sites exist ($p = 200$). Table 4 illustrates the average values of (1) the

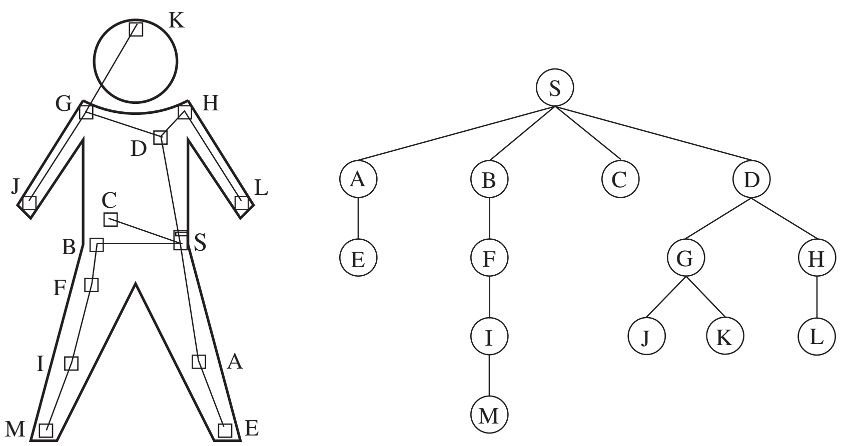

Fig. 1. WBAN topology with 13 sensors, and the corresponding tree topology under the multi-hop approach.

Table 3
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

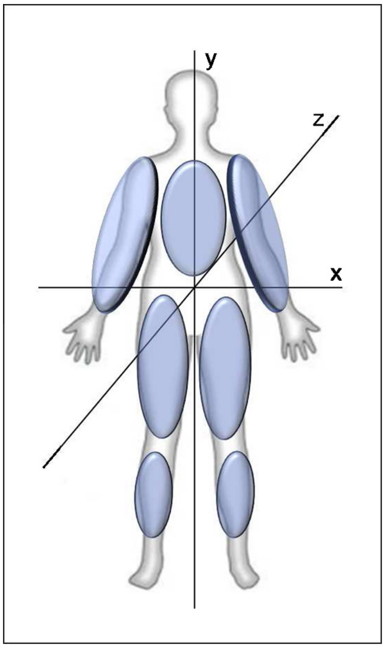

Fig. 2. Candidate sites for placing relays are chosen uniformly at random on the surface of ellipsoidal areas, along the clothes of the patient.

total energy consumed by the whole network (E_{tot}, measured in μJ/bit), which includes the energy consumed by all relays and sensors, (2) the energy E_R consumed by each relay, (3) the number N_R of relays installed in the WBAN, and (4) the computation time necessary to obtain the optimal solution, measured in seconds. On the other hand, Fig. 3 shows both energies E_{tot} and E_R as a function of p.

It can be observed that increasing the number of CSs increases the solution space; as a consequence, the model favors the solutions providing connectivity that have a lower impact on the energy consumed by the network, which in turn decreases with p. It is interesting to notice that, on the one hand, the average total energy consumed by the whole network is approximately 3.9 μJ/bit for $p = 40$, and decreases consistently to attain 1.9 μJ/bit for $p = 200$. Furthermore, both energies E_{tot} and E_R decrease sharply for small p values (see Fig. 3), thus proving the benefit of introducing even a small number of relays in the WBAN. On the other hand, the number of relays chosen by our model follows a decreasing trend with the number of CSs, and it is equal to 14 and 11, in average, for $p = 40$ and 200, respectively.

The computation time necessary to obtain the optimal solutions is, in average, below 0.1 s for $p = 40$, and remains below 12 min for $p = 200$ in all our considered scenarios; it is indeed a quasi linear function of the parameter p (see

Table 4
WBAN scenario: Total energy per bit consumed by (1) the whole network and (2) each relay, (3) number of relays installed in the WBAN, and (4) computation time (in average), obtained with our EAWD model, varying the number p of CSs.

p	E_{tot} (μJ/bit)	E_R (μJ/bit)	N_R	Time (s)
40	3.862	0.260	14.0	0.1
50	3.006	0.208	13.4	0.3
60	2.887	0.202	13.2	1.1
80	2.441	0.176	12.6	9.3
100	2.224	0.163	12.3	23.9
150	1.997	0.160	11.2	110.4
200	1.923	0.155	11.0	710.5

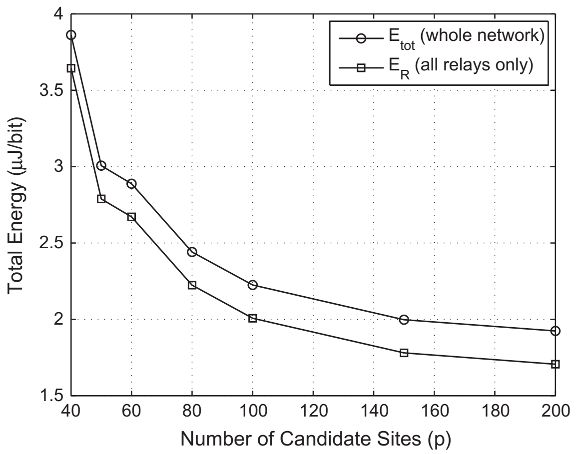

Fig. 3. Total energy E_{tot} consumed by the whole network (sensors and relays), and by relays only (E_R), in the network scenario of Fig. 1.

Fig. 4). Furthermore, it is important to underline that, in a real deployed wireless body area network, the candidate areas for placing relays on the human body are very restricted and, as a consequence, the total number of candidate sites is likely to be reasonably small (for example, $\leqslant$80). Hence, the computation time for obtaining the optimal solution will always be short in practical network scenarios (of the order of 9.5 s maximum when $p = 80$ CSs).

In all WBAN scenario instances, the total energy per bit consumed by each sensor (E_s) is equal to 16.7 nJ, in average. In fact, $E_s = E_{TXelec} + E_{amp}(n_{ij})R_s^{n_{ij}} = 16.7 + 1.97 \times 0.03^{3.38} = 16.7$ nJ.

5.2. Effect of the traffic demand

To gauge the effect of the traffic demand on the EAWD model, we consider the same WBAN scenario, varying p from 40 to 200 and increasing the demand from $w_{ik} = 100$ to 200 bit/s. Fig. 5 illustrates the total energy (E_{tot})

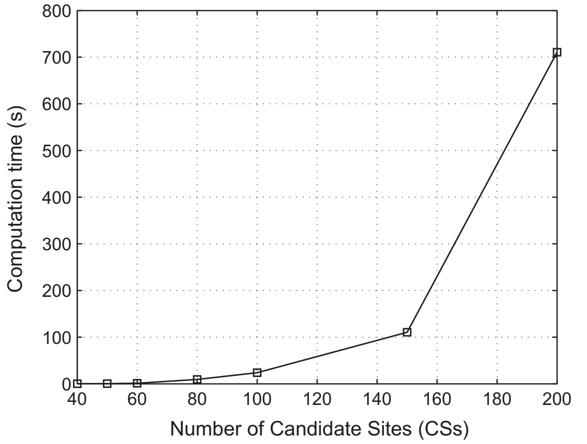

Fig. 4. WBAN scenario: Computation time to obtain the optimal solution as a function of the number of Candidate Sites (CSs).

consumed by the whole network as a function of p, for w_{ik} = 100 and 200 bit/s. The optimal solutions are obtained within a very short computation time, viz., 0.05 s and 40 s in average for p = 40 and 200, respectively.

It can be seen that the curve corresponding to w_{ik} = 200 bit/s follows the same decreasing trend as the one with a traffic demand equal to 100 bit/s; for small p values (p < 80), the gap between the energy E_{tot} for w_{ik} = 100 bit/s and for w_{ik} = 200 bit/s is quite large, and such gap decreases progressively when p increases. This is due to the fact that, for w_{ik} = 200 bit/s, the weight in objective function (1) of the second term (which represents the total energy consumed by the network) with respect to the first term (the network installation cost) is approximately 2 times higher than the one corresponding to w_{ik} = 100 bit/s, and therefore our model tends to install a different subset of relays and succeeds to find better strategies for routing the medical data when p increases, with respect to w_{ik} = 100 bit/s, thus reducing further the total energy consumption.

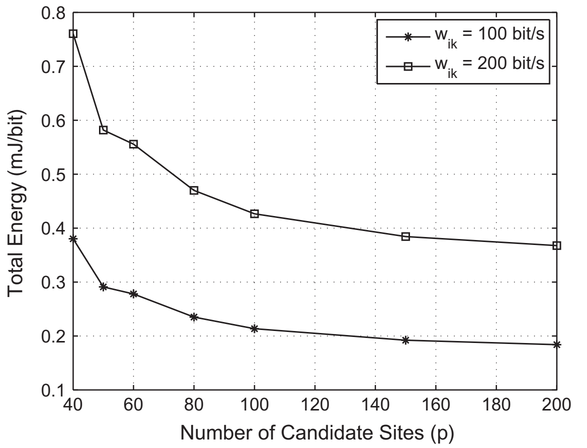

Fig. 5. Total energy consumed by the whole network (sensors and relays), in the network scenario of Fig. 1 with w_{ik} = 100 and 200 bit/s.

5.3. Effect of the weighting parameter (α)

We now investigate the impact of the α parameter on the EAWD model, considering the same WBAN scenario illustrated in Fig. 1, with p = 100 candidate sites. 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. Figs. 6(a) and (b) show respectively, the total energy consumed by the whole network (E_{tot}) and the total installation cost as a function of α.

It can be observed that the WBAN installation cost increases when α increases, ranging from 113 to 182 monetary units (61.1% higher), and the total energy consumed by the whole network decreases from 3.334 μJ/bit (for $\alpha = 0$) to stabilize at 2.166 μJ/bit (35.0% lower) when $\alpha \to \infty$. Moreover, for small α values, the EAWD model plans cheap WBANs with a small number of relays (≈11), but at the cost of quite a high energy consumption. In particular, for $\alpha = 0$, $N_R = 11$ relays are necessary to ensure the connectivity of the WBAN network. On the other hand, when $\alpha \to \infty$ the model plans an energy-efficient WBAN, reducing the energy by a factor of ≈1.5 with respect to the case of $\alpha = 0$; the average number of installed relays is approximately 18 in this case.

5.4. Comparison with existing approaches

We now compare the EAWD model with the most notable approaches proposed in the literature, considering the same WBAN scenario. Table 5 reports the average value of the total energy (E_{tot}), the energy consumed by each sensor (E_s), as well as the number of relays installed in the WBAN, using the EAWD model (with p = 200) and under the single-hop, multi-hop and Relay Network [13] approaches.

It can be observed that the proposed model reduces consistently both energies E_{tot} and E_s with respect to the single-hop and multi-hop approaches. This is due to the beneficial effect of installing relays 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 the single and multi-hop approaches, respectively, while the installation of relays permits to decrease such values significantly. On the other hand, if we focus on the energy consumed by each sensor to send one bit of traffic to the sink, we can observe that, with our model, such energy is significantly lower (0.017 μJ) with respect to the one obtained with the single-hop (9.826 μJ) and multi-hop (0.323 μJ) approaches.

Note that our model chooses in average 11 relays among 200 candidate sites, to route one bit of traffic from all sensors to the sink, consuming in average 1.923 μJ/bit. As for the Relay Network approach, 22 relays are installed in the WBAN with a total energy consumption equal to 1.383 μJ/bit. The number of relays N_R with this latter approach increases dramatically with the number of sensors, and in some WBAN scenarios it is impractical to have a large N_R which may limit the activity or mobility of the patient. For example, to relay the data of an additional sensor

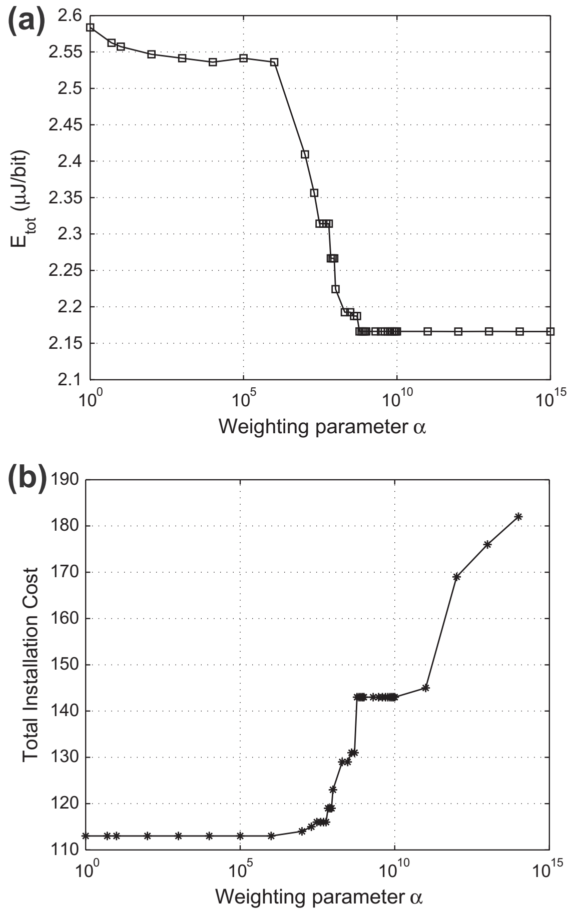

Fig. 6. (a) Total energy consumed by the whole network and (b) total installation cost as a function of the weighting parameter α.

Table 5
WBAN scenario: Total energy per bit consumed by (1) the whole network and (2) each sensor, and (3) number of relays installed in the WBAN (in average), in the single-hop, multi-hop, Relay Network approaches and with the EAWD model.

model	E_{tot} (μJ/bit)	E_s (μJ/bit)	N_R
Single-hop	127.740	9.826	–
Multi-hop	4.202	0.323	–
Relay Network	1.383	0.017	22
EAWD (p = 200)	1.923	0.017	11

situated far away from the sink (i.e., at 1.5 m from the sink), the Relay Network approach should install 4 additional relays (obtaining in total 26 relays), thus limiting the patient's movement; on the contrary, by using our model we do not need to install additional relays, but of course at the cost of slightly higher per-relay energy consumption.

Summary. Our model guarantees that all biosensors consume the least possible energy (0.017 μJ/bit), minimizing at the same time the number of relays (installing 50% less of relays with respect to the Relay Network approach) at the cost of slightly higher energy consumption for relays. We can conclude that the EAWD model provides a good compromise between the energy consumption and the number of relays installed in the WBAN, thus improving the patient comfort and mobility.

6. Performance evaluation: full binary tree topologies

To test the scalability of the proposed EAWD model in large-scale scenarios, we further consider the *full binary tree* topology depicted in Fig. 7. Such choice is motivated by the fact that previously reviewed works, like [12,13], evaluate their proposed schemes in the same scenario. Hence, to perform a fair comparison with such works, the same full binary tree topology will be adopted hereafter.

In a full binary tree topology, all nodes have exactly 2 children nodes. There are L levels in the network, which are numbered consecutively from level 1, for the nodes furthest away from the sink, up to level L for the nodes closest to the sink (see Fig. 7). Hence, the binary tree topology with 5 levels contains 62 nodes, excluding the sink. The distance between the levels is fixed, and we will denote it by d.

Due to the regular structure of this topology, in order to choose candidate sites, we consider the area underlying the full binary tree topology, which is approximately a $(dL) \times (2dL)$ rectangular area, and we extract uniformly at random the position of p CSs. 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 binary tree topology. This also increases the topology complexity (i.e., the number of possible links) and allows us to test how the proposed model scales with respect to network size. Other parameters' settings are the same as those in Section 4.

In the following, we first investigate the impact of the number of CSs on the EAWD model, and then, we compare its performance to a set of approaches [12,13], in terms of energy consumption and number of relays installed in the network.

6.1. Effect of the number of candidate sites

We gauge the effect of the number of candidate sites (p) on the EAWD model considering the binary tree topology

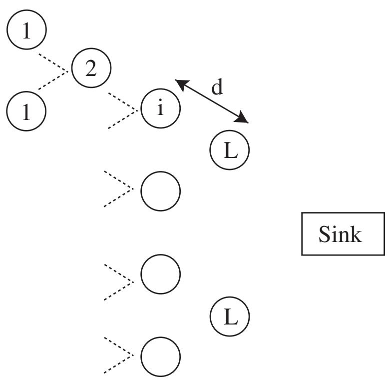

Fig. 7. Full binary tree with L levels and a fixed internode distance d.

with 5 levels ($L = 5$), $d = 20$ cm, and varying the parameter p from 50 to 300.

Fig. 8 reports an example of the planned network when applying the EAWD model to such binary tree, with $p = 80$ candidate sites. Relays, sensors and the sink are represented respectively by circles, triangles and a square. Note that the disconnected circles represent the CSs in which no relay has been installed in the optimal solution.

Table 6 analyzes the characteristics of the optimal solutions obtained by EAWD in such scenarios, in terms of the total energy consumed by the network (E_{tot}), the total energy consumed by each relay (E_R), the number of chosen relays (N_R), and the computation time (measured in seconds) needed to obtain the optimal solutions.

In line with what already observed in the WBAN scenarios of the previous section, it can be seen that the energies E_{tot} and E_R decrease when increasing the number of CSs (p). For instance, for $p = 300$, EAWD installs on average approximately 50 relays to cover all sensors and route data to the sink, with a total energy consumption equal to 11.219 μJ/bit; on the other hand, for $p = 80$, our model installs less relays (≈35 in average), but at the cost of a total energy consumption which is 18.4% higher than the one obtained with $p = 300$, maintaining nevertheless the same per sensor energy consumption (0.017 μJ/bit). In fact, there is a tradeoff between minimizing the number of installed relays and the total energy consumption. The computation time necessary to obtain the optimal solutions increases with p (while remaining reasonably small), and ranges from fractions of a second (0.8 s for $p = 50$) to slightly more than 10 min (694.0 s for $p = 300$). Similarly to the WBAN scenario, the computation time increases quasi-linearly with the total number of candidate sites (as illustrated in Fig. 9). Note that, even if we consider the case of 200 CSs, in average 150 s are already sufficient for obtaining the optimal solution.

In this scenario, the EAWD model tends to install more relays when the number of CSs increases, while in the WBAN scenarios the number of installed relays slightly decreases with p. This is due to the fact that, in the binary tree topology with full connectivity between CSs ($R_s = 30$ cm and $R_c = 500$ cm), our model tends to reduce the distances between installed relays when p increases, in order to decrease the energy consumption. In particular, the results show that the maximum distance between installed relays is equal to 43.4 cm (on average) for $p = 50$ and such distance decreases to 38.4 cm for $p = 300$. On the other hand, in the WBAN scenarios (where $R_c = R_s = 30$ cm, with limited connectivity between CSs), when p increases the model plans WBANs with less relays and performs better routing choices in order to reduce further the energy consumption.

Table 6
Full Binary Tree Topology: Total energy per bit consumed by the whole network and by each relay, number of relays installed in the network and computation time, obtained, in average, with our EAWD model.

p	E_{tot} (μJ/bit)	E_R (μJ/bit)	N_R	Time (s)
50	14.627	0.485	28.0	0.8
60	13.901	0.427	30.1	2.1
80	13.283	0.354	34.6	8.4
100	12.569	0.327	35.3	18.2
150	12.020	0.264	41.6	81.9
200	11.627	0.241	44.0	149.3
250	11.422	0.215	48.3	428.4
300	11.219	0.202	50.4	694.0

6.2. Comparison with existing approaches

We now compare our EAWD model to the following five approaches: (1) the *single-hop* and (2) *multi-hop* approaches, (3) the *Relaying* and (4) the *Cooperation* mechanisms proposed in [12], and (5) the *Relay Network* approach introduced in [13]. The main characteristics of these approaches are commented and compared in Table 7.

The results obtained in this scenario are illustrated in Table 8. The row corresponding to our model (EAWD, $p = 200$) considers the case where the number of CSs is quite large, i.e., equal to 200. In this case, the total energy per bit consumed by the network and by each relay are respectively 11.627 and 0.241 μJ. The average number of relays chosen by the EAWD model is equal to 44 and the computation time needed to obtain the optimal solutions is equal to 149.3 s.

In this binary tree scenario, the *Relaying* mechanism places relays at intermediate levels (i.e., ≈48 relays at level 4 in Fig. 7)) to forward the data from sensors far away from

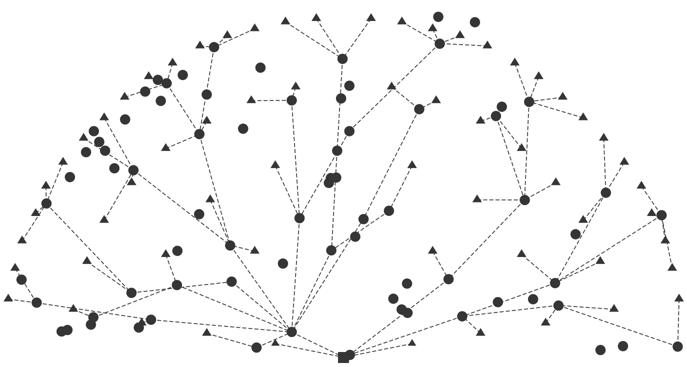

Fig. 8. Sample full binary tree topology planned by the EAWD model, with $L = 5$ levels (62 sensors), $p = 80$ CSs and an internode distance $d = 20$ cm. Relays, sensors and the sink are represented respectively by circles, triangles and a square.

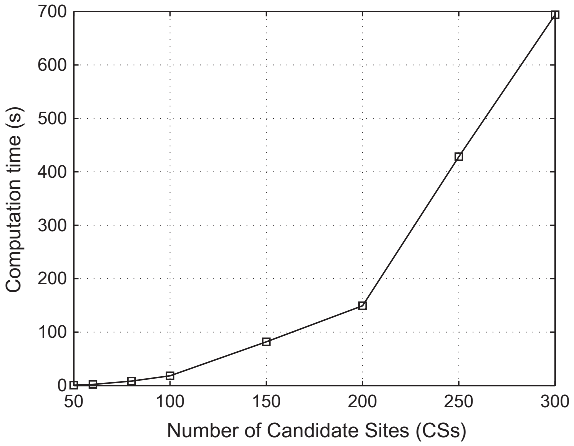

Fig. 9. Full binary tree topology: Computation time to obtain the optimal solution as a function of the number of Candidate Sites (CSs).

the sink (sensors at levels 1 and 2). Under this approach, the total energy per bit consumed by the whole network and by each sensor are equal to 21.702 and 0.281 μJ, respectively.

On the other hand, the *Cooperation* method lets sensors at levels 4 and 5 forward data from those at levels 1 and 2 to the sink. The number of relays used in the Cooperation method is 18 in average, and the total energy consumed by the network and by each sensor are 26.831 and 0.408 μJ/bit, respectively.

Note that with the Relaying mechanism, sensors consume less energy than with Cooperation, since with this latter sensors at intermediate levels should cooperate with those farther away from the sink in order to forward their traffic. Therefore, the number of relays used in Cooperation ($N_R = 18$) is smaller than the one used with Relaying ($N_R = 48$).

The *Relay Network* approach, instead, places at each level $l \in \{2,3,4,5\}$ N_l^R relays, such that $N_l^R = N_{l-1}^R + N_{l-1}^S$, where N_l^R and N_l^S are the number of relays and sensors, respectively, at level l. For example, for the full binary tree topology of Fig. 7, with 5 levels, 32, 48, 56 and 60 relays are

Table 7
WBAN design approaches [12,13] (reviewed in Section 2) and their main characteristics.

Approach	Main characteristics
Single-hop	Data is transmitted directly from each sensor to the sink
Multi-hop	Data is relayed by intermediate sensors towards the sink
Relaying [12]	Relays are placed at intermediate levels Relays forward the data of sensors far away from the sink
Cooperation [12]	Sensors cooperate in forwarding data Sensors close to the sink forward the data of those far away from the sink
Relay Network [13]	Relays are added until each node has at least one node in line of sight Each relay forwards the data of at most one node

Table 8
Full binary tree topology: Total energy per bit consumed by the whole network, by each sensor and by each relay, and number of installed relays, in average, in the approaches introduced in [12,13], and with our EAWD model.

Model	E_{tot} (μJ/bit)	E_s (μJ/bit)	E_R (μJ/bit)	N_R
Single-hop	294.266	4.746	–	–
Multi-hop	11.386	0.184	–	–
Relaying [12]	21.702	0.281	0.089	48
Cooperation [12]	26.831	0.408	0.085	18
Relay Network [13]	11.386	0.017	0.053	196
EAWD ($p = 200$)	11.627	0.017	0.241	44.0
EAWD ($p = 300$)	11.219	0.017	0.202	50.4

needed respectively at levels 2, 3, 4 and 5, to forward the traffic to the sink, thus obtaining in total 196 relays.

Let us now compare our model to these approaches. It can be observed that by using the single-hop approach, we obtain an average total energy consumption equal to 294.266 μJ/bit, and an average per sensor energy consumption equal to 4.746 μJ/bit, which are extremely high with respect to our model. Sensors farther away from the sink (i.e., sensors at level 1) consume a significant amount of energy (≈8.0 μJ/bit) and consequently will die first. Hence, the single-hop approach performs dramatically worse with respect to all other approaches, including ours.

As for the multi-hop approach, the total energy per bit consumed by the network and by each sensor are, in average, equal to 11.386 and 0.184 μJ, respectively. In the absence of relays, the sensors closest to the sink (i.e., those at level 5 in the binary tree), consume a large amount of energy (≈1.6 μJ/bit) since they have to forward all the data received from other sensors situated far away from the sink; hence they will die first, causing the failure of the whole network. Similarly to the single-hop approach, the multi-hop approach performs poorly with respect to our model, and also to the Relaying, Cooperation and Relay Network approaches.

The results reported in Table 8 further show that our model exhibits better performance than the Relaying and Cooperation mechanisms. The energy E_{tot} obtained with the Relaying and Cooperation approaches are approximately 2 times higher than the one given by our model, and the energy consumed by each sensor (E_s) is approximately 16 (Relaying) and 24 times (Cooperation) higher than the one obtained using the EAWD model.

Finally, we observe that the EAWD model performs similarly to the Relay Network approach, in terms of both the total energy consumed by each sensor and by the whole network. However, the major drawback of the Relay Network approach is that the number of relays (which is equal to 196) is dramatically high with respect to all other approaches, including our model (where such number is approximately 44), and it increases exponentially with the number of sensors.

Summary. One key feature of our model is that it permits to improve the network lifetime minimizing, at the same time, the number of relays. In other words, our model minimizes the energy consumed by all sensors (each consumes 0.017 μJ/bit), while maintaining both the number of relays and the consumed energy quite low.

7. Conclusion

In this paper we addressed the topology design problem for wireless body area networks, considering both *cost* and *energy* issues. We proposed 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. The model minimizes both the total energy consumption and the network installation cost, while ensuring full coverage and low energy consumption of all sensors.

We solved the EAWD model in realistic WBAN scenarios as well as in full binary tree topologies, and investigated the impact of different parameters (i.e., number of sensors and candidate sites, traffic demands, weighting parameter α) on the WBAN design problem. We further compared our model's performance to the most notable approaches in the literature, in terms of energy consumption and number of relays installed in the network. The numerical results we gathered illustrate the sensitivity of the optimal solutions to the main parameters considered in our optimization, and show that our model provides a very good compromise between the total energy consumed by each sensor (and the whole network), and the number of relays deployed in the network, compared to other approaches. Therefore, our optimization framework is very promising for the design of wireless body area networks.

References

[1] J. Elias, A. Mehaoua, Energy-aware topology design for wireless body area networks, in: Proc. of the IEEE International Conference on Communications 2012, Ottawa, Canada, June 10–15, 2012, pp. 3430–3434.

[2] S. Junnila, H. Kailanto, J. Merilahti, A.M. Vainio, A. Vehkaoja, M. Zakrzewski, J. Hyttinen, Wireless, multipurpose in-home health monitoring platform: two case trials, IEEE Transactions on Information Technology in Biomedicine 14 (2) (2010) 447–455.

[3] U. Varshney, Pervasive healthcare and wireless health monitoring, Mobile Networks and Applications 12 (2-3) (2007) 113–127.

[4] A. Milenković, C. Otto, E. Jovanov, Wireless sensor networks for personal health monitoring: Issues and an implementation, Computer Communications 29 (13) (2006) 2521–2533.

[5] M. Bächlin, G. Tröster, Swimming performance and technique evaluation with wearable acceleration sensors, Pervasive and Mobile Computing 8 (1) (2012) 68–81.

[6] E.H. Callaway, Wireless Sensor Networks: Architectures and Protocols, 3, CRC Press, 2004.

[7] I.F. Akyildiz, T. Melodia, K.R. Chowdury, Wireless multimedia sensor networks: a survey, IEEE Wireless Communications 14 (6) (2007) 32–39.

[8] K.A. Ali, H.T. Mouftah, Wireless personal area networks architecture and protocols for multimedia applications, Elsevier Ad Hoc Networks 9 (4) (2011) 675–686.

[9] M. Chen, S. Gonzalez, A. Vasilakos, H. Cao, V.C.M. Leung, Body area networks: a survey, Mobile Networks and Applications 16 (2) (2011) 171–193.

[10] H. Cao, V. Leung, C. Chow, H. Chan, Enabling technologies for wireless body area networks: a survey and outlook, IEEE Communications Magazine 47 (12) (2009) 84–93.

[11] H. Alemdar, C. Ersoy, Wireless sensor networks for healthcare: a survey, Computer Networks 54 (15) (2010) 2688–2710.

[12] E. Reusens, W. Joseph, B. Latré, B. Braem, G. Vermeeren, E. Tanghe, L. Martens, I. Moerman, C. Blondia, Characterization of on-body communication channel and energy efficient topology design for wireless body area networks, IEEE Transactions on Information Technology in Biomedicine 13 (6) (2009) 933–945.

[13] A. Ehyaie, M. Hashemi, P. Khadivi, Using relay network to increase life time in wireless body area sensor networks, in: Proc. of WoWMoM'09, Kos, Greece, June, 2009, pp. 1–6.

[14] X. Liang, X. Li, Q. Shen, R. Lu, X. Lin, X. Shen, W. Zhuang, Exploiting prediction to enable secure and reliable routing in wireless body area networks, in: Proc. of IEEE INFOCOM, Orlando, Florida, USA, March 25–30, 2012, pp. 388–396.

[15] Q. Zhang, K. Kortermand, R.H. Jacobsen, T.S. Toftegaard, Reactive virtual coordinate routing protocol for body sensor networks, in: Proc. of IEEE ICC, Ottawa, Canada, June 2012, pp. 3388–3393.

[16] A. Redondi, M. Chirico, L. Borsani, M. Cesana, M. Tagliasacchi, An integrated system based on wireless sensor networks for patient monitoring, localization and tracking, Elsevier Ad Hoc Networks 11 (1) (2013) 39–53.

[17] A. Natarajan, M. Motani, B. de Silva, K.K. Yap, K.C. Chua, Investigating network architectures for body sensor networks, in: Proc. 1st ACM SIGMOBILE Int. Workshop on Syst. and Netw. Support for Healthcare and Assisted Living Environ. (HealthNet 2007), San Juan, Puerto Rico, June 2007, pp. 19–24.

[18] A. Natarajan, B.D. Silva, K.K. Yap, M. Motani, To hop or not to hop: Network architecture for body sensor networks, in: Proc. of SECON'09, Rome, Italy, June 22–26, 2009.

[19] S.L. Cotton, W.G. Scanlon, Characterization and modeling of on-body spatial diversity within indoor environments at 868 MHz, IEEE Transactions on Wireless Communications 8 (1) (2009) 176–185.

[20] K.Y. Yazdandoost, K. Sayrafian-Pour, Channel model for body area network (ban), IEEE 802.15 Working Group Document, IEEE P802.15-08-0780-11-0006, September 2010.

[21] S.J. Marinkovic, E.M. Popovici, C. Spagnol, S. Faul, W.P. Marnane, Energy-efficient low duty cycle mac protocol for wireless body area networks, IEEE Transactions on Information Technology in Biomedicine 13 (6) (2009) 915–925.

[22] S. Marinkovic, C. Spagnol, E. Popovici, Energy-efficient TDMA-based mac protocol for wireless body area networks, in: Proc. of the 3rd International Conference on Sensor Technologies and Applications (SENSORCOMM'09), IEEE, Athens, Greece, 2009, pp. 604–609.

[23] G. Fang, E. Dutkiewicz, Bodymac: energy efficient tdma-based mac protocol for wireless body area networks, in: Proc. of the 9th International Symposium on Communications and Information Technology (ISCIT'09), IEEE, Incheon, Korea, 2009, pp. 1455–1459.

[24] W.-B. Yang, K. Sayrafian-Pour, Interference mitigation for body area networks, in: 22nd IEEE Symposium on Personal Indoor and Mobile Radio Communications (PIMRC), Toronto, Canada, September 2011, pp. 2193–2197.

[25] O. Omeni, A.C.W. Wong, A.J. Burdett, C. Toumazou, Energy efficient medium access protocol for wireless medical body area sensor networks, IEEE Transactions on Biomedical Circuits Systems 2 (4) (2008) 251–259.

[26] B. Latre, B. Braem, I. Moerman, C. Blondia, E. Reusens, W. Joseph, P. Demeester, A low-delay protocol for multi-hop wireless body area networks, in: Proc. 4th IEEE Int. Conf. MobiQuitous, Philadelphia, PA, USA, August 2007, pp. 1–8.

[27] G.R. Tsouri, A. Prieto, N. Argade, On increasing network lifetime in body area networks using global routing with energy consumption balancing, Sensors 12 (10) (2012) 13088–13108.

[28] H. Chebbo, S. Abedi, T.A. Lamahewa, D.B. Smith, D. Miniutti, L. Hanlen, Reliable body area networks using relays: restricted tree topology, in: Proc. of IEEE Int. Conf. on Computing, Networking and Communications (ICNC), Maui, Hawaii, USA, 2012, pp. 82–88.

[29] M. Quwaider, S. Biswas, Dtn routing in body sensor networks with dynamic postural partitioning, Elsevier Ad Hoc Networks 8 (8) (2010) 824–841.

[30] M. Quwaider, S. Biswas, Body posture identification using hidden markov model with a wearable sensor network, in: Proc. of the ICST 3rd International Conference on Body Area Networks, 2008, p. 19.

[31] E. Amaldi, A. Capone, M. Cesana, I. Filippini, Design of wireless sensor networks for mobile target detection, IEEE/ACM Transactions on Networking 20 (3) (2012) 784–797.

[32] A. Capone, M. Cesana, D. De Donno, I. Filippini, Deploying multiple interconnected gateways in heterogeneous wireless sensor networks: an optimization approach, Elsevier Computer Communications 33 (10) (2010) 1151–1161.

[33] R.R. Boorstyn, H. Frank, Large-scale network topological optimization, IEEE Transactions on Communications 25 (1) (1977) 29–47.

[34] C. Gabriel, Compilation of the dielectric properties of body tissues at RF and microwave frequencies, DTIC Document (1996).

[35] Italian National Research Council Institute for Applied Physics, Calculation of the dielectric properties of body tissues <http://niremf.ifac.cnr.it/tissprop/>.

[36] S.K.S. Gupta, S. Lalwani, Y. Prakash, E. Elsharawy, L. Schwiebert, Towards a propagation model for wireless biomedical applications, in: IEEE International Conference on Communications, Anchorage, AlasKa, USA, 2003, pp. 1993–1997.
[37] K. Sayrafian-Pour, W.-B. Yang, J. Hagedorn, J. Terrill, K.Y. Yazdandoost, A statistical path loss model for medical implant communication channels, in: IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications, Tokyo, Japan, 2009, pp. 2995–2999.
[38] D. Kurup, W. Joseph, G. Vermeeren, L. Martens, In-body path loss model for homogeneous human tissues, IEEE Transactions on Electromagnetic Compatibility 54 (3) (2012) 556–564.
[39] D. Kurup, W. Joseph, G. Vermeeren, L. Martens, In-body path loss model for homogeneous human muscle, brain, fat and skin, in: Proceedings of the Fourth European Conference on Antennas and Propagation (EuCAP), 2010, pp. 1–4.
[40] D. Kurup, W. Joseph, G. Vermeeren, L. Martens, Path loss model for in-body communication in homogeneous human muscle tissue, IET Electronics Letters 45 (9) (2009) 453–454.
[41] L. Galluccio, T. Melodia, S. Palazzo, G.E. Santagati, Challenges and implications of using ultrasonic communications in intra-body area networks, in: The IEEE 9th Annual Conference on Wireless On-demand Network Systems and Services (WONS'12), Courmayeur, Italy, January 2012, pp. 182–189.
[42] S.L. Cotton, W.G. Scanlon, An experimental investigation into the influence of user state and environment on fading characteristics in wireless body area networks at 2.45 GHz, IEEE Transactions on Wireless Communications 8 (1) (2009) 6–12.
[43] Q. Wang, T. Tayamachi, I. Kimura, J. Wang, An on-body channel model for UWB body area communications for various postures, IEEE Transactions on Antennas and Propagation 57 (4) (2009) 991–998.
[44] K. Takizawa, T. Aoyagi, J. Takada, N. Katayama, K. Yekeh, Y. Takehiko, K.R. Kohno, Channel models for wireless body area networks, in: 30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBS'08), Vancouver, Canada, 2008, pp. 1549–1552.
[45] L. Roelens, S. Van den Bulcke, W. Joseph, G. Vermeeren, L. Martens, Path loss model for wireless narrowband communication above flat phantom, Electronics Letters 42 (1) (2006) 10–11.
[46] P.S. Hall, Y. Hao, Y.I. Nechayev, et al., Antennas and propagation for on-body communication systems, IEEE Antennas and Propagation Magazine 49 (3) (2007) 41–58.
[47] A. Fort, J. Ryckaert, C. Desset, P. De Doncker, P. Wambacq, L. Van Biesen, Ultra-wideband channel model for communication around the human body, IEEE Journal on Selected Areas in Communications 24 (4) (2006) 927–933.
[48] A. Fort, C. Desset, P. De Doncker, P. Wambacq, L. Van Biesen, An ultra-wideband body area propagation channel model-from statistics to implementation, IEEE Transactions on Microwave Theory and Techniques 54 (4) (2006) 1820–1826.
[49] E.L. Lawler, D.E. Wood, Branch-and-bound methods: a survey, Operations Research 14 (4) (1966) 699–719.
[50] J.E. Kelley Jr., The cutting-plane method for solving convex programs, Journal of the Society for Industrial & Applied Mathematics 8 (4) (1960) 703–712.
[51] R.E. Gomory, Outline of an algorithm for integer solutions to linear programs, Bulletin of the American Mathematical Society 64 (5) (1958) 275–278.
[52] R.M. Karp, Reducibility Among Combinatorial Problems, Springer, 1972.
[53] M. Pióro, D. Medhi, Routing flow and capacity design in communication and computer networks, Morgan Kaufman, San Francisco, CA, 2004.
[54] H. Ren, Q.-H.M. Max, Bioeffects control in wireless biomedical sensor networks, in: Proc. of SECON'06, vol. 3, Reston, VA, USA, September 25–28, 2006, pp. 896–904.
[55] T. Zasowski, F. Althaus, M. Stager, A. Wittneben, G. Troster, Uwb for noninvasive wireless body area networks: channel measurements and results, in: IEEE Conference on Ultra Wideband Systems and Technologies, Reston, Virginia, USA, 2003, pp. 285–289.
[56] Nordic Inc. nRF2401 Single Chip 2.4 GHz Radio Transceiver Data Sheet <http://www.nordicsemi.com/eng/Products/2.4GHz-RF/nRF2401A/(language)/eng-GB>.
[57] W.R. Heinzelman, A. Chandrakasan, H. Balakrishnan, An application-specific protocol architecture for wireless microsensor networks, IEEE Transactions on Wireless Communications 1 (4) (2002) 660–670.
[58] AMPL: A Modeling Language for Mathematical Programming <http://www.ampl.com>.
[59] IBM ILOG CPLEX Optimizer <http://www-01.ibm.com/software/integration/optimization/cplex-optimizer/>.

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