Distance-Based Energy-Efficient Opportunistic Forwarding in Mobile Delay Tolerant Networks

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***Abstract*—Mobile relay-assisted forwarding can improve the network capacity, but meanwhile increase the energy consumption. In this paper, we propose two distance-based energy-efficient opportunistic forwarding (DEEOF) schemes in mobile delay tolerant networks (DTNs). The proposed schemes strike a balance between energy consumption and network performance by maximizing the energy efficiency while maintaining a high packet delivery ratio from two different angles. Specifically, in the developed algorithms, we introduce the forwarding equivalent energy-efficiency distance (FEED) to quantify the transmission distances achieving the same energy efficiency at different time instances. The expected energy efficiency can thus be estimated based on the FEED. Furthermore, the distribution of the greatest forwarding energy efficiency in the predicted period is investigated to provide more accurate prediction for the energy efficiency. The forwarding decision in the algorithms is made by comparing the current energy efficiency and the estimated future expectation. The performance improvement of the proposed algorithms is also demonstrated by simulation, especially for systems where the source has very limited battery reserves.**

I. Introduction

Node mobility was considered conventionally as an obstacle which needs to be intelligently overcome for seamless communication between nodes. Recently, it has been recognized that mobility can be exploited to improve the network performance. Grossglauser and Tse [1] introduced the advantages of mobility in mobile ad hoc networks. The multiuser diversity is exploited by forwarding the traffic to relays for additional "routes" between the source and the destination. Due to the uncertainty of node mobility, the intermittent connectivity between two mobile nodes is random. DTN forwarding algorithms usually spawn and keep multiple copies of the same packet in different nodes to increase the packet delivery ratio [2]. Recently, significant research efforts have been devoted to opportunistic forwarding [3]-[7], which try to reduce the number of packet copies while retaining a relatively high delivery probability. Groenevelt and Nain [8] proposed a two-hop forwarding algorithm, in which only the source of the message can replicate it, whereas the other nodes can only forward it to the destination.

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Recently, energy efficiency has attracted much research attention. The work reported in [9] and [10], introduced a discrete-time model and a continuous-time Markov model to analyze the problem of the energy-efficient optimal opportunistic forwarding policies in DTNs, respectively. Mao *et al.* [11] addressed the problem of selecting and prioritizing the forwarding list to minimize the total energy cost of forwarding data to the sink node in wireless sensor networks. An opportunistic routing protocol, which introduced a novel greedy forwarding algorithm and an efficient self-suppression scheme in multi-hop wireless networks, was proposed in [12].

In this paper, we explore the problem how mobility can be exploited to increase energy efficiency without degrading significantly the network performance in terms of packet delivery ratio. Obviously, it is not necessary to send as many copies as possible with the consideration of network cost, e.g., energy consumption, limited radio resources. Opportunistic forwarding is an efficient approach to achieve the balance of the tradeoff between network performance and energy consumption. However, there are several technical challenges in the design of energy-efficient opportunistic forwarding policies:

1) There exists a fundamental delay-energy tradeoff. The relationship between delay and energy is not straightforward in opportunistic forwarding scenarios.
2) Due to node mobility, the transmission power to reach a relay node varies in time and is related to the distance between the source and relay. Moreover, successful delivery also depends on the time difference to the tolerant delay constraint. It is challenging to determine the forwarding opportunities.

Therefore, we consider the delay-energy tradeoff and develop an optimal opportunistic forwarding strategy with high energy efficiency under the delay constraint. The main contribution of this paper is two-fold.

- We introduce the concept of *forwarding equivalent energy-efficiency distance (FEED)* to describe the relationship between the node distance and the delay for the equivalent energy efficiency. FEED makes it possible to compare the energy efficiency when both the node distance and the delay time are different, which helps the design of energy-efficient opportunistic forwarding.

- In order to maximize both the energy efficiency and the packet delivery ratio, we make use of the node mobility to propose two *distance-based energy-efficient opportunistic forwarding (DEEOF)* algorithms which significantly improve the energy efficiency and, meanwhile, achieve a high packet delivery ratio. Furthermore, the distribution of the greatest forwarding energy efficiency in the predicted period is derived to adjust the threshold for balancing the tradeoff between energy efficiency and packet delivery ratio.

The rest of this paper is organized as follows. Section II describes the system model. Section III gives the problem formulation. In Section IV, the DEEOF algorithms are presented and analyzed. Section V evaluates the proposed algorithms by simulation. Finally, the paper is concluded in Section VI.

II. System Model

Consider a mobile DTN situated in an $L \times L$ area composed of a set $\mathcal{N}$ of N nodes distributed sparsely. Any two nodes can communicate with each other once moving into each other's transmission range. Let R denote the maximum transmission radius of each node. We assume that all nodes in the network move independently with a speed $v \in [v_{min}, v_{max}]$ and their mobility patterns [13] are independent and identically distributed.

We focus on a communication session between a source and a destination in the network. The source wants to deliver a number of packets to the destination. Each packet should arrive at the destination within time T. In the paper, the two-hop forwarding scheme is adopted because it has the advantage that the control is operated only by the source and the main energy cost to deliver a packet is met by the source, not by relays. The energy consumption is ignored for the control signaling, e.g., discovering the uses inside the transmission region.

Time is assumed to be slotted with the slot duration being U. Consider a particular packet to be sent by the source at time $t_0 = 0$, the source probes the network to check if any relay moves into its maximum transmission radius at the beginning of each slot $t_0 = 0, t_1 = U, t_2 = 2U, \cdots, t_k = kU, \cdots$, until T when the packet should be dropped. If any relay is detected within the maximum transmission radius R, the source should determine whether or not to forward the packet copy to the nearest relay without a packet copy. When the relay receives the packet copy from the source and moves into the maximum transmission radius of the destination, the relay forwards the packet to the destination.

III. Energy-efficient Opportunistic Forwarding: Problem Formulation

In this section, we formulate the energy-efficient opportunistic forwarding problem as a multi-objective optimization problem.

As we know, the average large-scale path loss for an arbitrary T-R separation is expressed as a function of their distance: $\overline{PL}(d) \propto (\frac{d}{d_0})^n$, where n is the path loss exponent which indicates the rate at which the path loss increases with distance, d_0 is the close-in reference distance which is determined by measurements close to the transmitter, and d is the T-R distance. From the above equation we can see that given the received power, the transmission power is proportional to n-th power of the T-R distance. For simplicity, the equation can be expressed as follows:

$$P_t = d^n \cdot c \tag{1}$$

where P_t is transmission power, c is a constant.

Transmissions between two nodes only take place at meeting times and are assumed to be instantaneous (this is the case when the transmission radius is much smaller than the size of the area). The inter-meeting time (IMT) in our model is assumed to be exponentially distributed with parameter λ, which is equal to $1/E(IMT)$. The validity of this assumption for synthetic mobility models (including, e.g., random walk, random direction, random waypoint) has been discussed in [8]. There exist studies based on traces collected from real-life mobility [14] which argue that IMT may follow a power-law distribution, whereas the authors of [15] have shown that these traces and many others exhibit exponential tails after a cutoff point. As the exponential IMT for mobility models is analyzed in [8], it can be seen that parameter λ is a function of the transmission radius of nodes, so it is denoted as λ_d when the transmission radius is d in the following.

We are now ready to formulate the optimization problem of energy-efficient opportunistic forwarding. To that end, consider a packet arriving at the head of the outgoing queue of the source at time $t_0 = 0$, an opportunistic forwarding policy, denoted as ρ, is formally defined as follows

$$\rho \triangleq [a_1, a_2, \cdots, a_K], \tag{2}$$

where the action $a_k = 1$ (0, respectively) indicates that the source forwards (does not forward, respectively) the packet copy at time $t_k = kU$ and K denotes the largest integer not larger than T/U.

Given a policy ρ, let $S(t)$ denote the delivery predictability which is the packet delivery ratio estimated by the source at time t, let $E_c(t)$ denote the cumulated energy consumed in sending the packet at time t, we define the energy efficiency $\eta(t)$ as $\eta(t) \triangleq S(t)/E_c(t)$. In this paper, we are interested in seeking the optimal opportunistic forwarding policy that maximizes $\eta(T)$ and $S(T)$. The formal optimization problem is given as follows:

$$\begin{aligned} \max_{\rho} \quad & [\eta(T), S(T)] \\ s.t. \quad & E_c(T) \leq E, \end{aligned} \tag{3}$$

where E denotes the total battery reserve of the source.

IV. Distance-based Energy-efficient Opportunistic Forwarding: Algorithm Design

In this section, we present and analyze the energy-efficient opportunistic forwarding algorithms. The core idea of the developed algorithms is to forward the packet when the forward action can maximize the increment of the packet delivery ratio per unit energy, in other words, the source seeks to use its energy in the most efficient way.

As analyzed previously, in each probing instance t_k, the source can establish communication contact with all the relays that move into its maximum transmission radius. Then it selects the nearest relay without a packet copy and makes the decision whether or not to forward the packet copy to it. The relay forwards the received packet once it moves into the transmission range of the destination. If the source forwards the packet copy to a relay at time t, the delivery predictability is as follows:

$$S(t) = 1 - e^{-\lambda_R (T-t)}. \tag{4}$$

Without loss of generality, assume that at time $t_k = kU$, the source detects a number of relays in its maximum transmission radius R, among which relay i is the nearest one to the source with a distance d $(d \leq R)$ and has not received any packet copies. The delivery predictability is $S(t_{k-1})$. Now consider the moment t_k, if the source determines to forward the packet copy to relay i, it will incur a power consumption $E(t_k) = d^n \cdot c$, with the delivery predictability changing to $S(t_k)$, which can be derived as follows:

$$S(t_k) = 1 - [1 - S(t_{k-1})] \cdot e^{-\lambda_R (T-t_k)}. \tag{5}$$

A. Forwarding energy efficiency

Armed with previous analysis, we introduce in this subsection the forwarding energy efficiency.

Definition 1 (Forwarding Energy Efficiency): Consider any probing time instance t_k. Let $E(t_k)$ denote the energy consumed in forwarding the packet copy to the nearest relay without a packet copy and let $\Delta S(t_k) \triangleq S(t_k) - S(t_{k-1})$ if the source forwards the packet copy to the nearest relay. The forwarding energy efficiency, denoted as $\eta_f(t_k)$, is defined as

$$\eta_f(t_k) \triangleq \frac{\Delta S(t_k)}{E(t_k)}. \tag{6}$$

According to Definition 1, if the source forwards the packet copy to relay i at t_k, we can derive the forwarding energy efficiency $\eta_f(t_k)$ as follows:

$$\begin{aligned} \eta_f(t_k) &= \frac{S(t_k) - S(t_{k-1})}{E(t_k)} \\ &= \frac{[1 - S(t_{k-1})] \cdot [1 - e^{-\lambda_R (T-t_k)}]}{d^n \cdot c}. \end{aligned} \tag{7}$$

Taking the node mobility into account, relays may move closer to the source in the future, resulting in a shorter source-relay distance d' $(d' < d)$. Consequently, forwarding packet copy at this moment may consume less energy, in other words, the forwarding energy efficiency may be higher than $\eta(t_k)$. Therefore, at time t_k, the source has to predict the forwarding energy efficiency at time $t_{k+1}, t_{k+2}, \cdots, t_n, \cdots$. Here, we assume that the predicted period, which is denoted by Δ, is:

$$\Delta = \frac{E(t_k)}{E - \sum_{i=1}^{k-1} E(t_i)} \times (T - t_k) \tag{8}$$

where $E(t_i)$ denotes the energy consumption of the source at time t_i $(i = 1, 2 \cdots)$. It can be seen that the predicted period is related to the residual energy and the residual packet time-to-live, the source should efficiently use the residual energy while maintaining high packet delivery ratio. Actually, Δ has an impact on the balance of the tradeoff between energy efficiency and packet delivery ratio. A longer predicted period means the source values energy efficiency more than packet delivery ratio, and vice versa. To further quantify the impact of mobility on the forwarding energy efficiency, we introduce in the next subsection the concept of forwarding equivalent energy-efficiency distance (FEED).

B. Forwarding equivalent energy-efficiency distance (FEED)

As analyzed previously, If the source determines not to forward the packet copy until time t_n, then after forwarding the increment of the packet delivery ratio is

$$S(t_n) - S(t_{k-1}) = [1 - S(t_{k-1})] \cdot [1 - e^{-\lambda_R (T-t_n)}]. \tag{9}$$

Definition 2: (Forwarding equivalent energy-efficiency distance): Consider the time instance t_k with a source-relay distance d, the forwarding equivalent energy-efficiency distance (FEED), denoted as $\widehat{d_k^n}(d)$, is defined as the source-relay distance with which by forwarding the packet copy at time t_n $(n = k+1, k+2 \cdots$, no forwarding is performed between time t_k and $t_n)$, the source can obtain the same forwarding energy efficiency as that of forwarding at time t_k, i.e.:

$$\frac{S(t_n) - S(t_{k-1})}{[\widehat{d_k^n}(d)]^n \cdot c} = \frac{S(t_k) - S(t_{k-1})}{d^n \cdot c}, \tag{10}$$

equivalently,

$$\widehat{d_k^n}(d) = d \cdot \sqrt[n]{\frac{1 - e^{-\lambda_R (T-t_n)}}{1 - e^{-\lambda_R (T-t_k)}}}. \tag{11}$$

Generally, we can compute the FEED at time t_n $(n = k + 1, k + 2 \cdots)$. The engineering implications behind FEED are: if in a future time t_n, there are any relay with a source-relay distance shorter than $\widehat{d_k^n}(d)$, then forwarding the packet copy now at time t_k leads a smaller forwarding energy efficiency than that of the policy of waiting till t_n to forward the packet copy.

C. Distance-based energy-efficient opportunistic forwarding: Algorithm 1

Motivated by the above analysis, we propose the first DEE-OF algorithm (Algorithm 1) whose core idea is as follows: at each probing instance t_k, if there are at least one relay situated within the maximum transmission radius of the source, the source forwards the packet copy to the nearest relay without a packet copy if the probability of achieving a higher forwarding energy efficiency in the future doesn't reach a threshold. In other words, it determines to forward the packet copy if the probability that there are at least one relay whose distance to the source is smaller than $\widehat{d_k^n}(d)$ at time t_n $(t_n > t_k)$ is below a threshold. We denote this probability by P_{better}.

Define random variable φ_{t_n} as an indicator whether there are at least one relay that will be within $\widehat{d_k^n}(d)$ at time t_n, formally expressed as follows:

$$\varphi_{t_n} = \begin{cases} 1, & \text{if there are at least one relay within the} \\ & \text{transmission radius } \widehat{d_k^n}(d) \text{ at time } t_n \\ 0, & \text{otherwise.} \end{cases} \tag{12}$$

The probability P_{better} can be derived as follows:

$$P_{better} = 1 - P\{\varphi_{t_{k+1}} = 0 \cap \varphi_{t_{k+2}} = 0 \cap \cdots\}. \tag{13}$$

If at time t_n, there is no relay within $\widehat{d_k^n}(d)$, then the probability that there is no relay within $\widehat{d_k^{n+1}}(d)$ at time t_{n+1}

is the probability that there is no relay within $\widehat{d}_k^{n+1}(d)$ during the time interval $[t_n, t_{n+1}]$, denoted as $P\{\varphi_{t_n,t_{n+1}} = 0\}$. Thus we have:

$$P\{\varphi_{t_{n+1}} = 0\} = P\{\varphi_{t_n} = 0\} \times P\{\varphi_{t_n,t_{n+1}} = 0\}. \tag{14}$$

It follows that

$$\begin{aligned} P_{better} &= 1 - P\{\varphi_{t_k,t_{k+1}} = 0 \cap \varphi_{t_{k+1},t_{k+2}} = 0 \cap \cdots\} \\ &= 1 - e^{-[\lambda_{\widehat{d}_k^{k+1}(d)} + \lambda_{\widehat{d}_k^{k+2}(d)} + \cdots] \cdot U \cdot m} \end{aligned} \tag{15}$$

where U represents the slot duration, and m represents the number of relays without any packet copies at time t_k.

The proposed DEEOF algorithm based on the FEED is described using pseudocode as follows. In the algorithm, θ denotes the threshold of P_{better} above which the source determines not to forward the packet copy. An intuitively natural setting is $\theta = 0.5$. More generically, tuning θ is a tradeoff between energy efficiency and packet delivery ratio: smaller θ increases energy efficiency at the price of degrading system performance, and vice versa.

Algorithm 1 DEEOF: executed at the source at each contact time t_k

```
Initialization: Set threshold θ
if any relay is in the maximum transmission radius then
    Measure the distance to the nearest relay without a packet copy
    Calculate FEEDs at time t_n (n ≥ k + 1) and P_better
    if P_better < θ then
        Forward the packet copy to the nearest relay
    else
        Do not forward the packet copy
    end if
end if
```

D. Distance-based energy-efficient opportunistic forwarding: Algorithm 2

As previous analysis, we present the second DEEOF algorithm (Algorithm 2) based on the probability distribution function (p.d.f.) of the forwarding energy efficiency. The difference between the two algorithms is their different accuracy on the prediction of the expected forwarding energy efficiency in the predicted period. Algorithm 2 can predict not only how possible a better energy efficiency is achieved, but also how good it is by the p.d.f. analysis. Therefore, it can provide more accurate prediction result, and thus make more appropriate forwarding decisions with the price of higher computation complexity.

In order to derive the p.d.f. of the forwarding energy efficiency, first we need to derive the p.d.f. of the distance between two nodes. We assume that the stationary distributions of the location of the nodes are uniform, i.e.:

$$x_i \sim U(0, L) \quad \text{and} \quad y_i \sim U(0, L) \tag{16}$$

where (x_i, y_i) are the coordinate of the nodes.

If the nodes are located uniformly in the one-dimensional region, the p.d.f. of the distance is easily to got:

$$f(d) = \frac{2}{L^2}(L - d), \tag{17}$$

where L is the region length, d is the distance between nodes. Now we consider the case in the two-dimensional region to derive the p.d.f. of the distance between arbitrary two nodes (x_1, y_1), (x_2, y_2). Let $x = |x_1 - x_2|$, $y = |y_1 - y_2|$, so we have:

$$f_x(x) = \frac{2}{L^2}(L - x) \quad \text{and} \quad f_y(y) = \frac{2}{L^2}(L - y). \tag{18}$$

Since x and y are independent, the joint probability density function of x and y is:

$$f_{xy}(x, y) = f_x(x) \cdot f_y(y) = \frac{4}{L^4}(L - x)(L - y). \tag{19}$$

In order to get the p.d.f. of the distance, we make the following transformation.

$$r = \sqrt{x^2 + y^2} \quad \text{and} \quad \theta = \arctan\frac{y}{x}, \tag{20}$$

where r is the distance between two nodes and θ is the angle. So the joint probability density function of r and θ is:

$$f_{r\theta}(r, \theta) = \frac{f_{xy}(r\cos\theta, r\sin\theta)}{|J|}, \tag{21}$$

where J is the Jacobian:

$$J = \left| \begin{matrix} \frac{\partial r}{\partial x} & \frac{\partial r}{\partial y} \\ \frac{\partial \theta}{\partial x} & \frac{\partial \theta}{\partial y} \end{matrix} \right|_{x = r\cos\theta, y = r\sin\theta} = \frac{1}{r}. \tag{22}$$

Thus we have the following expression of $f_{r\theta}(r, \theta)$:

$$f_{r\theta}(r, \theta) = \frac{4r}{L^4}(L - r\cos\theta)(L - r\sin\theta). \tag{23}$$

If we take the integral of θ, the p.d.f. of the distance between two nodes is obtained as follows:

$$f(r) = \begin{cases} \frac{2\pi r}{L^2} - \frac{8r^2}{L^3} + \frac{2r^3}{L^4}, & 0 \le r \le L \\ \frac{4r(\frac{\pi}{2} - 2\arccos\frac{L}{r})}{L^2} - \frac{8r(L - \sqrt{r^2 - L^2})}{L^3} \\ + \frac{2r(2L^2 - r^2)}{L^4}, & L < r \le \sqrt{2}L. \end{cases} \tag{24}$$

Now we derive the p.d.f. of the forwarding energy efficiency at time t_k. The source can only establish communication contact with the relays that move into its maximum transmission radius, so we consider the case of $0 \le r \le R$. The cumulative distribution function (c.d.f.) of the distance between two nodes is:

$$F(r) = \int_0^r f(r)dr = \frac{\pi r^2}{L^2} - \frac{8r^3}{3L^3} + \frac{r^4}{2L^4} \quad (0 \le r \le R). \tag{25}$$

Let m denote the number of relays without any packet copies at time t_k, the c.d.f. of the nearest distance to the source among the m nodes is:

$$F_{min}(r) = 1 - [1 - F(r)]^m. \tag{26}$$

And the p.d.f. of the nearest distance to the source among the m nodes is:

$$f_{min}(r) = F'_{min}(r) = m[1 - F(r)]^{m-1} \cdot f(r). \tag{27}$$

From (7), we have:

$$\eta_f(t_k) = \mathrm{g}(d) = \frac{S(t_k) - S(t_{k-1})}{d^n \cdot c}. \tag{28}$$

Thus

$$d = \mathrm{h}(\eta_f(t_k)) = \sqrt[n]{\frac{S(t_k) - S(t_{k-1})}{\eta_f(t_k) \cdot c}} \tag{29}$$

where $\mathrm{h}(\eta_f(t_k))$ is the inverse function of $\mathrm{g}(d)$. Because $\mathrm{g}(d)$ is the descending function of d, the p.d.f. of the greatest forwarding energy efficiency at time t_k is:

$$f_{max}(\eta_f(t_k)) = f_{min}(\mathrm{h}(\eta_f(t_k))) \cdot |\mathrm{h}'(\eta_f(t_k))|. \tag{30}$$

Then the c.d.f. of the greatest forwarding energy efficiency at time t_k is:

$$\begin{aligned} &F_{max}(\eta_f(t_k)) \\ &\quad = \int f_{min}(\mathrm{h}(\eta_f(t_k))) \cdot |\mathrm{h}'(\eta_f(t_k))| \; d(\eta_f(t_k)) \\ &\quad = [1 - F(\mathrm{h}(\eta_f(t_k)))]^m. \end{aligned} \tag{31}$$

Thus the c.d.f. of the greatest forwarding energy efficiency in the predicted period is:

$$F_{max}(\eta) = F_{max}(\eta_f(t_{k+1})) \cdot F_{max}(\eta_f(t_{k+2})) \cdots, \tag{32}$$

and the p.d.f. of the greatest forwarding energy efficiency in the predicted period is:

$$\begin{aligned} f_{max}(\eta) = {} & f_{max}(\eta_f(t_{k+1})) \cdot F_{max}(\eta_f(t_{k+2})) \cdots \\ & + F_{max}(\eta_f(t_{k+1})) \cdot f_{max}(\eta_f(t_{k+2})) \cdots + \cdots. \end{aligned} \tag{33}$$

From (33), we can get the mean $\overline{\eta}$ and the standard deviation σ of the greatest forwarding energy efficiency in the predicted period. In Algorithm 2, the source calculates the forwarding energy efficiency $\eta_f(t_k)$ of the nearest relay i, whose distance from the source is d. Then the source predicts the p.d.f. of the greatest forwarding energy efficiency in the future. According to the mean $\overline{\eta}$ and the standard deviation σ of the greatest forwarding energy efficiency calculated by (33), let Ψ denote the threshold of $\eta(t_k)$ above which the source determines to forward the packet copy to the relay i. It is set as $\Psi = \overline{\eta} + \alpha \cdot \sigma$. The parameter α is used for controlling the forwarding decision. Tuning α is a tradeoff between energy efficiency and packet delivery ratio: larger α increases energy efficiency at the price of degrading system performance, and vice versa.

V. Simulation

In this section, we evaluate the performance of the proposed DEEOF algorithms. Under the circumstances where the total battery reserve of the source is unconstrained, and is seriously constrained, we evaluate the performance of Algorithm 1 and Algorithm 2 by simulation using Matlab. For performance comparison, two existing algorithms are adopted as baselines.

- *Two-hop forwarding* [8]: The forwarding probability is 1 (indicated by "Always" in figures).
- *Threshold dynamic policy* [10]: The source just sends packet copies to relays before a time threshold (indicated by "Threshold" in figures).

The performance metrics include the average energy consumption, the packet delivery ratio, and the energy efficiency with different packet time-to-live.

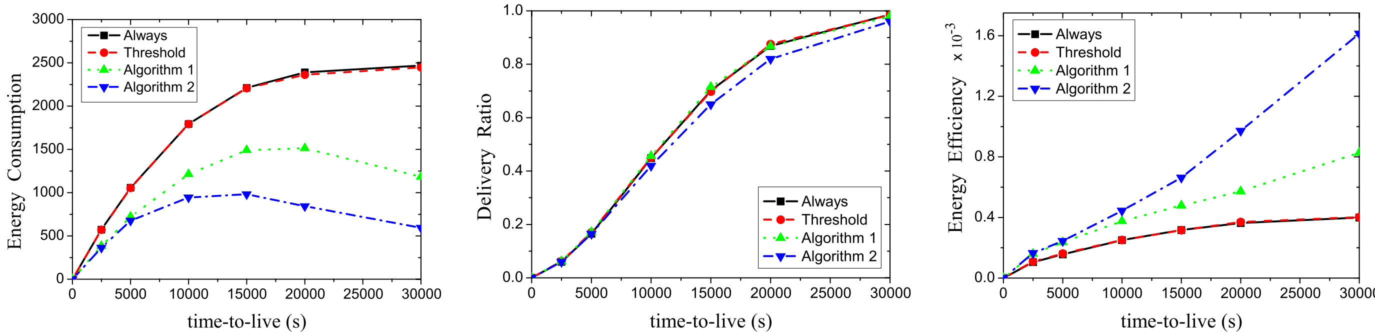
A. Simulation configuration

In the simulation, 100 mobile nodes are deployed in the network, in which one source-to-destination pair is investigated for collecting simulation results. Each node's movement is independent following random direction (RD) mobility model. The maximum transmission radius is 15m and the mobile nodes move at a speed of 5m/s in a square of size 5km×5km, without pausing. Thus for RD mobility model [8], the corresponding value of λ_R is $7.64 \times 10^{-6} s^{-1}$. We assume that the signal propagates in free space propagation model, so from (1) we have $P_t = d^2 \cdot c$. Without loss of generality, it is set as $c = 1$. We set the slot duration $U = 1$s. For the circumstances where the energy is unconstrained and is seriously constrained, the corresponding values of the total battery reserve of the source are 5000 and 1000, respectively. The thresholds in Algorithm 1 and Algorithm 2 are $\theta = 0.5$ and $\alpha = 0.1$, respectively.

B. Performance comparison

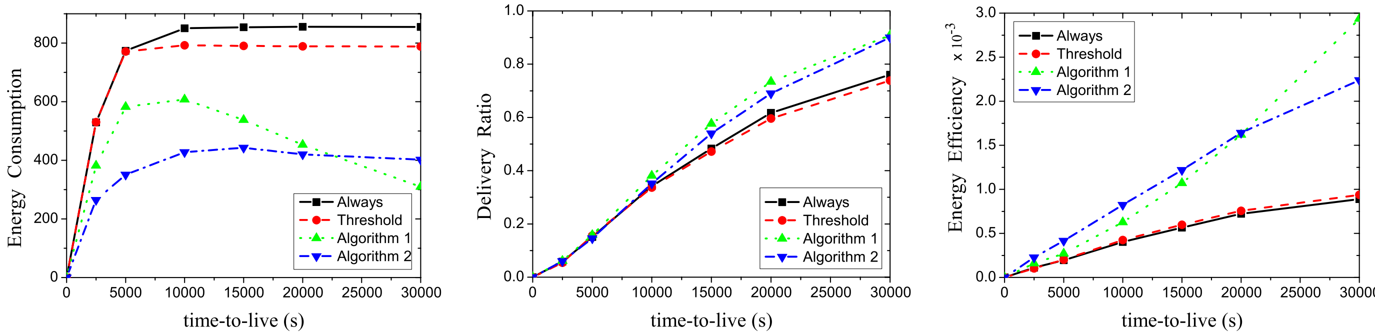
Fig. 1 shows the performance of the four forwarding algorithms with different packet time-to-live when the energy is unconstrained, i.e., E=5000. In this case, the packet delivery ratio of the four algorithms is almost the same, while the energy efficiency of Algorithm 1 and Algorithm 2 is higher than the other two algorithms. When $T = 20000s$, the average energy consumption of the DEEOF algorithms begin to decrease with the increase of T. The proposed DEEOF algorithms save about 50% energy compared to the other two algorithms when $T = 30000s$. The reason is that for the DEEOF algorithms, the source determines whether to forward the packet copy to the relays by predicting the movement of the relays in the future. From (8), when T increases, the source node should have a long-term consideration about the energy efficiency, therefore it will predict a longer period of time, which leads to a more exigent requirement to forward to the relay, namely, the source requires the relays closer so that it could consume the energy more efficiently. It can be also observed that Algorithm 2 achieves higher energy efficiency but a little lower packet delivery ratio than Algorithm 1 with different packet time-to-live. The reason is that by predicting the expected forwarding energy efficiency in the future, Algorithm 2 can provide more accurate prediction result, and thus the source has a more stringent requirement to forward to the relays.

Fig. 2 shows the performance of the four forwarding algorithms with different packet time-to-live when the energy is seriously constrained, i.e., E=1000. In this case, we can find the proposed DEEOF algorithms outperform $p(t) = 1$ and the threshold dynamic policy. Compared with the baseline algorithms, DEEOF algorithms consume less energy, and achieve both higher packet delivery ratio and higher energy efficiency with different packet time-to-live. For example, when $T = 30000s$, Algorithm 1 saves about 60% energy compared to the threshold dynamic policy. The packet delivery ratio of the DEEOF algorithms is about 15% higher than the other two algorithms and the energy efficiency is significantly higher. This is because that for the other two algorithms, once the relays move into the maximum transmission radius of the source, the source forwards the packet copies immediately with probability 1 without considering whether the relays will continue to move closer. The DEEOF algorithms are proposed under the consideration of energy efficiency and packet delivery ratio, the source will forward the packet copy to the relay if it predicts that the probability of achieving



(a) average energy consumption (b) packet delivery ratio (c) energy efficiency

Fig. 1. Performance comparison with unconstrained energy (E=5000)



(a) average energy consumption (b) packet delivery ratio (c) energy efficiency

Fig. 2. Performance comparison with seriously constrained energy (E=1000)

higher forwarding energy efficiency in the future does not reach the set threshold.

VI. Conclusion

In this paper, we propose two DEEOF algorithms to maximize both the energy efficiency and packet delivery ratio. Exploiting the node mobility, opportunistic forwarding is distance-based and dynamically adjusted in order to achieve energy saving. The concept of the FEED is developed by comparing the current energy efficiency and the estimated future expectation. Furthermore, the distribution of the greatest forwarding energy efficiency in the predicted period is investigated to provide more accurate prediction for the energy efficiency. Simulation results confirm that, compared with the two-hop forwarding and the threshold dynamic policy, our proposed algorithms greatly improve the energy efficiency while maintaining a high packet delivery ratio. The performance improvement of our algorithms is demonstrated by simulation, especially for systems where the source has very limited battery reserves.

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