EN-NEAT: Enhanced Energy Efficient Threshold-Based Emergency Data Transmission Routing Protocol for Wireless Body Area Network

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Abstract Wireless body area network (WBAN) is a network composed of tiny sensor nodes that can be placed on/in/around the body to measure physiological parameters in real time and transmit it through the Internet to a caregiver. The main aim of WBAN is to improve the overall quality of life. However, limited battery life is a major constraint especially for in vivo sensors since replacing and recharging the battery are not always feasible. Hence, EN-NEAT (ENhanced eNergy-efficient threshold based Emergency dAta Transmission) protocol is proposed in this work which is energy efficient, reliable and has high throughput. Furthermore, EN-NEAT utilizes multi-hop communication to reduce energy depletion and maximizes network longevity by: Firstly, avoiding the transmission of normal data. Secondly, comparing the sensed information, and if there is a variation, a transmission occurs, otherwise no transmission occurs. Lastly, a minimum cost function was proposed to carefully choose parent or forwarder node that has the highest residual energy and the shortest distance to sink. In addition, we model our proposed protocol mathematically using linear programming for the maximization of network lifetime, minimization of continuous data transmission and minimization of end-to-end delay. Our MATLAB simulation results prove that EN-NEAT protocol outperforms the compared routing protocols.

Keywords Multi-hop · Threshold · Network lifetime · Throughput
Energy depletion

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1 Introduction

Percentage of older people is significantly increasing in developed countries and developing countries as well. This alarming rise in population of older people is leading to overloading of healthcare systems and increase in healthcare cost. World Health Organization (WHO) has recently forecasted that the number of people above sixty-five-year-old will soon be greater than the number of children under five-year-old [1].

At the same time, millions of people die every year as a result of the following chronic or fatal disease such as cancer, cardiovascular diseases, diabetes, Parkinson's diseases. A major solution is a network that consists of intelligent low-power wearable or implanted patient monitoring system which is more affordable and proactive and concentrates on early detection of abnormalities, thus leading to major progresses in the quality of life. The network is called wireless body area network (WBAN) [2].

WBANs are ideally meant to operate correctly for long period of time without any battery reviving or substitution, particularly for in vivo (embedded) sensor nodes. As a result, energy efficient routing protocols are required that are adequately designed to avoid the depletion of communication energy and improve the network lifetime.

To this end, EN-NEAT (ENhanced eNergy-efficient threshold based Emergency dAta Transmission) routing protocol is proposed that minimize the energy depletion and maximize the network lifetime. Similar to the works of Javaid et al. [3], we deploy eight sensor nodes at fixed positions and sink node is positioned at the middle of the body to measure (data) vital signs and transmit the sensed data to the sink through a forwarder or parent node. A cost function is introduced which carefully chooses the parent node. The sensor node which has the shortest communication distance and highest residual energy is chosen as parent node. In addition, the sensed data is grouped into normal (vital signs are within the optimal limit), low-emergency (patient condition shows signs of becoming critical) and high-emergency data (patient's condition is critical and needs urgent attention) based on threshold. The normal data is saved in memory. For low-emergency data, its previously sensed data is compared with its currently sensed data and if a variation occurs, then multi-hop communication is utilized to forward the data to the sink node via the parent node, otherwise, no transmission occurs. And for the high-emergency data, single-hop communication is used to forward the data to sink node. Also, numerical model based on linear programming to maximize network lifetime, minimize continuous data transmission and to minimize end-to-end delay is formulated.

The rest of this paper is prepared in the following order. Section 2 reviews the related works. Section 3 presents the first-order radio model. The detail of our proposed EN-NEAT protocol is discussed in Sect. 4. Section 5 presents the mathematical models. Section 6 provides simulation results and discussion. Conclusion is discussed in Sect. 7, and Sect. 8 mentions the future works.

2 Related Works

Authors in Yousaf et al. [4], proposed an energy conscious shortest path algorithm that increase throughput and decrease end-to-end delay. Global routing protocols are studied by Tsouri et al. [5] whereby global routing is added to an original connection cost function aimed to stabilize energy depletion throughout the entire network. Ibarra Ramírez [6] unveil an involvement to the plan and assessment of new answers dedicated toward energy-aware resource management for WBANs powered by human energy harvesting. Arturo and Fernando [7] analyzed the latest literature about WBAN centering on applications and network properties and accomplished a coherent taxonomy for learning, teaching, and assessing WBAN networks.

The authors Kavitha et al. [8] improved the throughput and lifetime of nodes by designing an efficient and reliable transmission path for data flow from source to sink node. They formulate the energy depletion balancing issue as an optimal transmitting data distribution issue by joining the ideas of corona-based network division and mixed-routing technique in addition data gathering.

In the book of Dey and Mukherjee [9], the authors introduced a state-of-the-art open-source software and hardware system and the real-life application of the technology that takes the system to the future. The authors Dey et al. (2017) presented a revolutionary review and the made-known idea and logic wireless ECG monitoring systems. The authors additionally modeled the power consumption and ECG signal mathematically. Literature review was presented by Dey et al. (2017) to make known the data acquisition idea of the GI pictures by the use of endoscopy with a complete explanation of the endoscopy system constituents [10, 11] developed M-ATTEMPT and RE-ATTEMPT routing algorithm, respectively. Both algorithms utilized single-hop and multi-hop communication modes of WBAN. The single-hop was utilized for the communication of emergency data direct to the sink while the multi-hop was used for the communication of normal data to the sink via intermediate/forwarding node. This extends network lifetime. However, continuous data transmission caused extra energy consumption. Yousaf et al. [4] developed CEMob which is an improvement on the M-ATTEMPT and RE-ATTEMPT by avoiding continuous data transmission. This was achieved by comparing the normal data to the previously sense normal data and if there is a variation the data is transmitted, otherwise it is ignored.

A cost function is proposed by Nadeem et al. [12] that evenly distributes the energy depletion between the sensor nodes but guarantees successful packet delivery to sink. Their work was later improved by Javaid et al. (2015) by adding mobility and formulating the low-energy depletion and high throughput problems as an integer linear program.

3 First-Order Energy Model

A good amount of energy models are proposed in literature. In this work, Chipcon CC2420 and Nordic nRF 2401A transceivers proposed by authors in [13] are considered. Both transceivers have similar parameter values such as operational frequency. However, Nordic nRF 2401A transceiver is used because it consumes less power than Chipcon CC2420 transceiver.

4 The Proposed Protocol: EN-NEAT

In this work, we modify the work of iM-SIMPLE and CEMob. This is because iM-SIMPLE does not consider continues and repeated transmission of data and CEMob does not take it to account the intermediate sensor node which has the highest residual energy and shortest distance to sink. Table 1 shows the nodes deployment on the body.

The sink sends a small information packet containing its location to all nodes in the network. Each and everyone of the sensor node saves the location of sink and sends an information packet that has nodes location, energy status, and ID to each other. Next, sensor nodes sense data and group them according to threshold as in the case of a hypertensive patient in Table 2. The normal data is saved, thereby saving transmission energy. The high-emergency data is transmitted to sink via single-hop communication, and the low-emergency data is forwarded to the sink via the parent node.

Table 1 Radio parameters

Node number	X-axis (cm)	Y-axis (cm)
1	0.2	1.4
2	0.6	1.4
3	0.1	0.7
4	0.7	0.7
5	0.6	0.6
6	0.2	0.6
7	0.2	0.1
8	0.6	0.1

Table 2 Blood pressure readings

Blood pressure grouping	Systolic mm Hg	Diastolic mm Hg
Normal	<120	<80
Low-emergency	120–139	80–89
High-emergency	>140	>90

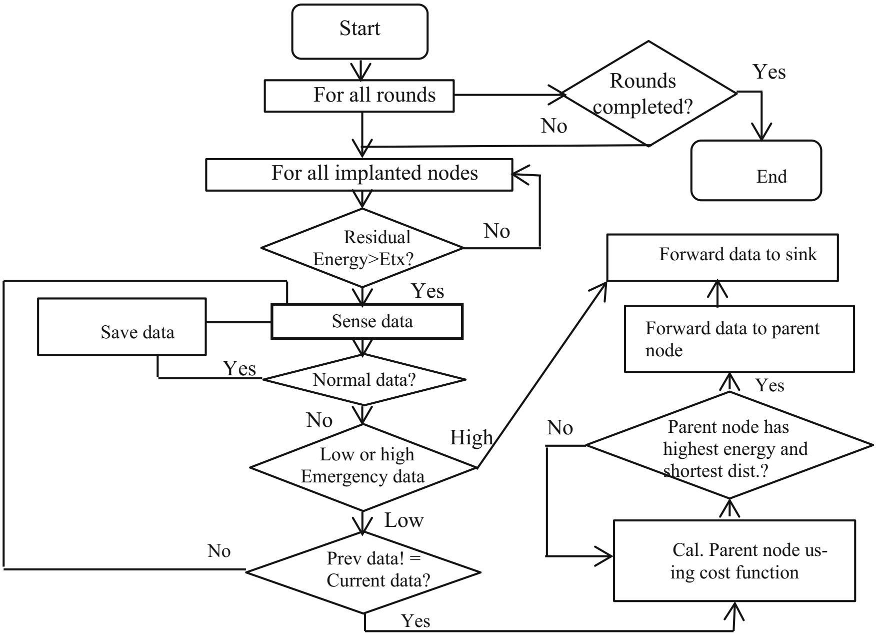


Fig. 1 EN-NEAT flowchart

To evenly distribute the energy depletion between sensor nodes, EN-NEAT protocol chooses a new parent node in every round. Equation 1 shows CF computation.

$$\text{CF(i)} = \frac{d(i)}{\text{RE}(i)} \tag{1}$$

Node's ID is i, distance between node i and sink are $d(i)$, and the residual energy of node i is RE(i). RE(i) is computed by means of deducting the presently expended energy from earlier total energy of the node. Once the cost function is calculated, the sink chooses the node that has the minimum cost function as parent node. Figure 1 shows the flowchart of our algorithm.

5 Linear Programming Mathematical Modeling

In this section, two mathematical models that are based on linear programming are presented, maximizing network lifetime, and minimizing continuous data transmission. The following subsections provide details.

5.1 Network Lifetime Maximization

The energy models presented by Elias and Mehaoua [13], Shirazi and Lampe [14], and Javaid et al. (2015) are used in this work. We select these models for the reason that they are in accordance to the assumptions of our EN-NEAT protocol. The objective which is network lifetime maximization T is computed below:

$$\text{Max } T \tag{2}$$

where

$$T = \sum_{r} t_r \forall_r \in Z^+ \tag{3}$$

$$E^p_{RX} = (N-1)E^p_{RX}(1) \tag{4}$$

$$E^p_{\text{TOT}} = N\emptyset E^p_{TX}(1, d) + NL\emptyset E^p_{\text{ELEC}} + E^p_{RX} \tag{5}$$

$$E^i_{\text{TOT}} = LE^i_S + LE^i_P + E^p_{TX}(l, d) \tag{6}$$

and

$$t_r = \frac{E_i}{\sum_i \left(LE^i_S + LE^i_P + E^p_{TX}(l, d)\right)} + \frac{E_p}{\sum_p \left(N\emptyset E^p_{TX}(l, d) + NL\emptyset E^p_{\text{ELEC}} + E^p_{RX}\right)} \quad \forall_{i,j} \in N \tag{7}$$

Subject to

$$E_i \le E_0 \quad \forall_i \in N \tag{2.1}$$

$$E_p \le E_0 \quad \forall_p \in N \tag{2.2}$$

$$\sum_i \left(LE^i_S + LE^i_P + E^p_{TX}(l, d)\right) \le qE_i \quad \forall_i \in N \tag{2.3}$$

$$\sum_p \left(N\emptyset E^p_{TX}(l, d) + NL\emptyset E^p_{\text{ELEC}} + E^p_{RX}\right) \le qE_p \quad \forall_i \in N \tag{2.4}$$

$$\sum_i F^t_{ip} \le C_{ip} \quad \forall_i \in N \tag{2.5}$$

$$F^t_{ps} \le C_{ip} \quad \forall_f \in N \tag{2.6}$$

$$d_{ip} \to d_{\text{min}} \quad \forall_i \in N \tag{2.7}$$

$$d_{ps} \to d_{\text{min}} \quad \forall_i \in N \tag{2.8}$$

The objective function in (2) deals with the network lifetime T, maximization. Equation (2) describes T as the addition of rounds through which the normal and parent nodes execute their operations before their energies E_i and E_p are depleted.

Equation (4) computes the received energy of the parent node, where $\emptyset$ is data gathering factor, N is the aggregate amount of nodes, l is the packet size, i represents normal node, p denotes parent node. If the per bit processing, transmission energy and sensing of normal nodes are represented as $E_S^i,\ E_P^i,\ E_{TX}^p(l,d)$, respectively, and if the per bit transmission, dissipation and reception energy of parent node are represented as $E_{TX}^p(l,d),\ E_{\text{ELEC}}^p,\ E_{RX}^p$, respectively. Then Eq. (7) gives full information about the energy depletion cost per round of the network. In constraint (2.1 and 2.2), the initial energy E_0 should always be greater than E_i and E_p because as time passes their energies decreases. A node ceases to function when E_i and E_p <= E_{TX}. Constraints in Eq. (2.3) consider sensing, processing, and transmission of data by normal node and ensure that these events represent their initial energy level ($q = \frac{1}{T}$). It is important to point out that there is no energy cost of $\emptyset$ and E_{RX} in normal node. They are only present at the parent node leading to minimizing and balancing of the energy consumption. Equation (2.4), on the other hand, does not consider E_s and E_p which are only present in normal nodes. This further minimizes and balances the energy consumption. Constraints in Eqs. (2.5 and 2.6) ensure flow management when data is sent from i to p and from p to s with their physical link capacities, C_{ip} and C_{ps}, respectively. When these two constraints are violated, this leads to rise in congestion which causes rise delay and eventually lead to high packets dropped rate. Additional energy is consumed when retransmission is done which result in diminished network lifetime. The constraint in Eqs. (2.7 and 2.8) points out that the routing protocol has to be efficient enough to minimize the transmission/reception distance d_{ip} and d_{ps} to its barest minimum value d_{min}.

5.2 Minimizing Continuous Data Transmission

Continuous data transmission leads to continuous energy depletion. Continuous transmission is addressed here and formulated as follows:

$$\text{Minimizing } \mathrm{CT}_{\mathrm{sp}} \quad \forall\, \mathrm{s}, p \in \mathrm{N} \tag{8}$$

where

$$\mathrm{CT}_{\mathrm{sp}} = \begin{cases} E_i - E_{TX}^i, & \text{if } D_s \neq D_{S'} \\ E_i - 0, & \text{if } D_s = D_{S'} \end{cases} \tag{9}$$

Subject to

$$n_{sp}^{re-tx} \rightarrow \forall n \in Z^{+} \tag{8.1}$$

The objective function in Eq. (8) aims to minimize the continuous transmission (CT) of data from source node s to parent node p. CT means continuous decrease in the node's energy E_i after each data is sensed. Equation (9) provides details in the first part of Eq. (9), and currently sensed data D_s is different from the previously sensed data D'_s, and as a result, E_i is decreased by E^i_{TX}. In the second part of Eq. (9), however, currently sensed data is the same as the previously sensed data, and as a result no transmission occurs leading to increase in network lifetime. Since the sensed data is randomly generated, we cannot determine the kind of data that is generated. What we can do is to make sure that anytime the second part of Eq. (9) occurs, and no data is transmitted which avoids transmission of same data and increase network lifetime. This is enforced in constraint (8.1). Violation of (14.1) will lead to retransmission of the same data which will result in increase in network lifetime.

6 Simulation Result and Discussion

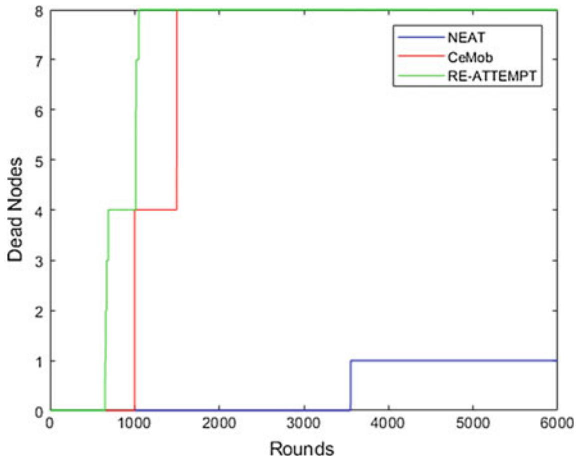
We evaluated the performance of our proposed EN-NEAT protocol using MATLAB R2017b, by comparing it with related protocols CEMob and RE-ATTEMPT in terms of selected performance metrics, stability period, and network lifetime. Eight sensor nodes are deployed at fixed positions on a human body of height 1.6 m and width 0.8 m as shown in Table 1. Sink node is placed in the center of the body ($X = 0.4$, $Y = 1.0$), and each node is equipped with initial energy 0.5 j.

A. **Network lifetime and stability period**

Network lifetime is the time span from start of the network till the death of all nodes, and *stability period* is usually defined as a time interval between the start of a network and the time at which the first node dies. Figure 2 shows that stability period of EN-NEAT is greater than that of CEMob and RE-ATTEMPT. This is due to the fact that normal data transmission is ignored, and continuous transmissions are avoided. Furthermore, introduction of cost function balances the energy consumption among sensor nodes.

The stability period of CEMob and RE-ATTEMPT is 1010 and 800 rounds, respectively, whereas the first node of EN-NEAT dies at the 3500th round. So EN-NEAT is 68 and 77% more stable than CEMob and RE-ATTEMPT, respectively.

Fig. 2 Network lifetime and stability



7 Conclusion

In this paper, we fixed eight in vivo sensor nodes strategically on the point of interest on person's body and sink at the center of the body. Our EN-NEAT extend the network lifetime, balances energy consumption, and improves packet delivery to sink. These are achieved by first avoiding the transmission of normal data, then transmit low-important data only when it is different from the previous low-important data and lastly select the forwarder node that has the shortest distance to sink and the maximum residual energy in every round. Mathematical model for maximizing the network lifetime and minimizing continuous data transmission was presented.

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