Original Article

A New Energy-Efficient Topology for Wireless Body Area Networks

Abstract

Wireless body area networks consist of several devices placed on the human body, sensing vital signs and providing remote recognition of health disorders. Low power consumption is crucial in these networks. A new energy-efficient topology is provided in this paper, considering relay and sensor nodes' energy consumption and network maintenance costs. In this topology design, relay nodes, placed on the cloth, are used to help the sensor nodes forwarding data to the sink. Relay nodes' situation is determined such that the relay nodes' energy consumption merges the uniform distribution. Simulation results show that the proposed method increases the lifetime of the network with nearly uniform distribution of the relay nodes' energy consumption. Furthermore, this technique simultaneously reduces network maintenance costs and continuous replacements of the designer clothing. The proposed method also determines the way by which the network traffic is split and multipath routed to the sink.

Keywords: *Energy efficiency, network topology design, relay nodes, wireless body area network*

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Introduction

Wireless body area networks (WBANs) is an emerging technology that is used to improve healthcare delivery, diagnostic monitoring, disease-tracking, and related medical procedures. WBANs have ability to provide highly reliable communications for medical devices that are implanted in the human body.[1] WBAN consists of a number of tiny, inexpensive, light weight wireless sensors, placed on a patient's body, in the clothes or under the skin. These sensors monitor various vital signs and provide real-time feedback to the patient, doctors, and other related persons.[1,2]

Replacement and recharging of sensors' batteries are troublesome or even impossible. Thus, energy budget of the sensor nodes is finite and efficient energy consumption is one of the most important challenges in WBANs.[3,4] Transmission power is the main source of energy consumption. Therefore, it should be as low as possible to increase the lifetime of body area sensor networks (BASNs). On the other hand, low transmission power is beneficial for the person's health, because of the energy absorption by the body tissues. This energy transforms to heat and can damage the tissues.[4] It is worth noting that attenuation of electromagnetic waves is considerable in body sensor network, due to high path loss of the human's body. Therefore, using of single-hop topology for BASN is not suitable and multihop communication is recommended.[4-6] For multihop communication, relay nodes can be used to gather data from sensors and forward it toward the sinks. Using of relay nodes embedded in the clothes or disposable coveralls protects human tissues from radiation and heating effects and decreases the energy consumption.[4,5,7-9]

In this work, a novel topology design is provided that minimizes energy consumption of the relay with the most energy usage among the relay nodes. This topology design determines the optimal placement of relay nodes in the network as well as the traffic routing and the way by which the network traffic is split and multipath routed to the sink. This method considers the setting up costs, total sensor and relay nodes' energy consumption, and also the maintenance costs. Simulation results demonstrate that the energy consumption of the relay nodes merges to the uniform distribution. Therefore, life time of the relay network increases and the maintenance costs are reduced.

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The rest of this paper is organized as follows: the "Related Works" section discusses related works. The "Proposed Method" section introduces our proposed method and the assumptions and parameters setting for the performance evaluation. The "Performance Evaluation" section evaluates the performance of the proposed method. Finally, the "Conclusion" section concludes the paper.

Related Works

Relaying and cooperation mechanisms are introduced to affect the energy consumption in WBANs.[7] In relaying mechanism, some relay nodes are used for communication. They are only responsible for the traffic relaying and not for any information sensing. The position of relay nodes is important and affects the network efficiency. In Cooperation mechanism, wireless devices cooperate to send the data from one node toward the sink. In this mechanism, relay nodes are not used and the residual energy of some nodes is used for data forwarding.

In Reference,[4] a relay network is used for data transmission. In this relay network, each sensor has a relay node in its line of sight (LOS) and connects to this transition network by one short hop. Relay network uses an energy-efficient protocol to access the channel and route the information. But it does not aim at minimizing the number of relays and relays will be added to the network until all sensors and relays have at least one relay in their LOS. Therefore, total relay network cost is high and the patients' comfort and mobility are greatly affected.

In Reference,[10] the effect of relaying on WBAN's life time is studied. In this work, lifetime of the routes with different relay placement setups along with optimum transmit power levels is evaluated. Ankle–waist and wrist–waist routes for a normal height male are investigated. The authors divide the source-sink path to n shorter hops with $n-1$ possible relays. Each node's energy consumption is defined as the energy it consumes to receive and forward a data packet successfully, including corresponding retransmissions, Acknowledgment (ACK1) or Negative Acknowledgment (NACK2) packets. Simulation results showed that this mechanism achieves 25% more energy conservation, with three-relay scheme compared to the single-hop transmission.

The energy efficiency of an incremental relay based cooperative communication scheme is investigated in.[11] In this work, three communication schemes are considered: direct communication, single-relay cooperation, and two-relay cooperation. In the first scheme, only direct transmission between the source and the destination nodes is allowed. In the second scheme, one relay node cooperates in communication between source and destination nodes. In the third scheme, a three-phase cooperation protocol is considered and two relay nodes are used to help the source node. Simulation results have shown that incremental relay based cooperative transmission schemes can improve the communication reliability and energy efficiency compared to the direct transmission.

A linear programing model called Energy-Aware WBAN Design (EAWD) model is proposed in[5,12] to improve the number and position of relay nodes. This model is simulated in several scenarios with different number of candidate sites (CSs) for relay nodes' placement. This model is designed to reduce the network installation cost and energy consumption simultaneously. Simulation results show that there is a tradeoff between minimizing the number of installed relays and total energy consumption.

Our proposed method is a modified version of EAWD model that will be described in the next section.

Proposed Method

EAWD model is designed to reduce the energy consumption and also the network's installation cost. However, the relay network's maintenance cost and its life time are not considered. The relay network's life time is defined as the time it will take for the first relay node to become discharged of energy. When a relay node's energy is finished, network's connectivity will probably be lost. Therefore, the patient will be forced to change the relay cloth or to replace the discharged node. In this paper, a new topology design is provided for WBAN, based on EAWD model. In this topology, relay nodes are placed in such a way that the amount of their energy consumption merges the uniform distribution. It also considers set up cost and total sensor and relay nodes' energy consumption in the design of the network. For this purpose, different CSs are examined for the placement of relay nodes and the relay node with the maximum energy usage is determined for each selection. The selected places that minimize this maximum value will be the proposed topology. It is shown that this topology design does not change the total nodes' energy consumption significantly. The basic notation used in this paper (similar to [5]) is summarized in Table 1. Based on the explained parameters and variables, the proposed method is formulated by the following utility function:

$$
\begin{aligned}
Min\{ & \sum_{j\in P} C_j^I Z_j + \sum_{i\in S, j\in P, k\in N} W_{ik} X_{ij}\left(E_{TXelec} + E_{amp}(n_{ij}) D_{ij}^{n_{ij}}\right) \\
& + Max\Big(\sum_{i\in S, k\in N} W_{ik} X_{ij} E_{RXelec} \\
& + \sum_{l\in P, k\in N} f_{jl}^{k} (E_{TXelec} + E_{amp}(n_{jl}) D_{jl}^{n_{jl}}) \\
& + \sum_{k\in N} f_{jk}^{t} (E_{TXelec} + E_{amp}(n_{jk}) D_{jk}^{n_{jk}}) \\
& + \sum_{l\in P, k\in N} f_{jl}^{k} E_{RXelec} \Big), \quad \forall j \in P \}
\end{aligned} \tag{1}
$$

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

$$X_{ij} \le Z_j a_{ij} \qquad \forall\ i\in S, j\in P \tag{3}$$

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

$$f_{jl}^{k} \le \sum_{i\in S} W_{ik} b_{jl} Z_j, \quad f_{jl}^{k} \le \sum_{i\in S} W_{ik} b_{jl} Z_l \quad \forall j, l\in P, \quad k\in N \quad (5)$$

$$\sum_{i\in S, k\in N} W_{ik}X_{ij} + \sum_{l\in P, k\in N} f_{lj}^{k} \le V_j, \quad \forall j\in P \quad (6)$$

$$f_{jk}^{t} \le \sum_{i\in S} W_{ik} e_{jk} Z_j, \quad \forall j\in P, k\in N \quad (7)$$

$$Z_{OR_i(a)} + \sum_{b\in I_i : b>a} X_{iOR_i(b)} \le 1, \quad \forall i\in S, a\in I_i \quad (8)$$

$$X_{ij}, Z_j \in 0, 1, \quad \forall i\in S, j\in P \quad (9)$$

Equation (1) minimizes the total installation cost, total energy consumption of the sensors, and the energy consumption of the relay with the maximum energy usage. The first term, $\sum_{j\in P} C_j^I Z_j$ takes the relay nodes' installation cost into account, while the second term represents the total energy consumed by the sensor nodes. The maximum amount of energy consumption between the relay nodes is calculated by the third term. This energy consumption consists of the total energy consumed by the relay to receive data from all the sensors, to forward data to the other relays and to the sinks and finally to dissipate for receiving data from other relays. The terms $\sum_{i\in S, k\in N} W_{ik} X_{ij} E_{RXelec}$, $\sum_{l\in P, k\in N} f_{jl}^{k}(E_{TXelec} + E_{amp}(n_{jl}) D_{jl}^{n_{jl}})$, $\sum_{k\in N} f_{jk}^{t}(E_{TXelec} + E_{amp}(n_{jk}) D_{jk}^{n_{jk}})$ and $\sum_{l\in P, k\in N} f_{jl}^{k} E_{RXelec}$ show these energy consumptions, respectively.

Now the constraints of the model will be explained as follows:

Relation (2) means that all the sensor nodes have at least one relay node nearby and all the sensor's incoming traffic will be sent to the connected relay to be forwarded to the other relay nodes and finally to the destination within few steps. The third relation says that Sensor i can be covered by Relay j, if there is a relay in CS_j and if they can communicate with each other. The fourth relation indicates the flow balance at Relay j for all the transmitted traffic to the sink k. The fifth constraint determines the connectivity existence between CS_j and CS_l. This connectivity depends on the relay installation at these two locations (j and l) and also the communication possibility defined by b_{jl} The relays' capacity limitation is applied by Relation (6), and the seventh relation says that no traffic will be traversed between Relay j and sink k, if they are not within each other's communication range. Relation (8) forces that each sensor node communicates with its nearest relay node and the last relation determines the binary decision variables.[5]

Table 1: Basic notations[5]

Notation	Description
S	Set of sensors, $s = \|S\|$
P	Set of candidate sites (CSs), $p = \|P\|$
N	Set of sinks, $n = \|N\|$
C_j^I	Cost for installing a relay at CS_j
W_{ik}	Traffic generated by sensor $i$destined to sink k
D_{ij}	Distance between node $i$and node j
V_j	Max. capacity of the relay installed at CS_j
a_{ij}	0–1 parameter that indicates if sensor $i$an communicate with CS_j
e_{jk}	0–1 parameter that indicates if CS_jcan communicate with sink k
b_{jl}	0–1 parameter that indicates if CS_jcan communicate with 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
n_{ij}	The path loss coefficient
E_{TXelec}	The energy dissipation of the radio for the transmitter
E_{RXelec}	The energy dissipation of the radio for the receiver
$E_{amp}(n_{ij})$	The energy for the transmit amplifier

Assumptions and Parameter Settings for the Performance Evaluation

In this section, the assumptions and parameter settings, used to evaluate the performance of our method are presented.

First of all, a WBAN scenario is considered according to EAWD model,[5] in which the body is in standing position with arms hanging along sides. Sensor nodes are placed on the body for data collection, and they are connected to the sink node through a set of relay nodes. Hence, WBAN is composed of three types of nodes: sensor, sink, and relay nodes. Several feasible relay positions CSs are analyzed. However, the sensor nodes and sinks' positions are usually predetermined and fixed, according to the medical application for which they are deployed. Also, it is assumed that the sensor nodes can share the same radio spectrum in a time division multiple access manner. Therefore, there is no interference between such wireless devices within a single WBAN.

The assumed WBAN includes 13 sensor nodes and one sink, as shown in Figure 1a. The CSs for placing the relays are chosen randomly. They are distributed uniformly on the ellipsoidal areas, along the cloth of the patients, as illustrated in Figure 1b.

Extremely low transmission power levels are used in WBAN to protect the human tissue. Therefore, all types of nodes can be connected if their distance is not greater than 30 cm.

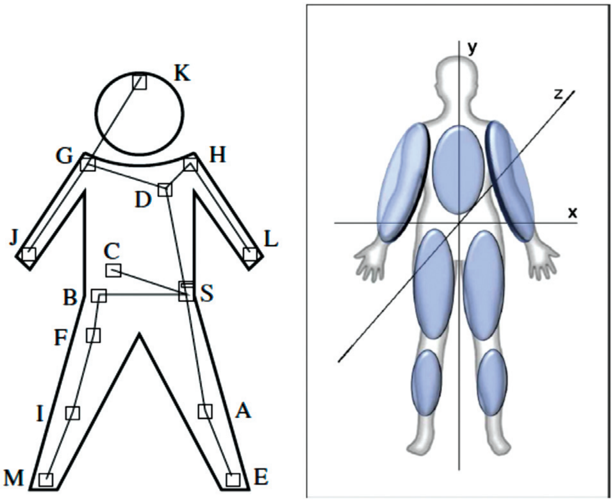

Figure 1: (a) WBAN topology with 13 sensors and 1 sink, (b) ellipsoidal areas of the candidate sites[5]

It is further assumed that the installation cost is equal to 10 monetary units per relay node, and the relay node's maximum capacity is equal to 250 kb/s.[5]

When the nodes are close enough to each other and when they are both in one side of the body (front or back), they are assumed as LOS and their path loss coefficient is assumed as 3.38 GHz. Otherwise, the nodes are assumed as non-LOS (e.g., one node on the front of the body and the other on the back) and their path loss coefficient is set equal to 5.9.

According to,[5,7] the sensors considered in this study use the Nordic nRF2401 (Nordic Semiconductor ASA, Vestre Rosten 81, N-7075 Tiller, Norway; http://www.nordicsemi.no) transceiver. The Nordic nRF2401 transceiver parameters' values are reported in Table 2.

The proposed method is simulated by MATLAB (MathWorks, Natick, Massachusetts, USA). Each scenario is run 10 times and the results are obtained by averaging over these 10 simulation attempts. A normal person with a height of 175 cm is considered in this simulation.

Performance Evaluation

A number of 40, 50, 60, and 70 CSs are investigated for the relays' placement in this performance evaluation. A number of 10, 11, 12, 13, 14, and 15 different selections of these available CSs are considered for placing the relay nodes and their effects on the network performance and energy consumption are analyzed. The energy consumed by each relay node for data transmission and reception are shown in Figures 2, 3, 4, and 5 for 40, 50, 60, and 70 CSs, respectively. When 40 CSs are considered, the best response is correspondent to 12 relay selections. This number is 11, when 50 or 60 CSs are considered and 10 in the case of 70 CSs' consideration. The consumed energy of each relay node in these best selections is presented in the figures. As it is shown, the proposed method results in a more uniform distribution of relays' energy consumption compared to EAWD.

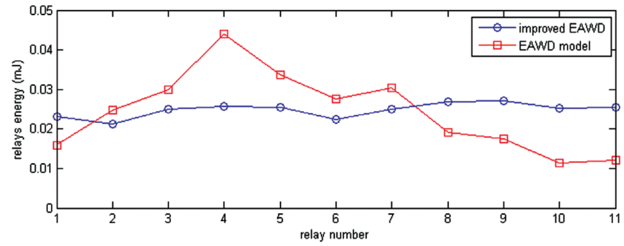

Figure 2: Energy consumption of the relay nodes in the improved EAWD for 40 CSs

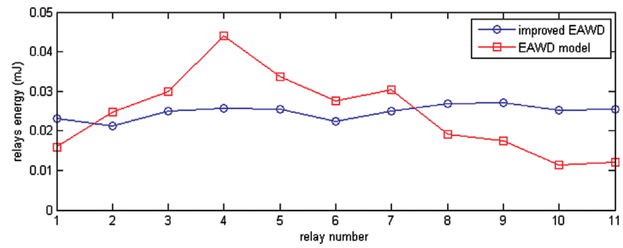

Figure 3: Energy consumption of the relay nodes in the improved EAWD for 50 CSs

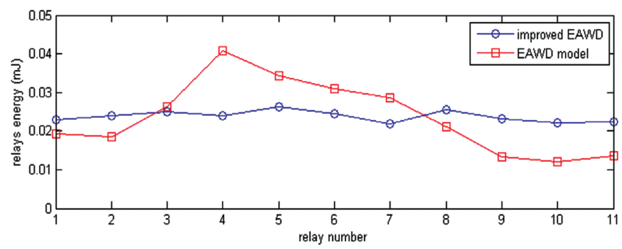

Figure 4: Energy consumption of the relay nodes in the improved EAWD for 60 CSs

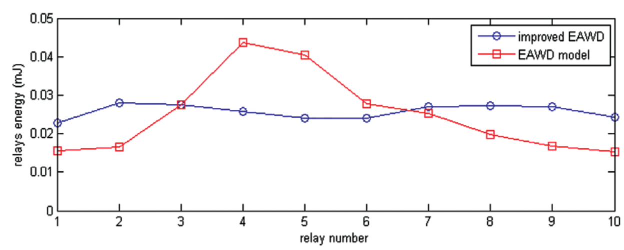

Figure 5: Energy consumption of the relay nodes in the improved EAWD for 70 CSs

Table 2: Energy consumption values for the Nordic nRF2401 transceiver[5]

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

Figure 6 shows the total energy consumption of relay nodes for different numbers of CSs. As it is obvious, the proposed method slightly increases the total energy consumption of relay nodes, because minimizing the total

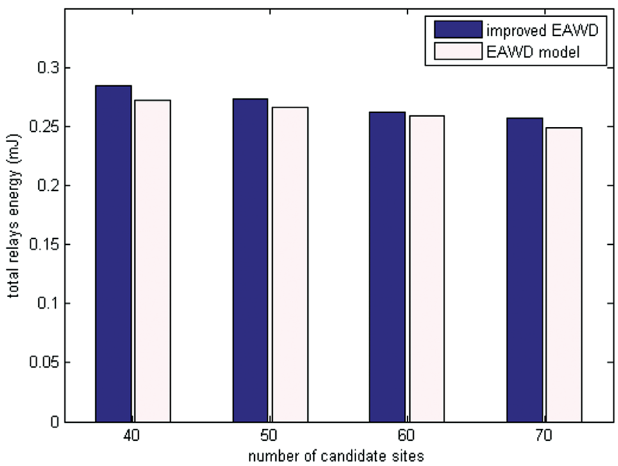

Figure 6: Total energy consumption of the relay nodes

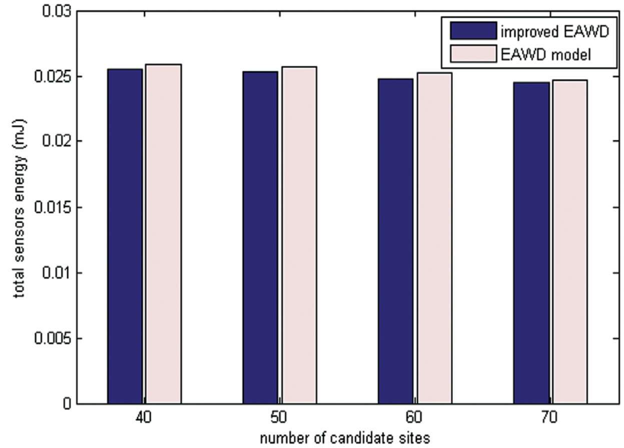

Figure 7: Total energy consumption of the sensor nodes

energy consumption of relay nodes is not the purpose of our method. The proposed method selects the scheme, which minimizes the energy consumption of the relay that uses the most energy among the relay nodes and, thus, merges the relay nodes' energy consumption to the uniform distribution.

Total energy consumption of the sensors for different numbers of CSs is shown in Figure 7. As the sensor nodes' collected data are sent to the nearest relay node in the both proposed and EAWD models, total energy consumption of the sensor nodes are not much different.

Some research works have been performed to identify the body situation and stationary and moving person have been diagnosed using special sensors. Some other methods can even identify the body postures.[13-15] Therefore, different body postures such as standing, sitting, sleeping, walking, running can be detected Thus two other postures of the body are investigated in this work and their best selection of relay nodes' placement is determined. Then, one of the previous research works can be used to identify the posture of body and their appropriate relays selection becomes active to do the network's best job. Figure 8 shows the second posture named as chair sat.

In this posture, 40, 50, and 60 CSs for relay nodes' placement are investigated and different selections of 10 to 15 sites out of available CSs are analyzed.

Energy consumption of the relay nodes in the 40, 50, and 60 CSs' consideration is shown in Figures 9, 10, and 11, respectively. Energy consumption of relay nodes has also become more uniform in the proposed method compared to EAWD model.

Figure 12 shows the third posture named as ground sat posture. In this posture, 40, 50, and 60 CSs are investigated similar to the chair sat posture. Different selections of 10 to 15 sites out of the available CSs are analyzed. Similar results to the previous postures have been obtained in this posture too.

Figure 8: Chair sat posture

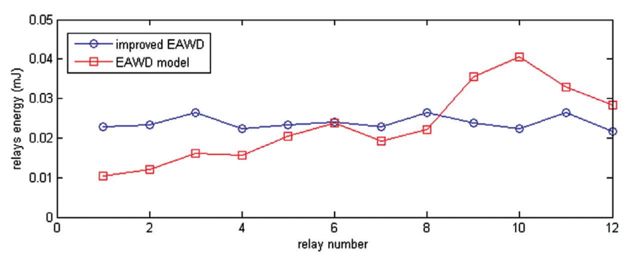

Figure 9: Energy consumption of the relay nodes in the improved EAWD for 40 CSs in the chair sat posture

By considering the different body postures, union of the relay nodes in the various postures can be used as the network topology.

Figure 13 shows the total number of relay nodes in the union of the three mentioned postures' results.

Based on the results of the proposed method, optimized routing and also the traffic distribution in the network are determined. The way by which the traffic is split and multipath routed in the network with 10 relay nodes is shown in Figure 14. In this figure, D_i represents the available data at Relay *i*.

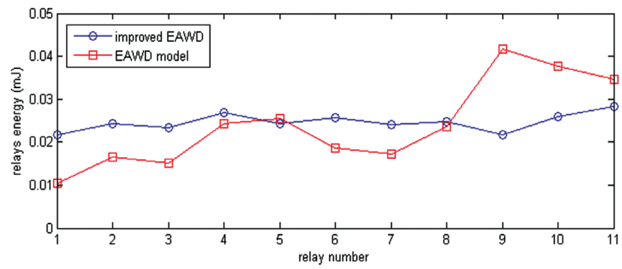

Figure 10: Energy consumption of the relay nodes in the improved EAWD for 50 CSs in the chair sat posture

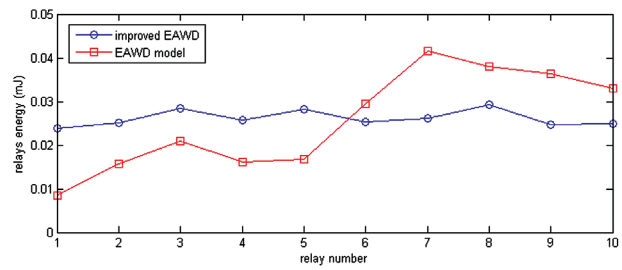

Figure 11: Energy consumption of the relay nodes in the improved EAWD for 60 CSs in the chair sat posture

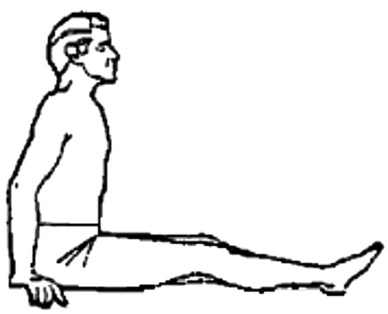

Figure 12: Ground sat posture

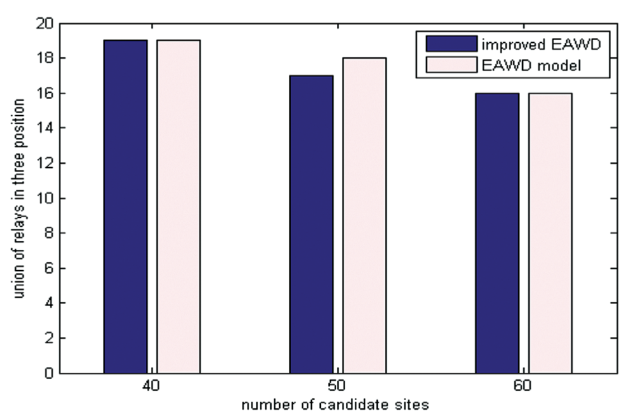

Figure 13: Total number of relay nodes in the union of the three mentioned postures' results

Another general approach, considering different body postures, is to minimize the expected value of the network's corresponding utility function according to Equation (2). X_i is the network's utility function in the i th body posture, calculated by Equation (1). As it is obvious,

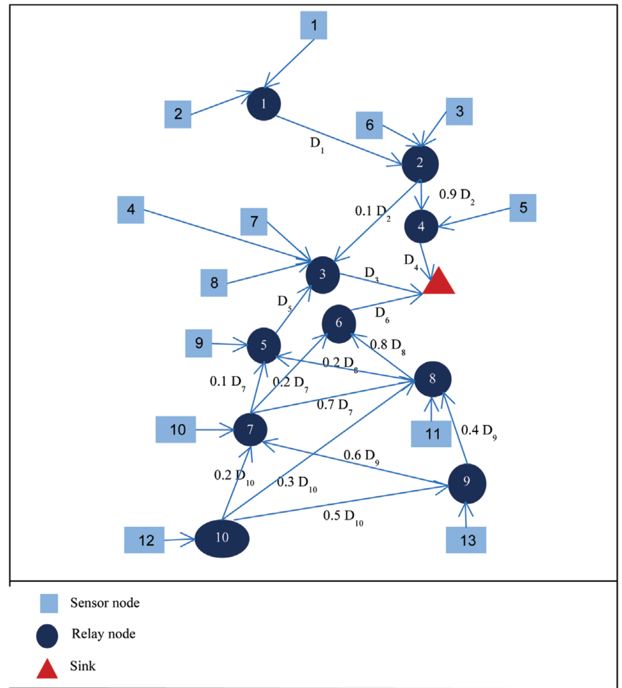

Figure 14: Traffic splitting and multipath routing in a network with 10 relay nodes

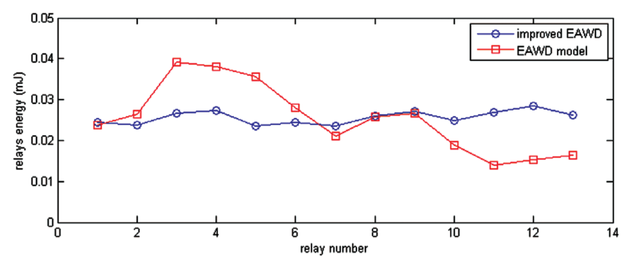

Figure 15: Energy consumption of the relay nodes in the improved EAWD for 40 CSs by considering the expected value of the utility functions

three body postures are considered in this paper. $P_X(X_i)$ is the i th body posture's probability, which is assumed 0.5, 0.208, and 0.292 for standing, chair sat, and ground sat postures, respectively. Along a day, the patients are assumed to be 12 hours in standing or sleeping postures, 5 hours in chair sat and 7 hours in ground sat postures.

$$E[X] = \sum_{i=1}^{n} X_i P_X(X_i) \quad (10)$$

Different selections of available CSs are investigated. These selections are the ones that provide network's connectivity in three assumed body postures. The desired set of relay nodes should minimize $E[X]$.

Energy consumption of relay nodes in 40, 50, 60, and 70 CSs' consideration is shown in Figures 15, 16, 17, and 18, respectively. Figures show that by considering the expected value of the utility functions, energy consumption of the relay nodes has also become more uniform in the proposed method compared to EAWD model.

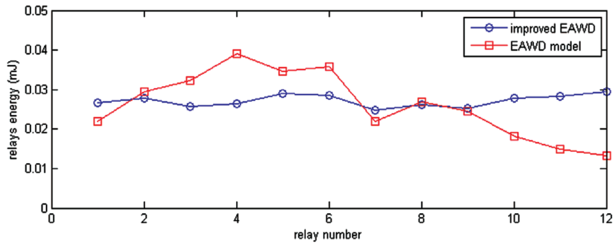

Figure 16: Energy consumption of the relay nodes in the improved EAWD for 50 CSs by considering the expected value of the utility functions

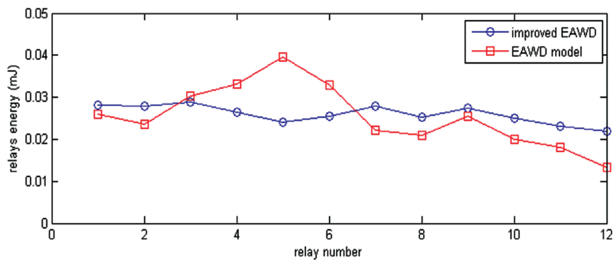

Figure 17: Energy consumption of the relay nodes in the improved EAWD for 60 CSs by considering the expected value of the utility functions

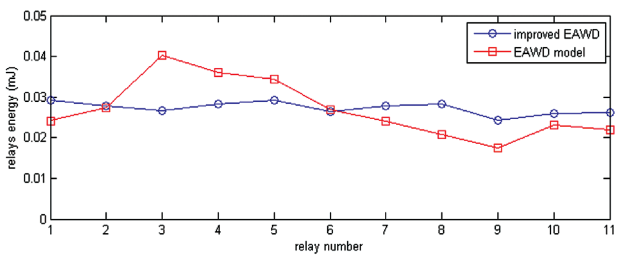

Figure 18: Energy consumption of the relay nodes in the improved EAWD for 70 CSs by considering the expected value of the utility functions

Conclusion

In this paper, we addressed a topology design problem for WBANs, considering both cost and energy issues. This topology is an improved version of EAWD model that minimizes the energy consumption of the most energy using relay among the relay nodes. Simulation results showed that energy consumption of relay nodes merges to the uniform distribution in the proposed method. Therefore, life time of the relay network increases and the maintenance costs are reduced compared to EAWD model. The proposed method also determines the way by which the network traffic is split and multipath routed to the sink.

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Nil.

Conflicts of interest

There are no conflicts of interest.

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