Energy Consumption Balanced Topology Variable Routing Algorithm for WWSN in Disaster Rescue Scenarios

https://doi.org/10.3991/ijoe.v15i07.10043

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Abstract—In recent years, the Wearable Wireless Sensor Network (WWSN) has become one of the most popular networks used in disaster and emergency scenarios. We propose a routing algorithm named Energy Consumption Balanced Topology Variable (ECB-TV) on the body of users in WWSN. In the ECB-TV algorithm, network topology can be variable according to the change of network state. A multi-hop topology is used in normal situation and the network will switch to single-hop topology at once when an abnormal event happens. We also design a novel multi-hop routing algorithm for multi-hop topology where we select the node with the highest energy balance factor as next hop node. Energy balance factor is innovatively designed by simultaneously taking into account both energy consumption of transmitting and receiving nodes, which can balance the energy consumption of sensor nodes well. The simulation results show that the proposed ECB-TV algorithm has better performance in terms of lifetime in normal situations and delay in abnormal situations.

Keywords—Wearable wireless sensor network, topology variable, routing algorithm, energy consumption balance

1 Introduction

With the rapid development of wearable technology, wearable wireless sensor networks (WWSN) have emerged in recent years [1-5]. Users in the network can carry one or more wearable devices (including sensor nodes), which can monitor various physiological indices of the human body and information from the surrounding environment, as well as communicate with other users [6-11]. The network is stable, efficient, and easy to deploy, and can be used as an emergency network in disaster and emergency situations to accurately predict and manage rescue operations and ensure the safety of personnel [12-14].

The structure of the WWSN network is shown in Figure 1.

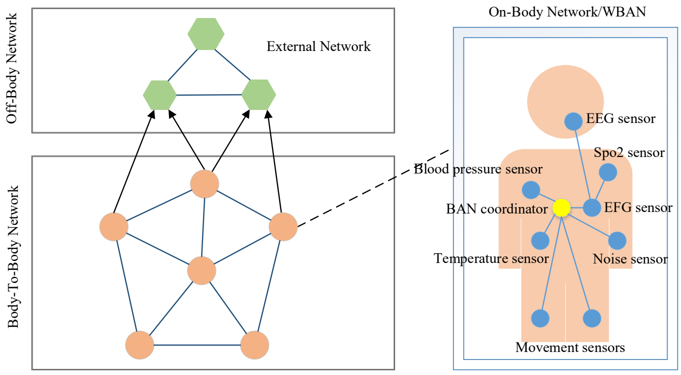

Fig. 1. The WWSN architecture

As shown in Fig. 1, the wearable wireless sensor network (WWSN) is mainly composed of On-Body Network/Wearable Body Area Network (WBAN), Body-To-Body Network, and Off-Body Network [1]. WBAN refers to the communication between the sensor nodes and the coordinator; Body-to-Body network refers to the communication among different WBANs; and Off-Body Network refers to the communication between the coordinator of each WBAN and other external networks.

In WBAN, because of the need to monitor different positions of the human body, the wearable device may be in any position of the human body. On the one hand, the path loss rate of data propagation in the Non-Line of Sight (NLOS) is very high (for example, the sending node is on the back and the receiving node is on the chest). Therefore, some nodes cannot directly communicate with the coordinator, which requires proper routing to ensure data transmission. On the other hand, the distances of sensor nodes to the coordinator is different, and the energy consumption is not balanced, potentially leading to the earlier death of individual nodes and affecting the information monitoring of the human body. In addition, unlike traditional WSNs [15-17], due to being worn on the human body, the excessively high transmission power of the wearable device may cause large radiation, thereby affecting human health. Most importantly, in emergency scenarios, once the data monitored by a sensor node is abnormal, the network needs to react quickly to transmit abnormal data with higher reliability and lower latency. In conclusion, appropriate routing is required between the sensor nodes and the coordinator, which can not only ensure information transmission and node life, but also quickly respond to abnormal conditions in disaster and emergency scenarios.

At present, previous works have studied the routing algorithm in WBAN. Peng Y. et al. proposed a routing optimization algorithm based on power control, allowing the wearable sensors to make better use of energy and reduce power when not being used.

In this way, the energy can be saved and the sensor can work for a longer period of time. However, they did not consider the reaction to emergency situations [18]. Based on batch-based clustering and routing protocols, Khalid A. et al. proposed a Balanced Power-Aware Clustering and Routing protocol (BPA-CRP), which provided an appropriate processing rule for node death. The algorithm allows the death of sensors without date loss and will not bring damage to the network, ensuring that the wireless sensor can work well in an emergency [19]. Wan Z. et al. proposed an energy-efficient multi-level adaptive clustering routing algorithm for underwater wireless sensor networks, guaranteeing that the sensor nodes can be used for rescue in extreme environments [20]. Literature [21] and [22] proposed a routing algorithm based on energy-efficient clusters in WSN. In order to save energy, this distributed algorithm increases the lifetime of the network by calculating the remaining energy, the distance from the base station, and the number of nodes. The above-mentioned works proposed solutions for energy consumption and/or emergency situations. However, the previous works do not simultaneously solve the issues of energy-saving and emergency strategy.

In this paper, we propose an Energy Consumption Balanced Topology Variable Routing algorithm (ECB-TV) in WBAN. When the network works properly, the multi-hop topology is selected, and the next hop of the sensor node is selected according to the energy balance factor to ensure that the energy consumption of the sensor nodes is balanced. Otherwise, when the network is abnormal, the network structure is changed to a single-hop topology to guarantee low latency of data transmission.

The remainder of this paper is organized as follows. In Section 2, we formulate the problems of sensor node energy consumption and topology switching. The proposed routing algorithm is proposed in Section 3. The simulation results are shown in Section 4. Finally, this paper is concluded in Section 5.

2 Description of the Problem

2.1 Notation

To simplify the description of the problem, we first introduce the following notations:

N_{ij}: packet size sent by the wearable sensor node i to the node j is N_j bit;

$E_T(N_{ij}, d_{ij})$: energy consumed by node i to send a packet of N_j bits to node j;

$E_R(N_{ij})$: energy consumed by the wearable sensor node i to receive a packet of N_j bits;

E_{total}: total energy consumption of the intermediate forwarding sensor nodes (including energy consumption for transmitting and receiving);

d_0: distance threshold between two nodes, and $d_0 = \sqrt{\frac{e_{fs}}{e_{mp}}}$;

d_{ij}: distance between sensor node i and sensor node j;

e_{fs}: power amplification factor in the energy consumption model of channel;

e_{mp}: power amplification factor in the energy consumption model of channel;

e_{tx}: energy consumption factor for wireless transmitter of the wearable sensor node;
e_{rx}: energy consumption factor for wireless receiver of the wearable sensor node;
P_e: energy balance factor;
E_{i_remain}: remaining energy of the wearable sensor node i.

2.2 Energy consumption model

In a WBAN, the energy consumed by node i to send a packet of N_{ij} bits to node j can be calculated according to Eq. (1):

$$E_T(N_{ij}, d_{ij}) = \begin{cases} N_{ij}e_{tx} + N_{ij}e_{fs}d_{ij}^2, \ d_{ij} < d_0 \\ N_{ij}e_{tx} + N_{ij}e_{fs}d_{ij}^2, \ d_{ij} \geq d_0 \end{cases} \tag{1}$$

Because the height and width of the human body are limited, the energy consumption model we adopt is proportional to d_{ij}^2.

The energy consumed by the receiving node j to receive a packet of N_{ij} bits is shown in Eq. (2), where e_{rx} is the wireless receiver energy consumption coefficient of the sensor node j.

$$E_R(N_{ij}) = N_{ij}e_{rx} \tag{2}$$

For those wearable sensor nodes selected as forwarding nodes, their energy consumption includes receiving energy consumption and transmitting energy consumption. This can be expressed in Eq. (3):

$$E_{total} = E_T(N_{ij}, d_{ij}) + E_R(N_{ij}) = N_{ij}e_{tx} + N_{ij}e_{fs}d_{ij}^2 + N_{ij}e_{rx} \tag{3}$$

2.3 Description of the problem

When the wearable sensor node does not detect an abnormality, the WBAN adopts a multi-hop tree topology for data transmission. Assuming that the maximum communication radius between the coordinator and the sensor node, and between the sensor and the sensor node are d_0, and the distance between the sensor node and the coordinator node is d_i, the communication method of the sensor node can be given in Eq. (4):

$$\text{Communication method} = \begin{cases} \text{Commicate with coordinator node}, d_i \leq d_0 \\ \text{Choose an appropriate next hop}, d_i > d_0 \end{cases} \tag{4}$$

When the wearable sensor node detects an abnormality (that is, when it is perceived that a certain information parameter exceeds the normal value range), the WBAN immediately switches the topology mode, and all nodes directly communicate with the coordinator node in the form of a single hop, improving the transmission speed of abnormality information.

We use ε_i to indicate the state of the information detected by sensor node i. 1 denotes that the sensor information is normal, while 0 signifies that the information is abnormal, as shown in Eq. (5).

$$\varepsilon_i = \begin{cases} 1, \text{the information is normal} \\ 0, \text{the information is abnormal} \end{cases} \tag{5}$$

The network status is represented by φ, which is determined by Eq. (6). When the data of all sensor nodes in the network are normal, the network is normal, φ=1. Otherwise, as long as the data of any one sensor node is abnormal, the network abnormality is determined, φ= 0.

$$\varphi = \begin{cases} 1 & \varepsilon_i = 1, \forall i \\ 0 & \varepsilon_i = 0, \forall i \end{cases} \tag{6}$$

In addition, the state of the sensor nodes can be divided into three types, as shown in Eq. (7), where *S* represents the state of the node.

- *S*=1 indicates that the node is in an active state. At this time, the remaining energy of the sensor node is greater than the set threshold value E_v, and it can either transmit its own perceived data or forward the data of other nodes as an intermediate node;
- *S*= 0 specifies that the node is in the reserved state. At this time, the remaining energy of the sensor node is less than or equal to the set energy threshold. Therefore, it only sends the data perceived by itself, and cannot forward the data of other nodes as the intermediate node;
- *S*= -1 indicates that the node is in a dead state. At this time, the remaining energy of the sensor node is 0. The sensor node has died and will no longer continue to work.

$$S = \begin{cases} 1, & E_i > E_v \\ 0, & E_i \le E_v \\ -1, & E_i = 0 \end{cases} \tag{7}$$

3 Energy Consumption Balanced Topology Variable Routing Algorithm (ECB-TV)

The ECB-TV routing algorithm proposed in this paper mainly includes two parts: topology switching and next hop selection. Topology switching refers to selecting a multi-hop tree topology in the normal state of the network, and switching to a single-hop topology when an abnormality occurs in the network. The network topology switching is shown as **Algorithm 1**.

First, the network is initialized to the normal state, that is, φ=1. Then, the information state of each sensor node is checked in succession. Once there is a sensor node information abnormality, the network state is abnormal, that is, φ=0.

Algorithm 1. Topology Switching

Input: $\varepsilon_i, \forall i$
Output: φ
Initiate $\varphi = 1$;
for *i*=0 to N
  if $\varepsilon_i = 0$;
   $\varphi = 0$;
  else goto 2;
  end if
 end for
Output φ.

Next hop selection refers to the sensor node being selected as the next hop, enabling the network energy to be balanced under a multi-hop tree structure. The detailed algorithm is shown in **Algorithm 2**.

Algorithm 2. Next hop selection

Input: E_i, d_i;
Output: next hop $Next_i$;
for *i*=0 to N
 if E_i=0 **then**
  $S_i = -1$;
 else if $0 < E_i \leq E_v$ **then**
  $S_i = 0$;
 else
  $S_i = 1$;
  $\emptyset \leftarrow n_i$;
 end if
end for
$\forall i$
if $d_i \leq d$ **then**
  $Next_i \leftarrow coordinator$;
else
  $\forall n_j \in \emptyset$,
  If $d_j \leq d_i$ $(j \neq i)$ **then**
   Taking the node $arcmaxp_e^j$ of the maximum p_e as the next hop node, i.e., $Next_i \leftarrow arcmaxp_e^j$;
  end if
end if

First, initialize the input data, including the energy consumption of the sensor nodes and their distance to the coordinator. Then, determine the state of each node, i.e., active, reserved or dead. Only the active nodes can become the candidate node of the next hop node and add the active node to the set $\emptyset$. Next, we select one of any nodes available in the network to verify whether the distance from the node to the coordinator is less than the threshold d. If yes, the sensed information data is directly transmitted to the coordinator node, that is, the next hop node is a coordinator. Here, $Next_i$ indicates the next hop node of the current node. Otherwise, if the distance from the current node to the coordinator is greater than the threshold d, then it is first necessary to find a node closer to the coordinator than the current node in the set of surrounding nodes. After this, find the node with the largest p_e as the next hop node among these nodes. Here, we define p_e as the energy balance factor, and its can be expressed in Eq. (8):

$$p_e = \alpha \frac{E_{i\_T}(N_{ij}, d_{ij})}{E_{i\_remain}} + \beta \frac{E_{j\_R}(N_{ij})}{E_{j\_remain}} \tag{8}$$

where E_{i_remain} and E_{j_remain} are the remaining energy of the wearable sensor node i and j, respectively; $E_{i\_T}(N_{ij}, d_{ij})$ is the energy consumed to transmit the packet of N_{ij} bits; $E_{j\_R}(N_{ij})$ is the energy consumed by the sensor node j to receive the packet of N_{ij} bits; and α and β are weight coefficients. In traditional energy consumption balanced routing algorithms, the node with the maximum energy is selected as the next hop. However, this method does not consider the impact of the current packet to transmit on both the energy consumption of transmitting and receiving nodes. Therefore, we design the energy balance factor to balance the energy consumption of all nodes in the network.

4 Simulation and Analysis

The WBAN studied in this paper consists of 15 sensor nodes and 1 coordinator. We study and analyze the multi-hop topology and single-hop topology models, respectively. The parameters of the energy, transmission rate, and transmitted packet size of each sensor node are shown in Table 1.

Table 1. Parameter setting

Parameter	Value
Simulated scene height (m)	1.8
Simulated scene width (m)	0.4
E_y(*J*)	0.1* Initial energy value of each sensor node
$d_0(m)$	0.4
e_{tx} (*J/bit*)	8e-8
e_{fx} (*J/bit-m^2*)	6e-8
e_{rx} (*J/bit*)	6e-11

Figure 2 shows the topology connectivity diagram of the WBAN. Node 16 is a coordinator node and is responsible for collecting information data perceived by all sensor nodes on the human body. The distance between the two wearable sensor nodes of each group is less than d_0, and can communicate directly.

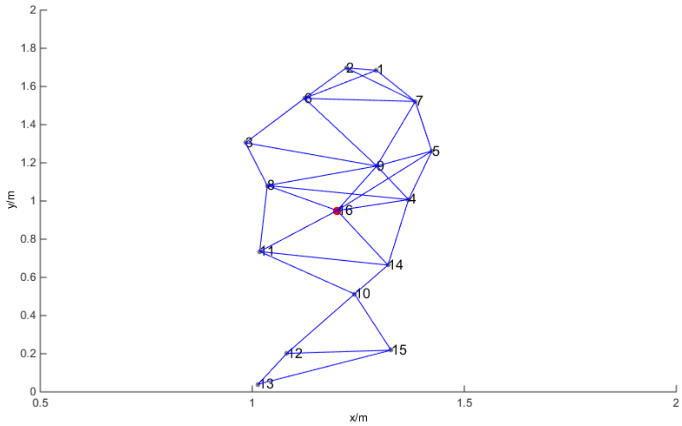

Fig. 2. Topological connectivity diagram of WBAN

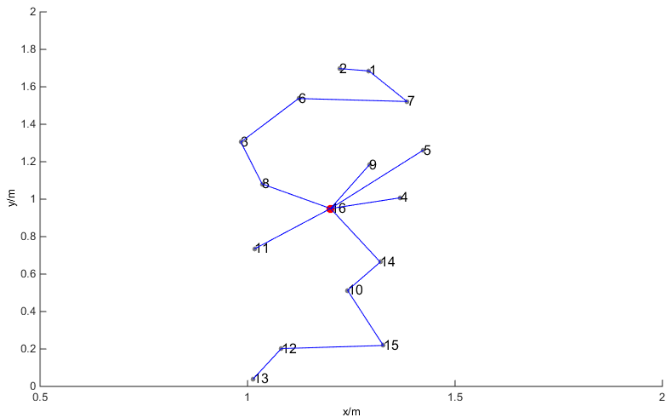

Fig. 3. Routing path diagram of WBAN in the normal state

Figure 3 shows the routing path diagram of the ECB-TV routing algorithm under normal WBAN conditions. The sensor node whose distance to the coordinator node is less than d_0 still directly communicates with the coordinator node in a single hop, whereas other nodes select the energy consumption balanced routing path to transmit data according to the remaining energy of the sensor node, the consumed energy of the data transmission, and distance. For example, sensor nodes 2 and 13 sequentially select the next hop node according to the routing algorithm, and aggregate the data of the sensor node until reaching the coordinator node.

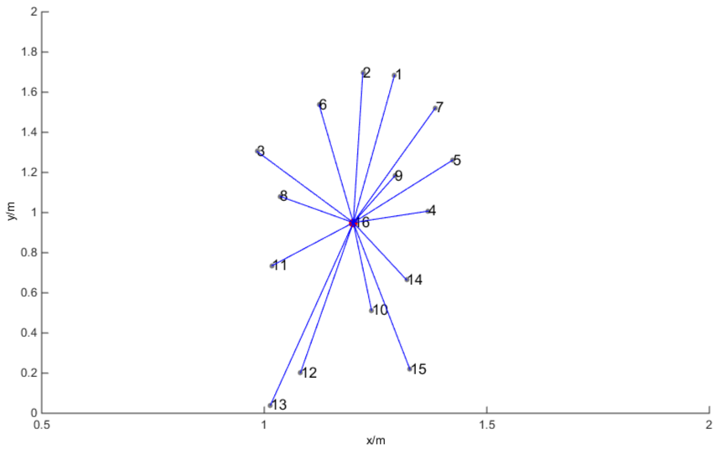

Fig. 4. The routing path diagram of WBAN in abnormal state

Figure 4 shows the routing path diagram of the ECB-TV routing algorithm when an abnormality is detected in the WBAN. When the information data collected by any wearable sensor node in the WBAN exceeds the normal range, the WBAN switches the network mode, and all sensor nodes directly communicate with the coordinator node in a single hop until the entire WBAN dies. By switching the network topology mode, abnormal information can quickly reach to the coordinator node. Therefore, it can be detected as soon as the life safety of the rescue personnel is threatened.

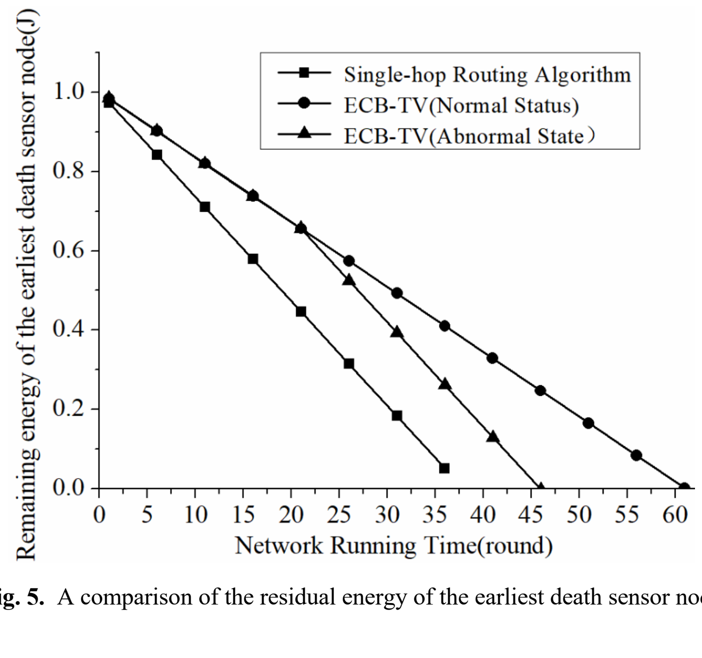

Fig. 5. A comparison of the residual energy of the earliest death sensor node

Figure 5 shows the remaining energy of the earliest death sensor nodes in the WBAN under different algorithms. When the WBAN adopts the single-hop routing algorithm, the first dead node appears at approximately the 37th round. When the ECB-TV routing algorithm is adopted, if the WBAN is in a normal state, the first dead node appears at about the 60th round. If some abnormality occurs at roughly the 21st round in the WBAN, the first dead node appears at about the 46th round. In summary, as long as the WBAN adopts multi-hop routing (including normal and abnormal scenarios), the node death time is later than that of the single-hop routing, that is, the node energy consumption is more balanced.

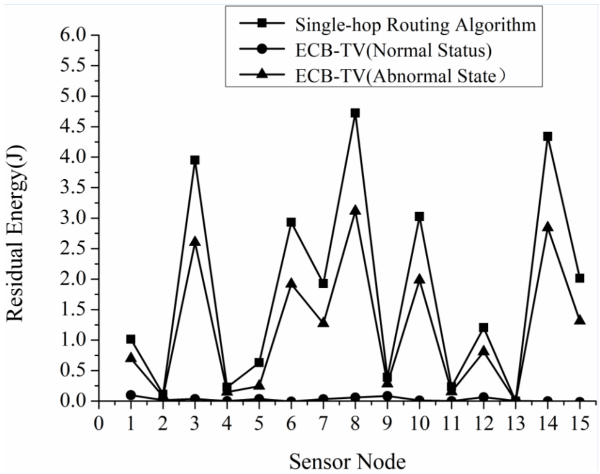

Fig. 6. A comparison of the remaining energy of sensor node

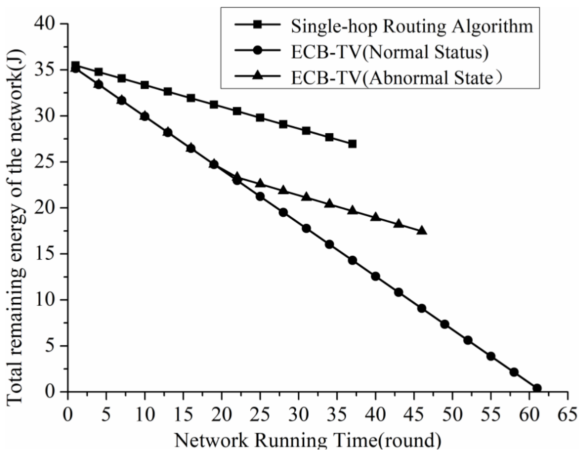

Fig. 7. A comparison of total remaining energy of all wearable sensor nodes

Figure 6 is a comparison of the remaining energy of each wearable sensor node when the first dead node appears in the WBAN. When the sensor nodes do not find abnormal data, the ECB-TV routing algorithm constantly maintains a reliable routing path with energy balance for data transmission. Therefore, when the first dead node occurs, each sensor node dies almost simultaneously, and the remaining energy of each node is almost zero. It can be seen that the WBAN switches to a single-hop route because of an abnormal situation, potentially causing unbalanced energy consumption to a certain extent. However, compared with the single-hop routing algorithm, most sensor nodes still maintain a relatively balanced energy consumption except for some sensor nodes. Hence, the life cycle of the entire WBAN can be extended to some extent.

Figure 7 is a comparison of the total remaining energy of all wearable sensor nodes in the WBAN when the first dead node occurs in the WBAN. When the single-hop routing algorithm is applied, all the wearable sensor nodes in the WBAN have the most total energy remaining and die as early as possible. This means that unbalanced energy consumption causes some nodes to die too early, but at this time, other sensor nodes still have a large amount of energy remaining. The ECB-TV routing algorithm can satisfactorily solve this problem, especially when there is no abnormality in the network. When the entire network dies, the remaining energy of all wearable sensor nodes is almost zero, which can suitably balance the energy consumption of all sensor nodes, thus extending the life cycle of the entire WBAN.

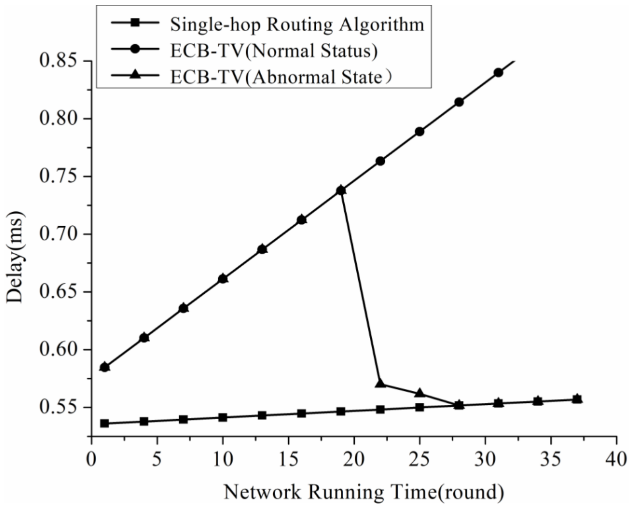

Fig. 8. A comparison of total delays of WBAN

Figure 8 is a comparison of the total delays of the WBAN under different algorithms. As shown in the figure, the WBAN using the single-hop routing algorithm has always performed well with delays. When the ECB-TV routing algorithm is adopted in a normal state, the WBAN has a large delay, which is significantly higher than the single-hop routing algorithm. In the case of a sudden abnormality at the 21st round, the WBAN switches to single-hop topology and the network delay is also rapidly reduced. This is only slightly higher than the traditional single-hop routing before at about the 28th round caused by topology switching. After the 28th round, the impact of topology switching on the delay disappears and the delay of ECB-TV in abnormal state is the same as sing-hop routing algorithm. It can be seen that the ECB-TV routing algorithm can be quickly transmitted to the coordinator node in an abnormal situation, so that the rescue personnel whose life safety is threatened can be rescued in a timely manner.

5 Conclusion

This paper proposes an ECB-TV routing algorithm, which can take multi-hop routing and single-hop routing for the normal state and abnormal states of the network, respectively, and considers the energy balance of sensor nodes in multi-hop routing. The simulation results show that multi-hop routing can effectively balance the energy consumption of sensor nodes, prolonging the network lifetime. In abnormal states, the single-hop routing can transmit the abnormal information with a shorter delay, allowing the rescue personnel to be rescued in a timely manner if his or her safety is threatened.

6 Acknowledgement

This work is supported by the National Natural Science Foundation of China (61501308), Science and technology research project of Liaoning Provincial Department of Education (LG2016/6), Postdoctoral Research Station project of Shenyang Ligong University (2016), Special Foundation of Doctoral Program of Shenyang Ligong University(2015), Key Laboratory Open Foundation of Shenyang Ligong University (2014, 2017), Liaoning Fourth Batch of Distinguished Professor Project (2014), Liaoning BaiQianWan Talents Program (2016), Liaoning Natural Science Foundation (20170540793), Distinguished Professor Project in Liaoning Province (2017), Program for Liaoning Innovative Research Team in University (2017).

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Article submitted 2018-12-22. Resubmitted 2019-02-23. Final acceptance 2019-02-27. Final version published as submitted by the authors.