Energy-Aware Online Routing with QoS Constraints in Multi-Rate Wireless Ad Hoc Networks

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ABSTRACT

Wireless ad hoc networks consist of hundreds to thousands of mobile nodes that are powered by batteries. To prolong the network operational time, energy conservation in such networks is of paramount importance. Energy optimization thus is one major objective in the design of routing protocols. However, in some stringent real-time applications including target tracking and bushfire surveillance, latency is an important concern, and little attention has been paid to it in the design of routing protocols for such applications to meet the specified Quality of Service (QoS) requirements like the end-to-end latency constraint. In this paper we focus on online energy-aware routing protocol design for routing requests to meet various end-to-end latency constraints under the multi-rate environment, we aim to maximize the network lifetime through striking the right balance among the node's transmission rate, the end-to-end latency, and energy consumption. Specifically, due to the NP-hardness of the problem of concern, we propose a joint optimization framework consisting of finding a routing path and assigning a specific transmission rate at each node in the path for each request such that the total energy consumption is minimized. We also devise novel heuristic algorithms for the problem, based on different energy cost metrics. We finally conduct extensive experiments by simulations to evaluate the performance of the proposed algorithms in terms of network lifetime. The experimental results show that the proposed algorithm incorporating the energy utilization ratio of the residual energy of a node to its initial energy capacity into the cost metric outperforms the others significantly.

Categories and Subject Descriptors

C.2.2 [**Computer-Communication Networks**]: Network Protocols; F.2.3 [**Analysis of algorithms and problem complexity**]: Tradeoffs between Complexity Measures; G.1.6 [**Numerical Analysis**]: Optimization—*Constrained optimization*

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General Terms

Algorithms, design, performance

Keywords

Energy optimization, energy-latency tradeoff, multi-rate ad hoc networks, QoS routing, network lifetime.

1. INTRODUCTION

Wireless ad hoc networks have been receiving significant attention recently due to their potential applications in environmental monitoring, security surveillance, object tracking, etc. Energy efficiency has been the major concern in the design of routing protocols to prolong the network operational time due to the limited energy batteries embedding in network nodes. However, in many real-time applications including target tracking and bushfire surveillance, the stringent real response like the end-to-end latency is a prominent concern, and little attention has been paid in designing energy-aware routing protocols for such applications. With the further development of wireless communication technology, mobile nodes now have multiple transmission rates. For example, IEEE 802.11 a/b standard allows ad hoc nodes to have multi-rate capabilities. However, there are very few studies on designing energy-aware routing algorithms by fully utilizing this multi-rate advantage that can be stated as follows: assuming the transmission power at each node is fixed, if the node operates in a lower transmission rate, it can reach a longer transmission distance, otherwise it only reaches a shorter distance. Meanwhile, in terms of the transmission delay incurred by transmitting a message from a node, a higher transmission rate leads to a shorter transmission delay, while a lower transmission rate results in a longer transmission delay. Therefore, there is a non-trivial tradeoff among the transmission rate, the latency, and energy consumption in the design of energy-aware, routing algorithms for multi-rate wireless ad hoc networks.

Tremendous effort on the design of online routing algorithms in a single rate ad hoc networks has been taken in the past. Most of these algorithms focus on maximizing the network lifetime when dealing with online requests without latency constraints, where the *network lifetime* is defined as the number of messages successfully routed before the first failed message route [12]. This problem was shown to be NP-hard [12] and several heuristics have been devised [7, 6, 12], and these works are based on the single rate wireless ad hoc networks. Under the multi-rate environment, existing studies [13, 14], however mainly focused on optimizing the throughput or minimizing the end-to-end delay.

The main contributions of this paper are as follows. We devise energy-aware online routing algorithms/protocols for user requests with various end-to-end latency constraints under the multi-rate wireless environment with the objective to maximize the network lifetime when dealing with online requests, through striking the elegant balance among the transmission rate, the end-to-end latency, and the energy consumption. Since this online problem is NP-hard, we instead propose a joint optimization framework that consists of finding a routing path and assigning a specific transmission rate at each node in the path such that the total cost of the path in terms of energy metric is minimized, provided that the end-to-end latency constraint of the request is met. We also devise several novel heuristic algorithms based on different cost metrics for the problem. We finally conduct extensive experiments by simulations to evaluate the performance of the proposed algorithms in terms of network lifetime. The experimental results show that one of the proposed algorithms that incorporates the energy utilization ratio of the residual energy to the initial energy capacity into its cost metric outperforms the others significantly.

The rest of the paper is organized as follows. Section 2 introduces the system model and problem definition. Section 3 presents the joint optimization framework and the proposed algorithms. To evaluate the performance of the proposed algorithms, extensive experiments are conducted in Section 4, and conclusions are drawn in Section 5.

2. PRELIMINARIES

2.1 System model

We consider a multi-rate wireless ad hoc network $S(N, A)$, where N is the set of nodes with $n = |N|$, A is the set of links with $m = |A|$. Assume that the nodes in N are homogeneous and each has M fixed transmission rates. We use $r_{i,l}$ and $d_{i,l}$ to represent node $v_i \in N$ using the transmission rate $r_{i,l}$ to transmit messages and $d_{i,l}$ is the corresponding longest transmission distance (radius) by $r_{i,l}$, $1 \leq i \leq n$, $l \in \{1, 2, \ldots, M\}$. We assume that $r_{i,l}$ can be set to a fixed value according to the IEEE 802.11 protocols. For example, $r_{i,l} \in \{6, 9, 12, 18, 24, 36, 48, 54\}$ $(Mbps)$ when IEEE 802.11a is exploited, or $r_{i,l} \in \{1, 2, 5.5, 11\}$ $(Mbps)$ when IEEE 802.11b is adopted. We further assume that the transmission power P_t of node v_i is fixed, then $d_{i,l_1} > d_{i,l_2}$ if $r_{i,l_1} < r_{i,l_2}$, where $1 \leq l_1 < l_2 \leq M$ and $1 \leq i \leq n$.

2.2 Problem definitions

A *unicast routing request* is a quadruple $q = (s, t, L, \Gamma)$, where s and t are the source and destination nodes, L is the message length, and $\Gamma \in \mathbb{R}^+$ is the end-to-end latency constraint[1] of q. We say that a request q is *implemented* by the network if there is a routing path P in S from s to t such that the residual energy of each node in P suffices for the L-length message transmission, subject to $\sum_{v_i \in P, i \neq t} \frac{L}{r_{i,l}} \leq \Gamma$,where $r_{i,l}$ represents that node v_i chooses transmission rate $r_{i,l}$ for the message transfer. Otherwise, we say that the request q is *rejected*.

Given a multi-rate wireless ad hoc network $S(N, A)$ with M transmission rates, and a sequence of unicast routing requests $Q = q(1), q(2), \cdots, q(k')$ arrived one by one without any knowledge of future requests arrival, the *Latency-Constrained network Lifetime Maximization* problem (LCLM for short) is to maximize the number of the requests that can be implemented until the rejection of the first request, where $q(k) = (s(k), t(k), L(k), \Gamma(k))$ represents the kth request, where $s(k)$ and $t(k)$ are the source and destination of $q(k)$, $L(k)$ is the message length, and $\Gamma(k) \in \mathbb{R}^+$ is the end-to-end latency constraint of $q(k)$, $1 \leq k < k' < \infty$. Clearly, LCLM is NP-hard, since the *lifetime maximization problem* [12] is one of its special cases where the latency constraint of each request is infinite and the transmission rate of each node is fixed and identical, while the latter is NP-complete.

2.3 Latency-constrained shortest path problem

Before we proceed, we re-introduce the well known *latency-constrained shortest path* problem that is to find a shortest path in a network between a pair of nodes subject to the end-to-end latency constraint, which has been shown to be NP-complete [3]. Considerable effort for finding efficient approxiamtion algorithms for this problem has been taken in the past. The well known results so far are due to Lorenz et al. [11] and Goel et al. [4]. Lorenz et al. [11] proposed an approximation algorithm with time complexity $O(mn(1/\epsilon + \log n))$, which delivers a solution within $(1 + \epsilon)$ times of the optimal, where ϵ is a constant with $0 < \epsilon \leq 1$. Goel et al. [4] proposed another approximation algorithm with time complexity $O(m + n \log n)(D/\epsilon)$, which delivers an exact solution by relaxing the delay to no more than $(1 + \epsilon)$ times of the given one, where D is the diameter of the network. Chen et al. [2] made use of both randomized discretization and path delay discretization by devising an approximation algorithm whose expected running time is much shorter than that of the algorithm in [4]. It must be mentioned that if link latency is integral and the end-to-end latency constraint is bounded by an integer η, the latency-constrained shortest path problem can be solved in time $O((n \log n + m)\eta)$ by the extended Dijkstra's algorithm [1].

3. JOINT OPTIMIZATION FRAMEWORK

In this section a joint optimization framework for LCLM is proposed. For each incoming request, the idea is to find an energy-efficient routing path for it and to assign each node in the path with a specific transmission rate such that the total energy cost of the path is as small as possible, provided that the end-to-end latency of the request is met too. The core challenge in designing online routing algorithms is how to deal with the right balance among energy, latency, and node transmission rates. To achieve that, we transform LCLM in a wireless ad hoc network into a latency-constrained shortest path problem in an auxiliary graph and solve the latter which corresponds to a solution of the original problem.

3.1 Constructing the auxiliary graph

Given a multi-rate wireless ad hoc networks $S(N, A)$ with M multiple transmission rates and a unicast request $q = (s, t, L, \Gamma)$, a weighted, directed auxiliary graph $G = (V, E, \omega, \tau)$ for q is constructed as follows.

For each node v_i in S, let $r_{i,1}, r_{i,2}, \ldots, r_{i,M}$ be its transmission rates with $r_{i,l_1} < r_{i,l_2}$, $1 \leq l_1 < l_2 \leq M$, a widget $W_i = (V_i, E_i, \omega, \tau)$ for node v_i is built, as shown in Fig. 1. $V_i = \{v_i, R_{i,1}, R_{i,2}, \ldots, R_{i,M}\}$ and $E_i = \{\langle v_i, R_{i,l}\rangle \mid 1 \leq l \leq M\}$, where V_i and E_i are sets of vertices and edges in W_i, v_i, namely the *original vertex* in G, represents the node in S,

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[1] In this paper we only consider the transmission latency and do not consider the other latencies such as queuing latency, etc.

$R_{i,l}$, namely the *auxiliary vertices*, represents v_i transmitting the message, using transmission rate $r_{i,l}$. Assign edge $\langle v_i, R_{i,l}\rangle$ with a pair of values $(\omega(v_i, R_{i,l}), \tau(v_i, R_{i,l}))$, where $\omega(v_i, R_{i,l})$ is the amount of transmission energy consumption of v_i by transmitting an L-length message of the request q, using transmission rate $r_{i,l}$, and $\tau(v_i, R_{i,l})$ is the corresponding transmission latency. It is obvious that $\tau(v_i, R_{i,l}) = L/r_{i,l}$ and $\omega(v_i, R_{i,l}) = P_t \cdot \tau(v_i, R_{i,l}) = P_t \cdot (L/r_{i,l})$.

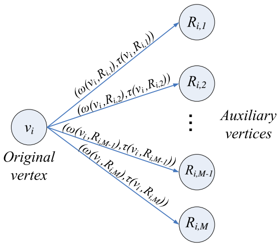

Figure 1: The widget $W_i = (V_i, E_i, \omega, \tau)$ for node v_i.

The auxiliary graph $G = (V, E, \omega, \tau)$ is then built, by making use of the built widgets, where $V = \cup_{i=1}^{n} V_i$ and $E = \cup_{i=1}^{n} E_i \cup E_{bridge}$, E_{bridge} is the set of edges between different widgets, defined as follows. For two nodes v_i and v_j in the S with $i \neq j$, if v_i transmits the message using $r_{i,l}$ and v_j is within its transmission distance $d_{i,l}$ (the maximum transmission distance of node v_i when it uses $r_{i,l}$), then there is a directed edge $\langle R_{i,l}, v_j\rangle$ in E_{bridge} with $\omega(R_{i,l}, v_j) = 0$ and $\tau(R_{i,l}, v_j) = 0$. For each $\langle v_i, R_{i,l}\rangle \in E_i \subset E$, $\tau(v_i, R_{i,l}) = L/r_{i,l}$ and $\omega(v_i, R_{i,l}) = P_t \cdot \tau(v_i, R_{i,l})$. We thus have the following lemma.

Lemma 1. *Given an auxiliary graph $G = (V, E, \omega, \tau)$ defined above, G contains $(M+1)n$ vertices and at most Mn^2 directed edges, where M is the number of transmission rates at each ad hoc node. i.e., $|V| = (M+1)n$ and $|E| \leq Mn^2$.*

Proof. For each widget W_i in G, it corresponds to $(M+1)$ vertices, and M edges in G, thus $|V| = (M+1)n$, $|E_i| = M$. For each auxiliary vertex $R_{i,l}$ in W_i, assume that all the other original vertices in G are within the transmission range of v_i when using $r_{i,l}$ to transmit the requested message, then there exist $(n-1)$ edges in G. Since there are Mn auxiliary vertices in G, $E_{bridge} \leq Mn(n-1)$. Also $E = \cup_{i=1}^{n} E_i \cup E_{bridge}$ and $E_i \cap E_{bridge} = \emptyset$, $|E| = |\cup_{i=1}^{n} E_i \cup E_{bridge}| = |\cup_{i=1}^{n} E_i| + |E_{bridge}| \leq Mn + Mn(n-1) = Mn^2$. ☐

It must be mentioned that Liang [8, 9] once solved the minimum-energy multicasting problem in wireless ad hoc networks under multiple power levels model, through a reduction to an optimization problem in an auxiliary graph, which in turn gives an approximate solution for the original problem. However, there are differences in comparison with his work. One is that the optimization problem he dealt with has only two parameters (the total energy consumption and the transmission power level adjustment) involved, while we here deal with three parameters, the transmission rate, transmission delay and the energy consumption with an assumption that the transmission power at each node is identical and fixed.

3.2 On finding latency-constrained shortest path

Having constructed the auxiliary graph G, what follows is to find the latency-constrained shortest path in G for request q, which corresponds to a routing path in $S(N, A)$ for the request. In general, for a given request q, the transmission latency of the message of q along an edge in the routing path and the end-to-end latency constraint are non-negative real numbers. In the following we show that for certain given transmission rates adopted in real systems, the problem with real latency constraints can be transformed to another problem with integral latency constraints.

Given a graph $G = (V, E, \omega, \tau)$ and a unicast request $q = (s, t, L, \Gamma)$, where $\Gamma \in \mathbb{R}^+$, let $G' = (V, E, \omega, \tau')$ be the corresponding graph of G by assigning the transmission latency $\tau'(v_i, R_{i,l}) = \tau(v_i, R_{i,l}) \cdot \Delta = (L/r_{i,l}) \cdot \Delta = B/r_{i,l}$ of edge $(v_i, R_{i,l})$ in G', where $B = LCM(r_{i,1}, r_{i,2}, \ldots, r_{i,M})$ is the Least Common Multiple for all transmission rates and $\Delta = B/L$. And $q' = (s, t, L, \Gamma')$ is the corresponding request of q in G', where $\Gamma' = \lfloor \Gamma \cdot \Delta \rfloor$. Having performing the transformation, the transmission latency at each edge and the end-to-end latency constraint of q' in G' becomes integers, while the latency-constrained shortest path problem with integral latency is polynomially solvable by employing the extended Dijkstra's algorithm [1], and we have the following lemma.

Lemma 2. *Given a directed auxiliary graph $G = (V, E, \omega, \tau)$ and a unicast request $q = (s, t, L, \Gamma)$ with $\Gamma \in \mathbb{R}^+$, let $G' = (V, E, \omega, \tau')$ and $q' = (s, t, L, \Gamma')$ be the corresponding graph and request derived from G and q after performing the transformation. An optimal path in G' for request q' corresponds to an optimal path in G for q.*

Proof. Assume that P and P' are the optimal paths in G and G' for requests q and q', respectively. The rest is to show that P' in G' corresponds to P in G exactly.

Let PS be the set of all the paths from s to t in G (also in G'). For any $P_i \in PS \setminus \{P\}$, let $\tau(P_i)$ and $\tau'(P_i)$ be the total transmission latency along P_i in G and G' respectively. Let $\omega(P_i)$ be the total cost along path P_i in G and G'.

For any $P_i \in PS \setminus \{P\}$ in G, we distinguish it into two cases: Case (i) $\tau(P_i) > \Gamma > \tau(P)$; or Case (ii) $\tau(P_i) \leq \tau(P) \leq \Gamma$ with $\omega(P_i) \geq \omega(P)$.

Case (i): $\tau(P_i) > \Gamma > \tau(P)$ is equivalent to $\sum_{v_j \in P_i, j \neq t} (L/r_{j,l}) > \Gamma > \sum_{v_k \in P, k \neq t} (L/r_{k,l'})$. Following the transformation, we have, $\sum_{v_j \in P_i, j \neq t} (B/r_{j,l}) > \Gamma' \geq \sum_{v_k \in P, k \neq t} (B/r_{k,l'})$, therefore, $\tau'(P_i) > \Gamma' \geq \tau'(P)$.

Case (ii): $\tau(P_i) \leq \tau(P) \leq \Gamma$ with $\omega(P_i) \geq \omega(P)$, is equivalent to $\sum_{v_j \in P_i, j \neq t} (L/r_{j,l}) \leq \sum_{v_k \in P, k \neq t} (L/r_{k,l'}) \leq \Gamma$. Following the definition of the transformation, we have, $\sum_{v_j \in P_i, j \neq t} (B/r_{j,l}) \leq \sum_{v_k \in P, k \neq t} (B/r_{k,l'}) \leq \Gamma'$, therefore, $\tau'(P_i) \leq \tau'(P) \leq \Gamma'$ and $\omega(P_i) \geq \omega(P)$. It can be seen that the optimal path in G' for q' corresponds to an optimal path P in G for q, while the former optimal path is P', which can be found by the extended Dijkstra's algorithm. ☐

The proposed algorithm for finding the latency-constrained shortest path in G for request q is illustrated by Fig. 2, which is referred to as the Multi-Rate Extended Dijkstra's algorithm (`MRED`), and we have the following theorem.

Theorem 1. *Given a multi-rate wireless ad hoc network $S(N, A)$ with M multiple transmission rates and a request $q = (s, t, L, \Gamma)$, algorithm `MRED` takes $O(\Gamma \cdot \Delta(n(M+1)\log(n(M+1)) + Mn^2))$ time to find an optimal routing path for q, where n is the number of nodes in S, B is the least common multiple of the M transmission rates, L is the message length of q, and $\Delta = B/L$.*

```
Algorithm MRED
Input: The auxiliary graph $G = (V, E, \omega, \tau)$ and a routing request $q = (s, t, L, \Gamma)$.
Output: A routing path $P$ from $s$ to $t$ such that $\sum_{v_i \in P, i \neq t} \omega(v_i, R_{i,l})$ is minimized, subject to $\sum_{v_i \in P, i \neq t} \tau(v_i, R_{i,l}) \leq \Gamma$.
begin
    1. $G' = (V, E, \omega, \tau')$ and $q' = (s, t, L, \Gamma')$ be the resulting graph and request after performing the transformation in $G$ and $q$;
    2. Find a path $P'$ in $G'$ for $q'$, using the extended Dijkstra's algorithm;
    3. A corresponding path $P$ in $G$ for $q$ is derived from $P'$ in $G'$ for $q'$.
end
```

Figure 2: The algorithm `MRED`.

Proof. Following Lemma 1, the construction of $G = (V, E, \omega, \tau)$ takes $O(Mn^2)$ time, due to $|V| = (M+1)n$ and $|E| \leq Mn^2$. Given a routing request $q = (s, t, L, \Gamma)$, the computational complexity of finding a latency-constrained shortest path in S from s to t using extended Dijkstra's algorithm is $O((|V| \log |V| + |E|)\eta)$ [1], where η is an integral latency constraint. Thus, the computational complexity of algorithm `MRED` is $O(\Gamma \cdot \Delta(n(M+1) \log(n(M+1)) + Mn^2))$. $\square$

3.3 Online routing algorithm

Having algorithm `MRED` for finding an optimal routing path in $S(N, A)$ for each individual request, we now deal with a sequence of requests Q injected into the network, our aim is to implement as many of them as possible such that the network lifetime is maximized. Since the network lifetime may not be prolonged by simply applying algorithm `MRED` whose cost metric does not incorporate the residual energy of a node into its formalization. What followed is to propose several heuristics for LCLM based on different energy cost metrics.

For a request $q(k)$, let $RE_i(k)$ and IE be the residual energy and initial energy of node v_i just before $q(k)$ arrives. The basic algorithm for LCLM, referred to as `LCLM-Basic`, is described by Fig. 3. Within the algorithm, Step 1 constructs a directed graph for each request $q(k)$. In Step 2, any edge $\langle v_i, R_{i,l} \rangle$ in G if its weight $\omega(v_i, R_{i,l}) > RE_i(k)$ will be removed, because otherwise v_i will run out of its energy to transmit this message by transmission rate $r_{i,l}$. Step 3 assigns a weight $\omega_1(v_i, R_{i,l})$ to each remaining edge $\langle v_i, R_{i,l} \rangle$ in G. Denote by the resulting graph G_1, and Step 4 finds a latency-constrained shortest path by algorithm `MRED` for request $q(k)$ in G_1. Clearly, it is vital to assign proper weights to the edges in G_1 to prolong the network lifetime. We should fully consider node parameters (transmission rate, residual energy, transmission range) to balance the energy consumption among the nodes to prolong the network lifetime. We thus propose the following three heuristics based on different cost metrics.

1. Assign edge $\langle v_i, R_{i,l} \rangle$ in G_1 a weight $\omega_1(v_i, R_{i,l}) = \omega(v_i, R_{i,l})$, which means the algorithm finds the latency-constrained shortest path in terms of the total energy consumption, this algorithm is referred to as `LCLMT`.

2. Assign edge $\langle v_i, R_{i,l} \rangle$ in G_1 a weight $\omega_1(v_i, R_{i,l}) = \omega(v_i, R_{i,l})/RE_i(k)$, indicating that the algorithm makes use of nodes whose energy consumption for the request are as small as possible, whereas their residual energy is as large as possible, this algorithm is referred to as `LCLMR`.

3. Assign edge $\langle v_i, R_{i,l} \rangle$ in G_1 a weight $\omega_1(v_i, R_{i,l}) = \omega(v_i, R_{i,l})(\lambda^{\alpha_i(k)} - 1)$, where $\lambda > 1$ is a positive integer, which will be determined later by simulations. $\alpha_i(k) = 1 - RE_i(k)/IE$, which is the *energy utilization ratio* of node v_i. This cost metric considers not only the total energy consumption but also the energy utilization ratio of each node. In other words, it tries to avoid choosing those nodes whose energy is relatively low or the energy utilization ratio of is relatively high. This algorithm is referred to as `LCLM(`α`)`.

```
Algorithm LCLM-Basic
Input: A request $q(k) = (s(k), t(k), L(k), \Gamma(k))$.
Output: A path enable to implement $q(k)$, if existence.
begin
    1. Construct an auxiliary graph $G = (V, E, \omega, \tau)$ for request $q(k)$ as it arrives;
    2. A reduced subgraph $G_1 = (V, E_1, \omega_1, \tau)$ of $G$ is obtained by removing the edges $\langle v_i, R_{i,l} \rangle$ from $G$ if $\omega(v_i, R_{i,l}) > RE_i(k)$;
    3. Assign each edge of $G_1$ a weight $\omega_1(v_i, R_{i,l})$;
    4. Find the latency-constrained shortest path for $q(k)$ by algorithm MRED in $G_1$;
    5. If no such a path is found, reject the request, otherwise implement $q(k)$.
end
```

Figure 3: The algorithm `LCLM-Basic`.

Theorem 2. *Given a multi-rate wireless ad hoc network $S(N, A)$ with M multiple transmission rates and a sequence of requests, there is an online algorithm for LCLM such that for each realized request, the proposed algorithm takes $O(\Gamma \cdot \Delta(n(M+1) \log(n(M+1)) + Mn^2))$ time, with n the number of nodes in S, B the least common multiple of all the transmission rates, L the message length of this request, and $\Delta = B/L$.*

Proof. The time complexity analysis of the proposed algorithm is as follows. Step 1 takes $O(Mn^2)$ time, because graph G contains $(M+1)n$ nodes and Mn^2 edges, by Lemma 1. Steps 2 and 3 take $O(Mn^2)$ time for the construction of graph G_1. Step 4 is the dominant time step, which takes $O(\Gamma \cdot \Delta(n(M+1) \log(n(M+1)) + Mn^2))$ by Theorem 1. Thus, the proposed algorithm take $O(\Gamma \cdot \Delta(n(M+1) \log(n(M+1)) + Mn^2))$ time to find a routing path for each incoming request, if the path exists. $\square$

4. PERFORMANCE EVALUATION

4.1 Simulation environment

We use MATLAB to generate a network consisting of 40, 60, 80, 100, and 120 homogeneous nodes that are randomly distributed in a 500×500 m^2 square region. We adopt the parameters of transmission rates and their corresponding transmission distances of IEEE 802.11a protocol used in [10]. Specifically, each node has a fixed transmission power $40mW$. Without loss of generality, we make use of four transmission rates at each node, which are $r_1 = 6Mbps$, $r_2 = 12Mbps$, $r_3 = 18Mbps$, and $r_4 = 24Mbps$. The corresponding maximum transmission distances of these rates are $d_1 = 170.62m$, $d_2 = 120.79m$, $d_3 = 95, 95m$, and $d_4 =$

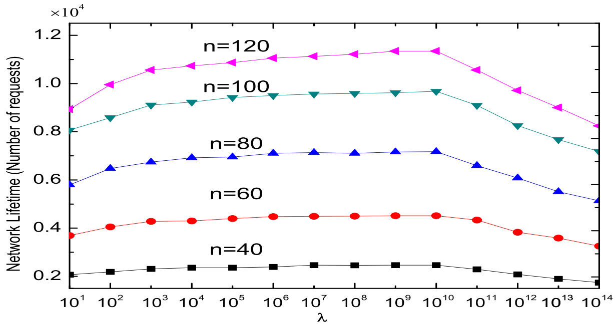

Figure 4: The impact of λ in algorithm `LCLM(`α`)` on network lifetime, where the network size $n = 40, 60, 80, 100,$ and 120, $\gamma \in (0, 1]$.

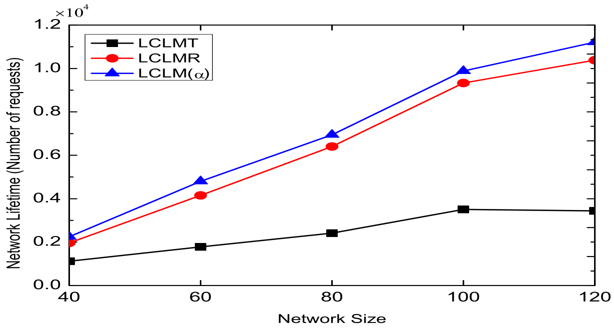

Figure 5: The network lifetime delivered by algorithms `LCLMT`, `LCLMR` and `LCLM(`α`)` respectively, where $\lambda = 10^{10}$ for algorithm `LCLM(`α`)`, $\gamma \in (0, 1]$.

$67.93m$, respectively. The initial energy capacity of each node is set to $5 \times 10^{-3}J$. For each different network size, 20 network instances are generated, and for each instance, 10 different request sequences with each sequence of 2×10^4 requests are randomly injected to the network, the message length associated with each request is ranged from $1K$ to $10K$ bits. Therefore, the value shown in all figures is the mean of 200 values.

A *reasonable latency constraint* for a request should be no less than the minimum transmission latency among all the paths for the request. To simulate a reasonable latency constraint for request $q = (s, t, L, \Gamma)$, its latency constraint is defined as follows. $\Gamma = \left\lceil \frac{d(s,t) \cdot L}{d^* \cdot r^*} \right\rceil \cdot \frac{1}{\gamma}$, where $\gamma \in (0, 1]$ denotes the *latency constraint coefficient*, which is used to adjust the degree of tightness of latency constraint Γ. γ is randomly drawn from 0.1 to 1.0 with increment of 0.1. The higher the value of γ, the tighter the latency constraint will be. $\{d^* \cdot r^*\} = \max_{1 \le i \le 4}\{d_i \cdot r_i\}$, $d(s, t)$ is the Euclidean distance between s and t and can be obtained through GPS.

4.2 Performance evaluation

We first analyze the impact of various λs on the performance of algorithm `LCLM(`α`)` through experimental simulations, where the value of λ is ranged from 10^1 to 10^{14}. Different λs will result in different routing paths, thereby leading to different network lifetimes. Fig. 4 shows that the network lifetime delivered by `LCLM(`α`)` depends on not only the value of λ but also the network size n. `LCLM(`α`)` exhibits the best possible performance when $\lambda = 10^{10}$. Without loss of generality, we set $\lambda = 10^{10}$ for `LCLM(`α`)` in the rest of the paper, which ensures that `LCLM(`α`)` have the best performance. We then evaluate algorithm `LCLM(`α`)` against algorithms `LCLMT` and `LCLMR`. Fig. 5 illustrates that algorithm `LCLM(`α`)` outperforms the other two algorithms in terms of network lifetime. The network lifetime delivered by `LCLM(`α`)` is 2.73 times and 1.1 times longer than those by algorithms `LCLMT` and `LCLMR`.

5. CONCLUSIONS

In this paper we have studied the network lifetime maximization problem for online routing with end-to-end latency constraints in multi-rate wireless ad hoc networks. We presented a joint optimization framework that consists of finding a routing path and assigning a specific transmission rate for each node in the path for each request such that the total cost of the path in terms of energy metric is minimized, provided that the end-to-end latency constraint of the request is met too. We have devised several heuristics based on different cost metrics for responding to online requests with the objective to maximize the network lifetime. We finally conducted extensive experiments by simulations to evaluate the performance of the proposed algorithms in terms of network lifetime. The experimental results showed that algorithm `LCLM(`α`)` outperforms the other two algorithms including `LCLMT` and `LCLMR`.

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