Opportunistic Forwarding in Energy Harvesting Mobile Delay Tolerant Networks

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***Abstract*—Opportunistic forwarding assisted by mobile relays is an effective way of improving network capacity and packet delivery ratio in delay tolerant networks (DTNs). However, such performance gain comes at the price of increased energy consumption due to the duplicated transmissions at relays. In this paper, we investigate how energy harvesting, a promising technique of enabling sustainable communications, can be exploited to improve the performance of opportunistic forwarding in mobile DTNs. Specifically, we formulate the problem using a Markov Decision Process (MDP) framework in which each source should strike a balance between *exploitation*, by forwarding the packet to the relay currently in contact, and *exploration*, by waiting for possible better relays in the future, given the harvested energy constraint. The formulated MDP having exponential complexity, we devise a heuristic relay-assisted opportunistic forwarding scheme, termed as adaptive M-step lookahead scheme, to alleviate the computation complexity, where M can be adjusted adaptively according to both the current energy and the energy that might be harvested in the future. Simulation results show that our proposed algorithm can use the harvested energy more efficiently, especially for the circumstance where the energy harvesting rate is low.**

I. Introduction

Mobile delay tolerant networks (DTNs) are composed of human carried mobile devices which are characterized by nodes with unpredictable mobility, heterogeneous contact rates and local information [1]–[4]. Node mobility was considered conventionally as an obstacle which needs to be intelligently overcome for seamless communication between nodes. However, it has recently been recognized that mobility can be exploited to improve network performance. Specifically, Grossglauser and Tse [5] introduced the advantages of mobility in the context of mobile ad hoc networks. The multiuser diversity is exploited by forwarding the traffic to relays for additional "routes" between the source and the destination.

The packet forwarding algorithms for DTNs usually spawn and keep multiple copies of the same packet in different nodes to increase the packet delivery ratio [6], with the price of significant energy consumption that may shorten the lifetime of the battery-powered devices. Recently, extensive research efforts have been devoted to opportunistic forwarding [7], [8], which tries to reduce the number of each packet while retaining a relatively high delivery ratio. Groenevelt and Nain [9] 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. Neglia and Zhang [10] presented an analytical study on the tradeoff between delivery delay and resource consumption for epidemic routing in DTNs. The optimal forwarding policy is a threshold on the number of copies in the network. Li *et al.* [11] introduced a continuous-time Markov model to analyze the problem of the energy-efficient optimal opportunistic forwarding policies in DTNs. An opportunistic, and energy efficient routing protocol (E^2R) was proposed in [12] which introduced a novel greedy forwarding algorithm and an efficient self-suppression scheme in multi-hop wireless networks.

Energy harvesting technique [13][14] can power the communication devices with renewable energy from the environment, it has been recently seen as a promising approach to address the energy supply problem. An online algorithm called ESA [15], which jointly manages the energy and makes power allocation decisions for packet transmissions, was developed to achieve close-to optimal utility performance in energy harvesting networks. Yang *et al.* [16] investigated a point-to-point communication system with an energy harvesting transmitter, and developed a packet scheduling scheme that minimizes the time by which all of the packets are delivered to the receiver. Li *et al.* [17] developed scheduling policies to choose the appropriate transmission mode according to the available energy at the nodes as well as the states of their energy harvesting and event generation processes in wireless sensor networks. However, existing works did not simultaneously exploit energy harvesting and node mobility to improve network performance.

The aim of this paper is to devise the opportunistic forwarding scheme to maximize the expected packet delivery ratio by taking into account both energy harvesting and node mobility. Such opportunistic forwarding scheme is by nature a distributed decision making process where each source should determine independently whether to forward the packet copy immediately, or to wait for a better relay that can potentially

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save more energy. Since the processes of energy harvesting and node contacts are random, the key challenge is to relate the energy consumption and the packet delivery ratio in the opportunistic forwarding process.

To this end, we formulate the opportunistic forwarding problem as an MDP and provide the associated optimality condition. The formulated MDP having exponential complexity, we develop a low-complexity adaptive M-step lookahead algorithm in which M is adjusted adaptively according to both the current energy and the energy which might be harvested in the future. According to the rate of energy harvesting, the source predicts M steps lookahead contact with the relays, and then makes the forwarding decision so as to use the harvested energy more efficiently and maximize the packet delivery ratio.

The rest of this paper is organized as follows. Section II describes the system model and gives the problem statement. Section III formulates the optimization problem using an MDP framework. In Section IV, a low-complexity adaptive M-step lookahead forwarding algorithm is proposed. Section V evaluates the proposed algorithms by simulation. Finally, the paper is concluded in Section VI.

II. System Model and Problem Statement

Consider a mobile DTN situated in an $L \times L$ area composed of a set $\mathcal{N}$ of N nodes distributed sparsely. The mobility patterns [18] of all nodes are independent and identically distributed, and each node in the network moves with a constant speed $v \in [v_{min}, v_{max}]$. Any two nodes can communicate with each other once moving into each other's transmission range denoted as r, i.e. they contact with each other. Packets are transmitted from a node to another at time instants during node contact intervals, after which both nodes hold packet copies.

We model the point process of the contact times between pairs of nodes as independent Poisson point process, so the inter contact times in our model is exponentially distributed. The validity of this assumption for synthetic mobility models (including, e.g., random walk, random direction, random waypoint) has been discussed in [9][1]. The contact rate of the pairwise nodes $\{i, j\}$ is denoted as $\lambda_{i,j}$:

$$\lambda_{i,j} \approx \frac{2\omega r \mathbb{E}[V^*]}{L^2}, \tag{1}$$

where $\omega \approx 1.3683$ is a constant specific to the random waypoint mobility model, r is the transmission range of each node and $\mathbb{E}[V^*]$ is the average relative speed between two nodes.

As the nodes in the mobile DTN move with different speeds, they are with heterogeneous contact rates which can be derived by (1). Nodes do not possess any a priori knowledge of the speed of other nodes except the probability distribution function of the speed $f(v)$. However, nodes can obtain the knowledge of the others' speeds when they contact.

Here, we focus on a communication session between a particular source and a particular destination in the network. A packet is generated by the source at time $t_0 = 0$ and should arrive at the destination within the lifetime T. It means that all nodes in the network should discard it after time T. It is assumed that mobile nodes can store and forward packets using mobility in two-hop fashion [9]: The source sends the packet copy to the relay when they contact with each other, then the packet copy is stored and brought by the mobile relays to the region close to the destination. Finally, the relays forward the packet to the destination. Transmissions between the two nodes are assumed to be instantaneous.

The source is equipped with a rechargeable battery for storing the harvested energy from the environment. The battery capacity is denoted as B. A discrete time model is assumed where time is slotted in intervals of unit length. The source can harvest a certain unit of energy in each slot and the energy harvesting process is modeled as a Bernoulli process with rate σ. Forwarding a fixed-length packet consumes one unit of energy.

Let $\{t_k,\ k = 1, 2, \cdots, K\}$, denote the contact time of the source with the relays, where t_k denotes the time of the k-th contact and t_K is the time of the last contact before the lifetime T. At any contact times, the source should determine whether to forward the packet copy now or achieve the energy saving potential to forward it to other possible better relays later. When the relay receives the packet copy from the source and moves into the transmission range of the destination, the relay forwards the packet to the destination.

The opportunistic forwarding decisions, denoted as $\mathbf{A}$, is formally defined as follows

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

where the action $a_k = 1$ (0, respectively) indicates that the source forwards (does not forward, respectively) the packet at the k-th contact with the relays. Given $\mathbf{A}$, let $D(t)$ denote the delivery predictability which is the packet delivery ratio estimated by the source at time t.

If the source forwards the packet to a relay at time t, the delivery predictability is as follows:

$$D(t) = 1 - e^{-\lambda_{*,d}(T-t)}, \tag{3}$$

where $\lambda_{*,d}$ denotes the contact rate between the relay and the destination. The initial delivery predictability $D(t_0) = 1 - e^{-\lambda_{s,d}T}$, where $\lambda_{s,d}$ denotes the contact rate between the source and the destination.

Without loss of generality, assume that at time t_k, the source establishes communication contact with the relay i. The delivery predictability is $D(t_k)$. Now consider the moment t_k, if the source determines to forward the packet copy to relay i, it will incur a unit energy consumption, with the delivery predictability changing to $D(t_{k+1})$, which can be derived as follows:

$$D(t_{k+1}) = 1 - [1 - D(t_k)] \cdot e^{-\lambda_{i,d}(T-t_k)}. \tag{4}$$

[1]There exist studies based on traces collected from real-life mobility [19] which argue that IMT may follow a power-law distribution, whereas the authors of [20] have shown that these traces and many others exhibit exponential tails after a cutoff point. For this reason, we choose to stick with the exponential meeting time assumption.

Our goal is to make the optimal forwarding decisions for maximizing the final delivery predictability $D(T)$. The optimization problem is formulated formally as follows:

$$\begin{aligned} \max_{\mathbf{A}} \quad & D(T) \\ s.t. \quad & E_{\Sigma}^{C}(k) \leq E_{\Sigma}^{EH}(k),\ \forall k \end{aligned} \tag{5}$$

where $E_{\Sigma}^{C}(k)$ denotes the cumulated consumed energy of the source forwarding packet copies at time t_k, and $E_{\Sigma}^{EH}(k)$ denotes the cumulated harvested energy of the source at time t_k. This constraint implies that the source cannot forward the packet copy without enough energy stored in its battery.

III. MDP Framework

In this section, we construct an MDP framework for the opportunistic forwarding problem, thereby allowing us to obtain the optimal condition. First, we discuss the key components in the MDP framework.

State Define the source state at the contact time t_k as $S_k = (E_k, F_k)$, where $E_k \in \{0, 1, 2\cdots, B\}$ denotes the energy available in the battery of the source at the time t_k before the decision, and $F_k \in \{1, 2\cdots, N\}$ denotes the number of the packet copies at the time t_k before the decision. The initial source state is $S_0 = (0, 1)$.

Action The source action at the time t_k is denoted as $a_k \in \{0, 1\}$, where $a_k = 1$ (0, respectively) indicates that the source forwards (does not forward, respectively) the packet at the k-th contact with the relays.

Transition Probability Let $P(E_{k+1} \mid E_k, a_k)$ denotes the transition probability from energy state E_k to E_{k+1} under action a_k. Since the source can harvest energy and the energy harvesting process is modeled as a Bernoulli process with rate σ, we have

$$P(E_{k+1} \mid E_k, a_k) = \begin{cases} C^{j}_{\tau(S_k,a_k)} \cdot \sigma^{j} \cdot (1-\sigma)^{\tau(S_k,a_k)-j} \\ \quad \text{if } a_k = 1, E_{k+1} = E_k - 1 + j \\ C^{j}_{\tau(S_k,a_k)} \cdot \sigma^{j} \cdot (1-\sigma)^{\tau(S_k,a_k)-j} \\ \quad \text{if } a_k = 0, E_{k+1} = E_k + j, \end{cases} \tag{6}$$

where $\tau(S_k, a_k)$ is the average transition time in state S_k under action a_k. We model the point process of the contact times between pairs of nodes as independent Poisson point process in Section II. As the superposition of independent Poisson processes is a Poisson process with rate equal to the sum of the rates, the contact process between relays with no packet copy and the source is a nonhomogeneous Poisson process. The average contact rate between the source and the relay, denoted as $\overline{\lambda}_{s,*}$, can be calculated by (1), where the speed of the relay is estimated by the average speed of the nodes, which can be estimated by $f(v)$. As $\tau(S_k, a_k)$ is the average transition time in state S_k under action a_k, equivalently it represents the average time that the source takes to contact the relays not carrying any packet copy in state S_k under action a_k. If a_k=0, then the number of the relays not carrying any packet copy does not change. The contact rate is $(N - F_k)\overline{\lambda}_{s,*}$. Otherwise, if a_k=1, then the number of the relays not carrying any packet copy decreases to $N - F_k - 1$, accordingly the contact rate is $(N - F_k - 1)\overline{\lambda}_{s,*}$. Therefore, the average transition time in state S_k under action a_k is as follows:

$$\tau(S_k, a_k) = \begin{cases} \lceil \frac{1}{(N-F_k-1)\overline{\lambda}_{s,*}} \rceil & \text{if } a_k = 1 \\ \lceil \frac{1}{(N-F_k)\overline{\lambda}_{s,*}} \rceil & \text{if } a_k = 0, \end{cases} \tag{7}$$

where $\lceil \cdot \rceil$ is ceiling function.

The transition probability from F_k to F_{k+1} under action a_k is determinate, thus the expression of F_{k+1} is as follows:

$$F_{k+1} = \begin{cases} F_k + 1 & \text{if } a_k = 1 \\ F_k & \text{if } a_k = 0. \end{cases} \tag{8}$$

Reward In order to correspond to the optimization problem (5), we define the immediate reward $R(S_{k+1}|S_k, a_k)$ as the increment of the delivery predictability in state S_k under action a_k. According to (4), $R(S_{k+1}|S_k, a_k)$ can be calculated as:

$$R(S_{k+1}|S_k, a_k) = \begin{cases} [1 - D(t_k)][1 - e^{-\lambda_{i,d}(T-t_k)}] & \text{if } a_k = 1 \\ 0 & \text{if } a_k = 0. \end{cases} \tag{9}$$

Value Function We define π as the policy vector which is a mapping from the source state S_k to the action a_k for all time t_k. The value function $V_\pi(S_k)$ is defined as the cumulative reward for starting in state S_k and acting according to π thereafter. Based on the Bellman equation [21], the value function is given as follows:

$$V_\pi(S_k) = R(S_{k+1}|S_k, a_k) + \sum_{S_{k+1}} P(S_{k+1}|S_k, a_k) V_\pi(S_{k+1}) \tag{10}$$

where $P(S_{k+1}|S_k, a_k)$ denotes the transition probability from state S_k to S_{k+1} under action a_k.

The value function also includes the reward from the packet arriving at the head of the outgoing queue of the source at time $t_0 = 0$ to the first contact time t_1. Note that in duration $[0, t_1)$ there is no decision from the source, hence the immediate reward does not depend on the policy. It holds:

$$V_\pi(S_0) = 1 - e^{-\lambda_{s,d}T} + V_\pi(S_1). \tag{11}$$

The optimal value function V^* is the unique solution of Bellman equation:

$$\begin{aligned} V_\pi(S_k)^* = \max_{a_k \in \{0,1\}} \{ & R(S_{k+1}|S_k, a_k) \\ & + \sum_{S_{k+1}} P(S_{k+1}|S_k, a_k) V_\pi(S_{k+1}) \} \end{aligned} \tag{12}$$

The corresponding optimal actions in each contact time can be calculated by backward induction, and then stored in a table. By searching the table in each source state for the corresponding optimal action, the optimal opportunistic forwarding scheme for maximizing the delivery predictability is obtained.

IV. Adaptive M-step Lookahead Opportunistic Forwarding Scheme

The optimal scheme for the opportunistic forwarding problem is provided in the last section. However, its value function $V_\pi(S_k)$ is obtained by calculating over all possible state transitions, which leads to the curse of dimensionality. Since the practical application of the optimal scheme is severely limited due to its exponential computation complexity, a low-complexity scheme is called for to achieve a desired balance between performance and computation complexity. In this section, we propose an adaptive M-step lookahead algorithm to make the forwarding decisions. According to the rate of energy harvesting, the source predicts an M-step lookahead contact with the relays, and then makes the forwarding decision to use the harvested energy more efficiently and maximize the packet delivery ratio in mobile DTNs.

As analyzed previously, in each contact instance t_k, the source makes the decision whether or not to forward the packet copy to the relay by taking into consideration the current energy state and the increment of delivery predictability. Forwarding the packet increases the delivery predictability, but the energy saving potential has the possibility to obtain a higher increment as the source meets a higher contact rate relay in the future. Therefore, forwarding the packet at the moment is likely to cause a hazard that the source will not harvest enough energy to forward a packet at the following contact times. Balancing the current reward and the future reward of energy consumption, we provide an adaptive M-step lookahead forwarding algorithm as follows.

First, we simplify the optimal forwarding problem according to its properties. At a given contact time t_k, no matter what the action a_k is, the delivery predictability at time t_{k+1} can be expressed as

$$D(t_{k+1}) = 1 - [1 - D(t_k)] \cdot e^{-\lambda_{*,d}(T-t_k)\cdot a_k}. \tag{13}$$

After some simple derivations, the expression of $D(t_{k+1})$ can be rewritten as

$$\frac{1 - D(t_{k+1})}{1 - D(t_k)} = e^{-\lambda_{*,d}(T-t_k)\cdot a_k}. \tag{14}$$

Thus, we can obtain the following equation of $D(t_K)$ by iteration:

$$D(t_K) = 1 - [1 - D(t_k)] \cdot \prod_{i=k}^{K-1} e^{-\lambda_{*,d}(T-t_i)\cdot a_i}. \tag{15}$$

As t_K is the time of the last contact before T, the expression of $D(T)$ is given as follows:

$$D(T) = 1 - [1 - D(t_k)] \cdot \prod_{i=k}^{K} e^{-\lambda_{*,d}(T-t_i)\cdot a_i}. \tag{16}$$

Now, we can specify the optimization problem of (5) as follows:

$$\begin{aligned} \max_{\mathbf{A}} \quad & 1 - [1 - D(t_0)] \cdot \prod_{i=1}^{K} e^{-\lambda_{*,d}(T-t_i)\cdot a_i} \\ s.t. \quad & E_\Sigma^C(i) \le E_\Sigma^{EH}(i),\ \forall i \end{aligned} \tag{17}$$

According to the monotonicity of $D(T)$, the optimization problem can be simplified as:

$$\begin{aligned} \max_{\mathbf{A}} \quad & \sum_{i=1}^{K} \lambda_{*,d} \cdot (T - t_i) \cdot a_i \\ s.t. \quad & E_\Sigma^C(i) \le E_\Sigma^{EH}(i),\ \forall i \end{aligned} \tag{18}$$

Next, we derive M, the number of steps that should be considered for future reward in solving the MDP. The source estimates if it can harvest enough energy to forward packet copies at the predicted time of the following contacts after the energy consumption of this forwarding. As energy harvesting process is modeled as a Bernoulli process, the expectation of the energy harvested during the average transition time in state S_k under action $a_k = 1$ is equal to $\sigma \cdot \tau(S_k, 1)$.

If $\sigma \cdot \tau(S_k, 1) \ge 1$, as $\tau(S_k, a_k)$ is a monotone nondecreasing function, then $\sigma \cdot \tau(S_{k+i}, a_{k+i}) \ge 1, \forall i$. Thus we have the following inequality

$$\sum_{i=0}^{n-1} \sigma \cdot \tau(S_{k+i}, a_{k+i}) \ge n \ge \sum_{i=0}^{n-1} a_{k+i}. \tag{19}$$

The inequality above means that if $\sigma \cdot \tau(S_k, 1) \ge 1$, the expected rate of energy harvesting is higher than the expected contact rate between source and relays not carrying any packet copy from the time t_k. As the source is expected to harvest enough energy to forward packets at the predicted time of the following contacts, we need to consider the current reward only and the source will forward the packet at the time t_k, i.e. $a_k = 1$.

On the other hand, if $\sigma \cdot \tau(S_k, 1) < 1$, the source may not harvest enough energy to forward a packet copy at the predicted time of the following contacts after the energy consumption of this forwarding. In that case, M should be adjusted adaptively according to the current energy and the harvested energy in the future. We determine M according to the following inequations.

$$\begin{cases} E_k - 1 + \sum_{i=0}^{M-2} \sigma \cdot \tau(S_{k+i}, 1) \ge M - 1 \\ E_k - 1 + \sum_{i=0}^{M-1} \sigma \cdot \tau(S_{k+i}, 1) < M. \end{cases} \tag{20}$$

The expressions above imply that the source can harvest enough energy to forward packets at the predicted time of the next $M-1$ contacts after the energy consumption of this forwarding, but cannot forward at the predicted time of the next M-th contact. Thus the source has to consider whether it is worth consuming one unit of energy at this time or achieving the energy saving potential to forward in the M-step future.

Lemma 1: There exists a unique integer value M by solving (20).

Proof: Define a function $f(n)$ as

$$f(n) = E_k - 1 + \sum_{i=0}^{n-1} [\sigma \cdot \tau(S_{k+i}, 1) - 1] \tag{21}$$

It is obvious that $f(0) = E_k - 1 \ge 0$. As $\sigma \cdot \tau(S_{k+i}, 1) < 1$, $f(n)$ is a strictly monotone decreasing function of n. Therefore, there exists a unique integer value M satisfying $f(n) < 0$ if $n \ge M$. ■

Let $t^{'}_{k+i}$ denote the predicted time of the next i-th contact which can be predicted by (7). If $t^{'}_{k+M} \geq T$, which means that the predicted time of the next M-th contact is after the packet lifetime, then the source will forward the packet copy to the relay i at the time t_k. Otherwise, according to the optimization problem in (18), at the given time t_k, the following expression should be maximized:

$$\lambda_{i,d} \cdot (T - t_k) \cdot a_k + \sum_{i=1}^{M} \overline{\lambda}_{*,d} \cdot (T - t^{'}_{k+i}) \cdot a_{k+i}, \qquad (22)$$

where $\overline{\lambda}_{*,d}$ denotes the average contact rate between the relay and the destination, which can be calculated by (1), where the speed of the relay is estimated by the average speed of the nodes, which can be estimated by $f(v)$. As the harvested energy is only enough to forward M packets during the predicted time, the first M maximum value among $\lambda_{i,d} \cdot (T - t_k)$ and $\overline{\lambda}_{*,d} \cdot (T - t^{'}_{k+i}), i = 1, \cdots, M$ should be chosen to maximize (22).

Lemma 2: Choosing the first M maximum value among $\lambda_{i,d} \cdot (T - t_k)$ and $\overline{\lambda}_{*,d} \cdot (T - t^{'}_{k+i}), i = 1, \cdots, M$ is only need to compare $\lambda_{i,d} \cdot (T - t_k)$ with $\overline{\lambda}_{*,d} \cdot (T - t^{'}_{k+M})$.

Proof: According to the monotonicity of $t^{'}_{k+i}$, the minimum value among $\overline{\lambda}_{*,d} \cdot (T - t^{'}_{k+i}), i = 1, \cdots, M$ is $\overline{\lambda}_{*,d} \cdot (T - t^{'}_{k+M})$, so we only need to compare $\lambda_{i,d} \cdot (T - t_k)$ with $\overline{\lambda}_{*,d} \cdot (T - t^{'}_{k+M})$. If $\lambda_{i,d} \cdot (T - t_k)$ is greater, the source will forward the packet copy to the relay i at the time t_k. Otherwise, the source will not forward in order to achieve the energy saving potential to forward in the M-step future. ■

Based on the results established in this section, we formally present the adaptive M-step lookahead algorithm in Algorithm 1.

Algorithm 1 Adaptive M-step lookahead algorithm: executed at the source at each contact time t_k

```
Calculate τ(S_k, 1)
if σ · τ(S_k, 1) ≥ 1 then
    Forward the packet copy to the relay
else
    Get the lookahead step M adaptively by solving (20)
    Look M steps ahead to predict t'_{k+M}
    if t'_{k+M} ≥ T then
        Forward the packet copy to the relay
    else
        if λ_{i,d} · (T − t_k) ≥ λ̄_{*,d} · (T − t'_{k+M}) then
            Forward the packet copy to the relay
        else
            Do not forward the packet copy
        end if
    end if
end if
```

V. Simulation

In this section, we evaluate the performance of the proposed adaptive M-step lookahead opportunistic forwarding algorithm by simulation using Matlab. Since there is no existing literature addressing the opportunistic forwarding problem considering energy harvesting, for performance comparison, the two-hop forwarding algorithm [5] (indicated by "Always" in figures) is adopted as a baseline in which the source will forward packet copies to relays with probability 1 if it has energy. The performance metrics include the packet delivery ratio and the average energy consumption.

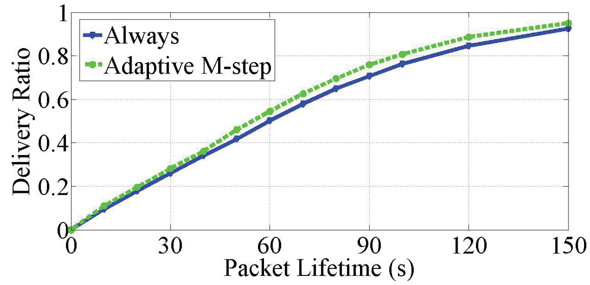

Fig. 1. Comparison of packet delivery ratio with different packet lifetime when $\sigma = 0.05$.

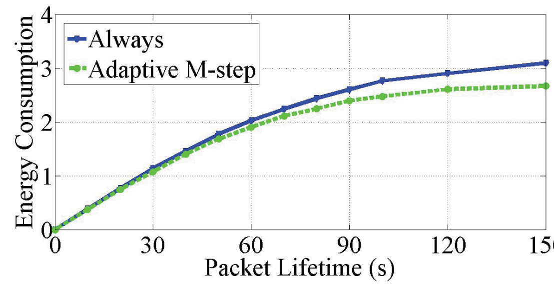

Fig. 2. Comparison of average energy consumption with different packet lifetime when $\sigma = 0.05$.

In the simulation, 40 mobile nodes are deployed in the network, in which one source-to-destination pair is investigated for collecting simulation results. The transmission range is 50m and the mobile nodes move in a square of size 600m×600m. Each node's movement is independent and following random waypoint mobility model. Node speeds follow a uniform distribution on $(0, 20]$m/s. The battery capacity is set as $B = 10$. For each algorithm, we run 100 simulations with random node speeds to obtain the average performance.

Fig. 1 and Fig. 2 show the packet delivery ratio and the average energy consumption of the two forwarding algorithms with different packet lifetime when $\sigma = 0.05$, respectively. It can be observed that compared with the "Always" algorithm, the proposed algorithm consumes less energy, and achieves higher packet delivery ratio as the packet lifetime increases. The reason is that when the packet lifetime increases, the source should have a long-term consideration about consuming the harvested energy more efficiently. For the proposed algorithm, the source can achieve the energy saving potential to forward it to other possible better relays later.

Fig. 3 and Fig. 4 show the packet delivery ratio and the average energy consumption of the two forwarding algorithms with different σ when $T = 150$s, respectively. The increase of σ simulates the circumstance where the rate of energy

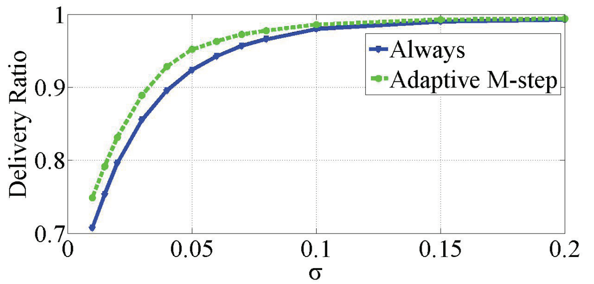

Fig. 3. Comparison of packet delivery ratio with different σ when $T = 150$s.

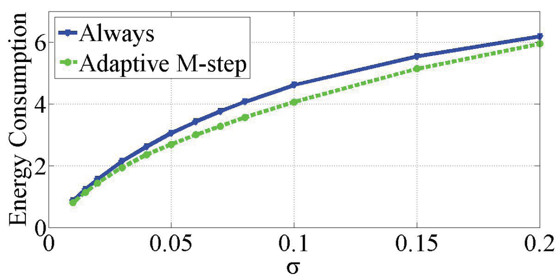

Fig. 4. Comparison of average energy consumption with different σ when $T = 150$s.

harvesting changes from low to high. We can find that the proposed algorithm outperforms the "Always" algorithm, especially for the circumstance where the rate of energy harvesting is low. It is observed that for the circumstance where the rate of energy harvesting is low, the proposed algorithm can obtain a better packet delivery ratio, meanwhile consume less energy. This is because for the proposed algorithm, the source determines whether to consume energy for forwarding at the moment or to achieve the energy saving potential to forward in the future. Although the "Always" algorithm can obtain the maximum immediate reward as it forwards packet copies to relays with probability 1 if it has energy, but it is likely to cause a hazard that the source will not harvest enough energy to forward a packet at the following contact times when the rate of energy harvesting is low. The reason why the average energy consumption of the two forwarding algorithms is almost the same when the rate of the energy harvesting is sufficient low is that in this case, all the harvested energy is expected to consume in order to increase the packet delivery ratio. Meanwhile, it can be also observed that when the rate of energy harvesting is sufficient high, the proposed algorithm degrades to the "Always" algorithm.

VI. Conclusion

In this paper, we investigate the problem how energy harvesting can be exploited to achieve the maximization of the packet delivery ratio in mobile DTNs. The opportunistic forwarding problem is formulated and solved as an MDP. At each contact time, the source determines whether to consume energy for forwarding at the moment or to achieve the energy saving potential to forward in the future. To achieve a desired balance between performance and computation complexity, we propose an adaptive M-step lookahead algorithm to make the forwarding decision, in which M is adjusted adaptively according to both the current energy and the energy which might be harvested in the future. The simulation results demonstrate that the proposed algorithm uses the harvested energy more efficiently, especially for the circumstance where the rate of energy harvesting is low.

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