Online Lifetime-Centric Multicast Routing for Ad Hoc Networks with Directional Antennas

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***Abstract*— We consider a wireless ad hoc network where each node employs a single-beam directional antenna and is provisioned with limited energy. We are interested in an online multicast routing algorithm for successive multicast communication requests with the aim of maximizing network lifetime. The beam-forming property associated with single-beam directional antenna introduces some unique problems that do not exist for omni-directional antennas and therefore significantly increases the design space for routing algorithms. The contributions of this paper are twofold. First, we provide some important theoretical understanding on various multicast problems and deduce that even an offline version of this problem is NP-hard. Second, we develop a highly competitive online heuristic algorithm that takes network lifetime consideration directly into iterative calculations and show that an algorithm designed under this methodology provides consistently better performance than the current state-of-the-art algorithm that takes remaining energy into iterative calculations. The theoretical results and heuristic algorithm in this paper offer some important insights on algorithmic design for energy-constrained wireless ad hoc networks with directional antennas.**

I. Introduction

In recent years, there has been tremendous interest in energy efficiency and lifetime problems associated with wireless ad hoc (and sensor) networks. As a result, new knowledge and understanding begin to build up on this important subject. For example, for an ad hoc network where each node is provisioned with limited energy (also called an energy-constrained network), it is now well understood that *an energy efficient routing usually cannot provide the best result for network lifetime performance* [26]. This important result has led to the evolution of two lines of research: one focuses on minimizing the total energy required to maintain a tree (broadcast/multicast) [2], [4], [5], [6], [14], [24], [25] and the other focuses on how to perform routing so that the network lifetime can be prolonged as much as possible [15], [26].

In parallel to algorithmic and protocol research in energy-constrained ad hoc networks, recent use of directional antennas in wireless communication has further enabled new approaches for energy saving for energy-constrained wireless networks. Indeed, use of directional antennas allows concentration of the beam toward the intended destination without wasting energy in unwanted directions. Further, because the beam is generated only toward a certain direction, it creates less interference to other nodes that are outside the beam, which enables greater information capacity in the network. Finally, since nodes outside the beam coverage cannot receive the source's signal, security concerns associated with omni-directional broadcast can be somewhat alleviated. As a result, it is expected that the use of directional antennas has a great potential in energy-constrained wireless ad hoc networks. From a theoretical perspective, the use of directional antenna has also introduced some unique difficulties in algorithmic design, particularly when each node is assumed to generate a *single* directional beam.[1] This is because single directional beam provides *partial* broadcast to those nodes that are within the beam coverage. Unlike the case of omni-directional antennas, where the design space depends solely on the radius (i.e., communication range), the algorithmic design space for directional antenna now encompasses three components: *beam radius, beam-width*, and *beam orientation*. Thus, a directional antenna based routing problem (assuming each node can generate only a single beam) needs to address the assignment of these three parameters on each node in the network.

In this paper, we consider the important problem of multicast routing with the objective of maximizing network lifetime for energy-constrained wireless ad hoc networks employing directional antennas. The significance of this problem lies in that not only is it a general problem that encompasses unicast or broadcast, but also it is a generalized problem for omni-directional antenna, which can be considered as a special case of directional antenna with 360 degrees beam-width. Therefore, advances along this investigation will yield significant intellectual merit. We assume that the directional antenna at each node can only form a single beam where the beam radius, beam-width, and beam orientation are adjustable. Instead of looking for an optimal multicast routing solution for a single multicast session, we are interested in an *online algorithm* for the problem where multicast requests arrive and depart over time without explicit knowledge of future request arrival pattern.

The contributions of this paper include both theoretical

[1]Although multiple beams can be formed by directional antenna arrays, the hardware cost and energy consumption are much higher than that for single-beam directional antenna [22].

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understanding and heuristic algorithm design for the multicast routing problem. From the theoretical perspective, we show that an "offline" version of this multicast routing problem is NP-hard. This result builds upon several intermediate results, each of which has it own significance and offers important understandings on closely related problems. In one intermediate result (Lemma 2), we prove that, for the case of omni-directional antennas, the problem of finding a static maximum-lifetime tree for a single multicast (or broadcast) session can be solved in polynomial time, This result does not assume uniform path loss model for omni-directional antennas and generalizes an earlier result in [9] that assumes uniform path loss model. In another important intermediate result (Theorem 1), we show that for directional antenna case, the static maximum-lifetime tree problem for a single multicast (or broadcast) session is NP-complete. The proof of this result gives insights on how a directional antenna can increase the computational complexity in algorithmic design.

Since even the offline multicast routing problem is NP-hard, for an online algorithm, only heuristic approach is feasible. In the second half of this paper, we aim to develop a highly competitive online multicast routing algorithm to maximize network lifetime. In [26], Wieselthier *et al.* made a major step in the systematic study of the online multicast routing problem. In particular, they designed the D-MIP algorithm, which incorporates nodal residual energy into the local cost metric for routing. Although this algorithm offers good performance to the multicast routing problem, there is a very subtle detail in the algorithmic design of D-MIP that motivates us to further investigate this important problem. Nodal residual energy is indeed closely related to node lifetime (and thus network lifetime), but it may be better to take lifetime consideration *directly* into the iterative calculations. Consequently, we make the following conjecture in our investigation. Suppose we incorporate lifetime consideration explicitly into the design of an online multicast routing algorithm. We should then expect to have an algorithm that outperforms the D-MIP algorithm. To prove this conjecture, we design a new algorithm called MLR-MD (for Maximum Lifetime Routing for Multicast with Directional antennas). The design experience for MLR-MD is quite interesting and offers important understanding on beam-forming behavior under single-beam directional antennas, particularly, the relationship between physical one-hop neighbor and logical one-hop neighbor concepts. Through simulation results, we conclusively demonstrate that MLR-MD offers consistent performance improvement over the D-MIP algorithm, which confirms our initial conjecture. Consequently, our effort in this heuristic algorithm development provides important methodology to future design of routing algorithms for energy-constrained wireless ad hoc networks employing directional antennas.

The remainder of this paper is organized as follows. In Section II, we describe the network system model and state the online multicast routing problem under investigation. Section III provides a detailed discussion on theoretical aspects of the multicast routing via closely related problems, thereby setting up the theoretical background for the problem in this research. In Section IV, we design a lifetime-centric online algorithm for the multicast routing problem. In Section V, we use simulation results to demonstrate the efficacy of the proposed algorithm. Section VII concludes this paper.

II. System Model and Problem Description

A. System Model

We consider a wireless ad hoc network consisting of N nodes located over a specified region. For wireless communication, we assume that each node is equipped with a directional antenna for transmission and an omni-directional antenna for reception.[2] Similar to [26], we assume that each node's transmitter has power control capability. That is, by adjusting the transmission power level, the sender could reach destination nodes located at different distances. Further, we assume that each node could also control the beam-width and beam orientation of its directional antenna. Then, a node's transmission coverage area can be effectively controlled by adjusting the power level, beam-width and beam orientation of the directional antenna. Figure 1(a) illustrates this concept. In this figure, a sending node s could transmit to nodes 1, 2, and 4 *simultaneously* by controlling the power level, beam-width and beam orientation at node s without causing interference at node 3.

Depending on the specific wireless environment and a node's hardware and software implementation, each node's energy consumption behavior may be different. In our theoretical development (Section III) and algorithmic design (Section IV), we model the transmission energy at a node u as a function of ρ, θ, and ω, where ω is the beam orientation, ρ is the reachable distance along this orientation, and θ is the beam-width. Denote $p_u^T(\rho,\theta,\omega)$ as the beam transmission cost function, which is node-dependent. Without loss of generality, we assume, in wireless communication environment, this function is an increasing function of ρ and θ, i.e.,

$$p_u^T(\rho_1,\theta,\omega) < p_u^T(\rho_2,\theta,\omega) \quad \text{if } \rho_1 < \rho_2 \,, \tag{1}$$

$$p_u^T(\rho,\theta_1,\omega) < p_u^T(\rho,\theta_2,\omega) \quad \text{if } \theta_1 < \theta_2 \,. \tag{2}$$

Further, to better model wireless environment in practice, we do not assume uniform path loss in all directions (ω). Instead, we let $p_u^T(\rho,\theta,\omega)$ not only depend on ρ and θ, but also be a function of beam orientation ω. Therefore, it is possible that $p_u^T(\rho,\theta,\omega_1) \neq p_u^T(\rho,\theta,\omega_2)$ if $\omega_1 \neq \omega_2$. Due to the non-uniform path loss along different directions, the beam coverage may not be a uniform sector. For ease of illustration, we use a uniform sector (e.g., in Fig. 1) to represent the coverage of a directional beam in all figures.

[2] It is possible to use a directional antenna for reception as well, although its energy saving may not be as significant as that for transmission, particularly for large-sized networks.

Since energy is also consumed for other nodal processing functions and reception, for each node u, we define p_u^P as other nodal transmission processing energy and p_u^R as the reception processing energy for each unit data. Then, the total energy consumed at a node u for one unit of data with beam (ρ, θ, ω) is

$$C_u(\rho, \theta, \omega) = p_u^T(\rho, \theta, \omega) + p_u^P + p_u^R \ . \tag{3}$$

Note that depending on the role of node u (i.e., sender, receiver, or both), the term $p_u^T(\rho, \theta, \omega)$ or p_u^R may not exist. Further, we assume that the adjustable range for the beam-width θ is $[\theta_{\min},\ \theta_{\max}]$.

B. The Multicast Problem

In the most general form, any node in the network may need to transmit to a subset of all other nodes in the network. Clearly this multicast communication includes both unicast and broadcast communications. Due to its power control capability, a source node could generate a single beam to reach all nodes in this subset in a single hop (e.g., Fig. 1(a)). Although simple, this approach is not energy efficient, particularly for large-sized networks, due to the power consumption behavior in Eqs. (1) and (2), i.e., the energy consumption increases when the distance ρ and beam-width θ increase. As a result, it is essential to explore a multi-hop relaying approach to minimize energy consumption and to extend network lifetime (e.g., Fig. 1(b) and (c)).

There are various definitions for network lifetime [3]. For simplicity, we define network lifetime as *the time instance when the network can no longer support a multicast communication session.* This happens when either the source node or any multicast receiving node runs out of energy during a multicast communication session. Clearly, the idle periods where there are no multicast sessions in the network should not be considered as part of the network lifetime since there is no energy expenditure during these periods. That is, network lifetime under consideration only consists of the sum of time intervals where there are active multicast communication sessions in the network. In the simple case where there is no time overlap between consecutive multicast communication sessions in the network, the accounting for network lifetime is the sum of successive time intervals for multicast communication sessions. In the case where there are multiple concurrent multicast communication sessions in the network, special care must be taken in the accounting of network lifetime. We will further elaborate this point in Section V.

We use an example to illustrate the multicast communication problem at a particular time instance. In Fig. 1, suppose that the multicast communication request arrives at node s (source node) and wishes to transmit to nodes 1, 2, and 4. Depending on the relay topology, there are various transmission behavior that can be employed. For example, in Fig. 1(a), node s transmits to nodes 1, 2, and 4 directly; in Fig. 1(b) node s transmits to node 1, node 1 transmits to node 2, and node 2 transmits

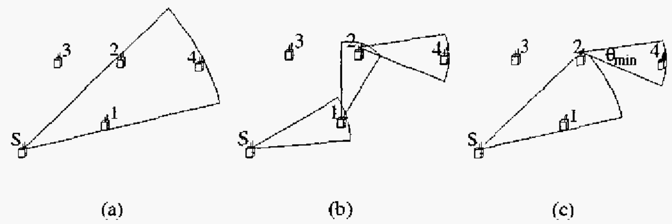

Fig. 1. Three different multicast routing solutions for the same multicast session.

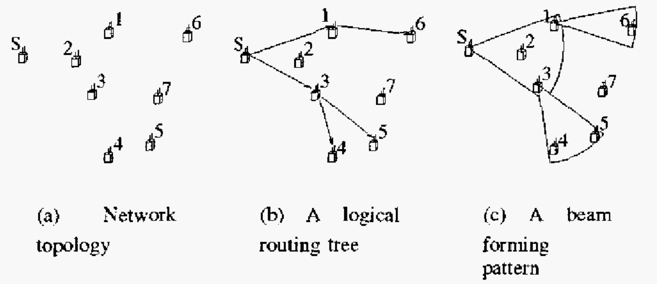

Fig. 2. A logical multicast routing tree and a physical beam forming behavior for a multicast session.

to node 4; and in Fig. 1(c) node s transmits to nodes 1 and 2, node 2 transmits to node 4. Clearly, topology and energy consumption behavior for each case is different, leading to different network lifetime performance. Note that in practice, there is a minimum beam-width requirement $\theta_{\min}$ for a beam, even in the case where the transmitting node may have only one downstream neighbor.[3]

An important concept in designing routing algorithms for wireless networks is the distinction between *physical one-hop neighbor* and *logical one-hop neighbor* [15]. To illustrate these two concepts in the context of multicast routing with directional antennas, we use the example in Fig. 2. In Fig. 2(a), we have an ad hoc network and a multicast request is initiated by node s, with multicast destination nodes being 4, 5 and 6. Figure 2(b) shows a particular logical multicast routing topology that can support this multicast communication session, where nodes 1 and 3 are used as relay nodes in the multicast tree. Figure 2(c) shows the corresponding physical beam-forming behavior at each node of the multicast tree. Note that in this example, a single beam from the source node s can possibly cover not only nodes 1 and 3, but also node 2. Although node 2 is not a logical one-hop neighbor to node s on the multicast tree, it is a *physical one-hop neighbor* to node s. An important application of physical one-hop neighbors is that should it become necessary to re-configure a new multicast tree, these physical one-hop neighbor nodes can be added (attached) to the

[3]Typically, the smaller the minimum beam-width requirement, the more complex and costlier the directional antenna [22].

logical multicast tree without changing current beam forming at any node.

In practice, multicast communication requests arrive at different nodes in the network over time and the corresponding multicast groups (destination nodes) also changes. For a given source node, the multicast group can change from request to request. For each request, there is an amount of data (also varies from multicast session to multicast session) that needs to be sent to the respective multicast group. Our objective is to pursue an optimal transmission behavior (assignment of beam radius, beam-width, and beam orientation at each node) so that the network lifetime is maximized.

III. A Theoretical Understanding of the Multicast Routing Problem

In this section, we explore some theoretical understanding of the multicast routing problem with lifetime objective. Our investigation builds upon several intermediate results, each of which summarizes the level of computational complexity of some closely related problems.

A. Minimum Power Routing

In [7], Das *et al.* studied a single-session minimum-power broadcast tree problem with omni-directional antennas. Although the authors proposed three mixed integer linear programming (MILP) formulations, no explicit solutions were given. It is well known that an MILP problem is NP-hard in general [10]. In [11], Guo and Yang studied the single-session minimum-power multicast tree problem in the context of directional antennas (with fixed beam-width). They also formulated the problem into an MILP. Again, there is no explicit analytic solution (due to NP-hardness). Although there is software available to solve MILP problems, a solution is obtainable only for small-sized problems.

It is important to realize that the minimum-power broadcast tree problem cannot be translated into a spanning-tree problem, which can be solved in polynomial time. The minimum cost spanning-tree problem addresses a connected graph with predefined edges and associated costs. The objective is to select edges with minimum total cost that connects all vertices in the graph, where the total cost is the sum of costs of selected edges. But in wireless networks, which are broadcast in nature (or partially broadcast in the case of directional antennas), the total cost at a node is not a simple summation of the cost of its outgoing links.

In [4], Cagalj *et al.* proved that, for omni-directional antennas, the minimum-power broadcast tree problem is NP-complete. Since 1) broadcast is a special case of multicast; and 2) omni-directional antenna is a special case of directional antenna, we conclude that the minimum-power multicast tree problem is NP-hard under either omni-directional or directional antennas, which we summarize in the following lemma.

Lemma 1: *For either directional or omni-directional antenna, the problem of finding a static minimum-power multicast tree is NP-hard.*

B. Maximum Lifetime Routing

From the lifetime performance perspective, it has been recognized that minimum-power routing usually cannot provide good network lifetime performance. Consequently, there have been recent efforts on exploring multicast routing, with an objective of maximizing network lifetime, for energy-constrained ad hoc networks. The problems along this line of research can be classified into three problems:

- **Problem 1:** maximizing the lifetime of a single static multicast tree;
- **Problem 2:** maximizing the lifetime of a single multicast tree with dynamic topology updates;
- **Problem 3:** maximizing the lifetime for a sequence of requests, each of which will generate a multicast tree, with dynamic topology updates for each multicast tree.

The third problem is our focus in this paper. Note that the first and second problems can be considered extreme cases under the third problem. We now discuss theoretical aspect of each problem as follows.

Problem 1. The first problem addresses network lifetime problem for a single static multicast tree (without dynamic topology updates). There are polynomial time algorithms [8], [15] to solve this problem for the broadcast case with omni-directional antennas. In [9], Floreen *et al.* proved that this problem can be solved in polynomial time for omni-directional antennas. All these prior results are obtained under the assumption that omni-directional antennas have uniform path loss behavior in all directions (i.e., a node's coverage is a disc). In the following, we extend the proof in [9] for the general case where path loss may be non-uniform (see discussion in Section II-A).

Lemma 2: *For omni-directional antennas, the problem of finding a static maximum-lifetime tree for a single multicast (or broadcast) session can be solved in polynomial time.*

Proof: Since broadcast is a special case of multicast, we only need to show a polynomial time algorithm for the multicast case. Suppose we have N nodes in the network. For each node in a multicast tree, the energy consumed on p_u^P term (source node) or $p_u^P + p_u^R$ term (non-source node) has only one value. Now we consider the p_u^T term. For the case of omni-directional antennas, given the value of p_u^T, the set of covered nodes is unique. To be energy efficient, we only need to consider $O(N)$ values of p_u^T term at each node, which correspond to the number of power levels to cover i neighbors ($0 \le i \le N-1$), where 0 represents the special case that the node does not transmit data to any node. Thus, there are $O(N)$ different total power consumption levels at each node, which correspond to $O(N)$ different node lifetimes. Since we have a total of N nodes, there exists a maximum of $O(N^2)$ different lifetime values. We only need to check which value among these $O(N^2)$ lifetime values can yield a maximum feasible lifetime solution for this multicast.

We now check if a given lifetime value t is feasible. If this t is feasible, then there exists a multicast tree such that each node has a lifetime of at least t. For each node, we first assume that they are all on the multicast tree and subtract the energy consumed on p_u^P term (for source node) or $p_u^P + p_u^R$ term (for non-source node) over t. For each node that has negative remaining energy after this subtraction, we check to see if it is the source node or a destination node in the multicast session. If yes, we can declare immediately that this t is not feasible. Otherwise, this node cannot be a node in the multicast tree and is thus removed from further consideration. For the remaining nodes, we compute the maximum transmission radius based on t and their remaining energies. Based on the coverage of each node ($O(N^2)$ complexity), we can quickly determine if a multicast tree exists (e.g., via depth first search) in $O(N)$ time. The complexity for this feasibility check is therefore $O(N^2)$.

Since we have $O(N^2)$ different lifetime values, we can sort them in non-decreasing order ($O(N^2 \log N)$ complexity). Then we use binary search ($O(\log N)$ times) to find the maximum-lifetime tree. The overall complexity, i.e., $O(N^2 \log N) + O(\log N) \cdot O(N^2)$, is therefore $O(N^2 \log N)$. ∎

For the case of directional antenna, Problem 1 becomes much harder. It's complexity is addressed in the following theorem.

Theorem 1: For directional antennas, the problem of finding a static maximum-lifetime tree for a single multicast (or broadcast) session is NP-complete.

Proof: Instead of proving the maximum-lifetime tree problem is NP-complete, it is sufficient to prove that the lifetime feasibility problem is NP-complete. This is because if we can find the maximum lifetime t^* in polynomial time, then for any given t, the lifetime feasibility problem can be solved by comparing t and t^*. On the other hand, if we can determine the feasibility of any given t in polynomial time, with the aid of simple estimates of lower and upper bounds of the lifetime, the maximum lifetime t^* can be obtained by binary search in polynomial time.

We begin with the directed Hamilton path problem with a given starting vertex. That is, for a given directed graph $G(V, E)$, with vertex set V and directed edge set E, and a designated vertex s, we want to find if there exists a directed Hamilton path with starting vertex s to each of the other vertices in V. It is well known that the directed Hamilton path problem (with any starting vertex) is NP-complete [20]. Note that by creating a dummy starting node and directed edges from this node to all other nodes, we can show that the directed Hamilton path problem with a given starting vertex is NP-hard. It is easy to show that this problem is also in NP. Since the directed Hamilton path problem with a given starting vertex is both NP-hard and in NP, it is NP-complete.

Now, given any instance of the directed Hamilton path problem with starting vertex s, we show how to reduce it to an instance of the lifetime feasibility problem in polynomial time. In the lifetime feasibility problem, we consider broadcast, a special case of multicast, where a node s needs to transmit data to all other nodes. We let $\theta_{\min} = \theta_{\max}$ and denote it as θ_f, i.e., the beam-width is fixed. For the given directed graph G, denote N_u the set of vertices that are "outgoing" neighbors of vertex u such that for any $q \in N_u$, there is a directed edge from u to q, i.e., $u \to q$.

Now we assign the parameter values of an N-node network for the feasibility problem. First, we arrange the N nodes such that there are no more than two nodes on the same line. As a result, we can set a value for θ_f such that a single beam from any node (with any ρ and ω) can cover at most one node. Further, we can arrange an energy consumption function $C_u(\rho, \theta, \omega)$ with such a property that for each node u, the energy cost to cover any node $q \in N_u$ is smaller than the energy cost to cover any node $z \notin N_u$. Now, for an arbitrarily given lifetime $t > 0$, we can always initialize the energy of each node u such that it can transmit to any node $q \in N_u$ over time t while it is unable to transmit to any node $z \notin N_u$ for the entire duration of t. As an example of how to define $C_u(\rho, \theta, \omega)$ and set initial energy for each node u, we can let $C_u(\rho_{uq}, \theta_f, \omega_{uq}) = a_u$ for every node $q \in N_u$, and $C_u(\rho_{uz}, \theta_f, \omega_{uz}) = b_u$ for every node $z \notin N_u$, where a_u and b_u are constants and $b_u > a_u > 0$, ρ_{uq} and ρ_{uz} are distances from node u to q and z, ω_{uq} and ω_{uz} are beam orientations from node u to q and z, respectively. The value of $C_u(\rho, \theta, \omega)$ at other locations are not of our concern and thus can be defined arbitrarily. The only requirement that $C_u(\rho, \theta, \omega)$ should have is that it is an increasing function of ρ for any fixed ω as we discussed in Eqs. (1) and (3) (note that θ is already fixed as θ_f earlier). Also, as we discussed in Section II-A, due to potential non-uniform path loss along different beam orientations ω in practical wireless environment, $C_u(\rho, \theta, \omega)$ also depends on beam orientation ω. In particular, even if $\rho_1 > \rho_2$, it is possible that $C_u(\rho_1, \theta_f, \omega_1) < C_u(\rho_2, \theta_f, \omega_2)$ if $\omega_1 \neq \omega_2$. Now we can set the initial energy at each node u in the network to be $t \cdot r \cdot a_u$, where r is the transmission data rate. Thus, node u can transmit to any node $q \in N_u$ over time t while is unable to transmit to any node $z \notin N_u$ for the entire duration of t since $a_u < b_u$. This completes the example.

Under the above setting, it follows that the lifetime t is feasible if and only if G has a directed Hamilton path with starting vertex s to all other vertices. Therefore, any instance of the directed Hamilton path problem with starting vertex s can be reduced to an instance of the lifetime feasibility problem. Thus, the lifetime feasibility problem is also NP-hard.

It is easy to show that the lifetime feasibility problem is in NP. Since the lifetime feasibility problem is both NP-hard and in NP, it is NP-complete. As a result, for directional antenna case, our static maximum-lifetime tree problem for multicast is also NP-complete. This completes the proof. ∎

Problem 2. We now move onto the discussion of the second problem, which addresses how to maximize the lifetime of one multicast tree under dynamic routing (i.e., routing topology may change over time for this single multicast). For omni-directional antennas, Floreen *et al.* [9] claimed that this problem is NP-hard. Based on this claim, the problem of maximizing the lifetime for one multicast tree under dynamic routing is also NP-hard since directional antenna is a general case of omni-directional antenna.

Problem 3. The third lifetime problem addresses how to perform multicast routing when successive multicast requests arrive to the network. This problem is substantially more difficult than multicast routing for a single request (e.g., [4], [7], [9], [11]) in that we are not interested in the maximum-lifetime tree for one request, but rather, we are interested in the network lifetime performance when successive multicast session requests (generated at different nodes in the network and with different multicast groups) arrive and depart over time. That is, we are looking for an "online" algorithm *without any knowledge of future request arrivals* with the aim of maximizing network lifetime.[4] This is in contrast to the "offline" optimization for maximum network lifetime problem, which assume the future multicast requests are known a priori. In [18], Li *et al.* proposed an online routing algorithm to maximize network lifetime for unicast case. They showed that an online algorithm does not have a constant competitive ratio to the offline optimum. Since unicast is a special case of multicast, we conclude that online algorithms for multicast routing do not have a constant competitive ratio.

As the online optimization cannot be solved analytically, one might ask whether it is possible to pursue an "offline" optimization algorithm. By "offline", we mean that we first record successive multicast request arrivals to the network over time. Then assuming we can "go back" in time with the knowledge of all these future arrivals, we attempt to pursue routing optimally for each successive request such that the network lifetime is maximized. Note that in the extreme case, when all multicast requests have the same source node and destination nodes, this problem reduces to Problem 2 that we discussed earlier, which is NP-hard. Therefore, we conclude that offline multicast routing for successive multicast requests is also NP-hard.

Theorem 2: For both omni-directional and directional antennas, an offline problem of optimal routing to maximize the network lifetime for a wireless ad hoc network with successive multicast requests is NP-hard.

Since the offline problem for multicast routing is NP-hard, for an online problem, only heuristic approach is feasible. This will be our effort in the next section.

IV. Lifetime-Centric Design for Online Multicast Routing Algorithm

Background. In [26], Wieselthier *et al.* made a major step in the systematic study of online multicast routing for energy-constrained ad hoc networks. In particular, they examined source-initiated, session-based multicast problem for successive requests and proposed an online heuristic algorithm (D-MIP) that was shown to have good performance in terms of network lifetime and traffic volume. In particular, in the design of D-MIP, the authors explicitly incorporated nodal residual energy into the local routing cost metric. Then they used a spanning-tree like technique to obtain a broadcast tree, which they called as broadcast incremental power (BIP) algorithm. A multicast tree can be obtained by pruning the non-necessary links. The algorithm for directional antenna case was called directional multicast incremental power (D-MIP) algorithm.

Motivation. Although the D-MIP algorithm is currently the state-of-the-art online algorithm to the multicast routing problem, there is a very subtle detail in the algorithmic design of D-MIP that motivates us to further investigate this important problem. Specifically, although nodal residual energy indeed is closely related to node lifetime (and thus network lifetime), it still may not be as effective as if we take network lifetime metric directly into iterative calculations. Consequently, we make the following conjecture in our investigation. *Suppose we incorporate lifetime consideration directly into the iterative calculation of the online multicast routing algorithm. We should then expect to have an algorithm that outperforms an algorithm based on nodal residual energy (e.g., D-MIP).* In this section, we develop an online multicast routing algorithm along this approach, and in Section V, we use simulation results to demonstrate that it indeed offers consistent performance improvement over D-MIP. Therefore, our efforts here improve algorithmic design methodology for online lifetime-based routing problems associated with energy-constrained ad hoc networks. For ease of reference, we name our algorithm MLR-MD (Maximum Lifetime Routing for Multicast with Directional antennas), which is intended to contrast with traditional MPR (Minimum Power Routing) [6], [24], [25] or variants of minimum cost routing [26]. It is worth pointing out that problems either addressing broadcast or considering omni-directional antennas can be considered as special cases under multicast or directional antennas (with $\theta = 360$), respectively. Consequently, MLR-MD can be applied to a wide range of network settings to address online lifetime-centric routing problems.

Basic Idea. For a given multicast request, the basic idea of the MLR-MD algorithm is to start with a multicast routing solution first (e.g., a single beam from the source covering all multicast destination nodes) and then iteratively improve lifetime performance of the current solution by identifying the node with the smallest lifetime and revising routing topology as well as corresponding beam-forming behavior for an increased network lifetime. In particular, for the case of directional antennas with power control capability, a node's lifetime can be increased via two techniques: *narrowing beam-width* θ and *reducing beam radius* ρ. A direct consequence of such operation is that some nodes in the multicast tree that are covered by the original beam could be exposed (uncovered) under the new beam with

[4]Recall that network lifetime is defined as the first time instance when a multicast communication fails, either due to energy depletion at sender or any receiver of the multicast group.

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Source node generates one beam to cover all destination nodes;
Sort all nodes in non-decreasing lifetime order and arrange the sorted
list with a stack L (with the top node having the smallest lifetime);
while (L != ∅){
    i = pop(L);
    Identify the logical downstream one-hop neighbors of node i that
    are on the border on node i's beam;
    Sort such nodes in non-increasing lifetime order and arrange the
    sorted list with a stack L_i (with the top node contributing to the
    largest lifetime increase on node i if removed);
    Improved = 0;
    while (L_i != ∅){
        j = pop(L_i);
        if (RemoveLink(i, j)==1){
            Improved = 1;
            break;
        }
    }
    if (Improved==1)
        Sort all nodes in non-decreasing lifetime order and arrange
        the sorted list with a stack L (with the top node having
        the smallest lifetime);
}
```

Fig. 3. Main program.

```
int RemoveLink(int i, int j){
    Remove link i → j;
    if (Case1B(i, j)==1) return 1;
    if (Case1A(i, j)==1) return 1;
    if (Case2A(i, j)==1) return 1;
    if (Case2B(i, j)==1) return 1;
    Add link i → j back, recover node i's beam;
    return 0;
}
int Case1A(int i, int j){
    Identify a node v (v ≠ i) so that
    1) v is in the multicast tree or ∃k, v is covered by node k's
    beam and k's lifetime>node i' old lifetime (in this case, add
    link k → v); and
    2) after adding link v → j, v's new lifetime> i's old lifetime:
    if such node exists {
        choose the best node (having the largest new lifetime);
        return 1;
    }
    return 0;
}
int Case1B(int i, int j){
    Identify a node v (v ≠ i) so that j is covered by node v's
    beam and v's lifetime>node i' old lifetime;
    if such node exists, choose any node and return 1;
    return 0;
}
int Case2A(int i, int j){
    Identify a pair of nodes (u, v) (u ≠ i) so that
    1) u is in the multicast tree or ∃k, u is covered by node k's
    beam and k's lifetime>node i' old lifetime (in this case, add
    link k → u);
    2) v is not covered by any beam of the multicast tree; and
    3) after adding links u → v → j, the pair lifetime (the smaller
    new lifetime of nodes u and v)>node i's old lifetime;
    if such pair exists {
        choose the best pair (having the largest pair lifetime);
        return 1;
    }
    return 0;
}
int Case2B(int i, int j){
    Identify a node v so that
    1) v is not covered by any beam of the multicast tree; and
    2) after adding links i → v → j, the pair lifetime (the smaller
    new lifetime of nodes i and v)>node i's old lifetime;
    if such node exists {
        choose the best node (having the largest pair lifetime);
        return 1;
    }
    return 0;
}
```

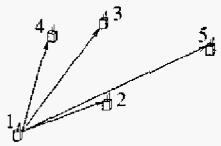
Fig. 4. Auxiliary functions.

reduced beam-width or beam radius. The MLR-MD algorithm has several approaches to "re-attach" these exposed nodes back onto the multicast tree. Since a re-attachment operation would decrease some other node's lifetime, a decision must be taken on whether a re-attachment operation is feasible. Naturally, a re-attachment operation is feasible only if the new network lifetime is increased. For the next iteration, we again repeat the same process, i.e., identifying the node among all the nodes in the network with the minimum lifetime and attempting to revise routing topology and beam-forming behavior to increase network lifetime.

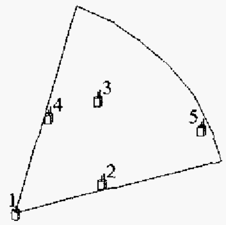
When nothing can be done to further improve this minimum lifetime, we move on to consider the node with the second smallest lifetime and attempt to increase its lifetime, under the condition that the lifetime for the first node (with minimum lifetime) will not decrease. In particular, MLR-MD does not increase downstream nodes on the first node. The motivation for attempting to re-configure the node with the second smallest lifetime is the following. Although the increase of this second smallest node lifetime may not increase the minimum node lifetime, it will enable the multicast routing topology to evolve to a better structure, thereby creating new optimization space for the first node (with minimum node lifetime) in the next iteration.

If nothing can be done for the node with the second smallest node lifetime, the MLR-MD algorithm will continue to try the node with the third smallest node lifetime and so forth. The algorithm terminates after it has tried all nodes (in the order of non-decreasing node lifetime) and cannot increase lifetime for all the nodes. The pseudo code of this basic idea is shown in Figs. 3 and 4, which are further elaborated as follows.

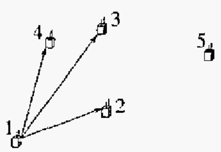
Some Details. We now consider some details in the MLR-MD algorithm. As described earlier, upon identifying a minimum-lifetime node at an iteration, we will attempt to reduce either its beam-width or beam radius in order to increase its lifetime. The immediate consequence of this operation is that some nodes along the border of the original beam are being pushed out of the new beam's coverage. We use an example to illustrate this point. Figure 5(a) shows the logical one-hop links on node 1, while Fig. 5(b) shows the beam-forming behavior on node 1. Suppose that we wish to extend node 1's lifetime by reducing either its beam-width or beam radius. Under either technique, it is only necessary to consider the three border nodes 2, 4, and 5. In the case of beam radius reduction, we can consider to expose node 5 and let the beam cover only nodes 2, 3, and 4 (see Fig. 5(d)). This will result in a new downstream logical topology for node 1 in Fig. 5(c), where the previous logical link between nodes 1 and 5 is removed. Since node 5 (or one node in node 5's subtree) may belong to the multicast group, it has to be re-attached back to the multicast tree through another link, by means of a procedure that we will describe shortly. In the case of beam-width reduction, we can consider to remove



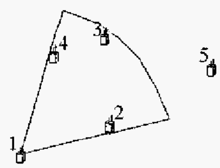
(a) Logical one-hop links



(b) Beam from node 1

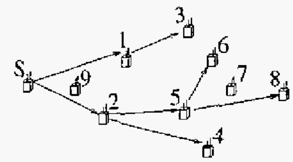


(c) New logical one-hop links

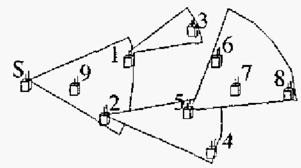


(d) New beam from node 1

Fig. 5. An example of reducing node 1's beam coverage.

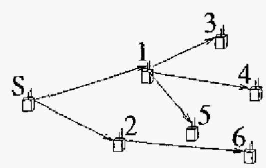


(a) A logical multicast tree

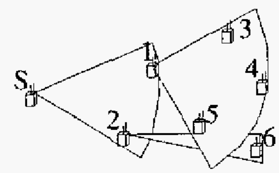


(b) A physical beam-forming behavior at each node

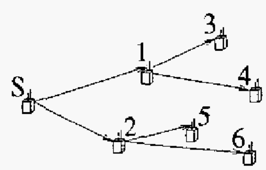
Fig. 6. Concept of logical one-hop neighbor and physical one-hop neighbor.



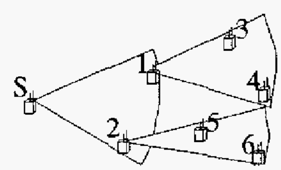
(a) Multicast tree



(b) Beam on each node



(c) New Multicast tree



(d) New beam on each node

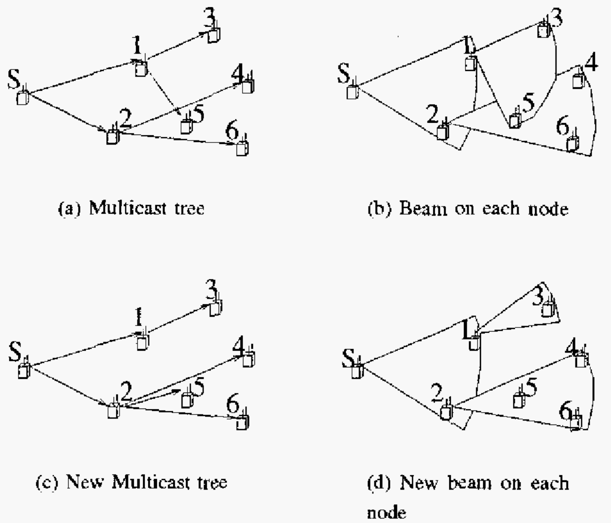
Fig. 7. Case I – Re-attachment without intermediate relay nodes.

node 2 or 4 following the same approach. As either beam radius reduction (i.e., remove coverage for node 5) or beam-width reduction (i.e., remove coverage for node 2 or 4) will increase node 1's lifetime, a decision must be made as which node we should remove (2, 4, or 5). In our implementation (Fig. 3), we rank the order of these three possibilities (nodes 2, 4, and 5), in terms of how much improvement each will bring to node 1's lifetime. We will first try to remove the node that yields the largest increase in nodes 1's lifetime. If the re-attachment of this node (node 5 in example) is feasible, then we are done. Otherwise, we declare removing this node as a failure and we will consider to remove the node that will yield the second largest increase in node 1's lifetime and so forth. From the perspective of logical one-hop neighbor, any of these node removal operations, either due to beam-width reduction or due to beam radius reduction, is equivalent to breaking a logical link among the logical one-hop neighbors. This observation is important in coding and implementation in the sense that a link removal subroutine (RemoveLink() in Fig. 4) can be used by either the beam radius reduction operation or the beam-width reduction operation.

We now discuss another important property associated with nodes that are not on the logical multicast tree but are within the coverage of one of the directional beams associated with the multicast tree (i.e., physical one-hop neighbor). Referring to Fig. 6, suppose node S is the source node and nodes 3, 4, 5, 6, and 8 are the multicast destination nodes. Figure 6(a) shows a multicast tree topology for a particular routing solution and Fig. 6(b) shows the areas that is being covered by the beams of the multicast routing solution. For those nodes that are not on this multicast tree but are within the coverage of these beams (e.g., nodes 7 and 9), we claim that there exists a path from the source of the multicast to each of them. For example, a path for node 7 is $S \rightarrow 2 \rightarrow 5 \rightarrow 7$, where logical link $5 \rightarrow 7$ can be added under node 5's current beam since node 7 is the physical one-hop neighbor of node 5. That is, if there is a need to add one of these nodes onto the multicast tree, all we need to do is to add one logical link in the multicast tree without any change to existing physical beams. We formally state this important property associated with directional antenna-based multicast routing as follows.

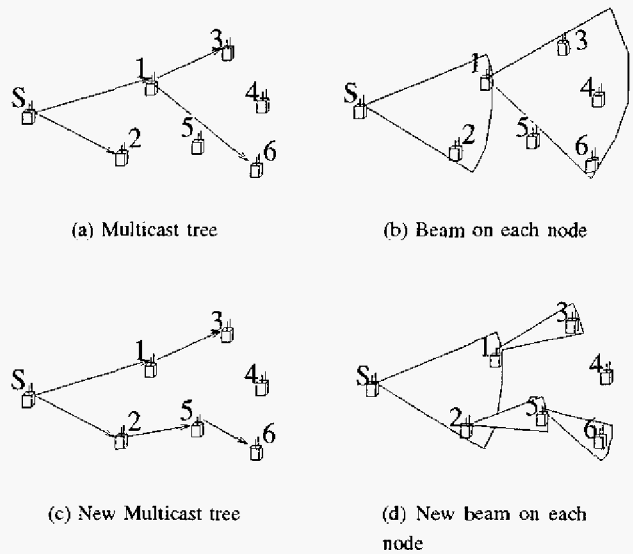
Property 1: **(Multicast Beam Coverage)** *Consider a node that is not in the logical multicast tree but is a physical one-hop neighbor of a node within the multicast routing tree. This node can be attached to the logical multicast tree by adding one logical link, without any change to the existing beam-forming structure in the network.*

We now discuss how the MLR-MD algorithm handles the "re-attachment" operation, i.e., the re-connection of an exposed node back to the multicast routing tree. This operation requires the re-configuration of existing beam-forming structures in the



(a) Multicast tree (b) Beam on each node (c) New Multicast tree (d) New beam on each node

Fig. 8. A special case of Case I.



(a) Multicast tree (b) Beam on each node (c) New Multicast tree (d) New beam on each node

Fig. 9. Case II – Re-attachment with Intermediate Relay Nodes.

network and can be classified into two cases: (1) without the use of intermediate relay nodes (Case I); and (2) with the use of intermediate relay nodes (Case II). An intermediate relay node is a node that is currently not within the coverage of any beam and is chosen as a relay for re-attachment.

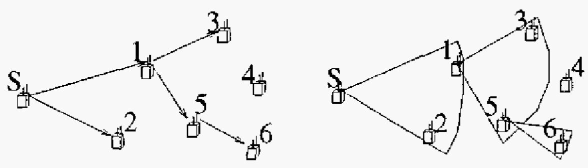
Case I: Re-attachment without Intermediate Relay Nodes. This case is best explained with an example. Suppose that we have a logical multicast tree in Fig. 7(a) with a physical beam-forming solution in Fig. 7(b), where node S is the source and nodes 3, 4, 5 and 6 are multicast destination nodes. Now we want to increase node 1's lifetime by pushing out node 5 from its beam. Consequently, a new beam can be formed to cover nodes 3 and 4 only and node 5 is exposed. It is necessary to re-attach node 5 back to the multicast tree. Under case I, no intermediate relay nodes are used. We only consider to adjust the beam at one of nodes S, 2, 3, 4, or 6 to cover 5 and the new lifetime of the corresponding node (with a modified beam) will decrease. The re-attachment operation is considered a success only if this node's new lifetime (with modified beam) is larger than node 1's lifetime before pushing out node 5. In the case when there are multiple successful re-attachments, we will choose the re-attachment that yields the longest node lifetime. For example, in Fig 7(c), suppose that node 2's new lifetime is the largest among others, then MLR-MD will choose node 2 to connect node 5, with a new beam-forming shown in Fig 7(d).

Figure 8 shows the special case that one can take advantage of when one node (i.e., node 5) already falls within the beam coverage of another node (i.e., node 2). In this case (recall our discussion for Property 1), there is no need to generate new beams or update beams in order to re-attach node 5 into the multicast tree. Instead, it is only necessary to update the logical multicast tree (see Fig. 8(c)) and mark node 5 to be a downstream node of node 2.

The pseudo code of Case I is shown in Fig. 4 as Case1A() and the special case of Case I is Case1B(). The algorithm tries Case1B() first because it is impossible to have a lifetime decrease under this special case.

Case II: Re-attachment with Intermediate Relay Nodes. Again, this case is best explained with an example. Suppose that we have a logical multicast tree in Fig. 9(a) where node S is the source and nodes 1, 2, 3 and 6 are multicast destination nodes. Figure 9(b) shows a beam-forming solution of this multicast tree. Now we want to increase node 1's lifetime by pushing out node 6 from its beam. Consequently, we re-generate a new beam from node 1 (with beam-width $\theta_{\min}$) to just cover node 3. Since node 6 is now exposed, we need to re-attach it back to the multicast tree. Under Case II, we will consider to employ one intermediate relay node (node 4 or 5) during the re-attachment process. In particular, we will adjust the beam on one of nodes S, 2, and 3 to cover the intermediate relay node. For the pair of adjusted node and intermediate relay node, define the pair-lifetime as the smaller lifetime of their node lifetimes. The re-attachment is successful only if the pair-lifetime is larger than node 1's lifetime before pushing out node 6. If there are multiple successful re-attachment options to choose from, we will choose the pair of nodes that yields the largest pair-lifetime. For example, suppose that the node pair 2 and 5 yields the largest pair-lifetime among all possible options, then the MLR-MD algorithm will choose this pair of nodes and generate a new beam at node 2 to cover node 5 and another new beam at node 5 to cover node 6, respectively (see Fig. 9(d)). The corresponding new logical multicast routing tree is shown in Fig. 9(c).

In the special case, suppose that we find the best option is to choose the node pair 1 and 5. In this case, we need to re-adjust the beam on node 1 to cover the intermediate relay node (i.e., node 5). Since each node is allowed to generate one beam



(a) New Multicast tree (b) New beam on each node

Fig. 10. A special case under Case II.

for the directional antenna under our investigation, we have to modify the existing beam from node 1 to cover both node 5 and node 3. In this case, node 1's beam-width is increased (after first decreasing its beam radius to push out node 6). This solution is shown in Fig. 10(b), with corresponding logical multicast routing tree shown in Fig. 10(a).

The pseudo code of Case II is shown in Fig. 4 as Case2A() and the special case of Case II is shown as Case2B(). In the special case, node i's lifetime is smaller than that in Case II, so MLR-MD tries Case2B() last.

As expected, the computational complexity of the MLR-MD algorithm is strictly polynomial. The details of this analysis is available in [12] and is omitted here due to paper length limitation.

V. Simulation Results

A. Simulation Settings

In this section, we use simulation results to illustrate the behavior and performance of the proposed MLR-MD algorithm and compare it to the D-MIP algorithm. For comparison, we also show results for multicast routing under the minimum power routing (MPR) paradigm, where a broadcast tree is obtained first by a spanning-tree like technique and then is pruned to a multicast tree [25].

In our numerical investigation, we assume that energy consumption in Eq. (3) is independent of ω. Further, we define $p^T_u(\rho, \theta)$ as follows [26]:

$$p^T_u(\rho,\ \theta) = \max\left\{\frac{\theta}{360}\rho^{\alpha},\ p_{\min}\right\}\ , \qquad (4)$$

where α is the path loss index and is typically within $2 \le \alpha \le 4$ [21], and $p_{\min}$ is the minimum power that is needed to generate a beam.

We consider networks of various sizes consisting of either 10, 20, 50 or 100 nodes. For 10-, 20- and 50-node networks, we assume that the nodes are randomly deployed in a 5 unit by 5 unit square region, where the distance unit is consistent to that for ρ in Eq. (4). For 100-node networks, we assume the nodes are randomly deployed over a 15 unit by 15 unit square region. In all cases, we assume that each node starts with 200 units of energy, with the energy unit consistent to that in Eq. (4).

We are interested in an online operation where multicast requests arrive sequentially over time. The source of the multicast request is chosen at random and the multicast group is also a random group of nodes in the network (excluding the source node). For each multicast request, the amount of data generated by the source node is uniformly chosen between [10, 100] units and transmission rate at the source node is 10 units of data per time unit. In our simulation, we assume $\alpha = 4$ in Eq. (4), $p^T_u \gg p^R_u$, and $p^T_u \gg p^P_u$. That is, RF transmission energy is the dominant source of energy consumption. We also assume $p_{\min} = 0$ in Eq. (4). For the bounds of beam-width for directional antennas, we assume $\theta_{\min} = 30$ and $\theta_{\max} = 360$ (both in degrees).

For both MLR-MD and D-MIP algorithms, routing topology is dynamically changed every time unit as discussed in Section V (if there is remaining data to send at the source node), where time unit can be defined to reflect practical settings. For MPR, routing is only performed for each multicast request and remains static (fixed routing).

Although multicast session requests arrive to the network sequentially, it is possible that a new multicast session request arrives (at a different source node) before the previous multicast session terminates. That is, we may have multiple multicast sessions in the network at the same time. Our online MLR-MD algorithm (so does D-MIP algorithm) still works since it will consider multicast routing for each session independent from other on-going sessions in the network. Although multiple concurrent sessions do not pose any difficulty to our algorithm, it does introduce a subtle issue for accounting of total network lifetime. A logical approach to address this issue may be taken from the perspective of data volume that is being transmitted. As data transmission rate is common for all nodes (10 unit of data/time unit), the total amount of data that has been transmitted successfully by each multicast source node should be directly related to network lifetime calculation. Following this reasoning, any time overlap of multiple multicast communication sessions should be counted multiple times corresponding to the time overlap of multiple concurrent multicast sessions.

B. Results

For each network size (10, 20, 50, 100), we will generate 100 network topologies randomly and run the three algorithms for each topology. Instead of showing the absolute network lifetime values, we find that it is more meaningful to show normalized network lifetime for easy comparison. Define normalized network lifetime as the network lifetime obtained by MLR-MD or D-MIP divided by the network lifetime obtained by MPR. The average, best case, worst case, and 95% confidence interval (all in percents) are shown in Table I. For 100-node networks, D-MIP obtains 207% improvement while MLR-MD is able to achieve 324% improvement on average than MPR. For the best case, MLR-MD obtains 1032% improvement while D-MIP obtains 873% improvement. Recall that D-MIP takes explicit consideration of a node's remaining energy in routing and is a

TABLE I

STATISTICAL DATA OF NORMALIZED NETWORK LIFETIME PERFORMANCE OF MLR-MD AND D-MIP ALGORITHMS WITH RESPECT TO MPR.

N	Algorithm	Average	Best	Worst	95% Conf.
10	D-MIP	245.68	1466.67	100.00	[205.72, 285.64]
	MLR-MD	336.54	1861.76	98.08	[278.18, 394.91]
20	D-MIP	276.91	1210.11	100.00	[242.40, 311.41]
	MLR-MD	359.72	1821.35	100.00	[307.63, 411.80]
50	D-MIP	383.15	1203.24	154.57	[344.41, 421.89]
	MLR-MD	504.38	1894.44	161.32	[444.54, 564.21]
100	D-MIP	307.62	973.91	98.98	[274.41, 340.83]
	MLR-MD	424.67	1132.61	105.26	[376.59, 472.75]

TABLE II

NETWORK LIFETIME OF MPR, D-MIP, AND MLR-MD FOR 50-NODE NETWORK.

Index	MPR	D-MIP	MLR-MD
1	246.5	699.8	872.7
2	74.4	191.9	249.3
3	167.2	497.9	730.2
4	165.2	552.9	684.4
5	147.3	328.9	505.0
6	93.1	268.9	699.1
7	207.1	610.9	820.2
8	161.6	412.8	424.3
9	69.8	490.6	549.0
10	158.2	337.9	401.9
11	207.1	576.9	642.4
12	71.5	707.8	883.3
13	145.0	425.9	579.4
14	92.8	231.9	293.3
15	311.5	774.2	775.4
16	237.8	738.9	950.5
17	55.3	344.9	488.1
18	21.6	259.9	409.2
19	72.5	491.8	676.3
20	114.7	496.7	540.5

cost-based algorithm. On the other hand, the proposed MLR-MD algorithm directly addresses the lifetime issue in algorithm design and thus is able to achieve better network lifetime performance over D-MIP on average. This confirms our initial conjecture in Section IV that a lifetime-centric approach should yield better results than a cost-based approach. Simulations on 10, 20, and 50-node network show similar results. To get a sense of what actual network lifetimes look like under different multicast routing algorithm in real time unit, Table II shows the first 20 sets of results for the 50-node network under the MPR, D-MIP, and MLR-MD algorithms.

VI. RELATED WORK

The most significant theoretical work related to this research (i.e., [4], [7], [9], [11], [15], [18]) has been discussed in detail in Section III. In this section, we briefly review other relevant work that contributed to the background of our investigation.

There have been many recent papers addressing minimum energy routing for broadcast or multicast problem. Since this problem is NP-hard (see Lemma 1 in Section III), many heuristics have been proposed for broadcast (e.g. [2], [4], [5], [14]) and multicast (e.g. [6], [24], [25]). In [23], Wan *et al.* explored the performance of several heuristic algorithms by analyzing their *competitive ratio* (the heuristic result divided by the optimal result). In particular, they analyzed the competitive ratios for the minimum spanning-tree, shortest path tree, and BIP (see discussion in Section IV) and found that BIP offers the best performance.

There is a rich literature on online algorithms (see [13] and references therein) and online algorithms for network routing in particular (see [17] and references therein). In [19], Li *et al.* proposed an online algorithm for minimum energy routing. As discussed, minimum energy routing may not provide good performance in network lifetime. In [16], Kar *et al.* offered an online algorithm to maximize the capacity for unicast communications in energy-constrained ad hoc networks. In [1], Adamou and Sarkar proposed an online algorithm to maximize node lifetime rather than network lifetime.

The problem for maximizing the lifetime for a sequence of multicast requests where the routing tree for each multicast can be updated over time is shown to be NP-hard (see Theorem 2 in Section III). Currently, there are only two heuristic algorithms addressing this problem, i.e., Kang and Poovendran's work in [15] for the broadcast problem (a special case of the multicast problem) and Wieselthier *et al.*'s work in [26], whose performance was shown in the numerical results in Section V.

VII. CONCLUSIONS

In this paper, we investigated multicast routing problem for energy-constrained wireless ad hoc networks where each node is equipped with a single-beam directional antenna. We are interested in an online multicast routing algorithm for successive multicast communication requests with the aim of maximizing network lifetime. The main contributions of this paper include: (1) some important theoretical understandings on various multicast problems for energy-constrained wireless ad hoc networks; and (2) the development of an online algorithm that takes into network lifetime consideration directly into iterative calculations. We showed that an algorithm designed under this methodology is able to provide consistent performance improvement over current state-of-the-art algorithm that takes remaining energy into iterative calculations. The theoretical results and online algorithm developed in this paper provide important understanding on routing algorithm design for energy-constrained ad hoc networks employing directional antennas.

ACKNOWLEDGEMENTS

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