Adaptive Time-Varying Routing for Energy Saving and Load Balancing in Wireless Body Area Networks

Zhiqi Lin, Xuxun Liu, *Member, IEEE,* Huan Zhou, *Member, IEEE,* Jie Wu, *Fellow, IEEE*

Abstract—Routing plays an essential role in ensuring normal and lasting operation of wireless body area networks (WBANs). However, existing routing schemes cause inefficient and unbalanced energy dissipation, which contributes to premature death of some nodes and high temperature within a small area of the body. In this article, we propose an adaptive time-varying routing (ATVR) protocol to address these issues. Unlike in conventional routing solutions, in our protocol a node may act as different roles (source node or relay node) and select different paths in disparate periods. This dynamic routing pattern helps to achieve a globally optimal routing solution. In ATVR, a node evaluation function and a path evaluation function are designed to reflect the node state and the path state respectively. Then, the path selection problem is transformed into a Hitchcock transportation problem, in which the nodes with worse node state act as source nodes (i.e., producers) and the nodes with better node state act as relay nodes (i.e., consumers). Then, this Hitchcock transportation problem is addressed by the AlphaBeta algorithm, in which the paths with less energy consumption and less path loss are selected to forward data. The experimental results show that our protocol has better performance in terms of energy consumption, network lifetime, and node temperature.

Index Terms—Wireless body area network (WBAN), routing protocol, time-varying, energy saving, load balancing.

1 Introduction

With the increase of the demand of smart and remote health care, Wireless Body Area Networks (WBANs) have been applied in a variety of scenarios, such as disease diagnosis and patient monitoring [1]. In general, a WBAN consists of a coordinator (sometimes called "sink") and several minuscule sensor nodes. Such nodes are attached to or implanted inside the human body for collecting various physiological parameters, such as pulse rate, heart rate, blood pressure, and electroencephalogram (EEG) [2], [3]. The collected data will then be sent to the coordinator and external servers for valuable medical diagnoses or early alerts [4], [5].

Routing plays a significant role in ensuring normal and lasting operation in WBANs. WBANs belong to wireless sensor networks (WSNs), but the routing of WBANs faces more severe challenges than that of WSNs [6]. On the one hand, in WBANs, energy must be used by an extremely economical way, because it is extremely difficult to replace the batteries of sensor nodes. If sensor nodes are implanted in the human body, it is too inconvenient to replace them [7]. If sensor nodes are attached to the human body, the operation of replacing batteries will seriously hamper the normal lives of patients. On the other hand, energy must be used by an extremely balanced way, or this will hurt the patient by causing high temperature spikes within parts of the body. Sensor nodes are energy sensitive, because high energy consumption easily causes high temperature spikes within the body. Therefore, traditional routing approaches of WSNs, such as [8], [9], [10], [11], cannot be used in WBANs.

1.1 Motivation

The routing in WBANs can be classified into two kinds: single-hop routing and multi-hop routing [12], [13]. Each node directly communicates with the coordinator in the single-hop pattern, while a relay scheme is used to send data from the sensor nodes to the sink in the multi-hop pattern. This single-hop routing consumes more energy and shortens the lifetime of WBANs, so multi-hop routing is more popular in WBANs. Usually, a cost function based on energy consumption is designed to select paths (e.g., [14], [15], [16], [17], [18]). Moreover, some researchers take into account the path loss to build paths (e.g., [19], [20], [21]). In addition, body temperature is considered in some protocols (e.g., [24], [25], [26]), where a temperature threshold is set to avoid burns.

However, existing routing protocols for WBANs cannot satisfy the high demand for energy saving and load balancing from a global perspective. Currently, routing selection adopts an independent and greedy pattern, in which each node selects its own best path by its self. The independent and greedy pattern cannot obtain the overall optimization of network performance, because it lacks the connection between one node's benefit and another one's loss. For example, if a

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node selects its own best path first, then another node may have to select a very inferior path from the residual available paths. On the contrary, if a node gives up its own best path and selects its own second-best path first, then another node may select its best path from the residual available paths. In other words, the independent and greedy routing can only obtain the local optimal solution, which may not the global optimal solution. Therefore, further studies are needed to achieve better network performance for WBANs.

1.2 Our Approach

In this paper, we propose an adaptive time-varying routing (ATVR) protocol to save energy consumption and balance load distribution. Using ATVR, the path selection problem is transformed into a Hitchcock transportation problem, which is addressed by the AlphaBeta algorithm. The unique features of this paper are outlined as follows:

First, our protocol adopts a flexible routing pattern in which a node may act as different roles (i.e., source node or relay node) and selects different paths across its lifespan. For example, a node may change its role from a relay node to a source node when it has much lower residual energy than most of other ones. This helps to save energy consumption and balance load distribution.

Second, our protocol adopts a collaborative routing pattern, in which the impact of each path on other nodes is fully considered for overall optimization of the network performance. For example, in order to avoid excessive data aggregation, any relay node only serves the source nodes who needs service most. This helps to obtain a globally optimal solution rather than a locally optimal solution.

1.3 Main Contributions

The main contributions of this paper are outlined as follows:

1) A node evaluation function and a path evaluation function are designed to build a significant foundation for overall performance optimization. The node evaluation function reflects the node state and is used to decide which role (source node or relay node) to utilize for each node, and the path evaluation function reflects the path state and is used to select paths for each source node.
2) A linear program problem is formulated to obtain the global optimal solution of the routing problem. Specifically, the path selection problem is transformed into a Hitchcock transportation problem, in which source nodes and relay nodes act as consumers and producers respectively. The nodes with better node evaluation functions are allocated as relay nodes, and the nodes with worse node evaluation functions are allocated as source nodes.
3) An AlphaBeta algorithm is utilized to address the Hitchcock transportation problem. Specifically, the Hitchcock transportation problem is transformed into a max-flow problem, which is solved by the primal-dual algorithm and the Fork and Fulkerson algorithm. The Fulkerson algorithm is used to solve the max-flow problem, and the primal-dual algorithm is used to confirm whether this solution is optimal.

The remainder of this paper is organized as follows. Section II summarizes the existing routing protocols for WBANs. The network model and assumptions are introduced in Section III. Section IV describes the details of the proposed routing protocol. In Section V, we analyze the experimental results for performance evaluation. Finally, a conclusion is drawn in Section VI.

2 Related Works

Routing protocols for WBANs can be classified into two kinds: single-hop patterns and multi-hop patterns. The routing protocols for WBANs can also be classified into several types based on different goals, such as energy efficiency, system reliability, and temperature control.

Most researchers focus on energy-efficient routing. Nadeem *et al.* [14] designed a new type of cost function to choose relay nodes. The sensor node with more residual energy and shorter distance to the coordinator is selected to act as the relay node. In [15], the same cost function is used to select relay nodes, and the energy consumption minimization problem is formulated as an integer linear program problem. The authors in [16] proposed an energy-balanced routing approach, in which alternative path is created to balance energy consumption of different paths. Mu *et al.* [17] introduced the concept of the gradient to obtain the path with the minimum number of hops in order to prolong the lifetime of nodes. The authors in [18] presented another load balancing routing protocol, which formulates the path cost function based on the current traffic load and the residual energy of nodes. The paths with high residual energy and low load are selected for data transmission.

Some researchers investigated another important factor: reliability. Ahmed *et al.* [19] introduced a concept of path loss into the path cost function, which is used to select the most feasible paths. In [20], the path loss is also considered to design a multi-hop routing protocol for better network reliability and higher energy efficiency. Waheed *et al.* [21] took the packet error rate into consideration for improving the reliability and efficiency of WBANs. The authors formulated analytical expressions for two-way relay cooperative communications. The authors in [22] adopted hierarchical routing to minimize energy overhead for longer lifespan, and used single-hop routing to transfer critical data directly to the coordinator for better reliability. Geetha *et al.* [23] proposed the cooperative energy-efficient and priority-based reliable routing protocol with network coding (CEPRAN), in which a cost function with path loss and residual energy is designed to select only a single relay node.

Other researchers investigated the body temperature for avoiding body burn. Selem *et al.* [24]. proposed a temperature-aware routing protocol, in which any sensor node does not act as a relay when its temperature exceeds the temperature threshold. The authors in [25] designed a temperature-aware routing protocol, in which a source node sends data packets in the route that results in the minimum temperature at the participating nodes. Galluccio *et al.* [26] proposed a thermal-aware multihop routing (TAMOR) protocol, in which source nodes can send their data packets to the coordinator in more than two hops. Source nodes choose

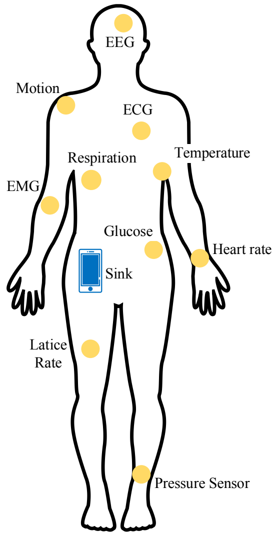

Fig. 1. The system model of a WBAN.

TABLE 1
Parameters and Explanations

Parameter	Explanation
N	Total number of nodes
ℓ	Size of the data packet
$d_{i,j}$	Distance from the i-th node to the j-th node
E_i^{int}	Initial node energy of the i-th node
E_i^{res}	Residual node energy of the i-th node
T_i^{int}	Initial node temperature of the i-th node
$E_{\text{tx-elec}}$	Per bit energy consumption by the transmitter
$E_{\text{Rx-elec}}$	Per bit energy consumption by the receiver
E_{amp}	Energy demanded for amplifier circuit
ΔT_{in}	Node temperature increase per packet delivered
ΔT_{de}	Node temperature decrease per round slept
T_0	Temperature threshold value
ω	The number of consecutive frames
ι	Path loss exponent
D_i^{node}	Node distance factor
E_i^{node}	Node energy factor
T_i^{node}	Node temperature factor
Φ_i^{node}	Node evaluation function
$E_{i,j}^{\text{route}}$	Path energy factor
$L_{i,j}^{\text{route}}$	Path loss factor
$\Phi_{i,j}^{\text{route}}$	Path evaluation function
U_k	Demand of the k-th relay node
W_{source}	The set of source nodes
W_{relay}	The set of relay nodes

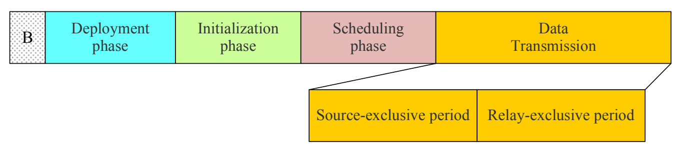

Fig. 2. The structure of a superframe.

the relay node according to the number of received packets and the node temperature.

Most routing protocols focus on static WBANs, while other routing protocols focus on mobile WBANs. The authors in [27] proposed a routing algorithm, which only relies on local data, i.e., the data close to transmitters, to calculate energy consumption. This algorithm connects transmission power control and routing design in the case of periodic body movements. Selem *et al.* [28] investigated mobile WBAN environment, and addressed the disconnectivity problem resulted from the human motion by minimizing packet transmission duplication and packet drop rate. To reduce the human postural movements on the network performance, the authors in [29] proposed a delay-tolerant routing protocol by dynamically selecting paths with low storage delay and buffering delay in disconnected networks.

Our proposed routing protocol belongs to the energy-based and temperature-aware classes, but we aim to address the existing inefficient and unbalanced energy dissipation problems. Different from existing solutions, our protocol is designed to not only achieve the overall optimization of the network performance, but also adaptively adjust routing with the status change of all nodes.

3 Preliminaries

3.1 Network Model

We assume that a WBAN is composed of one coordinator (sink) and N sensor nodes, as demonstrated in Fig. 1. The coordinator and all the sensor nodes are placed on the skin or implanted into the body of the patient. The coordinator is energy-infinite and is placed in a position that is easily accessible. Each sensor node with limited energy collects specific physiological data (e.g., body temperature, blood pressure) and forwards the collected information to the coordinator in a single-hop or two-hop pattern, which is similar to that in [30]. Each sensor node can act as different roles in different periods, i.e., vary its role from a source node to a relay node or from a relay node to a source node. Due to the need of fresh data, each node sends the collected physiological data to the coordination in every frame. For simplicity, each node has the same data generation rate. Similar to that in [31], [32], the time division multiple access (TDMA) pattern is used to send data for avoiding transmission conflicts and channel interferences. In other words, the time is divided into multiple timeslots, and each node uses different specific timeslots. The main parameters of this paper are listed in Table 1.

3.2 Energy Consumption Model

We use the first order radio model to calculate the energy expenditure of data transmission [33]. In this model, the energy for sending data and receiving data is respectively given by

$$E_{\text{Tx}}(\ell, d) = E_{\text{Tx-elec}} \times \ell + E_{\text{amp}} \times \ell \times d^2, \tag{1}$$

$$E_{\text{Rx}}(\ell) = E_{\text{Rx-elec}} \times \ell, \tag{2}$$

where $E_{\text{Tx-elec}}$ and $E_{\text{Rx-elec}}$ are the unit energy consumption of the transmitter and receiver circuitries; E_{amp} is the energy demanded for amplifier circuit; ℓ is the packet size; d is the distance between the transmitter and the receiver.

3.3 Superframes Structure

As shown in Fig. 2, the superframe used in our protocol mainly consists of four parts: deployment phase, initialization phase, scheduling phase, and data transmission phase.

In the deployment phase, each sensor node collects the physiological information and its own state (i.e., the residual energy and body temperature). Then, in the initialization phase, each node sends its state information to the coordinator. After that, in the scheduling phase, the coordinator determines the route of each sensor node based on the collected state information of all nodes. Finally, in the data transmission phase, each node sends data according to the assigned paths. This phase includes two sub-phases: source-exclusive period and relay-exclusive period. Source nodes send data to their relay nodes in the source-exclusive period, and relay nodes send data to the coordinator in the relay-exclusive period. To ensure timely transmission, we adopt our previous interval-based task ordering approach [32], in which each node uses the allocated timeslots in dispersed multiple intervals rather than a continuous time span. This guarantees short waiting time of any data packet.

4 The Proposed Routing Protocol

The proposed routing protocol aims to prolong the network lifetime and avoid injury caused by local high temperature of the body. In this protocol, a node evaluation function and a path evaluation function are designed to allocate node roles and select paths respectively. Then, the path selection problem is transformed into a Hitchcock transportation problem. In addition, an AlphaBeta algorithm is utilized to address the Hitchcock transportation problem.

4.1 Node Evaluation Function and Path Evaluation Function

The node evaluation function and the path evaluation function jointly help to build appropriate paths in order to achieve our goals.

(1) Node evaluation function

The function of the node evaluation function is to assess the node state of each node, i.e., the communication ability of each node. The node state is determined by three factors: node distance factor, node energy factor, and node temperature factor.

The node distance factor is used to measure the distance from the coordinator to any node. For any node i, its node distance factor can be denoted as

$$D_i^{\text{node}} = d_i^{\text{sink}}, \tag{3}$$

where d_i^{sink} is the Euclidean distance between node i and the coordinator. According to the same energy consumption model in [6], a longer transmission distance results in larger energy dissipation. Thus, under the same conditions, the node with short node distance factor has better node state.

The node energy factor is used to measure the residual energy of each sensor node. For any node i, its node energy factor is designed as

$$E_i^{\text{node}} = \frac{E_i^{\text{res}}}{E_i^{\text{int}}}, \tag{4}$$

where E_i^{res} is the residual energy of the node and E_i^{int} is the initial energy of the node. The initial energy is a constant and the residual energy declines during the communication process. Thus, under the same conditions, the node with larger residual energy has better node state.

The node temperature factor is used to measure the effect of the node temperature on the body. For any node i, its node temperature factor is designed as

$$T_i^{\text{node}} = T_i^{\text{CD}}, \tag{5}$$

where T_i^{CD} is the Celsius degree of node i. A source node's temperature will decrease by ΔT_{de} in each transmission round, and a relay node's temperature will increase by ΔT_{in} for forwarding each data packet [24]. To avoid injury of the body caused by high temperature, the node with lower temperature has better node state.

The node evaluation function is determined by the above three factors: node distance factor, node energy factor, and node temperature factor. According to equations (3), (4) and (5), the node evaluation function is designed as

$$\Phi_i^{\text{node}} = \begin{cases} \frac{E_i^{\text{node}}}{T_i^{\text{node}} \times D_i^{\text{node}}}, & \text{if } T_i^{\text{node}} \le T_0 \\ 0.0001, & \text{else} \end{cases} \tag{6}$$

where T_0 is the threshold of the node temperature factor.

It is known from equation (6) that the node with higher residual energy, shorter transmission distance, and lower temperature has a greater node evaluation function. Thus, the node with greater node evaluation function is preferable. Moreover, in this equation, if the node temperature factor exceeds the threshold T_0, the node evaluation function becomes extremely low, i.e., 0.0001, no matter its residual energy and transmission distance. This design is used to avoid high temperature of the node, and this will be analyzed latter.

(2) Path evaluation function

The function of the path evaluation function is to assess the path state of any path, i.e., the advantage of any path between a source node and a relay node. This function is determined by two factors: path energy factor and path loss factor.

The path energy factor is used to measure the energy consumption of data transmission in each path. According to the energy consumption model in equations (1) and (2), for any path from node i to node j, the path energy factor is designed as

$$\begin{aligned} E_{i,j}^{\text{route}} &= E_{\text{Tx}}(\ell, d) + E_{\text{Rx}}(\ell) \\ &= \ell(E_{\text{Tx-elec}} + E_{\text{Rx-elec}}) + \ell E_{\text{amp}} d_{i,j}^2, \end{aligned} \tag{7}$$

where ℓ is the size of the data packets, and $d_{i,j}$ is the distance of the path from node i to node j. Under the same conditions, the path with shorter transmission distance or less data has better path state.

The path loss factor is used to measure the reduction of the power density of the electromagnetic wave in each path. This reduction is caused by the radiation diffusion of transmitted power and the propagation characteristics of the channel. In WBANs, this reduction depends on the length of the path and the frequency of the radio wave. Based on the power density of the electromagnetic wave in [34], the path loss factor is designed as

$$L_{i,j}^{\text{route}} = L_0 + 10 \times \iota \times \log_{10}\left(\frac{d_{i,j}}{d_0}\right) + X_\sigma, \tag{8}$$

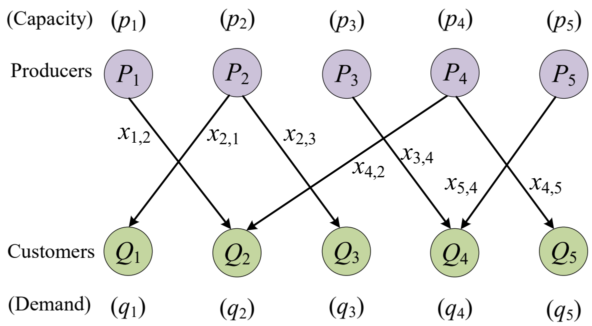

Fig. 3. An example of the transportation problem.

where ι is path loss exponent (for space its value is 2 and within the human body its value varies from 4 to 7); $d_{i,j}$ is the distance from sensor node i to sensor node j; X_σ is a Gaussian distribution value with standard error σ (always defined as $\sigma = 1$); L_0 is path loss at reference distance d_0 (always defined as $d_0 = 0.1$ m), and can be calculated by

$$L_0 = 10\log_{10}\left(\frac{4\pi d_{i,j}}{\lambda}\right)^2, \tag{9}$$

where λ is the wavelength of the radio wave. Here the smaller standard deviation means more stable path state. Thus, the path with smaller distance and smaller standard deviation has a better path state.

The path evaluation function is determined by the above two factors: the path energy factor and the path loss factor. According to equations (7) and (8), the path evaluation function is designed as

$$\Phi_{i,j}^{\text{route}} = E_{i,j}^{\text{route}} \times L_{i,j}^{\text{route}}. \tag{10}$$

It is known from equation (10) that the path with lower energy consumption and less path loss has a smaller path evaluation function. Thus, the path with a smaller path evaluation function is preferable.

4.2 Hitchcock Transportation Problem

In our solution, the routing problem is transformed into a Hitchcock transportation problem, in which some nodes act as producers and other nodes act as consumers. The producers and consumers are source nodes and relay nodes respectively. The source nodes and relay nodes are determined by the node evaluation function.

(1) Introduction of the Hitchcock transportation problem

The Hitchcock transportation problem is to find the cheapest way of transporting objects between multiple senders and multiple recipients. As shown in Fig. 3, there are three components in a Hitchcock transportation problem:

a) Producers P_1, ..., P_m with corresponding capacities p_1, ..., p_m respectively.

b) Customers Q_1, ..., Q_n with corresponding demands q_1, ..., q_n respectively.

c) Unit transportation cost $\zeta_{i,j}$ from producer P_i to customer Q_j for every $i \in \{1, ..., m\}$ and every $j \in \{1, ..., n\}$.

The Hitchcock transportation problem can be regarded as a linear program, which is given by

$$\min \sum_{i=1}^{m}\sum_{j=i}^{n} \zeta_{i,j} x_{i,j} \tag{11}$$

$$\text{s.t.} \sum_{j=1}^{n} x_{i,j} = p_i,\ \forall i \in \{1, ..., m\}, \tag{11a}$$

$$\sum_{i=1}^{m} x_{i,j} = q_j,\ \forall j \in \{1, ..., n\}, \tag{11b}$$

$$x_{i,j} \geq 0,\ \forall i \in \{1, ..., m\}, \forall j \in \{1, ..., n\}, \tag{11c}$$

where the variable $x_{i,j}$ represent the amount of traffic from P_i to Q_j, $\forall i \in \{1, ..., m\}$ and $\forall j \in \{1, ..., n\}$.

In this linear program, expression (11) aims to minimize the total costs of the Hitchcock transportation problem, equality (11a) means that the total amount of products shipped from each producer is equal to its capacity of the producer, equality (11b) means that the total amount of products received by each consumer is equal to the demand of the consumer.

The above linear program reflects the dynamic feature of our protocol. For any source node i, if the flow of its any path is less than its capacity, i.e., $0 < x_{i,j} < p_i$, this node has more than one path. This means it will select different paths in different periods.

Theorem 1. The transportation problem has a feasible solution if and only if it is balanced, i.e., if the capacities and the demands satisfy [37]

$$\sum_{i=1}^{m} p_i = \sum_{j=1}^{n} q_j. \tag{12}$$

Proof. We suppose that there is a feasible solution $X = (x_{i,j})$ for the Hitchcock transportation problem. According to the above two equations, we have

$$\sum_{i=1}^{m} p_i = \sum_{i=1}^{m}\sum_{j=1}^{n} x_{i,j} = \sum_{j=1}^{n}\sum_{i=1}^{m} x_{i,j} = \sum_{j=1}^{n} q_j \tag{13}$$

We also suppose that $\sum_{i=1}^{m} p_i = \sum_{j=1}^{n} q_j$ is satisfied. Let $\sum_{i=1}^{m} p_i = \sum_{j=1}^{n} q_j = \gamma$, and we define

$$x_{i,j} = \frac{p_i q_j}{\gamma},\ i \in \{1, ..., m\}, j \in \{1, ..., n\} \tag{14}$$

Then, due to $x_{i,j} > 0$, $i \in \{1, ..., m\}$, we have

$$\sum_{j=1}^{n} x_{i,j} = \sum_{j=1}^{n} \frac{p_i q_j}{\gamma} = \frac{p_i}{\gamma}\sum_{j=1}^{n} q_j = \frac{p_i}{\gamma} \times \gamma = p_i \tag{15}$$

Similarly, for every $j \in \{1, ..., n\}$, we have

$$\sum_{i=1}^{m} x_{i,j} = \sum_{i=1}^{m} \frac{p_i q_j}{\gamma} = \frac{q_j}{\gamma}\sum_{i=1}^{m} p_i = \frac{q_j}{\gamma} \times \gamma = q_j \tag{16}$$

□

Theorem 2. If a transportation problem has a feasible solution, it also has an optimal solution [37].

Proof. In a linear program, there are only three possibilities by the Fundamental Theorem of Linear Programming:

a) The linear program is infeasible, i.e., no feasible solution.

b) The linear program has an optimal solution.

c) The linear program is unbounded, i.e., the total costs satisfy $\sum_{i=1}^{m}\sum_{j=i}^{n}\zeta_{i,j}x_{i,j} = -\infty$.

Since there is a feasible solution, we only need to eliminate the possibility that the problem is unbounded. Due to $\zeta_{i,j} > 0$ and $x_{i,j} \geq 0$, we have

$$\sum_{i=1}^{m}\sum_{j=i}^{n}\zeta_{i,j}x_{i,j} \geq 0 \tag{17}$$

Therefore, the Hitchcock transportation problem has an optimal solution. □

(2) Determination of source nodes and relay nodes

In our proposed routing protocol, all nodes are divided into two groups: source nodes and relay nodes. This division is based on the node evaluation function of each node. The node with a larger value of node evaluation function has better node state, so it is more suitable to act as a relay node. In other words, the node with a smaller value of the node evaluation function is more suitable to act as a source node. Source nodes and relay nodes are respectively producers and consumers in the Hitchcock transportation problem. For convenience of calculations, we take two sets: a source node set W_{source} containing all source nodes and a relay node set W_{relay} containing all relay nodes.

As mentioned early, we consider path selection within several consecutive frames rather than only one frame. Let ω be the number of consecutive frames to be considered together for path selection. Thus, the capacity of each producer (source node) is ω, which means that each source node needs to send ω data packets in ω consecutive frames. There are two cases to assign capacity or demand to each node.

Case 1: The total number of nodes is even.

In this case, $\frac{N}{2}$ nodes with the $\frac{N}{2}$ smallest node evaluation function values act as source nodes and are put into the source node set W_{source}. The other $\frac{N}{2}$ nodes act as relay nodes and are put into the relay node set W_{relay}. Let source nodes and relay nodes be numbered $i = 1, 2, ..., \frac{N}{2}$ and $j = \frac{N}{2}+1, \frac{N}{2}+2, ..., N$ respectively. Note that, to ensure the total demands of relay nodes equal the total capacities of source nodes, the demand of the last relay node is obtained by subtracting the remaining relay nodes demand from the total capacity.

According to the above analysis, the capacity of any producer (source node) i is

$$p_i = \omega,\ i = 1, 2, ..., \frac{N}{2} \tag{18}$$

and the demand of any consumer (relay node) j is

$$q_j = \begin{cases} \left\lfloor \omega \cdot \frac{N}{2} \cdot \frac{\Phi_j^{\text{node}}}{\sum\limits_{k=N/2+1}^{N} \Phi_k^{\text{node}}} \right\rfloor, & \text{if } j = \frac{N}{2}+1, \frac{N}{2}+2, ..., N-1 \\ \omega \cdot \frac{N}{2} - \sum\limits_{k=N/2+1}^{N-1} q_k, & \text{if } j = N \end{cases} \tag{19}$$

Case 2: The total number of nodes is odd.

In this case, since the relay nodes consume more energy (because they are responsible for forwarding additional data), we set one more relay node to share the forwarding tasks and reduce the energy consumption of a single node. That is, $\frac{N-1}{2}$ nodes with the smallest $\frac{N-1}{2}$ node evaluation function values act as source nodes and are put into the source node set W_{source}. The other $\frac{N+1}{2}$ nodes act as relay nodes and are put into the relay node set W_{relay}. Let source nodes and relay nodes be numbered $i = 1, 2, ..., \frac{N-1}{2}$ and $j = \frac{N+1}{2}, \frac{N+3}{2}, ..., N$ respectively. As mentioned above, to ensure the total demand of relay nodes is equal to the total capacity of source nodes, the demand of the last relay node is calculated by subtracting the remaining relay nodes demand from the total capacity.

Algorithm 1 Formulation of the Hitchcock transportation problem

```
Input: E_i, T_i, d_i;
Output: The Hitchcock transportation problem;
for (i = 1 to i = N) do
    Calculate D_i^node, E_i^node, and T_i^node;
    Calculate Φ_i^node;
end for
Form W_source and W_relay;
Calculate p_i and q_j;
for (i ∈ W_source) do
    for (j ∈ W_relay) do
        Calculate E_{i,j}^route and L_{i,j}^route;
        Calculate Φ_{i,j}^route;
    end for
end for
Formulate the transportation problem;
return The Hitchcock transportation problem;
```

According to the above analysis, the capacity of any producer (source node) i is

$$p_i = \omega,\ i = 1, 2, ..., \frac{N-1}{2} \tag{20}$$

and the demand of any consumer (relay node) j is

$$q_j = \begin{cases} \left\lfloor \omega \cdot \frac{N-1}{2} \cdot \frac{\Phi_j^{\text{node}}}{\sum\limits_{k=(N+1)/2}^{N} \Phi_k^{\text{node}}} \right\rfloor, & \text{if } j = \frac{N+1}{2}, \frac{N+3}{2}, ..., N-1 \\ \omega \cdot \frac{N-1}{2} - \sum\limits_{k=(N+1)/2}^{N-1} q_k, & \text{if } j = N \end{cases} \tag{21}$$

The determination of source nodes and relay nodes reflects the dynamic feature of our protocol. For any node, its node evaluation function will change with the vary of its temperature and its residual energy. Thus, the node may change its role, i.e., from a relay node to a source node or from a source node to a relay node.

(3) Formulation of the Hitchcock transportation problem

The Hitchcock transportation problem consists of producers, consumers, capacities, demands, and costs. The formulation of the Hitchcock transportation problem is shown in Algorithm 1. The details of the formulation is described as follows.

The producers and customers are source nodes and relay nodes respectively. The source nodes and relay nodes are determined based on the node evaluation function in equation (6), which was described earlier. The determination

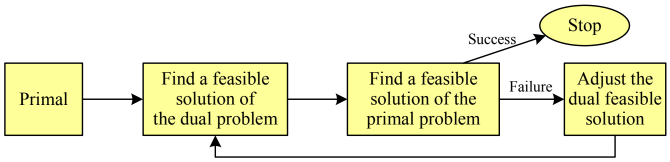

Fig. 4. The process of the primal-dual algorithm.

of source nodes and relay nodes indicates that the node with better node state acts as a relay node and has more communication tasks.

The capacities and demands are determined by the total number of nodes and the path evaluation function in (10). The details are described in equations (18)–(21). The demand assignment in equations (19) and (21) indicates that the node with the better node state has more demand. In other words, these kind of nodes take more data relaying tasks.

The costs are determined by the path evaluation function in equation (10). This function indicates that the path with a better path state has a lower cost. In other words, these kind of paths are more suited to deliver data.

After obtaining these components, based on the linear program (11), the Hitchcock transportation problem can be formulated as

$$\min \sum_{i\in W_{\text{source}}} \sum_{j\in W_{\text{relay}}} \Phi^{\text{route}}_{i,j} x_{i,j} \tag{22}$$

$$\text{s.t.} \sum_{j\in W_{\text{relay}}} x_{i,j} = p_i,\ \forall i \in W_{\text{source}}, \tag{22a}$$

$$\sum_{i\in W_{\text{source}}} x_{i,j} = q_j,\ \forall j \in W_{\text{relay}}, \tag{22b}$$

$$x_{i,j} \geq 0,\ \forall i \in W_{\text{source}}, \forall j \in W_{\text{relay}}, \tag{22c}$$

where the source node set W_{source} and the relay node set W_{relay} represent the producer set and the consumer set respectively; the path evaluation function $\Phi^{\text{route}}_{i,j}$ represents the cost of the path, i.e., the cost of delivering unit data from node i to node j; the traffic amount $x_{i,j}$ means the number of data packets that are delivered from node i to node j.

4.3 AlphaBeta Algorithm

The AlphaBeta algorithm is used to address the Hitchcock transportation problem, and it includes three parts: the primal-dual algorithm, the Ford and Fulkerson algorithm, and the combination of the two algorithms.

(1) Primal-dual algorithm

The primal-dual algorithm is used to address some basic linear problems. Each linear program can be expressed as the following standard form [35]:

$$\min \quad g_{\text{p}}(\eta) = c^{\text{T}}\eta \tag{23}$$

$$\text{s.t.} \quad A\eta = \mu, \tag{23a}$$

$$\eta \geq 0, \tag{23b}$$

where η is a decision variable vector, $g_{\text{p}}(\eta)$ is the objective function, c is the cost coefficient, A is a constraint matrix, and μ is a constraint vector. Equation (23) is the goal, which is to obtain the minimum value. Equation (23a) means that every feasible solution η of this problem must satisfy the given constraint matrix A and the given constraint vector μ.

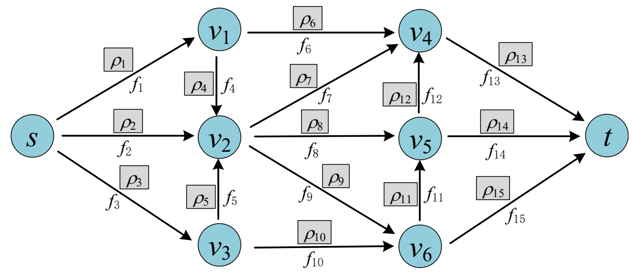

Fig. 5. An example of the max-flow problem.

This linear problem is also called a primal problem. For every primal problem, there is a dual problem, which is expressed as

$$\max \quad g_{\text{d}}(y) = y^{\text{T}}\mu \tag{24}$$

$$\text{s.t.} \quad y^{\text{T}}A \leq c^{\text{T}}, \tag{24a}$$

where y is the decision variable vector, and $g_{\text{d}}(y)$ is the objective function. In the dual problem, the goal is to obtain the maximum value. Equation (24a) means that each feasible solution y of the dual problem must satisfy the given matrix A and the given vector c.

Theorem 3. Weak duality theorem [36]—For any feasible solution η for the primal problem and any feasible solution y for the dual problem, we have

$$c^{\text{T}}\eta \geq y^{\text{T}}\mu, \tag{25}$$

which means that the value of the objective function of the primal problem is no less than that of the dual problem.

Theorem 4. Strong duality theorem [36]—If there are optimal solutions for the primal problem and the duality problem, we have

$$\min\ c^{\text{T}}\eta = \max\ y^{\text{T}}\mu, \tag{26}$$

which means that the optimal solution of the dual problem equals that of the primal problem.

Theorem 5. Complementary slackness theorem [36]— For any feasible solution η of the primal problem and any feasible solution y of the dual problem, both η and y are optimal solutions if and only if

$$(c_j - y^{\text{T}}A_j)\eta_j = y_i(A_i^{\text{T}}\eta - \mu_i) = 0 \tag{27}$$

is valid for all i and j.

The primal-dual algorithm is formed based on Theorem 3, Theorem 4, and Theorem 5. Theorem 5 indicates that once we know an optimal solution y^* of the dual problem, we can find an optimal solution η^* of the primal problem by finding a solution η satisfying equation (27). If a feasible solution η of the primal problem satisfies equation (27), y and η are optimal solutions of the dual problem and the primal problem respectively. If not, the solution y needs to be adjusted. The process of the primal-dual algorithm is shown in Fig. 4.

(2) Ford and Fulkerson algorithm

The Ford and Fulkerson algorithm is used to address the max-flow problem. Fig. 5 illustrates the max-flow problem,

Algorithm 2 Ford and Fulkerson Algorithm

Input: A network $G = (V, E_{\text{edge}}, s, t, \rho_\tau)$;
Output: A maximum flow f_τ in G;
Set $f_\tau = 0, S =$ FALSE
while $S =$ FALSE **do**
  Delete all existing points in array Υ (if any);
  $\Upsilon = \{s\}$;
  while $\Upsilon \neq \varnothing$ **do**
    Select any point from array Υ;
    Scan all edge connected to the selected point;
    if Any edge is unsaturated **then**
      Add the other endpoint into array Υ;
    else
      Scan the next point;
    end if
    if t is in the array Υ **then**
      Increase the flow f_τ in this path;
    else
      Set $S =$ TRUE and break;
    end if
  end while
end while
return the maximum flow f_τ;

Algorithm 3 AlphaBeta Algorithm

Input: $\Phi^{\text{route}}_{i,j}, p_i, q_j$;
Output: $x_{i,j}$;
Formulate the dual problem of the transportation problem;
Add a virtual beginning point and a virtual ending point;
Allocate volume for each edge;
Perform the Ford and Fulkerson Algorithm;
Check whether the solution is optimal;
if The solution does not satisfy Theorem 5 **then**
  Use the primal-dual algorithm to improve the solution;
else
  Determine the optimal solution;
end if
return $x_{i,j}$;

which is regarded as a digraph $G = (V, E, s, t)$ without loop. In this digraph, $V = \{v_1, ..., v_m\}$ denotes all points, $E_{\text{edge}} = \{e_1, ..., e_n\}$ denotes all edges, $s \in V$ is the beginning point, and $t \in V$ is the ending point. Every edge $e_\tau \in E_{\text{edge}}$ has its volume ρ_τ and its own flow f_τ. For each point $v_i \in V$, we define an entering edge set E_i^{enter} and a leaving edge set E_i^{leave}. The entering edge set includes all edges through which the flow enters the point, and the leaving edge set includes all edges through which the flow leaves the point.

The goal of the max-flow problem is to maximize the total flow h, and this problem can be expressed as

$$\max \quad h \tag{28}$$

$$\text{s.t.} \quad \sum_{\tau \in E_i^{\text{enter}}} f_\tau = \sum_{\tau \in E_i^{\text{leave}}} f_\tau, \ v_i \neq s, v_i \neq t, \tag{28a}$$

$$\sum_{\tau \in E_s^{\text{leave}}} f_\tau = \sum_{\tau \in E_t^{\text{enter}}} f_\tau = h, \tag{28b}$$

$$0 \leq f_\tau \leq \rho_\tau, \ \forall e_\tau \in E_{\text{edge}}, \tag{28c}$$

where equation (28a) ensure that the value of the flow in equals that of the flow out, equation (28b) ensures that the flow values of the leaving edge set of the starting point s and the entering edge set of the ending point t equal the total flow value h, and equation (28c) requires that the flow value in each edge is between zero and the volume value of the edge.

The Ford and Fulkerson algorithm is performed based on the idea of the repeated flow improvement (called augmentation). In each path $(s \to t)$, there are several edges e_τ, and the flow f_τ must be less than or equal to its volume ρ_τ. Thus, the maximum increment of the flow of the path $(s \to t)$ can be calculated as

$$\delta = \min \{\rho_\tau - f_\tau\}, \ \forall e_\tau \in (s \to t), \tag{29}$$

which is used to increase the flow of all possible edges in any path $(s \to t)$. For any path $(s \to t)$, if the flow of any edge e_τ satisfies

$$\rho_\tau = f_\tau, \tag{30}$$

the edge of this path is saturated, and thus the flow of the path cannot be improved anymore.

The details of the Ford and Fulkerson algorithm are shown in Algorithm 2. The main operation of this algorithm is to improve all unsaturated paths one by one. A logical variable S is defined to determine whether the flow has reached its maximum value in the digraph, and a point array Υ is defined to record the unsaturated path $(s \to t)$. Initially, the logical variable is set as $S =$ FALSE and the array Υ only contains the starting point s. A point v_i in the point array Υ is randomly selected to accept new members of the array. If an edge e_τ connected to point v_i is unsaturated (i.e., $f_\tau < \rho_\tau$), the other endpoint v_j of the edge will be added into the point array Υ. This process will be repeated until the ending point t is added into the array. Thus, an unsaturated path $(s \to t)$ is formed and its flow can be improved based on equation (29). After that, this unsaturated path becomes saturated. This process will be repeated until all paths become saturated.

(3) AlphaBeta algorithm

The AlphaBeta algorithm is to combine the primal-dual algorithm and the Ford and Fulkerson algorithm for addressing the Hitchcock transportation problem. The details of the AlphaBeta algorithm are shown in Algorithm 3.

Due to the similarity between Fig. 3 and Fig. 5, a Hitchcock transportation problem can be transformed into a max-flow problem, as shown in Fig. 6. A virtual beginning point s and a virtual ending point t are added to the digraph without loops. The volume of each edge from the beginning point s to each producer P_i is set as the corresponding capacity p_i, and the volume of the edge from each customer Q_j to the ending point t is set as the corresponding demand q_j. The volume of each edge from producer P_i to customer Q_j is set as infinity.

In this digraph, the total flow in must equal the total flow out according to the principle of flow conservation. Thus, the flow of the edges from the virtual beginning point

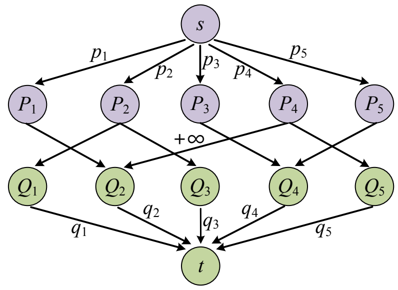

Fig. 6. The transformation of the Hitchcock transportation problem.

s to all producers (i.e., source nodes) is equal to that from all customers (i.e., relay nodes) to the virtual ending point t. For ease of calculations, the volume of any other edges is infinity. Based on this, any maximum flow in the digraph must saturate all paths from the beginning point s to P_i and from Q_j to the ending point t, otherwise there will be an unsaturated path $(s \to t)$. Thus, any maximum flow of this network is a feasible solution of the max-flow problem.

The Hitchcock transportation problem in (22) is a standard form, i.e., a primal problem. The corresponding dual problem can be obtained by linear programs (23) and (24). According to Theorem 4, the optimal solution of the dual problem equals that of the primal problem. For the sake of distinction, we set two kinds of dual variables: dual variables α_i are associated with the capacity equation (22a), and dual variables β_j are associated with the demand equation (22b). According to the transformation rule in equations (23) and (24), the objective function of the dual problem aims to maximize the value of α_i times capacity plus β_j times corresponding demand. Meanwhile, the value $\alpha_i + \beta_j$ should be less than or equal to the corresponding cost $\Phi_{i,j}^{\text{route}}$. Thus, the transportation dual problem can be expressed as

$$\max \quad \sum \alpha_i p_i + \sum \beta_j q_j, \quad \forall i \in W_{\text{source}}, \forall j \in W_{\text{relay}} \tag{31}$$

$$\text{s.t.} \quad \alpha_i + \beta_j \le \Phi_{i,j}^{\text{route}}, \quad \forall i \in W_{\text{source}}, \forall j \in W_{\text{relay}} \tag{31a}$$

Then, based on the complementary slackness theorem (Theorem 5) and equation (27), the specific complementary slackness equation is expressed as

$$(\Phi_{i,j}^{\text{route}} - \alpha_i - \beta_j)x_{i,j} = 0. \tag{32}$$

If equation (32) is satisfied for all source nodes and all relay nodes, the solution of the Hitchcock transportation problem is optimal, i.e., the minimal value of equation (22) is obtained. If equation (32) is not satisfied, the primal-dual algorithm is used to improve it. The solution is to adjust the feasible solution for the dual problem (24). To do this, we formulate the restricted primal problem [37], and obtain the optimal solution of the restricted primal problem. In equation (22), $\Phi_{i,j}^{\text{route}}$ is the path evaluation function, which is the combination of path energy factor and path loss factor. Based on this, the minimal value of equation (22) represents the paths with the least energy consumption and the least path loss.

5 Performance Evaluation

In this section, we use MATLAB as the simulation tool to evaluate the performance of our proposed routing protocol. ATVR and other protocols like CEPRAN [23] and TAMOR [26] are compared in terms of energy consumption, nodes temperature, node stability period, and network lifetime. The main simulation parameters are listed in Table 2. The total number of nodes is set as 10 or 16, and the locations of these nodes are demonstrated in Fig. 7.

TABLE 2
Simulation Parameters

Parameter	Value	Parameter	Value
N	10 or 16	ℓ	2000 bytes
E_i^{int}	1 J	T_i^{int}	37 °C
$E_{\text{tx-elec}}$	16.7 nJ/bit	$E_{\text{Rx-elec}}$	36.1 nJ/bit
E_{amp}	1.97 nJ/bit/mn	ΔT_{in}	0.01 °C
ΔT_{de}	0.02 °C	T_0	43 °C
ω	5	ι	5

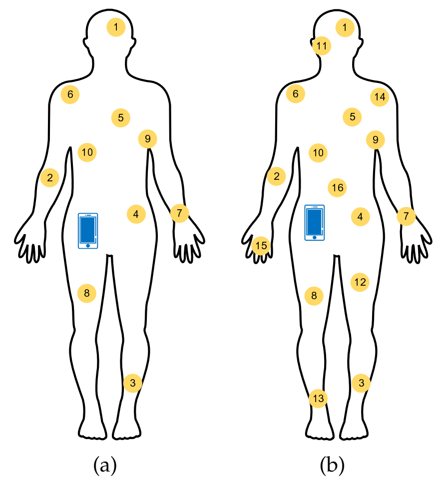

Fig. 7. Two kinds of node distribution. (a) The number of nodes is $N = 10$. (b) The number of nodes is $N = 16$.

5.1 Residual Energy of Each Node

Fig. 8 shows the residual energy of each node varying with the number of simulation rounds. In this figure, the nodes closer the coordinator have less residual energy than other nodes, because these nodes act as relay nodes and perform more data relay tasks than other ones. Moreover, the residual energy of nodes closer to the coordinator declines rapidly at the first several rounds (0–2500). For example, node 4 and node 10 belong to the relay node set and consume energy faster than other nodes in Fig. 8(a), and node 4 and node 16 belong to the relay node set and consume energy faster than other nodes in Fig. 8(b). This is because the node closer to the coordinator is more likely to be selected as a relay node and has more communication tasks. In addition, the residual energy of nodes closer to the coordinator does not decline quickly after 2500 rounds, due to ATVR's role rotation mechanism. When a relay node's residual energy decreases and its temperature increases after the first several rounds, its node evaluation function value will become small. Thus, the node will become a source node, and another node will act as a relay node although it is farther away from the coordinator.

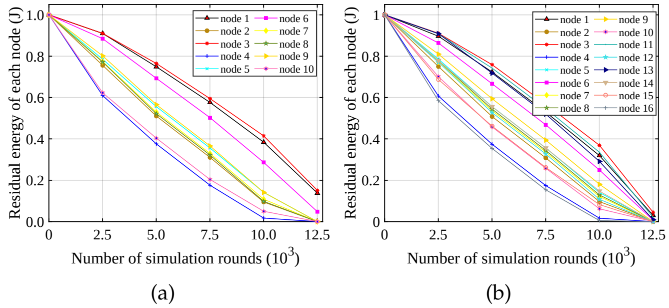

Fig. 8. The residual energy of each node. (a) The number of nodes is $N = 10$. (b) The number of nodes is $N = 16$.

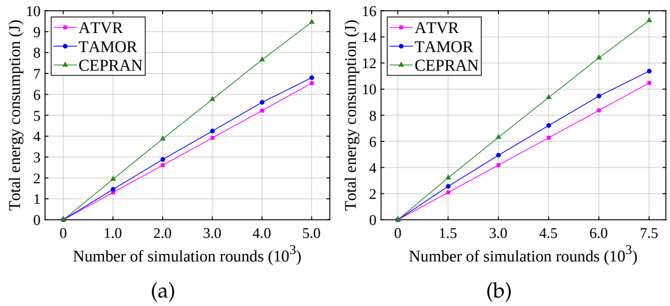

Fig. 9. The total energy consumption. (a) The number of nodes is $N = 10$. (b) The number of nodes is $N = 16$.

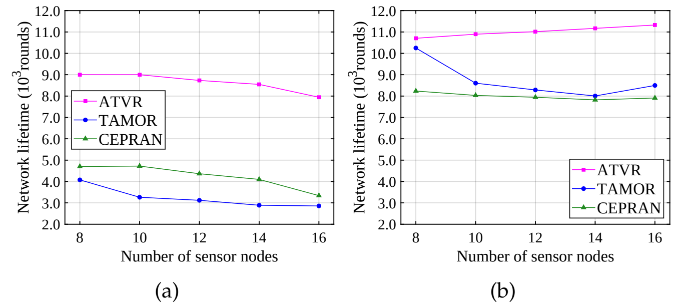

Fig. 10. The network lifetime. (a) The time interval from the start of the network operation to the death of the first node. (b) The time interval from the start of the network operation to the death of the half nodes.

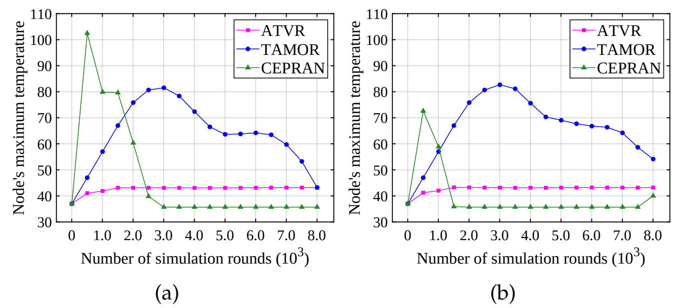

Fig. 11. The maximum node temperature after specific rounds. (a) The number of nodes is $N = 10$. (b) The number of nodes is $N = 16$.

5.2 Total Energy Consumption

Fig. 9 shows the total energy consumption with the rise of the simulation rounds. In this figure, the total energy consumption of the three protocols increases with the simulation rounds. This is because more simulations result in more energy dissipation. Furthermore, PRAN consumes much more energy than TAMOR and ATVR. Specially, the nodes in CEPRAN run out of their energy in about 5000 rounds and 7500 rounds in Fig. 9(a) and Fig. 9(b) respectively. This is because there exists only one relay node which receives data packets from all other nodes in CEPRAN. Other nodes far from the single relay node need much more energy for sending their data packets. Furthermore, ATVR has more energy consumption than TAMOR. This is mainly because of the differences between the relay patterns of the two protocols. TAMOR may adopt a three-hop or even four-hop relay pattern, while ATVR adopts a two-hop relay pattern. In TAMOR, too many hops result in too many occurences of data delivery, which will cause large energy dissipation. On the contrary, the two-hop relay pattern has much less occurences of data delivery in ATVR.

5.3 Network Lifetime

Fig. 10 shows the network lifetime of the three protocols. As seen in this figure, TAMOR has the shortest network lifetime. This is because TAMOR adopts a three-hop or even four-hop relay pattern, in which the last-hop relays need to deliver too many data packets and consume too much energy. Furthermore, CEPRAN has longer network lifetime than TAMOR in Fig. 10(a). The reason is that each relay of the two-hop relay pattern in CEPRAN needs to relay less data packets than that in TAMOR, although there is only one relay which consumes much energy in CEPRAN. However, TAMOR has longer network lifetime than CEPRAN in Fig. 10(b). This is because of the decrease of the data packets which need to be relayed. When the nodes near the coordinator die, other nodes far from the coordinator act as relays, but more nodes prefer to send their data to the coordinator directly. This balances the energy consumption of nodes in this period. In addition, ATVR has a much longer network lifetime than CEPRAN and TAMOR in both Fig. 10(a) and Fig. 10(b). This is because of the complete load balancing mechanism in ATVR. The number of data packets that relay nodes deliver is calculated according to the residual energy, node temperature, and transmission distance. This prevents sensor nodes from forwarding too many data packets in a single frame.

5.4 Maximum Node Temperature

Fig. 11 shows the maximum value of node temperature in different simulation rounds. As seen in this figure, the maximum temperature of CEPRAN varies sharply. For example, in 500 rounds, the peak values reach over 100 °C and over 70 °C in Fig. 11(a) and Fig. 11(b) respectively. This is because of the lack of the consideration of body temperature in CEPRAN, in which only a single node acts as the relay. When a node acts as the relay for too many consecutive frames, this node consumes too much energy and its temperature will rise rapidly. Moreover, the maximum temperature of TAMOR has a smoother change compared with that of CEPRAN. For example, it reaches the peak values over 80 °C in about 300 rounds in both Fig. 11(a) and Fig. 11(b). This is because of the consideration of body temperature in TAMOR, in which the relay will become an ordinary node if its temperature is high enough. In addition, the maximum temperature of ATVR does not change considerably in both Fig. 11(a) and Fig. 11(b). This is because of our temperature control mechanism, in which any node does not act as relay if its temperature is higher than the defined temperature threshold.

6 Conclusion

In this paper, we proposed an adaptive time-varying routing protocol to address the inefficient and unbalanced energy dissipation problem. The striking features of this protocol are that a node may act as different roles (source node or relay node) and select different paths in disparate periods. This dynamic routing pattern contributes to our multiple goals from an overall perspective. First, a node evaluation function and a path evaluation function are designed to reflect the node state and the path state. Then, the path selection problem is transformed into a Hitchcock transportation problem, in which the nodes with worse node state act as source nodes (i.e., producers) and the nodes with better node state act as relay nodes (i.e., consumers). Finally, this Hitchcock transportation problem is addressed by the AlphaBeta algorithm, in which the paths with less energy consumption and less path loss are selected to send data. The experimental results show the advantages of our protocol in terms of energy consumption, network lifetime, and node temperature. In the future, we will investigate the routing problem in mobile and disconnected WBANs. Our proposed method will be verified in real experiments, and will be demonstrated in practical applications as well.

Acknowledgments

The authors would like to deeply thank the associate editor and the anonymous reviewers for their helpful and constructive comments. This work was supported in part by the National Natural Science Foundation of China (NSFC) under Grants 62271209 and 62172255.

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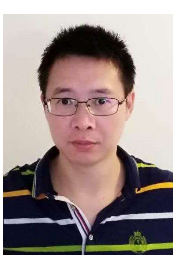

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