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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,