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Data collection in sensornets with heterogeneous duty cycles: pursuit of efficient opportunity

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Abstract

For sensornets with heterogeneous duty cycles, sensor nodes wake up with different sleeping periods, which combined with unreliable links, making it very challenging to enhance the network performance. This paper presents a new opportunistic routing protocol, called EOF (Efficient Opportunistic Forwarding), which mainly involves a forwarding metric that can efficiently exploit the single-hop forwarding opportunity and a delay-aware forwarder selection scheme. Different from previous opportunistic routings for sensornets, EOF comprehensively considers the effect of heterogeneous duty cycles and link unreliability on the overall network performance. The experimental results show that compared to the state-of-the-art protocol, EOF can achieve better overall network performance with almost identical energy cost, especially when it is applied to the sensornet with significant heterogeneity of duty cycle.

Keywords: Duty-cycled sensornet, Opportunistic routing, Throughput, Delivery delay, Energy efficiency

1 Introduction

In wireless sensor networks (also called *sensornets* in short), saving nodes' energy resource or prolonging the system lifetime is one of the most important topics [1, 2]. The duty-cycled communication is a promising approach of improving the energy efficiency of sensornets. In duty-cycled sensornets, sensor nodes sleep for most of their time and they can transmit or receive data only when they are in awake state; by doing so, the nodes can effectively preserve their energy for long-term operation. However, the duty-cycled communication paradigm results in time-varying network topology, i.e., intermittent connectivity, which makes it very hard to achieve desirable network throughput and delivery delay, especially when unreliable links and heterogeneous duty cycles come together into sensornet.

In a heterogeneous duty-cycled sensornet, sensor nodes can schedule their different duty cycles independently according to their different functions, energy supplies, and positions in the sensornet [3, 4].

In recent years, researchers have attempted to leverage the broadcasting nature of wireless signals, designing opportunistic routings [5] to improve network performance of duty-cycled sensornets with unreliable links. In opportunistic routing, the forwarder for a packet can be selected dynamically from multiple receivers, thereby significantly improving the transmission performance. Compared to the unicast routing [6, 7], opportunistic routing does not need to maintain the next hop information as timely as possible, and then it is able to adapt well to the network dynamics. The critical challenge of designing effective opportunistic routing for duty-cycled sensornets is to exploit the forwarding opportunity under unreliable connection and intermittent network topology.

The opportunistic routing protocols for traditional wireless ad hoc or mesh networks, such as ExOR [8], MORE [9], EHOR [10], and TOAR [11], were designed to achieve high throughput. They usually need to maintain much network information and are unsuitable for resource-constrained sensornets. Especially, they often suffer high end-to-end path delay and energy consumption in the scenario with duty-cycled communication. To address such issues, researchers have proposed some

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opportunistic routing protocols for duty-cycled sensor-nets [12–14]. These protocols can be applied in sensor-nets with homogeneous duty cycle and usually depend on strict global network synchronization [15].

Among these prior works, ORW [14, 16] was designed to improve the path delay by opportunistically forwarding packets in sensor-nets with unreliable links. Even though ORW is a prominent opportunistic routing protocol, it does not consider the heterogeneous duty cycles and especially the network throughput in its routing metric. EoR [4] is another opportunistic routing protocol recently proposed for heterogeneously duty-cycled sensor-nets, aimed at further reducing the path delay. The authors of EoR preliminarily illustrated the inadequateness of ORW with heterogeneous duty cycles; EoR only achieves the path delay performance slightly better than ORW. In sensor-nets with heterogeneous duty cycles, the heterogeneity of duty cycles and unreliable links collectively impact the network performance in terms of path delay, delivery ratio, and energy efficiency, in a sophisticated way. Then, designing opportunistic forwarding policy to improve the comprehensive network performance is literally a critical challenge in such sensor-nets.

In this paper, we present the EOF protocol (Efficient Opportunistic Forwarding) for sensor-nets with heterogeneous duty cycles. The major contributions are as follows:

First, EOF involves an effective metric that models the expected path delay but can well exploit the single-hop forwarding opportunity by taking into account the heterogeneity of duty cycle and lossy links; and EOF also involves an easy-to-deploy and delay-aware approach for forwarder selection. Second, EOF employs a new lightweight solution to coordinating multiple awake forwarders, being inspired by ORW's scheme. Third, we conduct extensive TOSSIM-based simulation experiments. The results show that in comparison with ORW, the proposed EOF achieves better overall network performance, especially when the heterogeneity of duty cycles is significant.

The rest of the paper is organized as follows: Section 2 introduces the related work and the motivation of our study. Section 3 describes the main designs of EOF and presents some discussions about EOF's implementation. Section 4 evaluates EOF's performance through experiments. Finally, Section 5 concludes this paper.

2 Related work and motivations

2.1 Related work

Opportunistic routing can improve the network throughput by employing potential forwarders dynamically and then it has always been an important topic in wireless ad hoc/mesh networks and sensor-nets [5, 17].

Early opportunistic routing protocols often focus on establishing source-to-sink shortest paths in terms of the ETX (expected transmission count) [8], the hop count

[18], or the coding efficiency [9]. These works yield good throughput with frequent message exchanges and network state maintenance. Additionally, they do not pay much attention on improving the end-to-end delivery performance [19]. Another kind of opportunistic routings for traditional wireless networks and sensor-nets, such as EHOR [10], AOR [20], SGOR [21], GeRaf [22], preferentially select the forwarders who are physically nearest to the sink. However, those works depend heavily on the priori knowledge of each node's position. In particular, they are often inefficient in guaranteeing comprehensive network performance because they might insist on selecting forwarding paths only according to the downstreaming nodes' position, neglecting the effect of unreliable links on both the throughput and the energy efficiency.

Recently, a few studies have been mainly concerned with the energy efficiency in opportunistic routing for wireless networks, such as EEOR [23] and EAOR [24]. Both protocols determine the forwarding nodes by taking into account their residual energy and single-hop link quality. In fact, however, both of them often consume significant extra energy and bandwidth resources before routing decisions can be made. Also there have been other efforts such as ORIA [25] and ORD [26] that employ aggregation-based approaches to schedule packet delivery, but they usually suffer long end-to-end delay because they need to stop the forwarding of some packets and to wait subsequent packets, in order to carry out packet aggregation.

For sensor-net applications, the energy resource dominates the system lifetime. A promising approach is to duty cycle the operation of sensor nodes, allowing them to sleep for most of their time to save energy. Early opportunistic routings for duty-cycled sensor-nets were proposed in [12, 13, 27]. These work analyze the effect of unreliable links and duty cycle of nodes on the forwarder selection. However, these protocols are designed for sensor-nets with homogeneous duty cycles, often requiring strict global time synchronization or extra communication overhead to stabilize network state. Landsiedel et al. [14] proposed ORW, an opportunistic routing protocol for duty-cycled sensor-nets, which improves the energy efficiency and the delivery delay performance, compared to previous similar works. However, ORW neither considers the case with heterogeneous duty cycles nor captures well the effect of packet retransmission on the path delay, estimating the single-hop transmission reliability over-optimistically. EoR [4] is an opportunistic routing metric for sensor-nets with heterogeneous duty cycles. EoR focuses on the transmission delay optimization and its resulted delivery delay is slightly better than ORW. And the authors of EoR did not fully evaluate the energy efficiency that it can achieve.

2.2 Motivations

In many real-world sensornet applications, the nodes do not have identical duty cycle and even length-identical working schedule. Typical for such a case is energy-harvesting sensornet, in which nodes are powered by environmental energy [28, 29]. In energy-harvesting sensornets, some nodes have higher energy harvesting rates than others, and then they can keep awake for longer time—affording higher duty cycle.

In the sensornets with heterogeneous duty cycles, a node needs different expected wait times for different potential forwarders. To investigate the essentials affecting the transmission performance in sensornets with heterogeneous duty cycles, we examined a three-node and one-hop network based on numeric simulation, in which as shown in Fig. 1, nodes R_1 and R_2 are two receivers of node S . In simulation, node S broadcasts a packet in each time slot with the probability of 1% and the two receivers are both of duty cycle 1%; specifically, R_1 and R_2 wake up periodically at time slots $(20 + 100 \times i)$ and $(10 + 100 \times i)$, respectively, where i represents a non-negative integer. Obviously, both receivers have different working schedules but identical duty cycle, and the time spans of their working schedules are both 100 time slots. In active slot, two receivers R_1 and R_2 can successfully receive the packet from S with the probabilities of q_1 and q_2 , respectively, each of which ranges in $(0, 1]$.

For the scenario depicted above, by ORW's delay model, node S will wait a time period of $\frac{0.5 \times 100}{q_1 + q_2}$, in average, before each of its packets can be correctly received by R_1 , R_2 , or both. Figure 1 plots the results of the experiments with different assignments of link quality and working schedules. If q_1 and q_2 are set to 0.25 and 0.5, respectively, ORW yields the one-hop delay of $\frac{50}{0.25+0.5} = 66.7$ slots with schedule I, but the actual expected wait time for S in experiment is 114.41 slots. From Fig. 1, it is easy to

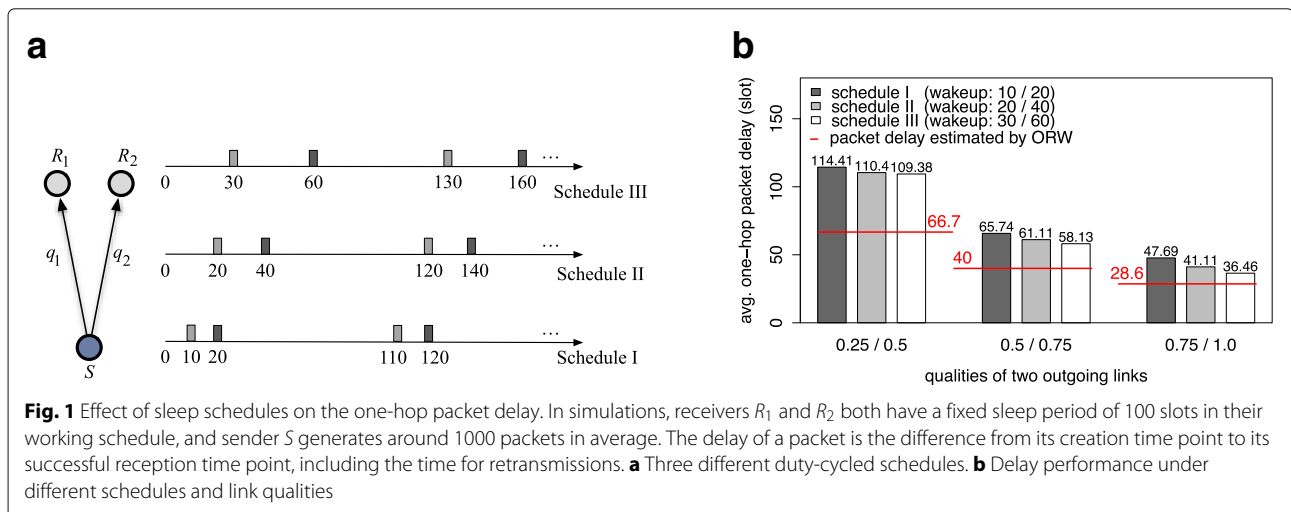
find that with the same working schedule, different link qualities will also result in different single-hop delay. It can be also seen in Fig. 1 that with the same assignment of link qualities, different working schedules result in different single-hop delays, even when they have the same duty cycle and time span.

By the above observations, therefore, we can conclude that the probability of “at least one receiver is available” cannot be expressed simply with the sum of the link qualities, even in the scenario only with one-hop transmission. In opportunistic forwarding, the current packet retransmission might be directed to another forwarder other than the previous one, because the sequence of alternate active slots is uncertain at runtime. Furthermore, the lossy links and the resulted multiple failures will further compound the difficulty in modeling the possible retries of a packet.

One interesting finding of the simulation experiment is that the distribution of awake slots in a schedule affects the delay performance—the more evenly the awake slots of receivers are distributed, the more opportunities for transmission the sender can have, especially when the link qualities are relatively high. For example, compared to schedule I, schedule III reduces the delay by 4.3% and by 23.5% if the qualities of the two outgoing links are set to be 0.25/0.5 and 0.75/1.0, respectively. Such a delay improvement will be surely significant for multi-hop delivery.

The reason is that schedule I has more evenly distributed active times of receivers than schedule III does, and thus, schedule I will be offered with longer retry time (i.e., more opportunities) before its maximum retransmission is hit.

ORW simplifies the model for the packet retransmission over unreliable link. In particular, ORW overlooks the effect of the distribution pattern of forwarder's active



times on the single-hop delay. For different senders, however, their forwarders easily render much different distributions of active times in sensornets with heterogeneous duty cycles. In a fundamental way, ORW has not well defined the “opportunity” in opportunistic routing with heterogeneous duty cycles.

3 Designs of EOF

This section will first introduce the network models and some assumptions used in our study, and then detail the design of EOF and some practical considerations.

3.1 Network models and assumptions

We consider a duty-cycled sensornet including a set of ID-distinctive sensor nodes and one sink node. These nodes are organized into a multi-hop wireless network and the sink node collects the data generated by sensor nodes. Each sensor node has two alternate states: the active (awake) state and the dormant (sleeping) state. In the active state, the node can create packets and communicate with other nodes; in the sleeping state, it only maintains an alarm clock to wake up itself, keeping its sensing and radio modules turned off. During term T , if a node keeps in the active and the sleeping states for T_1 and $T_0 = (T - T_1)$, respectively, the duty cycle of this node can then be expressed with $\frac{T_1}{T_1+T_0}$. The greater the difference between two nodes' duty cycles, the more significant the duty cycle heterogeneity of the sensornet.

In general, in duty-cycled sensornets, each node has a pre-configured duty cycle value in the form of percentage or periodic sleeping time (working schedule). The duty cycles maybe set from 1 to 10% [12, 13] or higher [4, 14]. Some energy harvesting sensor nodes can achieve 50% duty cycles [30]. In the TinyOS-compatible communication protocols, for instance, we can program the duty cycle of a node to be 25% or 256 ms of sleeping period, in order to obtain a duty-cycled communication paradigm. Additionally, a duty-cycled node is allowed to wake up at any time if it is going to send out a packet, but it can receive packets only after it enters the active state. In practice, therefore, the actual duty cycle of the node may be greater than its pre-configured value.

In this paper, we consider heterogeneous duty cycles assigned to all sensor nodes, different from lots of previous works in which all nodes are assumed to have the same duty cycle. Specifically, such a heterogeneity comes from different sleeping periods that are assigned to sensor nodes in network initialization. We also assume that a sensor node can share its sleeping period and the wake-up time with its neighbors, by exchanging handshake messages in network initialization or at runtime.

Since the low-power wireless links in sensornets are often unreliable and time-varying, the sending node may

not successively send packets to its forwarder at its first try. On the other hand, the sender cannot retransmit a packet unlimitedly because of the energy and the bandwidth constraints. Like most of wireless applications, we set a maximum number of retransmissions, denoted by K , in this paper. For the simplicity, we assume that hereafter, K covers the first transmission try.

3.2 Single-hop opportunistic transmission

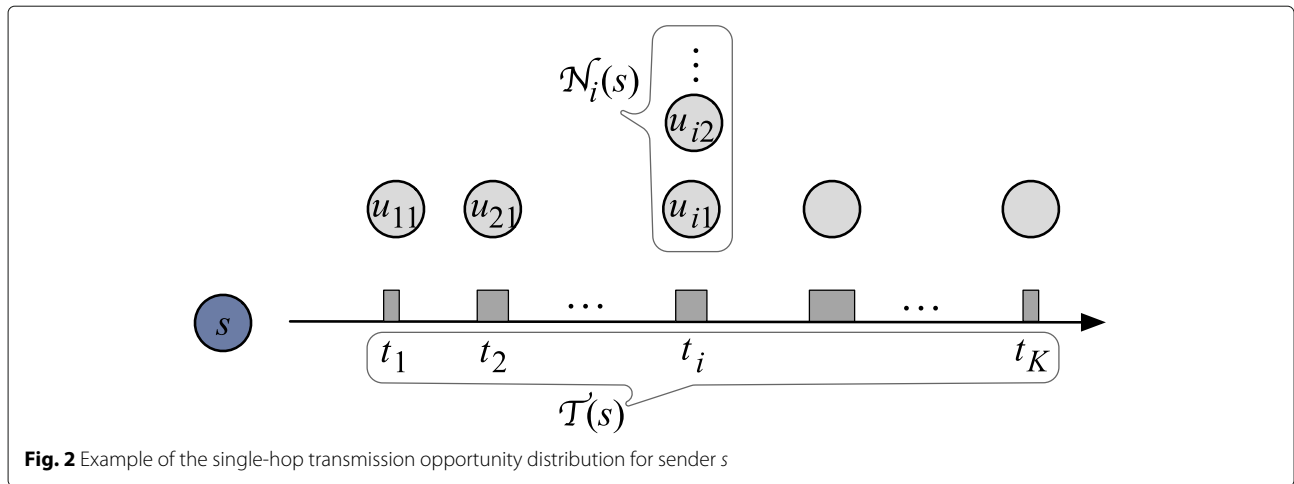
In opportunistic routing, for a sending node s , each of its neighbors could serve as its forwarder at runtime. Let $\mathcal{N}(s)$ be the neighbor list of s and p_{su} , the quality of link ℓ_{su} ($u \in \mathcal{N}(s)$).

If all the links between sender s and its neighbors are completely reliable, then the first awake one of $\mathcal{N}(s)$ might lead to delay-optimal forwarding. With the existence of lossy links, however, sender s may fail in transmitting the data to its neighbor at the first try. In opportunistic routing, therefore, sender s often reserves multiple potential forwarders, in order to successfully send out packets as soon as possible. We will next introduce how the proposed EOF models the delivery performance in opportunistic forwarding.

Consider a case which involves sender s and its neighbor list $\mathcal{N}(s)$, and suppose the sleeping periods of all nodes in $\mathcal{N}(s)$ are known. Denote by $\mathcal{A}(u)$ the set of awake time points of node u ; if u has a sleeping period of 10 s, for example, then $\mathcal{A}(u) = \{t, t + 10, t + 20 \dots\}$ where t is the time u first wakes up. Clearly $\mathcal{A}(u)$ is an infinite set of increasing time points, without considering the lifetime of u . For the easy use of $\mathcal{A}(u)$, let $\mathcal{A}_n(u)$ denote the subset of $\mathcal{A}(u)$ that includes only the first n time points of $\mathcal{A}(u)$. Furthermore, s can easily know about when any of its neighbors will wake up. First, at sender s , EOF makes a union $\mathcal{T}(s)$, which equals $\bigcup_{u \in \mathcal{N}(s)} \mathcal{A}_K(u)$, where K is the maximum allowed retransmission count. Second, EOF retains only the first K earliest time points in $\mathcal{T}(s)$, pruning out all the others from $\mathcal{T}(s)$. It is clear that $\mathcal{T}(s)$, which is size of K , covers all the possible transmission opportunities of sender s before its packet is dropped. The example in Fig. 2 illustrates the distribution of transmission opportunities of sender s , in which node u_{11} will wake up to receive packet from s at time t_1 and at least two nodes u_{i1} and u_{i2} will be awake to receive data at time t_i .

To model the one-hop forwarding performance as accurately as possible, we consider a general case which involves multiple simultaneously-awake potential forwarders of sender s . For each $t_i \in \mathcal{T}(s)$, EOF records the set of nodes who all enter the active state at time t_i ; we denote such a node set by $\mathcal{N}_i(s)$.

With the link quality information, therefore, the probability that at least one node of $\mathcal{N}_i(s)$ could successfully receive the packet from s at time t_i can be expressed



with Eq. (1). For sender s , if there is only one available forwarder u at time t_i , Eq. (1) will be reduced to $q_i(s) = p_{su}$.

$$q_i(s) = 1 - \prod_{u \in \mathcal{N}_i(s)} (1 - p_{su}) \tag{1}$$

Clearly, $q_i(s)$ is presented to model the expected one-hop throughput that sender s can achieve at time $t_i \in \mathcal{T}(s)$.

3.3 Profiling efficient forwarding opportunity

Multiple forwarding choices shorten the expected wait time for sender s . But the unreliable single-hop communication makes it difficult to model the delivery performance in opportunistic routing. For the single-hop forwarding evaluation, ORW only considers the probability that a packet can be correctly received at the first try and simply takes the reciprocal of this probability value as the expected single-hop delay, without paying careful attention to the effect of retransmission on the evaluation of single-hop forwarding capacity.

In this paper, the EOF routing metric defines the *expected path delay*, denoted by D_s , for any sensor node s , and D_s is formally given in Eq. (2), where $\mathcal{F}(s)$ is the set of potential forwarders chosen by s and it is the subset of $\mathcal{N}(s)$.

D_s sums up two terms: the first one measures the expected single-hop transmission delay from s to its forwarders and the second one, the expected delay of the path from the actually chosen forwarder to the sink node.

$$D_s = \frac{\frac{1}{K-1} \sum_{i=2}^K (t_i - t_{i-1})}{\frac{1}{K} \sum_{i=1}^K q_i(s)} + \frac{\sum_{u \in \mathcal{F}(s)} p_{su} \times D_u}{\sum_{u \in \mathcal{F}(s)} p_{su}} \tag{2}$$

In the first term, the numerator indicates the average wait time before sender s can start next try of a packet transmission, while the denominator indicates the probability that the packet of s could be successfully received before being dropped. Although the EOF forwarding metric is presented externally to quantify the delivery delay, it also implicitly takes into account the comprehensive effect of the link unreliability and the retransmission count limit on the single-hop opportunistic forwarding.

In sensor networks, a sensor node needs time in communication, which should be added to the D_s . Reasonably, we do not consider this factor in D_s because of three following facts. First, sensor nodes have almost the same time cost in sending and receiving packets; second, the actual time for these two communication operations are often in the order of tens of milliseconds and far shorter than the time to wait forwarders' wakeup. Third, D_s profiles the expected forwarding capacity, not the actual delivery time from node to sink. We next focus on the determination of the optimal forwarder set based on the EOF metric.

3.4 Selecting forwarders

Selecting potential forwarders from the neighbor list is a pivot in the opportunistic routing across unreliable networks. From the perspective of optimization, the forwarder selection for a given node is to optimize the delivery performance for this node. In our study, the forwarder selection undertakes the responsibility of forwarding packets as soon and reliable as possible. Formally, Eq. (3) describes the objective of our forwarder selection: for a given node s , we select a non-empty set, $\mathcal{F}(s) \subseteq \mathcal{N}(s)$ such that $\mathcal{F}(s)$ can offer s the optimal forwarding performance. In Eq.(3), x_u is an indicator function. If $u \in \mathcal{N}(s)$ is selected as a forwarder of s , then we have $x_u = 1$ and add u into $\mathcal{F}(s)$; otherwise, $x_u = 0$.

$$\begin{aligned} & \min : D_s & (3) \\ \text{s.t.} & \sum_{u \in \mathcal{N}(s)} x_u \leq |\mathcal{N}(s)| \\ & x_u = \begin{cases} 1 & \text{if } u \text{ is added into } \mathcal{F}(s) \\ 0 & \text{otherwise} \end{cases} \end{aligned}$$

For sender s , the last active time point of $\mathcal{A}(s)$ is t_K , which is last chance for s to retransmit its packet. Assuming that $u \in \mathcal{N}(s)$ switches into active state at time t_K , however, we cannot guarantee that the inclusion of u into $\mathcal{F}(s)$ will result in optimal delivery performance, even though s grasps its last opportunity for retransmission. If the brute-force approach is used to solve the problem in Eq. (3), we will need $O(2^{|\mathcal{N}(s)|})$ time to obtain one optimal $\mathcal{F}(s)$. Because of the NP-hardness, we then propose a greedy algorithm to achieve approximate solution for problem Eq. (3), which involves two steps.

First, we assign each node u in $\mathcal{N}(s)$ with a value, which is calculated by Eq. (4),

$$V_u = \frac{1}{2}T_u + D_u \quad (4)$$

where T_u is the sleeping period of u and D_u is the expected path delay of u . Obviously, $T_u/2$ represents the expected wait time of s before u wakes up to receive its packet. And then V_u represents the expected path delay of s if u is chosen as the unique forwarder of s and the first try of s to transmit packet to u succeeds. We sort $\mathcal{N}(s)$ in increasing order of V_u and denote the sorted neighbor list by $\mathcal{N}'(s)$. Such a sorting procedure takes $O(|\mathcal{N}(s)| \cdot \log |\mathcal{N}(s)|)$ time.

Second, we examine the nodes in $\mathcal{N}'(s)$ one by one, in order to make sure whether the inclusion of a node of $\mathcal{N}'(s)$ into $\mathcal{F}(s)$ will decrease the value of D_s . Suppose the i -th node of $\mathcal{N}'(s)$, u_i , has been added into $\mathcal{F}(s)$ to be a potential forwarder; and denote by $D_s^{(i)}$ the expected delay performance defined in Eq. (2). Next, we will examine the $(i + 1)$ -th node of $\mathcal{N}'(s)$, u_{i+1} . If the inclusion of u_{i+1} results in $D_s^{(i+1)} < D_s^{(i)}$, we then add it into $\mathcal{F}(s)$; otherwise, we do not choose u_{i+1} and stop the iteration procedure, returning the set of nodes to have been chosen as $\mathcal{F}(s)$. Such an iterative procedure needs $O(|\mathcal{N}(s)|)$ time obviously.

3.5 Discussions and practical considerations

Though it is not a certain event in duty-cycled sensor-nets, multiple forwarders that are awake for a common period of time may still happen to some sender s . If more than one forwarders of s are in awake state at some time

point, the key problem facing s is that of deciding which of its forwarders it should choose, in order to avoid the duplicate forwarding of the same packet and reduce the consequent resource waste. To deal with the case with multiple awake forwarders, we propose an easy-to-deploy coordination scheme in EOF. When sender node s has data packet ready to be sent, it will send out the packet to know whether there exists awake potential forwarders. Specifically, a forwarder u of s will reply an ACK to s if $D_u < D_s$, telling s that a forwarder is ready to provide routing progress. Under the circumstances that s receives more than one ACKs from multiple awake forwarders, it must figure out one as its unique forwarder. To coordinate those awake forwarders, s will continually retransmit its packet after it receives multiple ACKs. During such a retransmission-based polling process, some forwarders of s may not successfully reply ACK, either because they enter sleeping state or because of the poor link. The above procedure will be iterated until s receives only one ACK from some forwarder, say u ; and then s selects u as its unique forwarder. When replying the ACK, each forwarder will back off a random period of time in order to restrain the possible co-channel collisions. A special case is that the sink node serves as a forwarder. If the sender s receives an ACK from the sink, s will broadcast a short message to other awake forwarders, notifying them to stop replying ACK and forwarding the packet received. In ORW, each of multiple awake forwarders returns ACK to sender with the probability of 50% to reduce ACK duplications; this way is very likely to prune out forwarders with higher single-hop link quality and better routing progress. Different from ORW, the coordination of EOF leverages the ACK-based handshaking such that EOF can retain the opportunity that all the awake forwarders can offer, and tends to pick out the forwarder with more reliable connection and earlier forwarding opportunity.

In practical wireless networks, the link quality is time-varying and the link dynamics might affect the performance of protocols. For sensor-nets with low-power wireless links, the link dynamics is not so significant [31–33]. Therefore, frequent link updates, which demands for extra network resources, are unnecessary for sensor-nets. Additionally, the opportunistic routing protocol delivers packet along multiple paths and then the individual forwarding path has minor impact on the overall quality of the forwarding set. In EOF, we employ a light-weight link updating scheme. Each sensor node u records the forwarding and overhearing information. Let $N_{\text{fwd}}(u)$ be the count of packets that node u has forwarded, and $N_{\text{oh}}(u)$ be the count of packets that u has overheard. For a symmetric link ℓ_{uv} connecting nodes u and v , we weigh its quality by $\frac{N_{\text{fwd}}(v)}{N_{\text{oh}}(v)}$. The link quality update is done at receiving node v . By piggybacking the updated link information in the

ACK from v to u , EOF can allow u to complete the link information update and then update its local D_u value. Thus, EOF does not need extra bandwidth for link quality updates.

4 Evaluation

To evaluate the performance of the proposed scheme, we established the simulation environment based on TOSSIM [34]. TOSSIM is a simulator based on TinyOS and nesC [34]. It comprises the components of physical and link layers. The codes developed for TOSSIM simulation can be ported to real-world platforms running TinyOS, almost without needing any modifications. Therefore, our experiments based on TOSSIM can produce convincing evaluation.

Though centering the delivery delay, EOF also takes into account the energy efficiency and the network throughput in opportunistic routing. We then evaluate EOF's performance in terms of the following metrics.

- *Network throughput*: the ratio between the number of packets received by the sink during experiments and the number of packets generated by all nodes.
- *Per-node throughput*: if a node u generates or receives n_u packets during experiment and among them, m_u packets are sent out by u successfully, then u 's throughput is $\frac{m_u}{n_u}$.
- *Average delivery hops*: for any packet p received by the sink, if it traverses over h_p hops before arriving at the sink, then the average delivery hop is $\frac{1}{|\mathcal{P}|} \sum_{p \in \mathcal{P}} h_p$ where \mathcal{P} is the set of packets that are received by the sink at the moment the experiment terminates.
- *Average single-hop delay*: if a packet p consumes d_p time before arriving at the sink with h_p hops, then the average single-hop delay is $\frac{\sum_{p \in \mathcal{P}} d_p}{\sum_{p \in \mathcal{P}} h_p}$.
- *Total energy cost*: let \overline{dc}_u be the actual average duty cycle of node u during experiment, and then the total energy cost $\frac{1}{|\mathcal{S}|} \sum_{u \in \mathcal{S}} \overline{dc}_u$ where \mathcal{S} is the set of all sensor nodes.

4.1 Experimental settings

The simulation experiments were conducted with a deployment of involving 100 wireless sensor nodes, all of which was organized into a 5×20 grid topology. The sink node is located at a corner. To make our simulation experiment close to the real-world one, we configured the network with realistic physical channel parameters that were obtained from several sensor network testbeds [35]. Specifically, we set the path loss exponent to 4.7, the shadowing standard deviation to 3.2 dB, the noise floor to -105 dBm; these parameter settings collectively profile the wireless channel of CC2420 radio chip in the football field environment.

On the above network topology, our experiments were conducted under four scenarios with distinctive duty cycle ranges: 5~20%, 5~40%, 5~60%, and 5~80%.

In actual environment, with the development demands for monitoring different information using the same sensor network, sensor nodes responsible for various tasks and energy supplies have to operate in different duty cycles. Most of the time, the difference may be large. For example, in forest ecological monitoring sensor networks, some sensor nodes for collecting growing information of trees such as tree diameter may work at very low duty cycles (e.t. 1~10%), some nodes for collecting environment information such as sunshine, temperature may work at normal duty cycles (e.t. 20~50%), some nodes for monitoring disasters such as fire, soil erosion are required to work in high duty cycles (e.t. 50~90%) [36]. In experiments, we assigned each node a duty cycle randomly chosen within the specified range. In each experiment, additionally, we randomly chose 5% nodes as the source nodes that produced a packet every 6 min. We did not consider more aggressive traffic load due to the inherently limited capacity of duty-cycled sensor network, in which the system lifetime is the overriding constraint. The maximum allowed retransmission count was set to 10. For a given scenario, we repeated the experiment of each scenario 100 times and reported the average results as to the evaluation metrics mentioned above. Each experiment ran 10 h in the time scale of TOSSIM.

4.2 Results and analyses

Figure 3 compares the throughput achieved by two protocols. We can see that with the duty cycle increasing, the throughput of EOF and ORW increase from 0.69 to 0.92 and from 0.59 to 0.85, respectively. Such a throughput improvement is because the increase of duty cycle will offer the nodes longer awake time for communication. It can also be seen in Fig. 3 that for each scenario, EOF achieves a throughput level almost 17% higher than ORW. Noticeably, the throughput of EOF with the duty cycle of 5~40% is very close to that of ORW of 5~80%. This observation indicates that in average, even though the EOF node sleeps for a period of time twice that of the ORW node, EOF can yield the throughput as the same as that of ORW.

Figure 4 plots the path delay result achieved by two protocols. We can see that the average path delay results of EOF and ORW are both decreasing, as the upper bound for duty cycle increases; such a tendency is in line with the results shown in Fig. 3. When the heterogeneity of duty cycle becomes more significant in scenarios with duty cycle ranges 5~60% and 5~80%, EOF and ORW lead to almost similar path delay, which means that EOF is more adaptive for sensor networks with heterogeneous duty cycles.

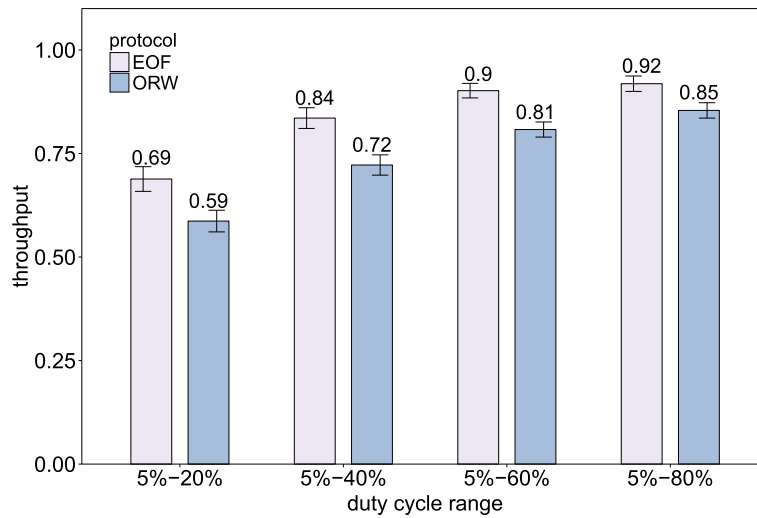


Fig. 3 Comparison of network throughput

Figure 5 plots the per-node throughput against the node position in an experiment where the sink locates the left bottom corner. In Fig. 5 the color intensity measures the per-node throughput. From Fig. 5 we can see that EOF covers a larger network area than ORW—for the nodes far away from the sink, EOF can forward more packets for them than ORW does. In other words, EOF can achieve better monitoring coverage of the interest area.

It also helps explain the path delay in Fig. 4. Better coverage means packets longer path in average to the sink.

Furthermore, Fig. 6 illustrates the distribution of the hop count of the packets received by the sink in the above experiment. To some degree, Fig. 6 argues for the delivery pattern shown in Fig. 5. Recall that for a given scenario, we repeated the experiment 100 times. We plotted and

analyzed each repetitive experiment and the per-node throughput and the hop count distribution are similar with the results shown in Figs. 5 and 6, respectively.

To evaluate the forwarding delay performance, we compare both protocols in terms of single-hop delay, the results are shown in Fig. 7. With the duty cycle of 5~20%, the single-hop delay of EOF is 0.25 s longer than that of ORW; with the duty cycle of 5~40%, EOF's single-hop delay is very close to ORW's. When the range of duty cycle is set with 5~60% and 5~80%, EOF performs better than ORW in single-hop delay. We can also see from Fig. 7 that EOF reduces its single-hop delay from 1.33 to 0.54 s by 60%, when the duty cycle range is changed from 5~20% to 5~80%, while ORW reduces its single-hop delay only by 45% for the same duty cycle change.

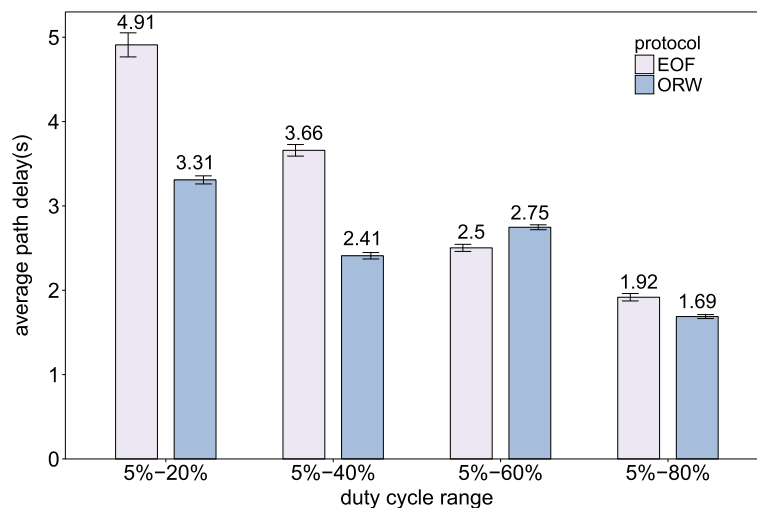


Fig. 4 Comparison of path delay

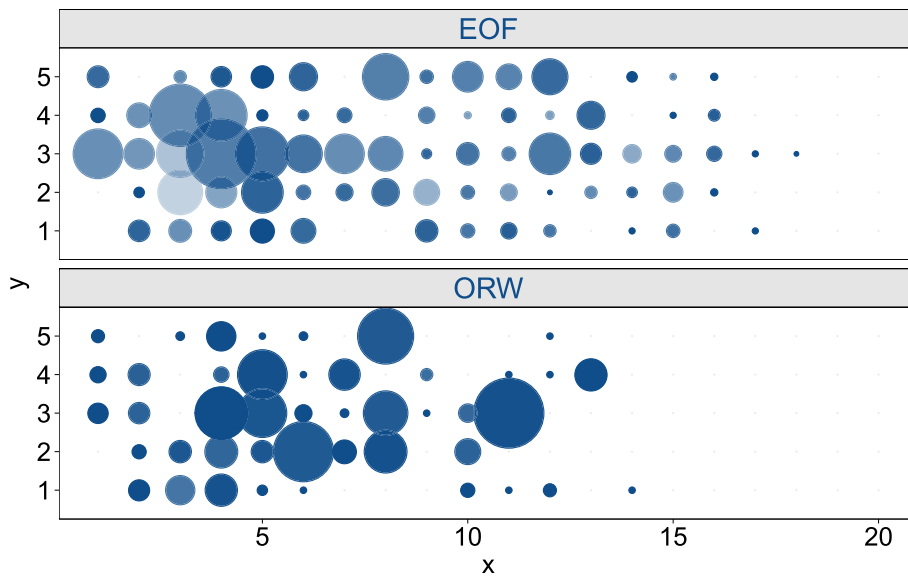


Fig. 5 Per-node throughput against node’s position. Here, the color intensity and the size of bubbles represent the per-node throughput and the count of per-node communicating operations, respectively

In fact, nodes near the border of sensornets have fewer neighbors than those in the center, which means they will cost more waiting time to forward the packets to wake up neighbors. EOF achieves better coverage than ORW. More nodes far away from the sink have longer single-hop delay. When the difference of duty cycles is not significant, like in the scenarios of 5~20% or 5~40%, such a small difference of duty cycles contributes less to improve delay performance under the situations with better coverage. So the single-hop delay in EOF is not better than ORW in the 5~20% and 5~40% scenarios but better than ORW in the 5~60% and 5~80% scenarios.

The above results indicate that EOF is more adaptive to heterogeneously duty-cycled sensornets than ORW.

We evaluate the energy efficiency by the actual duty cycle of nodes in experiments, as ORW did. Figure 8 shows that higher duty cycles lead to more energy consumption because the network can deliver more packets. In addition, we can find that the total energy consumption levels of ORW and EOF are almost the same for different scenarios. It is hard to tell which of both protocols are more energy efficient only by the results of Fig. 8. Nevertheless, referring to the network throughput comparison shown in Fig. 3, we can conclude that in average, EOF

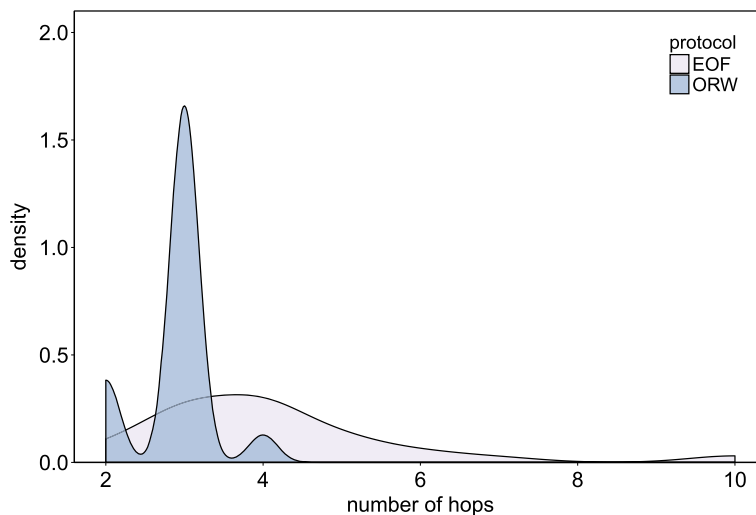
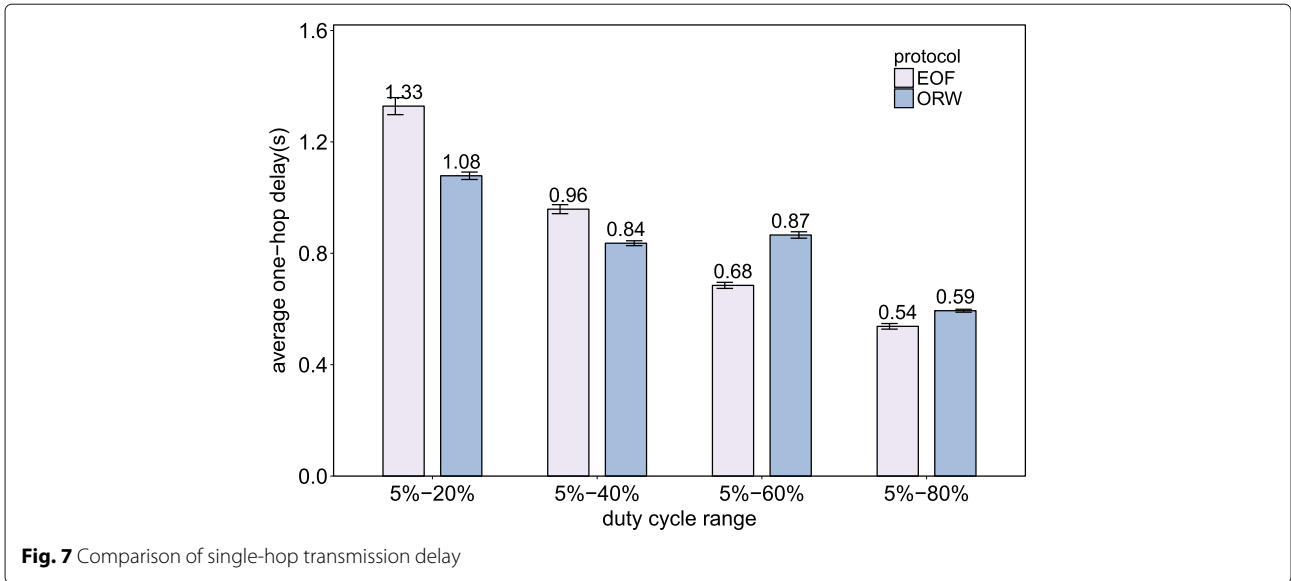


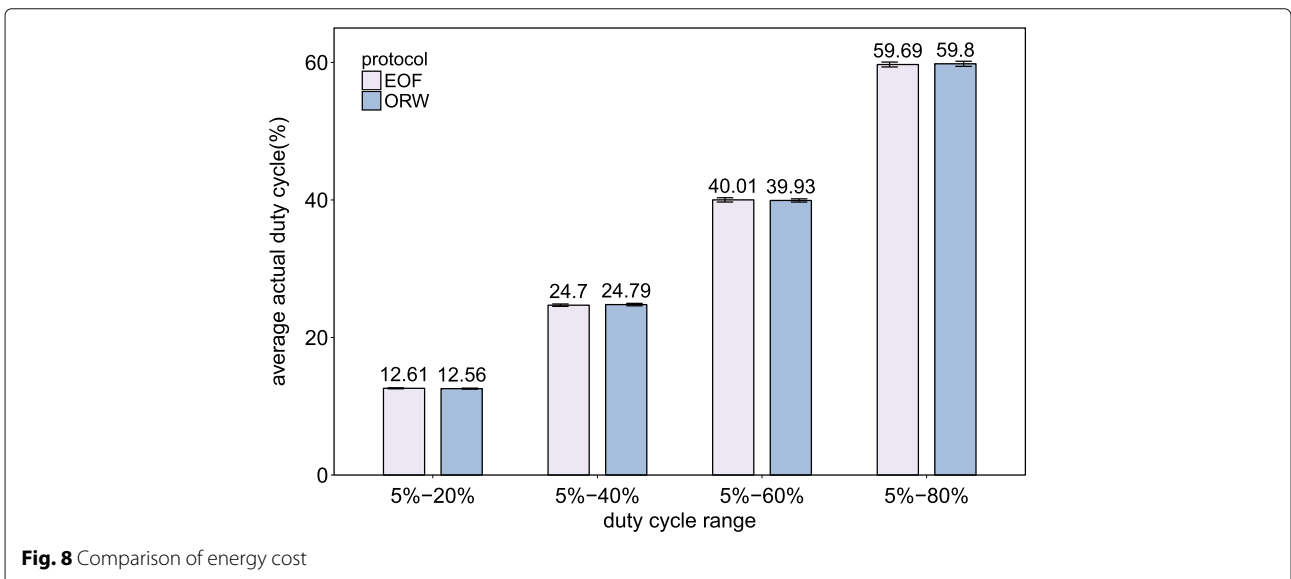
Fig. 6 Comparison of the hop count distribution of the packets received by the sink



delivers a single packet with less energy than ORW. From Fig. 5, it is also worth noting that in ORW, a small fraction of nodes take traffic loads (measured by the communication count) which are obviously higher than others, giving rise to unbalanced energy consumption among nodes. We can see from Fig. 5, however, that EOF involves more nodes in packet routing such that the traffic loads distribute more evenly than ORW, thereby achieving better energy balance.

Figure 9 compares the sizes of EOF's and ORW's forwarder sets with different duty cycle ranges. We can see in Fig. 9 that with each of the four duty cycle ranges,

EOF can basically recruit more forwarders than ORW. In the case with the duty cycle of 5~20%, for instance, the maximum forwarder set size of ORW is five, while that of EOF is ten. Noticeably, as the heterogeneity of duty cycle increases, ORW keeps relatively stable in terms of the size of forwarder set. On the contrary, EOF can recruit more forwarders—exploiting more forwarding opportunities, which can be seen from the long tail of EOF with duty cycle range 5~80%. The results in Fig. 9 also help explain EOF's improvement over ORW in terms of network throughput and single-hop delay, as shown in Figs. 3 and 7.



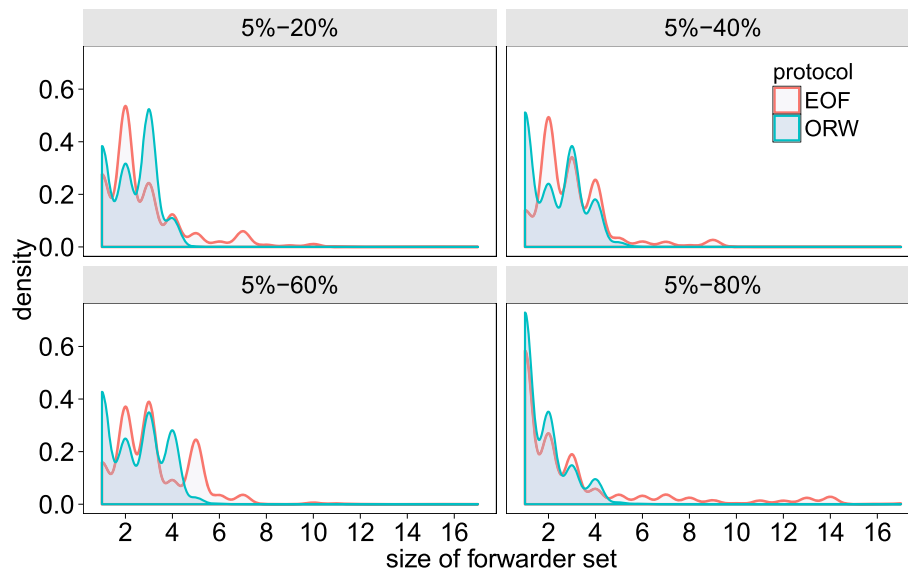


Fig. 9 Comparison of forwarder set's size

5 Conclusions

In this paper, we have presented EOF, an opportunistic routing protocol, which provides comprehensive design considerations for the opportunistic forwarding of heterogeneously duty-cycled sensor networks. The TOSSIM-based experiment with realistic settings show that compared to ORW, the state-of-the-art protocol, EOF can enhance the throughput with larger network coverage, and reduce the single-hop delay, even though both pay similar energy budget. In essence, EOF efficiently profiles the forwarding opportunity, thereby better leveraging the broadcasting nature of wireless channels in duty-cycled sensor networks. In the future, we will extend our study from two aspects. One is to implement and evaluate EOF with real-world testbed deployments. The other is to investigate more energy-efficient and delay-aware scheme for coordinating multiple awake forwarders that are prone to occurring in dense sensor networks.

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Authors' contributions

GS and XS designed the proposed routing metric. GY implemented the simulation environment for experiments. XS and GY conducted the experiment and completed the analyses of experimental results. ZC gave some advices on the selection of forwarder and on this paper presentation. XS, GS, and GY wrote this paper with almost equal contribution. All authors read and approved this submission.

Competing interests

The authors declare that they have no competing interests.

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