IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received June 17, 2019, accepted June 23, 2019, date of publication July 1, 2019, date of current version August 20, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2925909

Simplified Energy-Balanced Alternative-Aware Routing Algorithm for Wireless Body Area Networks

JIASONG MU[1], (Member, IEEE), XIANG LIU[2], AND XIANGDONG YI[2]

[1]Tianjin Key Laboratory of Wireless Mobile Communications and Power Transmission, Tianjin Normal University, Tianjin 300387, China

[2]College of Electronics and Communication Engineering, Tianjin Normal University, Tianjin 300387, China

Corresponding author: Jiasong Mu (mujiasong@aliyun.com)

This work was supported in part by the Natural Youth Science Foundation of China under Grant 61401310 and Grant 61701345, in part by the China Scholarship Council under Grant 201608120043, and in part by the Natural Science Foundation of Tianjin under Grant 18JCZDJC31900 and Grant 18JCYBJC86400.

ABSTRACT Nowadays, the needs of healthcare for the elderly are growing rapidly. To provide continuous all-day medical monitoring and diagnoses at low cost, wireless body area networks (WBANs) have become a forward-looking technology since it is regarded as a potential solution for the remote collecting of physical and symptoms information. Because of its application characteristics, reliability and delay are the most important, as the energy consumption also needs to be considered. However, due to the limitation of the large propagation loss and the complicated channel conditions, the existing routing algorithms cannot completely address the above problems. To balance the node energy consumption and reduce the transmission delay, a simplified energy-balanced alternative-aware routing algorithm (SEAR) for WBANs is proposed in this paper. The residual energy and the current load of a candidate of the next hop destination are considered during the routing request forwarding procedures. The required information is exchanged during the improved routing request and routing request response procedures, and the routing cost is modified accordingly. To improve the compatibility and robustness, the added path is introduced as an alternative path in our algorithm. The simulation results show that SEAR achieves significantly higher network residual energy and network throughput, and end-to-end delay is also reduced. Therefore, the lifetime of the network is extended effectively.

INDEX TERMS Wireless body area networks (WBANs), routing request, residual energy, routing algorithm, simplified, NS2.

I. INTRODUCTION

According to statistics from the World Health Organization, there are about 17.5 million people who die of chronic diseases every year in the world. The deaths caused by cardiovascular and cerebrovascular diseases in the world account for 30% of the global death toll. Approximately 3.5 million people die of cardiovascular and cerebrovascular diseases every year in China, and about 4 million people die of cardiovascular disease every year in Europe. There are approximately 422 million people worldwide with diabetes; this number has been growing and is expected to reach 629 million by 2045 [1], noticed mostly in developing countries [2]–[4]. In addition, more and more elderly people pay less attention to their own physical problems, and their health problems are becoming increasingly prominent. It is well known that aging is one of the main causes of health problems of the elderly. Therefore, they urgently need a comprehensive and high-quality healthcare system to help the elderly to live more comfortably and independent [5]. So, people have now turned their attention to the healthcare field [6]. In order to improve this situation and provide continuous and all-weather health monitoring for the elderly [7], [8], wireless body area networks (WBANs) have become a promising and widely used technology. As a typical representative of human health monitoring and disease prevention in the future, it mainly uses microelectronics, wireless communications, embedded system, integrated circuits, and sensor technology.

Although WBAN is an application branch of wireless sensor networks (WSNs), there are still some differences between the two networks [9]. The scale of wireless sensor networks is usually large whether the number of nodes or the

The associate editor coordinating the review of this manuscript and approving it for publication was Qilian Liang.

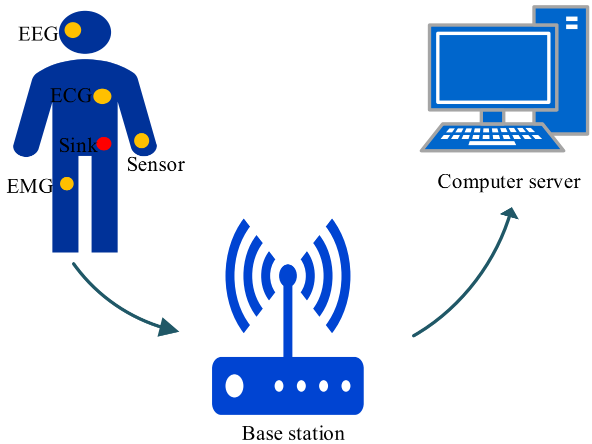


FIGURE 1. An overview of communication model in WBANs.

geographical range. However, WSNs can use redundant nodes so that individual robustness is usually not a priority, whereas, owing to the critical concern of the user's wearing comfort, WBANs must use a minimum number of nodes, each node can ensure high data packet transmission rate and low latency [10]. For the same reason, sensor nodes have higher requirements in terms of physical dimensions, weight, biocompatibility, and ergonomics. In contrast, as far as energy supply is concerned, since batteries in wireless sensor network nodes can usually be recharged or replaced more easily, the tradeoffs between requirements tend to be accurate, whereas WBANs have strict low power constraints [11]. In addition, WBAN applications typically require higher sensor sampling, data transmission rates, and continuous monitoring. Finally, the vast majority of WBANs adopt star network topology, while WSNs are essentially multi-hop networks. Further, WBAN communication is real-time, wireless, and short-range [12], [13]. Biomedical sensors can be widely divided into three categories, namely, in-body, on-body, and off-body sensors [14]. In-body sensors are implanted inside the patient's body to transmit monitored data to the sink node, whereas on-body sensors are placed on the patient's body surface to monitor health data and send them to a sink node, and off-body sensors are located several centimeters away from a patient's body to obtain monitored data [15]. Finally, the monitored data are transmitted to the base station through the sink node and to the medical institution or medical staff [16]. The responsibility of a sink node is to allocate slots or channels to the monitored vital signs based on the category of data. An operation framework of WBANs with these sensors is shown in Fig. 1. Firstly, biomedical sensors are deployed to monitor the various vital signs of a patient's body, which forward these data to a sink node [17]. Secondly, a sink node transmits these data to the base station (BS), which eventually forwards the results of the vital signs to destinations such as a computer server, doctors, or transportation facilities through dedicated internet communication links [18]–[20]. Then doctors use monitored data to determine whether a patient's vital signs are problematic and to develop appropriate treatment options. The vital signs monitored via biomedical sensors include temperature, heartbeat rate, respiratory rate, EEG, ECG, blood pressure, and glucose level [21]. Each category of vital signs is represented by a specific type of medical data, and is completely different from the other categories. Therefore, biomedical sensor data are heterogeneous and have different processing requirements from the medical team, based on the category of data. Although WBANs can effectively monitor human health, the requirements of complexity, flexibility, and changeability of the network still pose big challenges, caused by limited energy, processing power, large propagation loss, and complicated channel conditions [22].

The rest of this paper is organized as follows: Related work is summarized in Section 2. The system and channel models are introduced in Section 3, while Section 4 describes the simplified energy-balanced alternative-aware routing algorithm (SEAR) in detail. The simulation results are given in Section 5. Finally, Section 6 concludes this paper.

II. RELATED WORK

In recent years, there are numerous articles about wireless body area networks. An energy-efficient and reliable adaptive routing protocol (EERARP) in WBANs was proposed [23]. The protocol does not adopt a specific routing structure such as a spanning tree, and does not limit the relative position or link attributes (such as symmetry) of the node but calculates the external link quality of each node in the network. It is trained by the Hidden Markov Model (HMM) [24] to select the best routing path, which significantly enhances the robustness of the network and reduces the energy dissipation caused by route reconstruction and data retransmission. The simulation results show that compared with other existing predictive routing protocols, this algorithm has unique advantages in terms of packet loss rate, energy consumption, and time delay, and it effectively solves the link interruption problem caused by the change of communication link in WBANs [25]. However, the protocol does not use the remaining energy of the node as a reference point when selecting the optimal routing path. Thus, research on energy consumption control routing algorithm (ECCRA) for the wireless body area network is proposed [26]. The ECCRA adopts the node-independent transmission link and comprehensively considers the routing path hop count, node transmission power, and residual energy to select a path with the least energy consumption, which ultimately reduces the energy consumption of the network and prolongs the life cycle of the network. However, ECCRA does not consider the intermittent problem of the network caused by changes in body posture. Therefore, probability routing protocol (PRP) based on delay tolerance in a wireless body area network (PRP) was proposed [27]. PRP allows the nodes to communicate with each other by constructing a path with the highest probability of transmission to avoid intermittent connection states between the sensor nodes owing to frequent changes in body posture. As the above-mentioned routing protocols do not consider

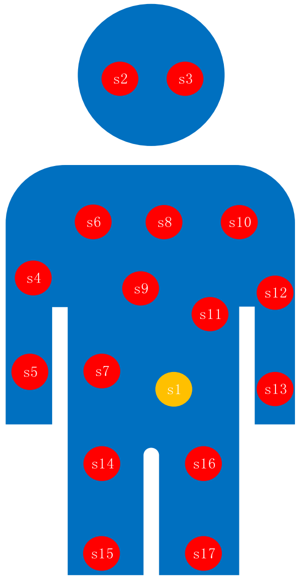


FIGURE 2. Human body model.

the channel changes in the wireless body area network, Han S *et al.* proposed an energy-efficient routing protocol (EERP) for wireless body area networks [28]. The EERP mainly calculates the weight of each path to judge the quality of the channel and considers the remaining energy of the node, the path energy consumption, and the node service type, which effectively saves the energy consumption of the network transmission. However, although these routing algorithms consider the energy balance or the changes of network link owing to human movement, they do not consider the two together.

Therefore, in this paper, we propose a simplified energy-balanced alternative-aware routing algorithm for wireless body area networks. Compared with the above-mentioned routing algorithms, SEAR firstly uses two paths with smaller hops between the source node and the destination node for data transmission, one as the main path and one as the alternative path, Secondly, it improves the routing request forwarding mechanism by taking into account the impact of the remaining energy and load of the node. Finally, it estimates the status of the network communication link and node by adding a link field to the routing table.

III. SYSTEM AND CHANNEL MODEL

A. SYSTEM MODEL

In this study, we design the system model of wireless body area networks. Our description will be similar to that in reference [29]. We deploy 17 sensor nodes on the human body surface. The specific human body model is shown in Fig.

In Fig. 2, S2 to S17 are common sensor nodes and S1 is a sink node which collects the monitored data sent by all the sensor nodes and is responsible for communicating with the Base station. Each node has a unique ID and they are nothing to do with each other. All nodes deployed on the human surface use short-distance transmission with very low power to transmit the monitored data. It is not necessary to synchronize the time between the nodes, but it is assumed that the time of each node is relatively synchronous.

TABLE 1. Parameter values of the path loss model.

Parameters	LOS transmission	NLOS transmission
d_0	10cm	10cm
σ	6.2dB	5dB
P	35.7dB	48.8dB
N	3.38	5.9

B. CHANNEL MODEL

We use the surface channel model in our algorithm. The electromagnetic wave mainly propagates through the crawling wave on the human body surface, which is more susceptible to the influence of the human body and the surrounding environment, in which path loss and the shadow effect are the most prominent. In this section, we will also discuss the construction of the human body surface channel model from two aspects: path loss and shadow effect.

Most current path loss studies are based on the free space Friis equation, and a semi-empirical model for estimating path loss is obtained as [30]:

$$P_{dB}(d) = P + 10 \times n \times \log\left(d/d_0\right) \tag{1}$$

where P is the path loss at reference distance d_0 and n is the path loss exponent. When the model is used for intra-line-of-sight (LOS) transmission, n = 3. When the model is used for non-line-of-sight (NLOS) transmission, n = 7. When the model is used for free space transmission, then n = 2. It can also be seen that the attenuation caused by the human body during signal transmission cannot be ignored.

In addition, Braem *et al.* conducted a comparative study of the above models in the LOS and NLOS scenarios, as shown in Table 1 [30]. In the table, σ represents the independent measurement of deviation of the model.

As can be seen from Table 1, when the reference distance is the same, the path loss under NLOS transmission is much higher than that under LOS transmission. The main reason behind this is that the signals from the body surface are transmitted by the diffracted waves, and the body has a large absorption rate of electromagnetic signals.

In summary, the semi-empirical path loss model is only applicable to scenarios under far-field radiation, but not to low and medium-frequency cases [31]. In this case, the path loss model can be established as follows.

Let the transmitted and received signals be s(t) and r(t), and their power spectral densities be $S_s(f)$ and $S_r(f)$ respectively. Then, in linear systems:

$$S_r(f) = S_s(f)\,|H(f)|^2 \tag{2}$$

where H(f) represents a transfer function and can be expressed as:

$$|H(f)|^2 = \frac{S_r(f)}{S_s(f)} \tag{3}$$

If the dB is used, the corresponding path loss of the transmission channel is:

$$|H(f)|^2_{dB} = S_r(f)_{dB} - S_s(f)_{dB} \tag{4}$$

According to (4), the path loss of the transmission channel is the root mean square of the difference between the transmitted signal and the received signal. However, in the actual test, only the amount of channel change generated by the human body is generally considered, instead of the absolute value of the transmission loss [32]. Hence, the following model is used to represent the path loss:

$$PL(t) \triangleq PL'(t) + G_{antenna} = P_{tx}(t) - P_{rx}(t) \tag{5}$$

where PL(t) is the total path loss, PL'(t) is the actual path loss of the communication channel, $G_{antenna}$ is the amplification gain of the antenna, $P_{tx}(t)$ is the transmission power of the signal at time t or the mean of $S_s(f)$, and $P_{rx}(t)$ is the received power of the signal at time t or the mean of $S_r(f)$. If the signal is transmitted at a constant transmission power P_{tx}, the path loss of the transmission channel can be equivalent to the change in received power $P_{rx}(t)$:

$$PL(t) \triangleq PL'(t) + G_{antenna} + P_{tx} = -P_{rx}(t) \tag{6}$$

The shadow effect is mainly caused by the movement of the body's limbs, which reflect the degree of deviation between the signal's transmission power and the received power. It can be well described by a log-normal distribution. In practice, to achieve reliable communication of data, the shadow effects must be considered. At this time, the path loss of the transmission channel is represented as a random variable:

$$PL = PL_{dB} + PL_s \tag{7}$$

where PL_s is the zero mean Gaussian random variable with standard deviation σ, i.e.,

$$PL_s = \sqrt{2}erfc^{-1}[2(1-p)] \times \sigma \tag{8}$$

where $erfc^{-1}()$ represents the inverse of the standard cumulative error function and p is the percentage of required reliability.

IV. A DETAILED DESCRIPTION OF SEAR

A. ROUTING DISCOVERY

SEAR is an active routing protocol designed to establish route discovery and route maintenance procedures [33]. SEAR first establishes the routing request phase. When the source node needs to send data, if there is no available route to the destination node in the routing table of the node, the source node sends a routing request (RREQ) to the entire network. After each intermediate node receives the RREQ of the source node, it automatically establishes the reverse route to the source node and forwards the RREQ. When the destination node receives the RREQ, it sends a routing request response (RREP) along the path to the source node to establish path. The source node chooses two paths with the smallest hops to the destination node, one as the main path and one as the secondary path. We add a relationship field to the routing table to represent the master-slave relationship between two paths. We first set R = 1 to represent the main path, then set the R = 2 to represent the secondary path, and finally we set the R = 0 to represent path failure. When the main path fails, the alternative path is used to transmit data, and the relationship of the original primary path is set to 0. When both paths fail, the two paths are deleted and the route request command is sent again. The flow chart of the routing request process is shown in Fig. 3. By adding an alternative path and restarting routing requests when both paths fail, SEAR can reduce the impact of RREQ storms on network performance.

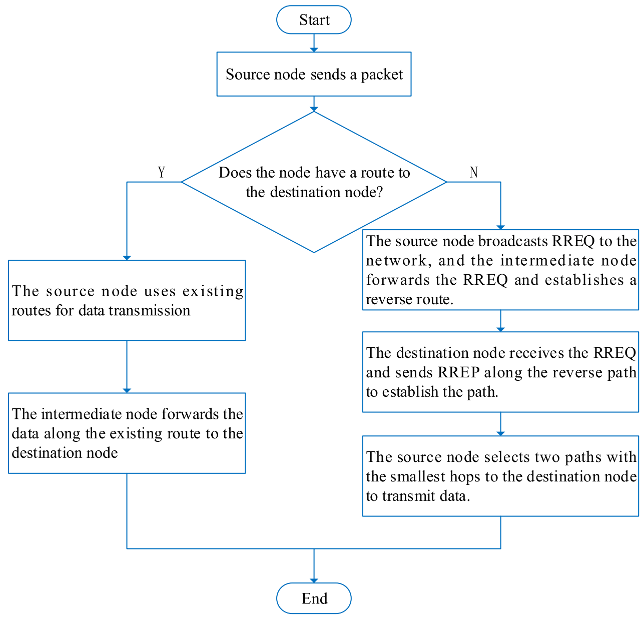


FIGURE 3. Flow chart of routing request.

B. ROUTING REQUEST FORWARDING MECHANISM

Because each intermediate node always delays forwarding RREQ for a period of time to avoid the storm of routing request. SEAR considers the residual energy of the node and the current load of a candidate of the next hop destination in delay time. When the intermediate node receives RREQ information, SEAR calculates the forwarding delay time according to formula (9):

$$T = Randomtime \times t_1 \times t_2 \tag{9}$$

The value of t_1 represents the weighting coefficient for residual energy. When the residual energy of the node is more than 25%, $t_1 = 2$, and when the residual energy of the node is between 15% and 25%, $t_1 = 6$. When the energy is less than 15%, $t_1 = 12$. The value of t_2 is a weight factor for the load. A number is added to the head node of the load-to-column to represent the number of messages to be delivered in the current queue. When the number of information packets to be transmitted exceeds 25, the value of t_2 is 2. When it exceeds 25, the value of t_2 will increase

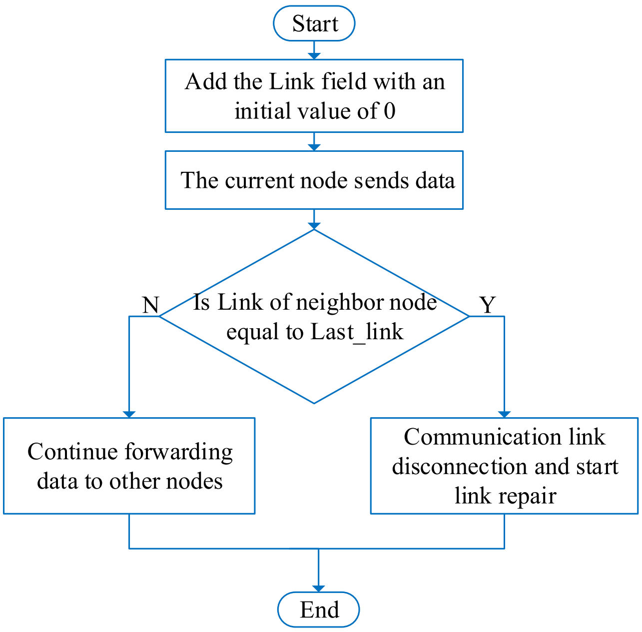


FIGURE 4. Flow chart of link failure judgement.

by 0.1 for each additional load. Randomtime is a random number between 0 and 1. When the remaining energy of the node is lower, the value of a is larger, and as the load packet increases, the value of b also increases. Thus, the value of T is significantly increased after using this formula. Finally, the time required for the RREQ message to be delivered to the destination node increases correspondingly.

C. LINK FAILURE JUDGEMENT

Because of the variability of human body posture, the link state in wireless body area networks often changes. Therefore, we need to assess the link failure situation in time to take route maintenance measures in advance. First, we add a link field to the routing table and initialize it to zero. When a node sends data to a neighbor node and the neighbor node receives the data, the neighbor node increases the link field value by one in its own routing table. However, when a node sends data to the neighbor node, the neighbor node compares the link field value in the routing table with the Last_link field value. If two values are found to be unequal, we assume that the two nodes are in communication. If the two values are the same, we think that the link has been disconnected and the route repair process has started. SEAR uses this strategy to judge the connectivity of communication links to implement the route repair process in advance and improve the overall performance of the network. The flow chart of the link failure judgement is shown in Fig. 4.

V. SIMULATION AND RESULT ANALYSIS

We consider putting human body in two kinds of simulation models: one is fixed model, the other is mobile model. The simulation environment is based on Ubuntu 16.04 LTS and NS2 2.35 software [34]. NS2 (Network Simulator, version 2) is an object-oriented network simulator, which is essentially

TABLE 2. Parameter settings.

Parameters	Values
Area	(3m, 3m)
Number of nodes	17
Initial energy	2 J
Radio range	70 cm
Network interface type	WirelessPhy
ifqType	DropTail
antType	OmniAntenna
Energy model	EnergyModel
txPower	0.066J
rxPower	0.0395J
idlePower	0.0035J
Packet size	70 bits
MAC	IEEE 802.15.4
Time	100 s

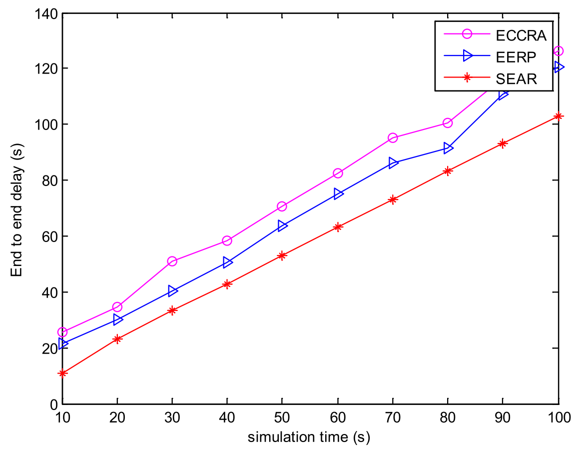


FIGURE 5. End-to-end delay of different routing algorithms.

a discrete event simulator developed by UC Berkeley. It has become a type of network simulation software widely used in academic circles.

A. SCENE AND PARAMETER SETTINGS

In this study, under these two different simulation models, we compare SEAR with EERP and ECCRA to test the performance of SEAR. The different and specific parameters are shown in Table 2.

B. SIMULATION RESULTS PERFORMANCE COMPARISON

1) FIXED TOPOLOGY MODEL

In this experiment, we first compare the end-to-end delay, network residual energy and network throughput of SEAR, ECCRA and EERP in a fixed topology. The simulation result of end-to-end delay is shown in Fig. 5.

We observed that the end-to-end delay curve of SEAR was significantly lower than that of ECCRA and EERP with the increase of simulation time. This is because when the primary path fails, SEAR can use an alternative path to transmit data to reduce the delay of data transmission, and then it avoids local congestion and reduces the queue delay of each

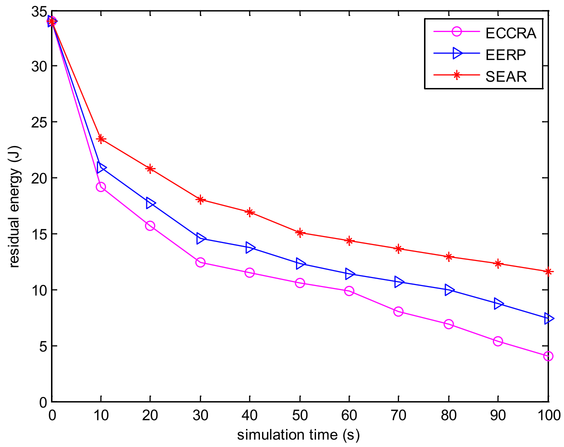


FIGURE 6. Residual energy of different routing algorithms.

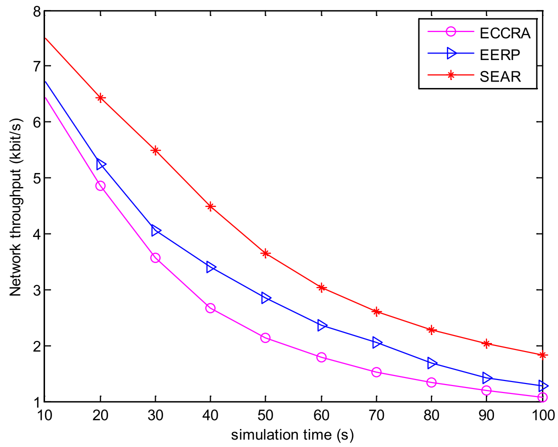


FIGURE 7. Network throughput of different routing algorithms.

packet in the node cache queue. Moreover, because of the link failure judgement process, SEAR performs link repair ahead of time, which reduces the waiting time of data transmission. In conclusion, compared with the other two routing algorithms, SEAR effectively reduces end-to-end delay during data transmission.

Due to the limitation of sensor volume, the battery capacity of biomedical sensor is limited, so how to reduce energy consumption has become one of the hot topics of many scholars. The comparison of residual energy between different routing algorithms is shown in Fig. 6. As can be seen from the figure, when the simulation time is 0-10 seconds, the source node broadcasts a RREQ in the network to establish two shortest paths, so the energy consumption is faster. As the network tends to be stable, the energy consumption in the network tends to be flat. Compared with other two routing algorithms, SEAR has more network residual energy. Because when the main path fails, SEAR uses the alternate path for data transmission, thereby reducing the energy consumption of restarting routing requests. ECCRA and EERP take the residual energy of nodes into account in their respective algorithms, but when the main path fails, they do not use alternative paths to continue data transmission. For WBAN, SEAR has more redundant residual energy than ECCRA and EERP. Therefore, SEAR can easily control and reduce energy consumption in the network. Because the total energy of sensor nodes in wireless body area network is limited, SEAR is more suitable than the other two routing algorithms.

Fig. 7 shows the network throughput of different routing methods in a fixed topology model. It is clear from the graph that SEAR has the best network throughput performance compared with ECCRA and EERP. The reason behind SEAR's high performance is that it improves the routing request forwarding mechanism to avoid premature death caused by overload of intermediate nodes. Furthermore, SEAR adds an alternative path to avoid the failure of the main path, thereby increasing the data forwarding capability of the intermediate node. However, EERP has better network throughput performance than ECCRA because it makes full use of the nodes leaving the network. These nodes only provide data forwarding services. Therefore, many data packets are forwarded in the network. From Fig. 7, we can also find that the throughput of the network decreases gradually because of the energy exhaustion of the nodes and the data congestion of the network as the simulation time increases.

By comparing the end-to-end delay of packet transmission, network residual energy, and network throughput of different routing algorithms in the fixed topology model, we conclude that SEAR performs well in terms of residual energy of the network, network throughput, and end-to-end delay in the fixed topology model compared to ECCRA and EERP.

2) MOBILE TOPOLOGY MODEL

Because the human posture in wireless body area networks is changing constantly, it is necessary to compare the performance of these performance parameters under various conditions of human motion, such as end-to-end delay, energy consumption and network throughput. Therefore, we first test the performance of each parameter under different routing algorithms. Secondly, we compare the test parameters in the mobile topology model with those in the fixed topology model. Finally, we compare the performance differences between different routing algorithms and draw effective conclusions.

Fig. 8 shows end-to-end delay comparison of the different routing algorithms using a mobile topology model. It is obvious from the graph that SEAR has the best performance compared with other routing schemes. With the increase of simulation time, the end-to-end delay of SEAR, ECCRA and EERP increases, but the end-to-end delay of SEAR is significantly lower than EERP and ECCRA. We compare the end-to-end delay in the mobile topology model with that in the fixed topology model. The end-to-end delay of the three routing algorithms increases correspondingly because of the change of human body posture and the communication failure of the links in the network, which results in the increase of data transmission delay. However, we observed that SEAR still has lower latency performance, and the gap between them is larger than that between the other two routing algorithms under the fixed model. The reason behind the

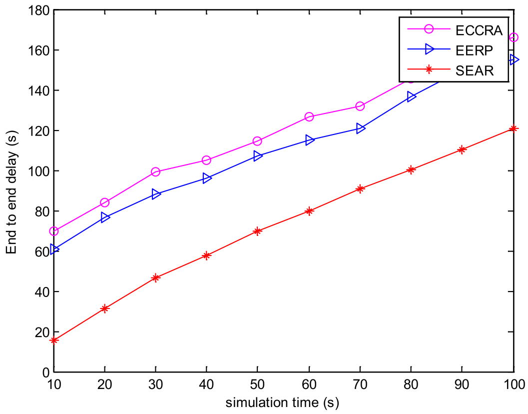


FIGURE 8. End-to-end delay of different routing algorithms.

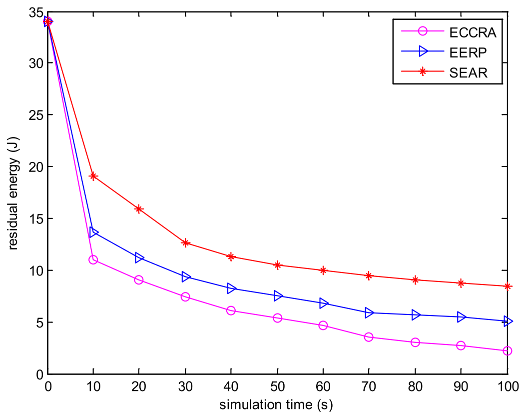


FIGURE 9. Residual energy of different routing algorithms.

poor performance of ECCRA and EERP is that they do not consider the high and mobile path changes of the biomedical sensor nodes. When the human body continues to move, the biomedical sensor on the body surface may be disconnected from the entire communication network, or the sensor on a certain path may be fail, causing the interruption of the communication link. In this case, the route discovery process has to be re-initiated. However, SEAR considers the link changes in the mobile model and reduces their impact through link failure judgment. Therefore, we conclude that SEAR effectively reduces end-to-end delay of data transmission in the network, whether in the fixed or mobile topology models.

Fig. 9 compares the residual energy of the different routing algorithms in the mobile topology model. It is apparent that the energy consumption of SEAR for WBANs decreases slowly compared with ECCRA and EERP. It can be seen from the graph that the residual energy in the network decreases rapidly in the simulation time of 0–10 seconds. This is because of the variability of human posture and the frequent changes of node location, the links in the network are prone to failure and have to initiate routing repair and rebuild paths. Later, as the human body slowly becomes stationary, the energy consumption in the network is relatively flat.

We compare the residual energy parameters of the three routing algorithms in the fixed and mobile topology models, and conclude that there is lower residual energy in the mobile

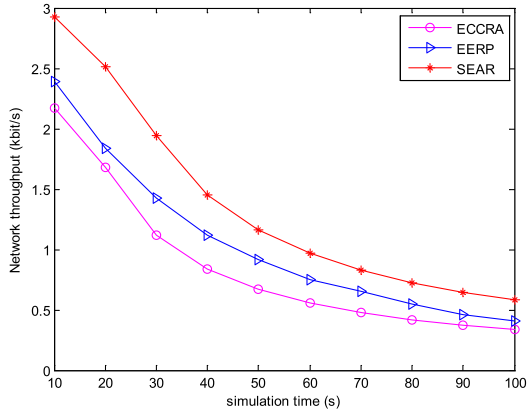


FIGURE 10. Network throughput of different routing algorithms.

topology model. At the same time, we also observe that SEAR still has the largest residual energy whether using the fixed topology model or the mobile topology model. ECCRA and EERP routing algorithms have the same reason for their poor performance. When links are interrupted or nodes are lost in the network, they do not have a backup path to transmit data, so they have to relaunch the routing discovery process to increase network overhead. However, SEAR adds alternative path and link fault detection mechanisms to address the increase in energy consumption caused by human state changes. Compared with ECCRA and EER, SEAR has more residual energy. Therefore, SEAR has better energy performance than ECCRA and EERP, while effectively reducing energy consumption in the network and improving the stability of the whole network. Because the total energy of sensor nodes is limited in wireless body area network, it is obvious that SEAR is more advantageous than ECCRA and EERP in wireless body area network whether using the fixed topology model or the mobile topology model.

The throughput comparison of different routing methods in the mobile topology model is shown in Fig. 10. From the graph, we can clearly conclude that SEAR has higher performance than other routing schemes. And we also compare the performance of network throughput of three different routing algorithms under fixed topology model. We find that SEAR has better performance in both mobile and static models. SEAR has the highest throughput and the performance of EERP is better than ECCRA. However, with the increase of simulation time, network throughput shows a downward trend. More importantly, in the mobile model, network throughput of the three routing algorithms decreases more. The reason behind the poor performance of ECCRA and EERP routing algorithms is that they do not consider the mobile link changes of biomedical sensor nodes on the body surface. EERP shows higher throughput than ECCRA because it can adequately protect the nodes that are about to quit the network. They do not collect human physiological parameters, but only provide data forwarding services. Therefore, we conclude that SEAR has better network throughput performance than ECCRA and EERP under the mobile model and static model. This is because SEAR improves the routing request forwarding mechanism to avoid the premature death of intermediate nodes due to excessive load and increases the data transmission capability.

VI. CONCLUSIONS

In this paper, we proposed SEAR to deal with the harsh environmental conditions of wireless body area networks. In the routing request process, the source node chooses two paths with the smallest hops, one as the main path and one as the alternative path. Therefore, when the link is disconnected or the human body posture changes, the source node sends data directly through the alternative path without requiring the source node to re-initiate the routing request process, thus reducing the data transmission delay and network overhead. In addition, SEAR considers the residual energy of the node and the current load of the next hop destination in the forwarding delay time. By balancing the load and the residual energy of the node, the intermediate node can be selected more reasonably to forward data. At the same time, SEAR fixes links faster by adding link fields to routing tables to determine whether links are disconnected or nodes are invalid. The simulation results show that SEAR can not only reduce end-to-end delay and energy consumption, but also improve network throughput. Therefore, SEAR can improve routing performance, network balance and stability. Our further work will focus on two aspects of the problem. One is to improve the routing algorithm to test the performance more accurately and apply it to practical application. The other is to consider the effect of temperature of biomedical sensors on human skin.

REFERENCES

[1] E. Jovanov, A. Milenkovic, C. Otto, and P. C. de Groen, "A wireless body area network of intelligent motion sensors for computer assisted physical rehabilitation," *J. NeuroEng. Rehabil.*, vol. 2, no. 1, p. 6, Mar. 2005. doi: 10.1186/1743-0003-2-6.

[2] C. H. W. Oey and S. Moh, "A survey on temperature-aware routing protocols in wireless body sensor networks," *Sensors*, vol. 13, no. 8, pp. 9860–9877, Jul. 2013. doi: 10.3390/s130809860.

[3] S. Movassaghi, M. Abolhasan, and J. Lipman, "A review of routing protocols in wireless body area networks," *J. Netw.*, vol. 8, no. 3, pp. 559–575, Apr. 2013.

[4] H. Alemdar and C. Ersoy, "Wireless sensor networks for healthcare: A survey," *Comput. Netw.*, vol. 54, no. 15, pp. 2688–2710, Oct. 2010. doi: 10.1016/j.comnet.2010.05.003.

[5] C. Chen, A. Knoll, H.-E. Wichmann, and A. Horsch, "A review of three-layer wireless body sensor network systems in healthcare for continuous monitoring," *J. Mod. Internet Things*, vol. 2, no. 3, pp. 24–34, Aug. 2013.

[6] N. Katayama, K. Takizawa, T. Aoyagi, J.-I. Takada, H.-B. Li, and R. Kohno, "Channel model on various frequency bands for wearable body area network," *IEICE Trans. Commun.*, vol. E92-B, no. 2, pp. 418–424, Feb. 2009. doi: 10.1587/transcom.E92.B.418.

[7] S. Ullah, H. Higgins, B. Braem, B. Latre, C. Blondia, I. Moerman, S. Saleem, Z. Rahman, and K. S. Kwak, "A comprehensive survey of wireless body area networks: On PHY, MAC, and network layers solutions," *J. Med. Syst.*, vol. 36, no. 3, pp. 1065–1094, Jun. 2012. doi: 10.1007/s10916-010-9571-3.

[8] M. M. Baig and H. Gholamhosseini, "Smart health monitoring systems: An overview of design and modeling," *J. Med. Syst.*, vol. 37, no. 2, p. 9898, 2013. doi: 10.1007/s10916-012-9898-z.

[9] X. Lai, Q. Liu, X. Wei, W. Wang, G. Zhou, and G. Han, "A survey of body sensor networks," *Sensors*, vol. 13, no. 5, pp. 5406–5447, Dec. 2013. doi: 10.3390/s130505406.

[10] G. Park, T. Rosing, M. D. Todd, C. R. Farrar, and W. Hodgkiss, "Energy harvesting for structural health monitoring sensor networks," *J. Infrastruct. Syst.*, vol. 14, no. 1, pp. 64–79, Mar. 2008.

[11] P. Jiang, Y. Wen, J. Wang, X. Shen, and A. Xue, "A study of routing protocols in wireless sensor networks," in *Proc. 6th World Congr. Intell. Control Automat.*, Dalian, China, Jun. 2006, pp. 266–270.

[12] A. Argyriou, A. C. Breva, and M. Aoun, "Optimizing data forwarding from body area networks in the presence of body shadowing with dual wireless technology nodes," *IEEE Trans. Mobile Comput.*, vol. 14, no. 3, pp. 632–645, Mar. 2015. doi: 10.1109/TMC.2014.2321768.

[13] M. Monowar and F. Bajaber, "On designing thermal-aware localized QoS routing protocol for in-vivo sensor nodes in wireless body area networks," *Sensors*, vol. 15, no. 6, pp. 14016–14044, Jun. 2015. doi: 10.3390/s150614016.

[14] D. K. Rout and S. Das, "Hybrid relaying in ultra-wideband body area networks," *Wireless Pers. Commun.*, vol. 86, no. 2, pp. 435–449, Jan. 2016. doi: 10.1007/s11277-015-2938-5.

[15] A. Boulis, D. Smith, D. Miniutti, L. Libman, and Y. Tselishchev, "Challenges in body area networks for healthcare: The MAC," *IEEE Commun. Mag.*, vol. 50, no. 5, pp. 100–106, May 2012.

[16] J. I. Bangash, A. H. Abdullah, M. H. Anisi, and A. W. Khan, "A survey of routing protocols in wireless body sensor networks," *Sensors*, vol. 14, no. 1, pp. 1322–1357, Dec. 2014.

[17] F. Ullah, A. H. Abdullah, O. Kaiwartya, S. Kumar, and M. M. Arshad, "Medium access control (MAC) for wireless body area network (WBAN): Superframe structure, multiple access technique, taxonomy, and challenges," *Hum.-Centric Comput. Inf. Sci.*, vol. 7, no. 1, p. 34, Dec. 2017.

[18] M. S. Akbar, H. Yu, and S. Cang, "Delay, reliability, and throughput based Qos profile: A MAC layer performance optimization mechanism for biomedical applications in wireless body area sensor networks," *J. Sensors*, vol. 2016, Nov. 2016, Art. no. 7170943.

[19] M. Quwaider and S. Biswas, "DTN routing in body sensor networks with dynamic postural partitioning," *Ad Hoc Netw.*, vol. 8, no. 8, pp. 824–841, Nov. 2010.

[20] F. T. Zuhra, K. A. Bakar, A. Ahmed, and M. A. Tunio, "Routing protocols in wireless body sensor networks: A comprehensive survey," *J. Netw. Comput. Appl.*, vol. 99, pp. 73–97, Dec. 2017.

[21] Y. Kim and S. Lee, "Energy-efficient wireless hospital sensor networking for remote patient monitoring," *Inf. Sci.*, vol. 282, no. 5, pp. 332–349, Oct. 2014.

[22] J. Xing and Y. Zhu, "A survey on body area network," in *Proc. 5th Int. Conf. Wireless Commun., Netw. Mobile Comput.*, Beijing, China, Sep. 2009, pp. 1–4.

[23] L. X. Ling, P. N. Ming, and X. B. Guo, "Energy efficient and reliable adaptive routing protocol in WBANs," *J. Electron. Inf. Technol.*, vol. 35, no. 6, pp. 1520–1524, Jun. 2013.

[24] J. Yamato, J. Ohya, and K. Ishii, "Recognizing human action in time-sequential images using hidden Markov model," in *Proc. IEEE Comput. Soc. Conf. Comput. Vis. Pattern Recognit.*, Champaign, IL, USA, Jun. 1992, pp. 379–385.

[25] B. Kim, J. Cho, S. Jeon, and B. Lee, "An AHP-based flexible relay node selection scheme for WBANs," *Wireless Pers. Commun.*, vol. 89, no. 2, pp. 501–520, Jul. 2016.

[26] P. Yi and Z. Song, "Research on energy control routing algorithm for wireless body area network," *Softw. Guide*, vol. 16, no. 12, pp. 83–86, Dec. 2017.

[27] L. Yan, W. Cheng, and X.-J. Feng, "Probability routing protocol based on delay tolerant in wireless body area network," *Comput. Sci.*, vol. 42, no. 6, pp. 274–289, Jun. 2015.

[28] H. S. Ping, Q. Liang, and Y. N. Jian, "A novel energy-constrained routing protocol for wireless body area network," *Inf. Technol.*, vol. 6, no. 11, pp. 27–30, Nov. 2009.

[29] T. Jin, W. Y. Jing, and Z. M. Man, "A timely and reliable transport protocol for body area networks," *Chin. J. Sens. Actuators*, vol. 27, no. 2, pp. 233–240, Feb. 2014.

[30] B. Braem, B. Latre, I. Moerman, C. Blondia, E. Reusens, W. Joseph, L. Martens, and P. Demeester, "The need for cooperation and relaying in short-range high path loss sensor networks," in *Proc. Int. Conf. Sensor Technol. Appl.*, Valencia, Spain, Dec. 2007, pp. 566–571.

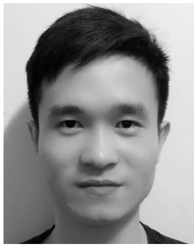
[31] S. Z. Kun, "Research on spectrum detection algorithm in wireless body area network medical application environment," Ph.D. dissertation, Dept. Elect. Inf. Elect. Eng., Shanghai Jiao Tong Univ, Shanghai, China, 2008.

[32] S. Nan, ''Research on channel model and synchronization technology of wireless body area network,'' Ph.D. dissertation, Dept. Elect. Inf. Elect. Eng., Shanghai Jiao Tong Univ, Shanghai, China, 2010.

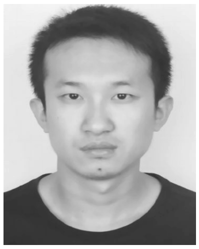
[33] D. Kim, J. Park, C. K. Toh, and Y. Choi, ''Power-aware route maintenance protocol for mobile ad hoc networks,'' in *Proc. 10th Int. Conf. Telecommun.*, Tahiti, French, Apr. 2003, pp. 501–506.

[34] T. Issariyakul and E. Hossain, ''Introduction to network simulator 2 (NS2),'' in *Introduction Network Simulator NS2*, vol. 2. Boston, MA, USA: Springer, 2012, pp. 21–40.

JIASONG MU received the B.S. degree in electric information engineering from the Harbin Institute of Technology, China, in 2005, and the M.S. degree in signal and information processing and the Ph.D. degree in electronic circuit and system from Tianjin University, China, in 2007 and 2012, respectively. He has been an Associate Professor with the College of Electronic and Communication Engineering, Tianjin Normal University, China, since 2014. His research interests include wireless sensor networks, body area networks, 5G, smart grid, and wireless communication. He was the TPC Co-Chair of the International Conference on Communications, Signal Processing, and Systems, from 2015 to 2019.



XIANG LIU was born in Anhui, China, in 1994. He received the B.S. degree from Anqing Normal University, in 2016. He is currently pursuing the master's degree with Tianjin Normal University. His research interests include wireless sensor networks and wireless body area networks.



XIANGDONG YI was born in Shandong, China, in 1993. He received the B.S. degree from the Shandong University of Architecture, in 2016. He is currently pursuing the master's degree in communications engineering with Tianjin Normal University. His research interests include wireless sensor networks, wireless body area networks, and data-centric routing protocols.