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# Dynamic Co-Operative Energy-Efficient Routing Algorithm Based on Geographic Information Perception in Opportunistic Mobile Networks

**Tong Wang [1,2], Jianqun Cui [2,*], Yanan Chang [2], Feng Huang [1,2] and Yi Yang [3]**

[1] School of Physical Science and Technology, Central China Normal University, No. 152 Luoyu Road, Wuhan 430079, China; wt2020010377@mails.ccnu.edu.cn (T.W.); huangfeng@ccnu.edu.cn (F.H.)
[2] School of Computer Science, Central China Normal University, No. 152 Luoyu Road, Wuhan 430079, China; ynchang@mail.ccnu.edu.cn
[3] Department of Computer Science, Northeastern Illinois University, Chicago, IL 60625, USA; y-yang8@neiu.edu
* Correspondence: jqcui@126.com

**Abstract:** Opportunistic mobile networks, as an important supplement to the traditional communication methods in unique environments, are composed of mobile communication devices. It is a network form that realizes message transmission by using the opportune encounter of these mobile communication devices. Consequently, mobile communication devices necessitate periodic contact detection in order to identify potential communication opportunities, thereby leading to a substantial reduction in the already limited battery life of such devices. Previous studies on opportunistic networks have often utilized geographic information in routing design to enhance message delivery rate. However, the significance of geographic information in energy conservation has been overlooked. Furthermore, previous research on energy-efficient routing has lacked diversification in terms of the methods employed. Therefore, this paper proposes a dynamic co-operative energy-efficient routing algorithm based on geographic information perception (DCEE-GIP) to leverage geographic information to facilitate dynamic co-operation among nodes and optimize node sleep time through probabilistic analysis. The DCEE-GIP routing and other existing algorithms were simulated using opportunistic network environment (ONE) simulation. The results demonstrate that DCEE-GIP effectively extends network service time and successfully delivers the most messages. The service time of DCEE-GIP increased by 8.05∼31.11%, and more messages were delivered by 14.82∼115.9%.

**Keywords:** opportunistic mobile networks; energy-efficient; geographic information

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## 1. Introduction

Opportunistic mobile networks (OMNs) [1] are an extension of mobile ad-hoc networks (MANETs) [2] and an instance of delay tolerant Networks (DTNs) [3,4], which have received much attention from the industry and research community [5–8]. However, MANETs must have a complete end-to-end communication link between the source node and the destination node to support message passing, while OMNs can use the storage capacity of mobile devices to complete communication tasks without the continuous connection state of nodes. Its characteristics can provide a wider range of technical support for the Internet of Things (IoT). Nodes in OMNs are usually composed of people carrying mobile communication devices, vehicles, etc., and the opportunity to transmit messages is obtained through the movement of people and vehicles. Data propagation for OMNs is inherently delay tolerant, which is widely used in emergencies, natural disasters, military operations, and remote area networks.

In OMNs, the delivery of messages relies on the assistance of relay nodes. Therefore, nodes should be constantly explored to find suitable relay nodes, and this process often consumes a lot of energy. In [9], the author measured (on a Samsung Nexus S smartphone) the average energy consumption of a phone to complete different tasks. The experimental results show that contact detection via Bluetooth or Wi-Fi radio on a smartphone consumes almost the same amount of energy as watching a video on a cell phone or calling. Very frequent exploration consumes enormous energy, while sparse exploration can make messages miss suitable forwarding opportunities. Therefore, the reasonable avoidance of invalid detection can prolong the lifetime of the battery.

In addition, due to the fact that messages are sent through mutual co-operation between nodes in DTNs, the geographic information of nodes has significant relevance for routing performance [10]. GPS modules are already installed in the mobile communication products currently on the market during production. Therefore, we can simply acquire the location information of the nodes. Previous research has predominantly focused on utilizing the geographic information of nodes to enhance the delivery rate of messages, but this has neglected its potential in aiding energy management. This study explores the utilization of geographic information, specifically node location and node movement direction, to determine the optimal sleep duration for nodes. By doing so, the network service time is effectively prolonged, hence enhancing the successful delivery of messages by nodes.

The main contributions of the DCEE-GIP routing proposed in this paper are as follows:

- DCEE-GIP designs a token adjustment mechanism to achieve dynamic co-operation between nodes. Nodes can only act as relay nodes to assist in forwarding messages when they have tokens. The token distribution through node geographic information can effectively limit message flooding and reduce the energy consumption of nodes.
- DCEE-GIP proposes two dormancy mechanisms, which are those based on node states and those based on probability prediction. The former discovers the inert and lonely nodes in the environment through the node's own state and the node's geographic information and makes them enter the dormant state. When the message enters the wait period, the latter determines the sleeping time by modeling and predicting the meeting interval between the message and the destination node.
- We have simulated and analyzed the existing and proposed algorithms with ONE simulation [11,12], and the result shows that DCEE-GIP extends the network service time and successfully delivers the most messages. When compared with the five existing algorithms, the service time of DCEE-GIP increased by 8.05∼31.11%, and more messages were delivered by 14.82∼115.9%.

The rest of this study is organized as follows. In Section 2, studies related to energy-efficient routing in the OMNs are discussed. In Section 3, some definitions and models are presented, and the design of DCEE-GIP is elucidated. In Section 4, the efficiency of DCEE-GIP is demonstrated by comparing it with existing algorithms from multiple perspectives through simulation experiments. Lastly, in Section 5, this paper is concluded, and the direction of future work is highlighted.

## 2. Related Work

OMNs search for forwarding opportunities through continuous exploration, and the exploration of mobile devices in random environments is extremely energy-intensive [13]. Therefore, more and more research tends to be energy-efficient solutions [14–17].

In previous studies on the energy control of opportunistic networks, strategies such as optimizing detection intervals, restricting the blind copying of messages, and node dormancy have proved effective in terms of achieving energy-efficient purposes. Refs. [18–20] realize energy saving through beacon control. Among them, Ref. [19] models message propagation under variable beacon rates with a continuous-time Markov model. Based on this model, an optimization problem for optimal beaconing control for epidemic routing is proposed, and the optimal threshold policy is obtained from the solution to this optimization problem, which achieves a balance between energy saving and message delivery. The above routing algorithms employ mathematical calculations to derive an optimal conjecture for the beacon strategy. However, in practical OMN environments, node movements may be unpredictable, and GPS can provide precise location information, which is more conducive to obtaining the optimal solution.

Other scholars believe that controlling the forwarding of messages can be energy efficient; Ref. [21] achieves the purpose of energy saving by constraining message forwarding. Based on the theory of the Bayesian signaling game, the authors determine the number of forwarding tokens according to the accumulation of the observed values of the destination node and the update system of the node's belief value, which realizes energy-constrained forwarding, promoting the balance of energy consumption and keeping the network running for a longer time. Ref. [22] proposes a cyber-physical system (CPS) communication layer based on adaptive energy awareness. The scheme designs three states for the node, and automatically adjusts the wake-up time of nodes according to the current energy value and relay rate of the node while keeping the node inactive during the remaining time, thereby achieving energy savings. Ref. [23] proposes EASE, which designs an asynchronous sleep mechanism and controls the sleep and wake-up time of the node according to the node's own energy status, real-time status, and other information to help the node save energy. Ref. [24] also focuses on energy conservation, but it is biased toward the layout design of practical application scenarios. The authors applied Ge-prophet, an improvement strategy based on prophet [6], to an actual earthquake disaster scene, introduced the "inventory sharing" mechanism, and proposed an energy-efficient distributed post-disaster resource management scheme, DPDRM. This solution solves the problem of the timely updating of resource lists and queries and searches among camps in a post-disaster environment.

The aforementioned studies have deliberately selected specific energy control strategies and subsequently demonstrated their efficacy in energy management. Nevertheless, insufficient attention is given to the application of node location information, and there is a lack of integration among various methodologies. Furthermore, the significance of geographic information in OMNs is often overlooked as it primarily serves message routing techniques [25–27] rather than energy conservation purposes, despite its equal importance in the energy management of nodes within OMNs.

Recent studies have incorporated geographic information into energy-efficient routing strategies, as demonstrated by the works of [28,29], which utilize GPS technology to acquire precise geographical location data for each node. The GEER algorithm, proposed by [28], dynamically determines the optimal number of nodes for data transfer based on geographic area and degree centrality. It achieves a reduction in energy consumption across the overall system through dynamic settings of a threshold related to the node density and residual energy. For future smart cities, Ref. [29] specifically proposes an energy protection mechanism based on human encounter characteristics, which can be applied to various existing OMN routing protocols. In accordance with city scenario rules, nodes can sleep dynamically to save energy. However, although the aforementioned two energy-efficient approaches utilizing geographic information employ GPS for node localization, they primarily focus on map area partitioning and are, thus, limited to specific scenarios. Furthermore, the static area division of the map and the reliance on a single energy-saving method in the algorithm hinder the effectiveness of node location information.

In contrast, the DCEE-GIP routing proposed in this paper not only designs a token mechanism based on the geographical information characteristics of nodes to promote dynamic co-operation between nodes but also uses a Markov stochastic process for modeling to predict the meeting time between nodes and describes the dormancy strategy and sleep time along with the geographical information of nodes. The experimental results demonstrate that the algorithm has superior energy-efficient properties, leading to enhanced energy utilization efficiency and extended service time without reducing the message delivery rate.

## 3. DCEE-GIP Algorithm

In this section, we propose some assumptions and design a dynamic co-operative energy-efficient routing algorithm based on geographic information perception in OMNs. First, we model the system environment and display the symbols involved in the algorithm. On this basis, a dynamic adjustment mechanism of a node communication token is defined to promote dynamic co-operation between nodes and help messages find a better relay. Additionally, we also divide nodes into "inert nodes" and "lonely nodes" states according to their geographical status and their own status and let them sleep according to the node state, which not only helps nodes save energy consumption but also ensures that they will not miss the destination node.

### *3.1. Network Model*

In OMNs, nodes are usually composed of people, vehicles, or wild animals carrying mobile communication devices and moving toward their destinations on their own tracks. We describe the opportunity contact between nodes as an opportunity encounter graph $G(V, E)$, where $V = \{v_n | 0 < n < N\}$ is the node set, representing the fact that $N$ nodes holding OMN communication modules are set in the model, and $E$ is modeled as the edge formed when nodes meet to establish connections. Additionally, we assume that the node has its own GPS (global positioning system) and agrees to use the pointing position of the North Pole of wgs84 at a certain moment. The nodes can track each other's location information, but the movement of the nodes is not affected by the location of other nodes. In the model, there are three states $S = (SA, SD, D)$ in a certain time region $(t_1, t_2)$ during the running of any node $v_n$, where $SA$ is the awake state, $SD$ is the dormant state, and $D$ is the dead state. The node state transition chart is shown in Figure 1. A state phase of $v_n$ is expressed as $P_n = (t_1, t_2, S)$. When the node is in $SA$ status, it can scan the surrounding environment and communicate with other nodes according to the routing protocol. In the $SD$ state, the node only moves along the predetermined route and does not participate in any communication behavior. Nodes are constrained by limited energy. Each node has the initial energy $E_i$. When its energy is exhausted, the node enters state $D$. The node in state $D$ will not generate new messages and will never communicate with other nodes.

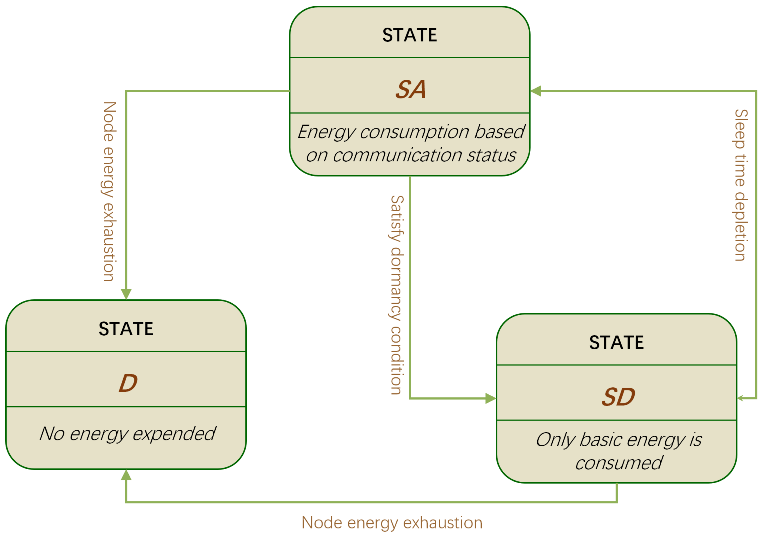


**Figure 1.** Node state chart.

Nodes consume energy via the following actions: $E_b$ is the basic energy consumption per unit of time. The node itself will consume $E_b$ over time. $E_s$ is the scanning energy consumption per unit of time. Nodes will regularly explore neighboring nodes, which consume $E_s$. $E_{sr}$ is the scanning response energy consumption per unit of time. When a neighbor node enters the communication range, the neighbor node will give scanning feedback and will consume $E_{sr}$. $E_t$ is the transmission energy consumption per unit of time. When nodes transmit or receive messages, they will consume $E_t$. Assuming that the system model starts at time $t_0$ and ends at time $t_e$, the distribution of node energy consumption is as follows:

The total basic energy consumption is shown in Equation (1). As long as the node is not dead, it will consume basic energy. Take $t_0$ as the start time of the network, $t_e$ as the end time of the network, and $t_d$ as the death time of the node; that is, the survival time of the node in the environment.

$$\sum_{t=t_0}^{t=t_e} E_b = \begin{cases} E_b \times (t_e - t_0) & \nexists t_d \\ E_b \times (t_d - t_0) & \exists t_d < t_e \end{cases} \tag{1}$$

The total scanning energy consumption is shown in Equation (2). The node consumes scanning energy only in the $SA$ state. Take $t_a$ and $t_b$ as the start and end time of each phase of the $SD$ state.

$$\sum_{t=t_0}^{t=t_e} E_s = \begin{cases} E_s \times (t_e - \sum_{P_n(t_a,t_b,SD)}(t_b - t_a)) & \nexists t_d \\ E_s \times (t_d - \sum_{P_n(t_a,t_b,SD)}(t_b - t_a)) & \exists t_d < t_e \end{cases} \tag{2}$$

The total scanning response energy consumption is shown in Equation (3). It is the total time of establishing a connection with other nodes multiplied by $E_{sr}$, where $t_{connection}$ is the duration from establishing a connection to disconnecting between nodes.

$$\sum_{t=t_0}^{t=t_e} E_{sr} = E_{sr} \times \sum_{t=t_0}^{t=t_e} t_{connection} \tag{3}$$

The total transmission energy consumption is shown in Equation (4). It is the total time of forwarding and receiving messages multiplied by $E_t$, where $t_{forward}$ is the time taken for the node to forward a message, and $t_{receive}$ is the time taken for the node to receive a message.

$$\sum_{t=t_0}^{t=t_e} E_t = E_t \times \sum_{t=t_0}^{t=t_e} (t_{forward} + t_{receive}) \tag{4}$$

From the above description, it is not difficult to see that to save energy and prolong the lifetime of nodes; we should consider how to reduce the scanning energy, scanning response energy, and the energy consumed by the message transmission because the basic energy is fixed, unless the node dies.

The mathematical symbols used in this study are listed in Table 1.

**Table 1.** Symbols description list.

| Symbols | Symbolic Meanings |
|---|---|
| $v_i$ | node $i$ |
| $S = (SA, SD, D)$ | state of node: $SA$ is the awake state, $SD$ is the dormant state, $D$ is the dead state |
| $P_n = (t_1, t_2, S)$ | a state phase of $v_n$ |
| $E_b$ | the basic energy consumption per unit time |
| $E_s$ | the scanning energy consumption per unit time |
| $E_{sr}$ | the scanning response energy consumption per unit time |
| $E_t$ | the transmission energy consumption per unit time |
| $cos(\overrightarrow{\alpha}, \overrightarrow{\beta})$ | Cosine similarity of two vectors |
| $\Gamma_a$ | the token counter of $v_a$ |

**Table 1.** *Cont.*

| Symbols | Symbolic Meanings |
|---|---|
| $Token_a^n$ | the number of tokens $v_a$ has to $v_n$ |
| $\overrightarrow{C_a}$ | the moving direction vector of $v_a$ |
| $\overrightarrow{C_{d-a}}$ | the position vector of $v_d$ relative to $v_a$ |
| $\Theta_a$ | the set of blind nodes of $v_a$ |
| $E_{free}^a$ | the current residual energy value of $v_a$ |
| $E_i^a$ | the initial energy value of $v_a$ |
| $\mu$ | the number of times that the node goes into the inert state |
| $\Phi_a$ | the set of neighbor nodes of $v_a$ |
| $D_a$ | the set of all destination nodes of messages carried by $v_a$ |
| $R_{com}$ | the communication radius of node $v_a$ |
| $V_a$ | the current velocity of $v_a$ |
| $T_{inert}$ | the sleep time of the inert node |
| $T_{lonely}$ | the sleep time of the lonely node |
| $X = \{X(t), t \in T\}$ | the event that nodes meet and establish a connection |
| $N(t)$ | the number of occurrences of $X$ in time $t$ |
| $P\{N(t) = k\}$ | the probability of occurrence of $X$ for $k$ times in time $t$ |

### *3.2. Token Adjustment Mechanism*

To control the flood propagation of messages between nodes and to reduce the energy consumption of $E_t$, we set forwarding tokens for nodes. Messages can only be forwarded to nodes with forwarding tokens. In the cache of each node, a token counter is placed, and its format is $\Gamma_a = \{< v_n, Token_a^n > | v_n \in (V \setminus v_a)\}$. $\Gamma_a$ is the token counter carried by $v_a$, which has $Token_a^n$ times of assistance forwarding opportunities for node $v_n$. The token counter is initialized when two nodes meet for the first time, and the initial number of tokens is 1 by default.

The number of tokens is not fixed. We designed a self-service adjustment mechanism for tokens based on geographic information. As shown in Figure 2, $v_a$ carries the message for which the destination is $v_d$ and meets its neighbor $v_b$. The current moving direction vector of $v_b$ is expressed as $\overrightarrow{C_b} =< \overrightarrow{x_b}, \overrightarrow{y_b} >$, the position vector of $v_d$ relative to $v_b$ is expressed as $\overrightarrow{C_{d-b}} =< x_d - x_b, y_d - y_b >$. The cosine similarity of the two vectors, Equation (5), is used to judge whether $v_b$ and $v_d$ are likely to meet. If the cosine similarity is 1, it means that the moving direction of $v_b$ is the same as $v_d$. If the cosine similarity is $-1$, it means that the moving direction of $v_b$ is opposite to $v_d$. We set the threshold $t_c$. When $cos(\overrightarrow{C_b}, \overrightarrow{C_{d-b}}) > t_c$, the neighboring node $v_b$ adds a forwarding token for $v_a$.

$$cos(\overrightarrow{C_b}, \overrightarrow{C_{d-b}}) = \frac{\overrightarrow{x_b} \times (x_d - x_b) + \overrightarrow{y_b} \times (y_d - y_b)}{\sqrt{\overrightarrow{x_b^2} + \overrightarrow{y_b^2}} \times \sqrt{(x_d - x_b)^2 + (y_d - y_b)^2}} \quad (5)$$

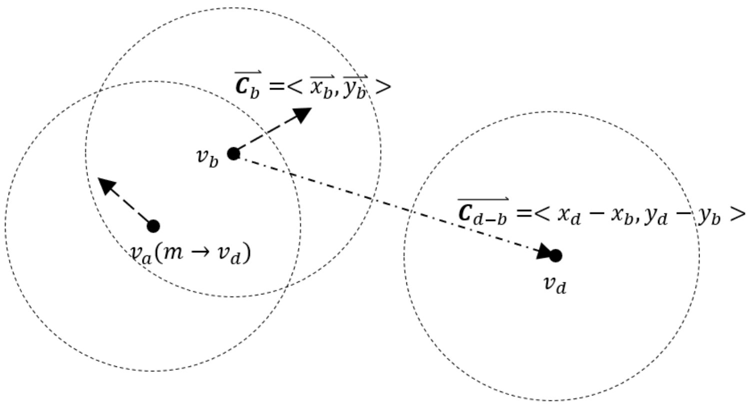


**Figure 2.** Cosine similarity of nodes.

By employing cosine similarity computation, $v_a$ identifies the surrounding nodes that exhibit a comparable movement direction to the target node and subsequently allocates a forwarding token. The implementation of token restrictions can effectively regulate the quantity of transmitted messages, thereby limiting the excessive utilization of $E_t$ energy.

### 3.3. Dormancy Mechanism

According to previous research experience, when the node is in a poor environment that is not conducive to message transmission, it can effectively save the energy consumption of $E_s$ and $E_{sr}$ by allowing the node to sleep. However, when to sleep and when to wake up are extremely important for the dormancy mechanism. In this section, two dormancy mechanisms are designed for the node based on geographic information, namely, a dormancy mechanism based on node state and a dormancy mechanism based on probability prediction.

*(1) Dormancy mechanism based on node state*

According to the token state and geographic information state of the node, three node types are identified: "blind node", "inert node" and "lonely node". The "blind node" is employed to explain the relationship between two nodes. The "inert node" shows a one-to-many node state, and the "lonely node" refers to the status of a node based on location information. Among them, both the "inert node" and "lonely node" are characterized by a state of dormancy. The definitions of the three entities are provided below.

**Definition 1 (Blind Node).** *If $v_a$'s $Token_a^b$ is 0, indicating that $v_a$ is incapable of assisting $v_b$ in message forwarding, then we classify $v_a$ as the blind node of $v_b$, and record it as $\Theta_a = \{v_b\}$. The set $\Theta_a = \{v_b, v_e, v_k \ldots\}$ denotes the blind node for multiple other nodes in a network, where $|\Theta_a|$ represents the number of nodes that $v_a$ is blind to.*

**Definition 2 (Inert Node).** *The energy of a node will gradually deplete over a period of time. The variable $E_{free}^a$ denotes the present remaining energy of $v_a$. $E_i^a$ denotes the initial energy value of $v_a$. An inert node is defined as a node $v_a$ that satisfies Equation (6). When the node is an inert node, it will transition into a phase of SD state.*

$$\frac{|\Theta_a|}{|\Gamma_a|} > 1 - e^{-(E_{free}^a / E_i^a)} \tag{6}$$

$|\Gamma_a|$ is the number of nodes recorded in the token counter. The expression $1 - e^{-(E_{free}^a / E_i^a)}$ is the emotion regulation item. When the free energy $E_{free}^a$ is sufficient, $v_a$ will transition to the inert state only when $|\Theta_a|$ is large enough. When the energy level of $v_a$ is insufficient, provided that the value of $|\Theta_a|$ is small, $v_a$ will go into the inert state in order to conserve energy and prolong its lifespan.

The sleep period of an inert node can be calculated using the formula $T_{inert} = \mu / (1 - e^{-(E_{free}^a / E_i^a)})$, where $\mu$ represents the number of times in which the node enters the inert state. The more times, the longer $T_{inert}$ will be.

When the sleep time ends, the node wakes up and re-establishes connections with its neighbor nodes, obtaining reward tokens according to the token adjustment mechanism.

Each time the node goes to sleep, the scanning energy consumption saved is $\widetilde{E_s} = \mu \times E_s / (1 - e^{-(E_{free}^a / E_i^a)})$.

**Definition 3 (Lonely Node).** *Let $\Phi_a = \{v_i \ldots\}$ represent the set of neighbor nodes of $v_a$, where $v_i$ is the node that establishes a connection with $v_a$. $D_a = \{v_d \ldots\}$ represents the set of all destination nodes of the messages carried by $v_a$. If node $v_a$ meets Equation (7), we call it a lonely node. When the node is a lonely node, it will transition into a phase of SD state.*

$$cos(\overrightarrow{C_{\Phi_a}}, \overrightarrow{C_{a-D_a}}) < 0 \tag{7}$$

When $v_a$ is a lonely node, it means that the angle between all the moving directions of the neighboring nodes of $v_a$ and the directions of the destination nodes of messages carried by $v_a$ are greater than 90°, which is not conducive to the forwarding of messages. Therefore, it should temporarily go into a sleep period, and this period should not be too long.

The sleep period of a lonely node is $T_{lonely} = \frac{2 \times R_{com}}{V_a \times E^a_{free}}$, where $R_{com}$ is the communication radius of the node, and $V_a$ is the current velocity of $v_a$.

*(2) Dormancy Mechanism Based on Probability Prediction*

In OMNs, we assume that node movement is a stochastic process with a Markov property, so the behavior of establishing connections between nodes is also stochastic. Therefore, we know that the encounter probability between nodes is the Poisson distribution, and the time interval between node encounters follows an exponential distribution. The event that nodes meet and establish a connection is a random process, expressed as $X = \{X(t), t \in T\}$; $N(t)$ represents the number of occurrences of $X$ in time $t$, and $P\{N(t) = k\}$ represents the probability of occurrence of $X$ for $k$ times in time $t$. $P\{N(t) = k\} = \frac{(\lambda t)^k}{k!} e^{-\lambda t}$ is a Poisson process [21,30,31].

In order to save transmission energy consumption $E_t$, we must prevent the flooding propagation of messages. Therefore, it is necessary to control the number of copies of messages. From [32], we know that among several classical routing algorithms, spray & wait has the highest delivery rate and the lowest energy consumption. This is because it effectively controls the flooding propagation by limiting the number of replicas in the spray phase, whereas in the wait phase, it restricts the consumption of $E_t$. We adopted the replica control strategy of spray & wait. When the number of message copies is 1, the message will enter the wait phase. In the wait phase, the node will carry the message until it meets the destination node.

In the wait phase, the proper dormancy of a node can help it save a lot of energy, but improper sleep time will cause messages to miss the destination node. Therefore, we attempted to predict the time interval between the message and the destination node and determine the sleep time. Here, we assume that $P\{X < t\}$ represents the probability of nodes meeting in time $t$. $s$ is the sleep time of the node that we want to get. We should ensure that the node can meet the destination node within the remaining ttl of the message and does not meet within time $s$. The probability of meeting the above conditions is $P\{X < t | N(s) = 0\}$.

According to Bayes' theorem,

$$\begin{aligned} P\{X < t | N(s) = 0\} &= P\{X < t, N(s) = 0\} / P\{N(s) = 0\} \\ &= P\{X < t, N(t-s) = 1\} / P\{N(s) = 0\} \end{aligned} \tag{8}$$

Due to the characteristics of random processes, the event that nodes encounter each other at any period is independent; therefore

$$\begin{aligned} \text{Equation (8)} &= P\{X < t\} \cdot P\{N(t-s) = 1\} / P\{N(s) = 0\} \\ &= P\{N(t) = 1\} \cdot P\{N(t-s) = 1\} / P\{N(s) = 0\} \\ &= \frac{\lambda t e^{-\lambda t} \cdot \lambda (t-s) e^{-\lambda (t-s)}}{e^{-\lambda s}} = \lambda^2 t (t-s) e^{-2\lambda (t-s)} \end{aligned} \tag{9}$$

Generally, we want to maximize the probability of the node encounter; so, let $P\{X < t | N(s) = 0\} = 1$. Solving the sleep time $s$ in Equation (10).

$$\lambda^2 t (t-s) e^{-2\lambda (t-s)} = 1 \tag{10}$$

Let $t - s = x$ to get

$$\begin{aligned} \lambda^2 t x e^{-2\lambda x} &= 1 \\ x e^{-2\lambda x} &= 1/\lambda^2 t \\ x &= -LambertW(-1/\lambda^2 t) \end{aligned} \tag{11}$$

where $LambertW$ is the Lambert W function [33].

$$s = t - x = t + Re[LambertW(-1/\lambda^2 t)] \tag{12}$$

Here, we set $t$ as the remaining ttl of the message closest to its destination node. $\lambda$ is the expectation of an encounter with the destination node, and the node encounter probability is taken here.

The probability calculations may have errors. We adjust the sleep time according to the geographic information of the node. According to Section 3.2, we know that cosine similarity can be used to judge the similarity of the moving direction of the node and the destination node. When $cos(\overrightarrow{C_a}, \overrightarrow{C_{d-a}}) \leq 0$, it means that the angle between the node's moving direction and the destination node's direction is greater than or equal to 90°, and it is difficult to meet in a short time. Therefore, we let $P\{X < t|N(s) = 0\} = 1$, that is, the sleep time at maximum probability, $s = t + Re[LambertW(-1/\lambda^2 t)]$. When $cos(\overrightarrow{C_a}, \overrightarrow{C_{d-a}}) > 0$, it means that the angle between the node's moving direction and the destination node's direction is less than 90°, and we let $P\{X < t|N(s) = 0\} = 1 - cos(\overrightarrow{C_a}, \overrightarrow{C_{d-a}})$ to shorten the sleep time. Then, $s = t + Re[LambertW((cos(\overrightarrow{C_a}, \overrightarrow{C_{d-a}}) - 1)/\lambda^2 t)]$. Therefore, the sleep time of the dormancy mechanism based on probability prediction is expressed as Equation (13).

$$T_{wait} = \begin{cases} s = t + Re[LambertW(-1/\lambda^2 t)], & cos(\overrightarrow{C_a}, \overrightarrow{C_{d-a}}) \leq 0, \\ s = t + Re[LambertW((cos(\overrightarrow{C_a}, \overrightarrow{C_{d-a}}) - 1)/\lambda^2 t)], & cos(\overrightarrow{C_a}, \overrightarrow{C_{d-a}}) > 0. \end{cases} \tag{13}$$

### *3.4. Pseudo Code for DCEE-GIP*

The construction process of DCEE-GIP is shown in Algorithm 1. In Algorithm 1, line 1 sets a count, $c$, for the dormancy mechanism based on probability prediction and a $flag$ for a lonely node. Lines 4–7 indicate that when the encountering node $v_j$ is the destination node, the message is directly forwarded to $v_j$. Lines 8–10 indicate if the $v_j$ meets the criteria for an inert node; then, $v_j$ is set to $SD$ state, and the sleep time is $T_{inert}$. Lines 11–13 are the copy spray phase, in which messages are copied to $SA$ state nodes with the token. Lines 14–20 are the update mode of $c$ and $flag$. Lines 23–25 indicate that if the $flag$ of the node is false, then set the node to $SD$ state, and the sleep time is $T_{lonely}$, and lines 26–28 indicate that if the number of copies of all messages carried by the node is 1, then set the node to $SD$ state, and the sleep time is $T_{wait}$. The time complexity of the DCEE-GIP algorithm is O($nm$), where $n$ is the number of neighbor nodes, and m is the number of messages carried.

**Algorithm 1** Pseudo Code for DCEE-GIP

**Input:** $List < Messages >$, list of messages of $v_i$
$List < Connections >$, list of connections that $v_i$ with
$Nrof_{m_l}$ is the number of copies of $m_l$
**Output:** $Tuple < Message, Connection >$, node connections for message forwarding
set c = 0, $flag_{lonelynode}$ = true
**for** $m_l$ of $List < Messages >$ **do**
    **for** con of $List < Connections >$, $v_j$ is the neighbor node **do**
        $v_d$ = $m_l$'s destination;
        **if** $v_d == v_j$ **then**
            $v_i$ forwards message $m_l$ to $v_j$;
        **end if**
        **if** $v_j$ meets Equation (6) **then**
            set $P_j = (t_{now}, t_{now} + T_{inert}, SD)$;
        **end if**
        **if** $Nrof_{m_l} > 1$ and $Token_j^i > 0$ and $v_j$ is $SA$ state **then**
            $Tuple < Message, Connection >$ add $< m_l, con >$;
        **end if**
        **if** $Nrof_{m_l} = 1$ **then**
            c = +1;
        **end if**
        **if** Equation (7) is workable for $v_i$ **then**
            break;
        **else** $flag_{lonelynode} = false$
        **end if**
    **end for**
**end for**
**if** $flag_{lonelynode}$ *is false* **then**
    set $P_i = (t_{now}, t_{now} + T_{lonely}, SD)$;
**end if**
**if** c = the number of messages in $List < Messages >$ **then**
    set $P_i = (t_{now}, t_{now} + T_{wait}, SD)$;
**end if**

## 4. Simulations and Results

In order to assess the routing performance of DCEE-GIP, the opportunistic network environment (ONE) [11,12] simulator was adopted to perform numerous simulation experiments. For attesting to the superiority of DCEE-GIP, we chose direct delivery (DD) [5], which is the most energy-efficient routing algorithm (in theory), epidemic [8], which is the representative of flooding algorithms without any constraints, spray & wait [7], which is the classic routing algorithm with the best comprehensive performance, and EASE [23], which is an energy-efficient algorithm based on the sleep mechanism published in 2021 and GEER [28], another geographic and energy-aware epidemic strategy published in 2020 for OMNs. These algorithms were selected to conduct comparative tests on both energy consumption and routing performance.

From studies [32,34] on the energy consumption of opportunistic networks, we know that in classical routing, the DD algorithm only delivers messages to the destination node due to its routing characteristics, so each message can only be delivered by one hop, which greatly saves $E_t$ consumption. Therefore, among all the classical routes, DD exhibits the best performance in energy saving. Although the spray & wait algorithm limits the number of message copies and shortens the message delivery delay, it greatly improves the message delivery rate on the premise of less energy loss. Among all classical routing algorithms, its comprehensive performance is optimal. The epidemic algorithm is the most energy-unfriendly algorithm. It neither limits the transmission of replicas nor controls the number of replicas, so it consumes the most energy. We use epidemic as the lowest reference value.

### 4.1. Evaluation Index

The evaluation indicators selected in this experiment are as follows:

*Delivered*: The number of messages generated by the source node and successfully transmitted to the destination node during the simulation time.

*ARE*: Average remaining energy, the average residual energy of all nodes after simulation.

$$ARE = \frac{\sum_{i=1}^{i=All\ Nodes} E_{remain}(i)}{Number\ of\ All\ Nodes} \tag{14}$$

*Delivery Rate*: The ratio of the number of messages successfully transmitted to the destination node in the simulation time to the number of messages generated.

$$Delivery\ Rate = Delivered/Created \tag{15}$$

*Delay*: It refers to the average latency, which means the time spent from the source node sending a message to the destination node receiving the message.

$$Delay = \frac{\sum_{i=1}^{i=All\ Delivered\ Messages} Latency(i)}{All\ Delivered\ Messages} \tag{16}$$

*Overhead*: The ratio of the total number of relay-forwarding messages to the total number of messages successfully delivered.

$$Overhead = \frac{Relayed\ Messages - Delivered\ Messages}{Delivered\ Messages} \tag{17}$$

*SDRE*: Standard deviation of residual energy, the standard deviation of node residual energy during simulation, which is used to measure the dispersion of node energy consumption.

$$SDRE = \sqrt{\frac{\sum_{i=1}^{i=All\ Nodes} (E_{remain}(i) - ARE)^2}{All\ Nodes}} \tag{18}$$

### 4.2. Simulation Parameters

We choose shortest path map-based movement, which uses Dijkstra's algorithm to find the shortest paths between two random points. Its movement model can be approximately a random walk. The environment simulation parameters are listed in Table 2. The energy simulation parameters are listed in Table 3. This simulation environment is utilized for the execution of each method involved in the comparative experiment.

**Table 2.** Environment simulation parameters.

| Parameters | Values |
|---|---|
| Map Size (m) | Width: 4500, Height: 3400 |
| Node Movement | Shortest Path Map-Based Movement |
| Default Number of Nodes | Pedestrians: 80, Cars: 40, Trams: 6 |
| Number of Copies of a Message L | 5 |
| BT Transmission Range (m) | 10 |
| Wifi Transmission Range (m) | 100 |
| High-Speed Interface Transmission Range (m) | 1000 |
| Message Size (MB) | 0.5∼1 |
| Message Creation Interval (sec) | 25∼35 |
| BT Transmission Speed (Kbps) | 250 |
| HS Transmission Speed (Mps) | 10 |
| Moving Speed (m/s) | Pedestrians: 0.5∼1.5, Cars: 2.7∼13.9, Trams: 7∼10 |
| Simulation Time (hours) | 6∼15 |
| Buffer Size (MB) | 30 |
| TTL (min) | 300 |

**Table 3.** Energy simulation parameters.

| Parameters | Values (J) |
|---|---|
| Initial Energy $E_i$ | 4800 |
| Basic Energy Consumption $E_b$ | 0.01 |
| Scanning Energy Consumption $E_s$ | 0.1 |
| Scanning Response Energy Consumption $E_{sr}$ | 0.1 |
| Transmission energy consumption $E_t$ | 0.2 |

### *4.3. Simulation Results and Analysis*

In the absence of a charging design, the energy of the node decreases gradually over time. Therefore, we observed the experimental results by varying the simulation time.

Figure 3 presents the number of messages successfully delivered by six algorithms under different simulation times, where DCEE-GIP delivers the most messages. In the first 12 h of the simulation, spray & wait delivered more messages than DCEE-GIP and performed best among all the algorithms. However, after 12 h, DCEE-GIP exceeded spray & wait, and the number of messages delivered by spray & wait remained relatively stable after 12 h, as the energy of spray & wait nodes was exhausted within approximately 12 h. Consequently, all nodes transitioned into the *D* state, ceasing the generation and transmission of messages. On the contrary, the DCEE-GIP algorithm continues to provide network service due to its energy-efficient advantages after 12 h. DCEE-GIP delivered 195 more messages than spray & wait, an increase of 14.82%. This is because, although DCEE-GIP's energy-saving strategy causes nodes to miss some delivery opportunities, it helps nodes save energy and prolong their lifetime, and finally, it successfully delivers the most messages. EASE is the same. EASE is an improvement on epidemic; it delivered 74 more messages than epidemic, an increase of 7.54%. Because it does not constrain the message replica, it is restricted by replica flooding, which is not as good as nonflooding algorithms. The GEER algorithm is an enhanced version of n-epidemic, which incorporates improvements aimed at reducing energy consumption in the network. By employing degree centrality and residual node energy, it effectively limits the number of message copies forwarded. However, due to its simplistic energy-saving strategy that solely focuses on minimizing energy consumption, it fails to consider the potential opportunities for message forwarding. Consequently, GEER achieved a successful delivery rate that is 5.19% lower than epidemic, transmitting 51 fewer messages.

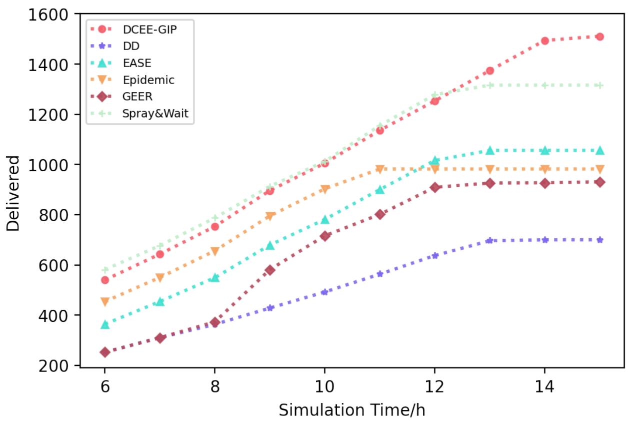


**Figure 3.** Comparison of the number of messages successfully delivered by various algorithms under different simulation times.

Figure 4 presents the *ARE* of six algorithms under different simulation times, where DCEE-GIP helped the node survive and work for the longest time. The running time from the start of simulation to the death of all nodes is 51,000 s for DCEE-GIP, 47,200 s for DD, 45,000 s for spray & wait, 44,600 s for EASE, 43,600 s for GEER and 38,900 s for epidemic.

It can be seen that DCEE-GIP effectively extends the lifetime of the nodes in OMNs and improves the quality of the service of the network.

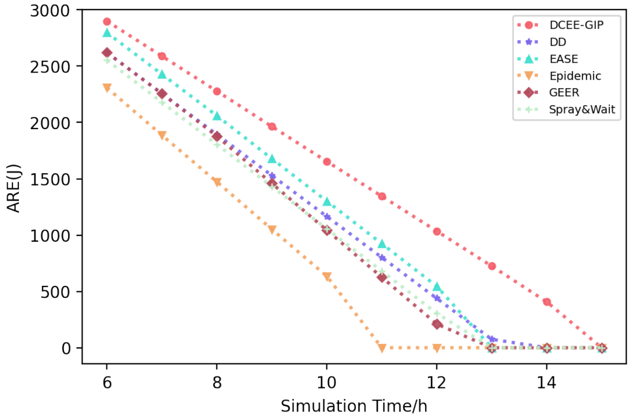


**Figure 4.** Comparison of average remaining energy of various algorithms under different simulation times.

Figure 5 presents the delivery rate of the six algorithms when the simulation time changed from 6–15 h. In the beginning, the delivery rate of spray & wait was the highest, even higher than that of DCEE-GIP; this is because DCEE-GIP's sleep mechanism restricted the delivery of some messages in the early stage. However, in the later stage of the simulation, the delivery rate of spray & wait was almost the same as that of DCEE-GIP, which indicates that DCEE-GIP ensures the successful delivery of messages within its lifetime, but the delay is slightly higher. Additionally, because DCEE-GIP makes nodes run longer, this can help deliver more messages successfully. From the picture, we can also see that the delivery rate of all algorithms tended to be stable in the end; this is because the node will not generate new messages after the energy is exhausted.

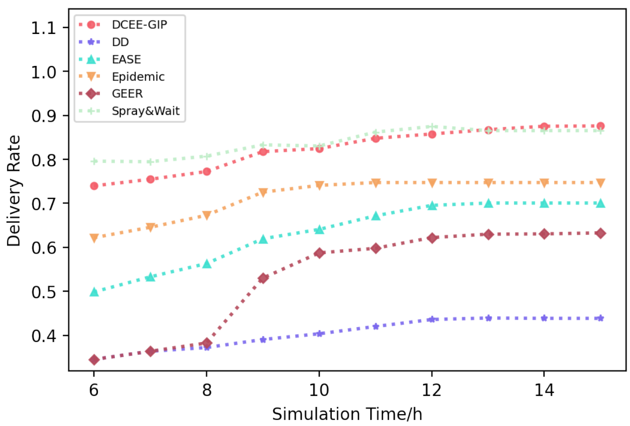


**Figure 5.** Comparison of delivery rate of various algorithms under different simulation times.

Figures 6 and 7 illustrate the comparison of the average latency and overhead of the six algorithms when the simulation time changed from 6–15 h. From Figure 6, we can confirm that the *Delay* of the DCEE-GIP algorithm is, indeed, higher than that of spray & wait. However, due to its reasonable sleep time design, it can maintain a lower *Delay* than the other four algorithms. The average latency of DCEE-GIP was nearly 20%, 26.94%, 31.99%, and 34.72% lower than that of epidemic, DD, GEER, and EASE, respectively. Among the six algorithms, the *Delay* of EASE was the highest, even higher than that of DD, which indicates that the sleep time of EASE is too long, causing it to miss some opportunities to meet the target node. But its delivery rate was far higher than that of DD; this is because EASE is a multi-copy routing, so a long sleep time cannot prevent the successful delivery of messages, but it also saves the energy of the nodes. In Figure 7, the *Overhead* of DD was the lowest, and the *Overhead* of DCEE-GIP was significantly better than that of EASE and epidemic. DCEE-GIP was on par with spray & wait for *Overhead*.

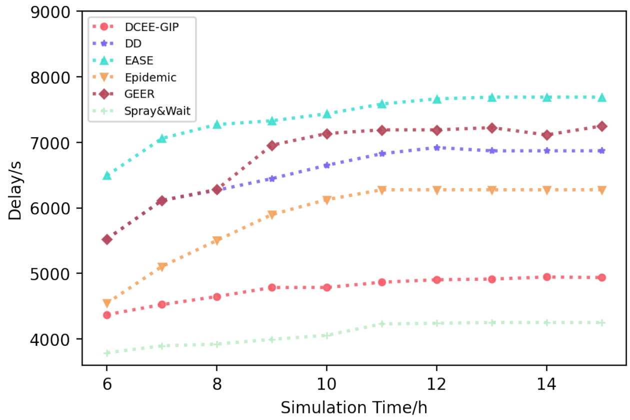


**Figure 6.** Comparison of the average latency of various algorithms under different simulation times.

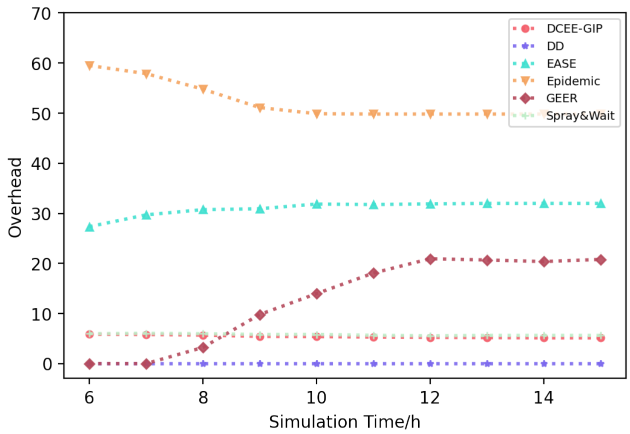


**Figure 7.** Comparison of the *Overhead* of various algorithms under different simulation times.

In the process of conducting the simulation experiments, we also observed that an imbalance in energy consumption among nodes leads to accelerated energy depletion in other nodes once one node is exhausted. Figure 8 illustrates the average residual energy of epidemic routing every 100 s. It can be observed that until 38,800 s, node energy consumption decreases linearly with simulation time at a rate of approximately 11 J per 100 s. However, it abruptly drops to zero at 38,900 s. Therefore, we analyzed node energy at 38,800 s. Figure 9 reveals that during this period, the average remaining energy of the epidemic nodes is measured as 308.08 J, whereas the C65 nodes only have a remaining energy level of merely 5.32 J. The node enters the *D* state and becomes unable to accept or transmit messages when its energy is depleted in the subsequent time period. It hinders the transmission of other messages within the network, particularly when the destination node of a message is no longer operational, resulting in perpetual blind forwarding and the rapid depletion of energy resources from other active nodes within the subsequent 100 s. This phenomenon is similar to the broken windows theory [35], which is one among several theories elucidating disparities in outcomes across neighborhoods, thereby highlighting the significance of the uniform consumption of node energy for network services.

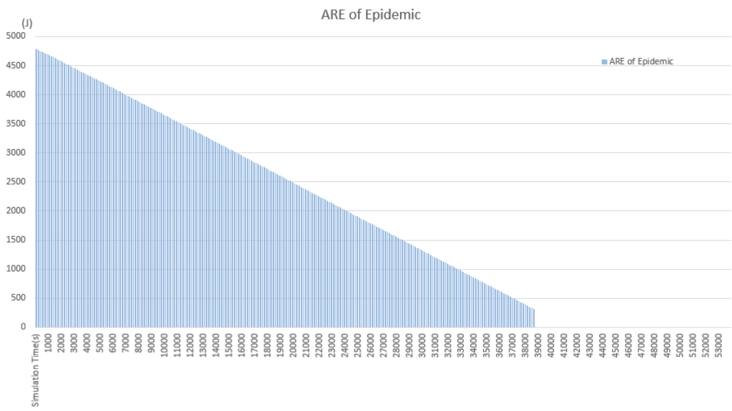


**Figure 8.** The *ARE* of epidemic displayed every 100 s.

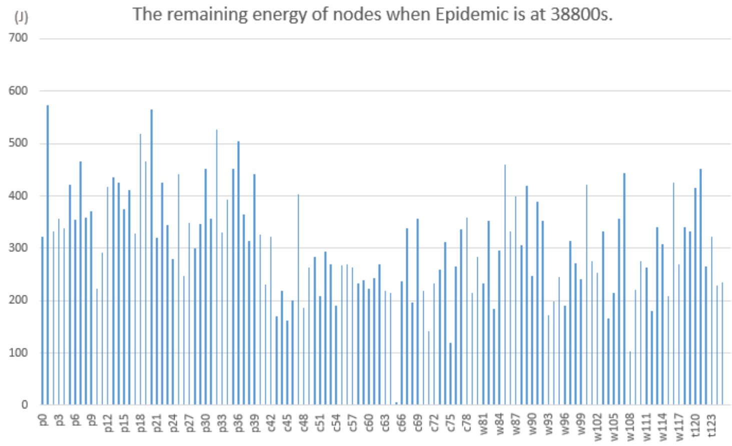


**Figure 9.** The remaining energy of the nodes when epidemic is at 38,800 s.

Therefore, the relative uniformity of energy consumption of each node is conducive to the continuation of the network. We used the *SDRE* index to measure the dispersion of node energy consumption. The lower the value of *SDRE*, the lower the dispersion of node energy consumption, and the better the algorithm. Figure 10 illustrates the residual energy of the nodes of the six algorithms after 10 h of simulation. Figure 11 presents a comparison of the standard deviation of the residual energy of these algorithms. In these two figures, we can see that the *SDRE* value of DD is the minimum. This is because there is no relay transmission of messages in the DD algorithm. Each message has only one hop at most in its lifetime, and the probability of each node generating messages is the same. Therefore, the energy consumption gap between nodes is insignificant. Among the other five algorithms, DCEE-GIP performs best, 36.37, followed by GEER, 45.63. spray & wait is close to GEER. This is attributed to the limitation on the number of message copies, which hinders the unrestricted dissemination of replicas. The energy consumption of algorithms such as epidemic and EASE, which do not limit the number of copies, is not uniform enough.

In brief, DCEE-GIP outperforms other algorithms in most cases. DCEE-GIP effectively extends the network service time, ensures a high delivery rate, and helps more messages be delivered successfully. The reason for the above result is that the overall performance of DCEE-GIP is the best, thus confirming the superiority of DCEE-GIP.


**Figure 10.** Display of the residual energy of the nodes of the six algorithms after 10 h of simulation. (**a**) Residual energy of nodes of DCEE-GIP. (**b**) Residual energy of nodes of DD. (**c**) Residual energy of nodes of EASE. (**d**) Residual energy of nodes of epidemic. (**e**) Residual energy of nodes of spray & wait. (**f**) Residual energy of nodes of GEER.

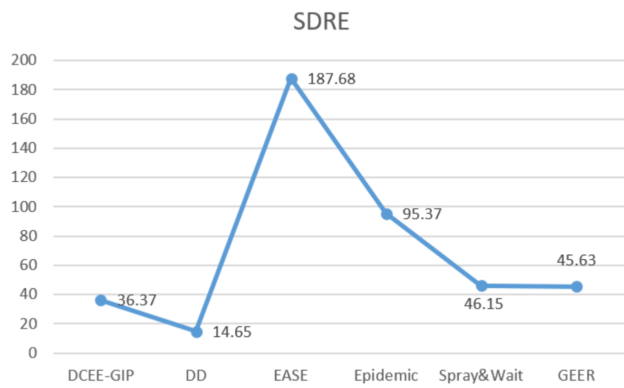


**Figure 11.** Comparison of the *SDRE* of the six algorithms after 10 h of simulation.

## 5. Conclusions

In this study, a novel dynamic co-operative energy-efficient routing algorithm, DCEE-GIP, is presented based on geographic information perception. First, with the help of the token adjustment mechanism of DCEE-GIP, nodes can effectively co-operate dynamically.

Second, DCEE-GIP has two dormancy mechanisms: one is based on node state and the other is based on probability prediction, which helps the node enter the sleep state appropriately to avoid wasting energy. As revealed by the simulation results, DCEE-GIP outperforms the five existing routing algorithms to a certain extent. The service time of DCEE-GIP was increased by 8.05∼31.11%, and more messages were delivered by 14.82∼115.9%.

This study will be deepened in the following way. During the experiment, we found that the uniform consumption of node energy is crucial to the long-term operation of the network. Once a node dies in the network, the energy of other nodes will be exhausted quickly. This phenomenon is similar to the broken windows theory. We think that this phenomenon is very meaningful for research in this area and should be investigated in depth in future research.

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