

On Lifetime Extension and Route Stabilization of Energy-Efficient Broadcast Routing over MANET

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Abstract

In this paper, we address the problem of energy efficient multicast routing in wireless Mobile Adhoc NETWORK (MANET). It is a challenging environment because every node operates on limited battery resource and multi-hop routing paths are used over constantly changing network environments due to node mobility. We define the network lifetime as duration of time until first node failure due to battery energy exhaustion and show that network lifetime for a multicast session can be significantly extended by additionally considering the residual battery energy as a parameter in cost metric functions for constructing a power efficient routing tree. Using simulation results, we show that the lifetime extension can lead to oscillatory behavior of routing path selection. We propose a solution to stabilize the oscillations by considering a statistical measure in our cost metric and present simulations that show the oscillation can be reduced greatly at a small cost of network lifetime.

Keywords

MANET, Adhoc Networks, Energy Efficient Routing, Multicasting Tree, BIP Algorithm

1. Introduction

The military mobile network consisting of soldiers on the move, emergency search and rescue, dynamic coalitions and ubiquitous computing are some of the applications that make use of wireless mobile adhoc networking that make extensive use of multicast/broadcast communications (Singh *et al*, 1998). A salient feature of many of these networks is the use of micro-processor embedded, energy constrained devices that have the capability to perform advanced computations. Due to the battery energy constraint of these devices, it is essential to develop computational/networking algorithms and protocols that are optimized for energy consumption under each clock cycle. The battery energy of a transmitting node can be depleted due to : (a) computational processing at the node, (b) transmission attenuation due to path loss, and (c) the need to maintain the transmission above a certain threshold due to signal interference.

Designing energy-efficient unicast algorithms and protocols has been an active area of research (Singh *et al*, 1998), (Chang and Tassiulas, 2000), and (Toh, 2001). A recent study (Lee *et al*, 2000) presents extensive comparison on the performance of different multicast routing protocols suitable for MANET and concludes that ODMRP which combines on-demand and mesh-based approach has the best performance when energy is not a constraint. Since the ODMRP uses a flooding scheme to set up the routes, the use of it in the case of energy constrained networks will lead to rapid battery exhaustion. Hence, new approaches that incorporate energy constraints and increase lifetime of the node battery are needed.

In a series of recent papers, (Wieselthier *et al*, 2000) and (Wan *et al*, 2001) presented an approach that tries to develop energy-efficient broadcast routing trees. They presented a tree construction algorithm that makes use of needed power expenditure by the nodes in developing an energy-efficient routing solution.

In this paper, we show that their solution can be improved to extend the overall lifetime of the network significantly. Such an extension also comes with the additional challenges of route path oscillations that need to be reduced/damped using statistical techniques.

In the next section, some preliminary background on BIP algorithm is outlined. In section 3, we discuss the problem of determining and exchanging transmission power level, which is essential for actually constructing a power efficient tree. In sections 4 and 5, we propose different metrics to increase network lifetime and reduce oscillations. Section 6 presents our simulation model and summarizes the main simulation results and section 7 concludes this paper with our future research.

2. Background

In this paper, the best effort to conserve energy at each instance of time and to extend the lifetime of the multicast session is made using a power efficient multicast tree and by updating this tree regularly in a strategic manner. We use a recently proposed power-efficient multicast tree construction algorithm as a building block and construct our cost functions. Based on these newly proposed cost functions, we derive solutions that lead to significant improvements in extending the network lifetime while reducing the oscillations in routing algorithms. We now review the broadcast advantage feature of the omni-directional antenna in wireless medium, also available in (Wieselthier *et al*, 2000).

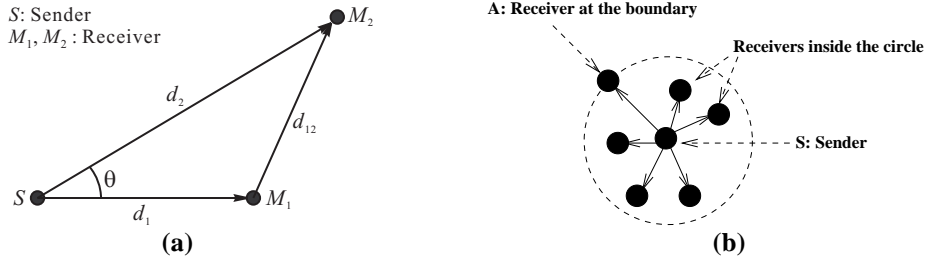


Figure 1: (a) Geometric construct of a sender S and receivers M_1 and M_2 (b) Wireless broadcast advantage

2.1 Wireless Broadcast Advantage

Fig.1(a) shows a single sender S with receivers M_1 and M_2 at distances of d_1 and d_2 , respectively, from the sender. We assume that $d_2 > d_1$ and the received power at a node varies as $d_i^{-\alpha}$ ($i=1, 2$) where α is the path loss factor satisfying ($2 \leq \alpha \leq 4$). Hence, the transmission power required to reach a node at a distance d_i is proportional to d_i^α assuming the proportionality constant is 1. Fig.1(b) shows the broadcast nature of the wireless medium for omni-directional antenna in which a unit of message sent to receiver A at the boundary of the circle reaches every node within the circle for “free.” In order to transmit an identical message to nodes M_1 and M_2 , S can use two unicast transmissions with individual power d_1^α and d_2^α with total expenditure of $(d_1^\alpha + d_2^\alpha)$. However, it can be reduced to $\max(d_1^\alpha, d_2^\alpha)$ by taking advantage of the fact that the wireless medium is naturally “broadcast.” Under this assumption, the sender has to choose between the following two strategies: (a) if $d_2^\alpha > d_1^\alpha + d_{12}^\alpha$, transmit to M_1 and let M_1 transmit to M_2 , (b) otherwise, transmit to M_2 (M_1 will automatically receive it due to wireless broadcast advantage since $d_2 > d_1$). Hence, joint consideration of transmission and routing leads to savings in battery energy.

For an arbitrary network topology, the construction of a routing tree with globally minimum total power expenditure does not have a known algorithm. However, there is a sub-optimal solution (Wieselthier *et al*, 2000) called the *Broadcast Incremental Power* (BIP) algorithm that uses a greedy approach to construct a tree. We describe it below.

2.2 Description of the BIP Algorithm

Input: given an undirected weighted graph $G(N, A)$, where N : set of nodes, A : set of edges

Initialization: set $T := \{S\}$ where S is the source node of multicast session.

Set $P(i) := 0$ for all $1 \leq i \leq |N|$ where $P(i)$ is the transmission power of node i .

Procedure: while $|T| \neq |N|$

find an edge $(i, j) \in T \times (N - T)$ such that incremental power $\Delta P_{ij} = d_{ij}^\alpha - P(i)$ is minimum.

add node j to T , i.e., $T := T \cup \{j\}$.

set $P(i) := P(i) + \Delta P_{ij}$.

The BIP algorithm uses the broadcast advantage property while constructing a power efficient tree. As with other heuristic greedy algorithms, this algorithm is not globally optimal in producing a multicast tree with minimum total power expenditure. Currently, there is no known algorithm (except exhaustive search) that leads to a globally optimal solution and is also computationally efficient. Moreover, due to the distributed nature of adhoc networks, the source node may not have global knowledge of network topology in advance without which tree construction is not possible. This point is not addressed in the original paper (Wieselthier *et al*, 2000). We present schemes to collect network topology information for three specific cases.

3. Transmitting Power Information for Power-Efficient Tree Construction

Since the senders (source/relaying nodes) do not know the appropriate transmission power level a priori to reach intended receivers, some strategies should be developed to decide the power level based on the feedback from the receivers. The mechanism of exchanging power information is important to maintain the network connectivity. We present solutions to this problem for three different cases depending on the availability of location information or the ability for a receiver to sense the power level. In presenting our solutions, we assume that a transmitter can adjust its power level dynamically.

3.1 Proposed solution when the location information is available

In this scenario, it is assumed that location information is provided by using global positioning system (GPS) and each mobile host is equipped with a GPS receiver. The idea of applying GPS to unicast routing was first reported in (Ko and Vaidya, 1998), but their use of GPS was to limit the search space in route discovery process to reduce control overhead, not to determine the transmission power level.

We assume that each node i knows (x_i, y_i) coordinates of itself at every instance of time. By including these coordinates into the header of each packet, and by collecting the positions of multicast member nodes, the sender can easily construct a multicast tree based on the BIP algorithm. Since the coordinate pair can be inserted directly into the IP header, a routing algorithm which resides in the network layer can easily utilize that information. Now the sender node i transmits its beacon or HELLO packet with maximum available power P_{\max} where the node i inserts its coordinate. If a receiver node j is within the transmission range, it can record the coordinate of node i (the backward channel is established). As a response, node j also transmits with its maximum power by inserting its coordinates in the beacon packet (the forward channel is established). Hence, the amount of minimum transmit power to maintain the link can be easily calculated and the senders can switch to power efficient mode and transmit data packets with minimum required power to preserve battery resource. Because high reliability is usually required for control packets, they have higher priority than data packets, and thus flooding with maximum power P_{\max} is assumed for the controls packets. If additional in-

formation such as velocity is given by GPS, we can constructively utilize this information to optimize several other criteria.

3.2 When receiver can measure the power level of the received signal

Let the sender and the receiver be denoted by indices i and j . If a receiver can sense the power level of the received signal denoted as P_j , it can record and transmit this value back to the sender i . The sender can make use of the knowledge about the attenuation factor α and the maximum power P_{\max} to compute the required power to node j as $P_{ij} = P_{\max}/P_j$. Note that since the power level keeps changing in a wireless environment depending on the node speed and surrounding environment due to multipath fading and shadowing, the recorded value should be a statistical average value over a short term interval.

3.3 Location information is unavailable and receiver cannot measure the power level

This is the most strict environment in the sense that no information is available which facilitates easy determination of relevant transmit power. One possible solution to determine the power level in this environment is to use an *expanding ring search*, which is a technique sometimes used in other network applications such as in IGMP. At the network layer, a series of packets are generated with specified power level, $P_1 < P_2 < \dots < P_L \leq P_{\max}$. Every bit in each control packet is transmitted with the same power level specified in the header. Note that once one of the packets with power P_i ($1 \leq i \leq L$) is captured by the receiver, it can extract the specified power level from the packet header and ignores all the subsequent packets with larger power levels $P_{i+1}, P_{i+2}, \dots, P_L$. This can be achieved by utilizing a broadcast ID and the source address together. Notice that the same broadcast ID should be used for each packet because only one of them will be captured at the receiver and all the others are discarded, i.e., if the source address and the broadcast ID of the packets are the same, only the first captured one with minimum attainable power level is kept.

A guard time between the control packets is desirable to reduce the collision at the receiver and to give enough transition time for a RF transceiver to switch to relevant transmission power level. In this way, a receiver can determine the minimum amount of power level to establish a link from a sender to itself. Although there is a continuous range of assignable power levels, the number of levels should be quantized to a finite number to reduce delay. The choice of individual power level P_i and the number of levels will induce inherent performance degradation (accuracy of minimum power level) which is an inevitable result due to the unavailability of local information and direct power measurement.

4. Proposed Cost Metrics for Network Lifetime Extension

We define the *network lifetime* as duration of time until the first node in a network fails due to the battery exhaustion. If all the nodes have identical initial energy levels, the node which dies first will be the one which spends the battery energy at the highest rate. If we want to extend the lifetime of the network, it is critical to incorporate the residual battery energy into route updates. Although the BIP algorithm produces a power efficient multicast routing tree for a single transmission of a packet (which is efficient for a short term period), it does not deal with maximization of the lifetime (which is a long term concept) of a network. Moreover, in a more realistic scenario, the tree structure derived by BIP can not be maintained for a long period of time due to the host mobility, changing environment and dynamic membership change in multicast session, and eventually it has to be updated either periodically or when the network configuration changes. We reformulate the BIP as an optimization problem and propose a modified metric for lifetime extension.

4.1 Reformulation of the BIP algorithm

Finding a multicast routing tree T_{BIP} with BIP algorithm can be reformulated as a corresponding optimization problem as follows:

$$T_{BIP} \cong \arg \min_{T \subset G(N,A)} \sum_{(i,j) \in T} \Delta P_{ij} \quad (1)$$

over all possible trees T that are subgraphs of $G(N,A)$ and all edges (i, j) contained in the tree T . Note that (1) is written as an approximation not an equality, because BIP algorithm is not guaranteed to produce a global solution. Similar formulation will be adopted throughout this section for notational simplicity. The exact meaning of it should be interpreted as an algorithmic description explained in section 2.2. The objective here is to minimize the total incremental transmission power defined as a sum of all non-zero incremental powers. The corresponding total transmit power assigned to the tree is:

$$P_{total}(T_{BIP}) = \sum_{(i,j) \in T_{BIP}} \Delta P_{ij} = \sum_{i \in N} P(i).$$

It was the main contribution of (Wieselthier *et al*, 2000) that the total power can be approximately minimized in wireless environment by solving the optimization problem (1).

4.2 Proposed cost metric for extending network lifetime using Weighted BIP (WBIP)

We noted that the original BIP algorithm in (1) does not incorporate the residual battery energy into route tree selection. In order to incorporate the residual battery energy into the cost function, we weigh the incremental power ΔP_{ij} while constructing the total weighted cost function C_{ij} . The weighting function denoted by W_i for node i is a time dependent function. The corresponding optimal tree is given by:

$$T_{WBIP} \cong \arg \min_{T \subset G(N,A)} \sum_{(i,j) \in T} W_i \Delta P_{ij} \quad \text{where } W_i = E_{total} / (E_{total} - \sum_{k=0}^n E_{ik}) \quad (2)$$

and E_{total} is the initial battery energy of node i , and E_{ik} represents the amount of energy consumed at node i during the k -th update interval (Δt). Therefore, the denominator of W_i represents the remaining battery energy of node i at time $t = n \Delta t$. Notice here that the weighting factor W_i is initially set to unity (therefore, BIP) and as time progresses and as more energy is consumed, W_i is monotonically increasing (i.e., $W_i \geq 1$). The cost metric $C_{ij} \equiv W_i \Delta P_{ij}$ (WBIP) includes both *node-based* cost and *link-based* cost. The battery energy, which is a characteristic of a node, is represented in W_i . The more a node has remaining energy, the less W_i is and, therefore, there is a greater chance for this node with large battery capacity to be assigned with a larger transmit power. The reason for W_i being called node-based cost is that this value is equally weighted to all links to which this node is incident. On the other hand, ΔP_{ij} is a link-based cost because different values are assigned for each link (i, j) . Although the new cost metric will lead to extension of lifetime of the network, it can often lead to an undesirable oscillatory behavior among paths of the route tree. We first illustrate this behavior and then propose a convex cost function that can reduce the oscillations among routes.

5. Routing Path Oscillations and Proposed Solution

In Fig.2, we present the WBIP based routing tree solution at different time instances for 15 nodes in 10×10 grid with $\alpha = 2$. The oscillations of the route paths for different time instances are visually clear if we consider the lower half of the network. The remaining battery level is represented with a shaded rectangle. It can be observed that the battery depletion is evenly distributed among the nodes with this metric. However, the oscillations can have an adverse

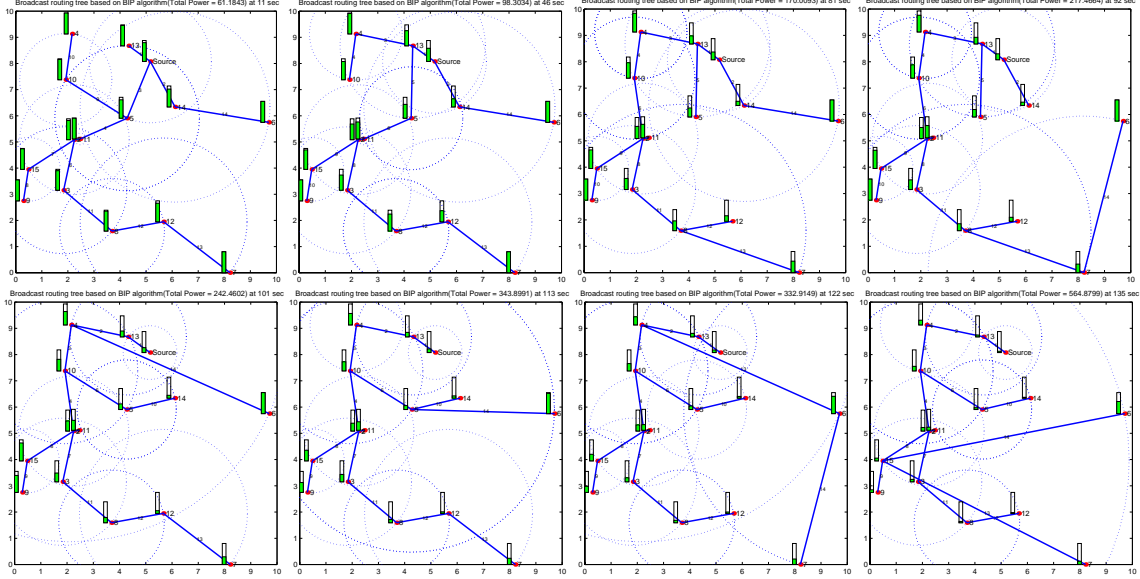


Figure 2: Routing tree oscillation problem for a sample network configuration with 15 nodes

effect on designing a routing protocol because it can result in out of order packet arrivals. We now present a modification to the cost metric function that will reduce the route oscillations.

5.1 Proposed cost metric for simultaneously extending lifetime and reducing route path oscillations (WBIPST): Oscillations in routing paths is not a new problem. Some counter measures for oscillation problem are provided in (Khanna and Zinky, 1989). In the case of energy-efficient broadcast, the oscillations arise since the WBIP is sensitive to any small change in remaining battery energy level of a node. Our approach uses a statistical measure to reduce oscillations by averaging the costs of links over a time period spanning more than one update intervals (minimizing variance of the link costs is another possible choice). The cost metric proposed for longer lifetime of the network with stability (WBIPST) is given as:

$$T_{WBIPST} \cong \arg \min_{T \subset G(N,A)} \sum_{(i,j) \in T} \bar{W}_i^t \Delta P_{ij} \quad \text{where} \quad \bar{W}_i^t = \lambda_t W_i^t + (1 - \lambda_t) \bar{W}_i^{t-1} \quad (3)$$

and λ_t is a time dependent function satisfying $0 \leq \lambda_t \leq 1$ for all time. This is a modification to (2) with a convex combination of the weighted average of the previous average value and current cost metric value. This cost metric is also a time dependent function and less sensitive to residual battery energy. Note that trees found with these newly proposed metrics (2) and (3) are constructed in the same greedy fashion as BIP and also not guaranteed to be optimal but better than BIP in terms of lifetime extension.

6. Simulation Results

In this section simulations are performed with a simplified network model according to the different metrics BIP, WBIP and WBIPST presented in the previous section. Within a 10×10 square grid region, network configurations are randomly generated with uniform distribution of nodes and multicast trees are constructed from the source node. Path loss exponents of $\alpha = 2, 3$ and 4 are separately considered in the simulation. To isolate the effect of each metric, all the generated nodes are assumed to be in the multicast group (broadcasting). Initial energy of the battery in each node is assumed to be 1000 units and the broadcast tree is updated at every specified update interval (Δt). Constant bit rate (CBR) traffic model is used. The simulation results are for the static network topology without node mobility and no restriction on the

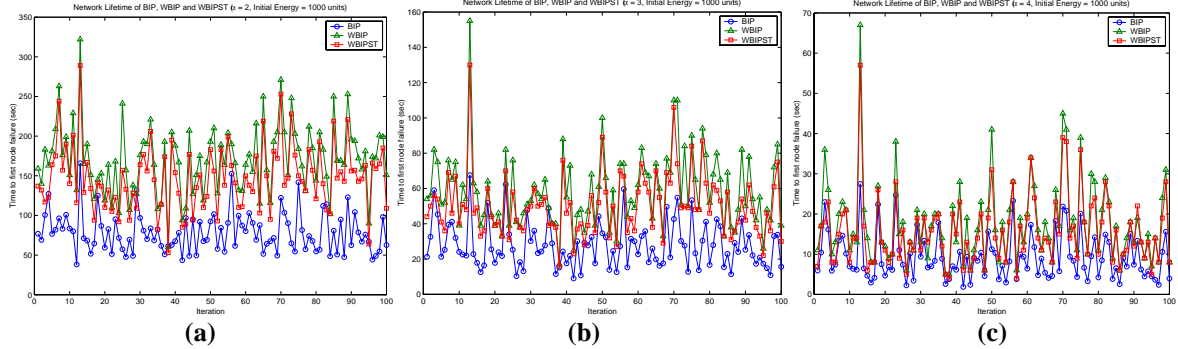


Figure 3: Network lifetime of BIP, WBIP and WBIPST for (a) $\alpha=2$ (b) $\alpha=3$ (c) $\alpha=4$ (100 network instances)

| Path Loss | Mean/STD of Network Lifetime(sec) | | | Gain (%) | Mean/STD of Oscillation | | |
|------------|-----------------------------------|------------|------------|----------|-------------------------|--------------|-------------|
| | BIP | WBIP | WBIPST | | BIP | WBIP | WBIPST |
| $\alpha=2$ | 78.1/24.8 | 170.8/43.5 | 147.4/40.5 | 118.7 | 0 | 2203.1/655.3 | 920.1/495.9 |
| $\alpha=3$ | 27.7/12.8 | 58.9/20.9 | 50.3/17.6 | 112.6 | 0 | 667.3/290.1 | 283.8/155.6 |
| $\alpha=4$ | 9.2/5.7 | 17.7/10.1 | 15.6/8.7 | 92.4 | 0 | 173.6/124.7 | 90.4/63.7 |

Table 1: Mean and standard deviation of network lifetime and oscillations for 100 network instances: 20 nodes, $\Delta t = 1$ (sec) where gain $\equiv (WBIP - BIP) / WBIP \times 100\%$

maximum available transmission power $P_{\max} = \infty$ is imposed. At every update interval, the amount of energy consumed during the time period is subtracted from the corresponding remaining energy level. Also, the energy consumption by transmission power only is assumed because reception or idle period power is relatively small compared to transmission power.

In Fig.3, the network lifetime is compared for different values of $\alpha = 2, 3$ and 4 and for $\Delta t = 1$ second with 20 nodes. We used the function $\lambda_t = 1/t$ in (3), which is equivalent to recursive formulation of time average, but other functions are also under investigation. In each case, 100 different network topologies are generated and network lifetime was calculated. The same random seeds are used for each metric for valid comparison.

Table 1 summarizes the performance in terms of network lifetime and oscillation count, in which the mean value, standard deviation (STD) and gain (percentage increase in lifetime over BIP) are shown. The number of oscillations is counted as a total sum of the number of link changes from a previous tree to a current tree until the first node failure. As propagation constant α becomes larger, the lifetime of the network is shortened significantly because the power expenditure is much larger ($d_{ij}^4 \gg d_{ij}^2$). However, standard deviation becomes smaller as α becomes larger. We can observe that, by using WBIP and WBIPST, network lifetime is roughly prolonged by a factor of two ($\sim 100\%$) compared to BIP when $\Delta t = 1$, which is a significant enhancement assuming the given fixed amount of initial battery energy. By using WBIPST, more than half (58%) reduction in oscillation from WBIP is achieved at the cost of around 14% decrease in network lifetime and this is the price paid to reduce route oscillation. We note that oscillation for BIP is identically zero for static network.

The dependence of percentage increase in mean network lifetime of WBIP on the update interval for 100 instances with 20 nodes is shown in Fig.4(a) for $\alpha = 2, 3$ and 4. For an update interval of 1 second ($\Delta t = 1$), there is about 100% increase in lifetime which is consistent with the result in Table 1. It is evident from Fig.4(a) that if tree is updated more frequently, the lifetime is prolonged further. A higher update rate translates to greater control overhead. Therefore the control overhead should be further analyzed so that we can choose a proper update interval in protocol specification. The dependence of lifetime and oscillations on the node density (number of nodes per 10×10 region) with $\Delta t = 1$ second is presented in Fig.4(b)

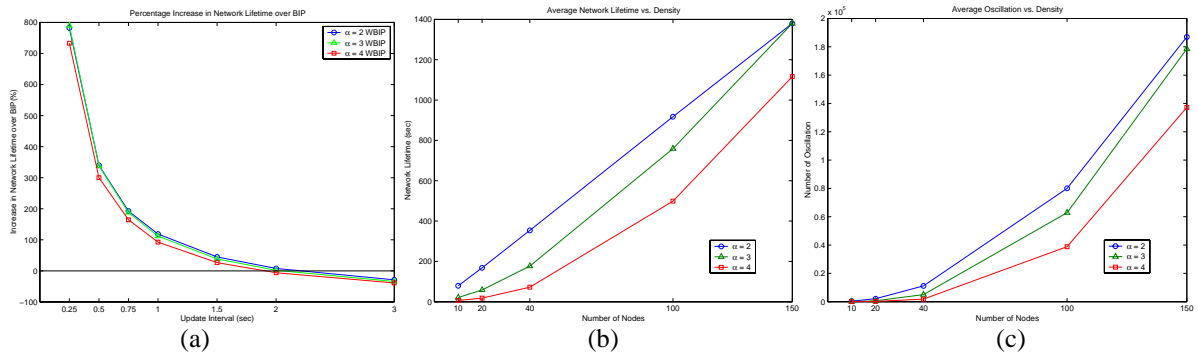


Figure 4: (a) Percentage increase in mean network lifetime vs. route update interval: 20 nodes (b) Network lifetime vs. node density: $\Delta t = 1$ sec (c) Routing path oscillation vs. node density: $\Delta t = 1$

and c). For $\alpha = 2$, lifetime increases almost linearly to the node density whereas the increase is more steep for $\alpha = 3$ and 4. In summary, our results show that there are essential trade-offs between network lifetime, oscillations, and update interval and therefore proper values should be chosen for protocol design.

7. Conclusions

Our contributions in this paper are, first, we looked at schemes that make the construction of a power-efficient tree possible for different scenarios, which will be used for protocol design. Second, we then presented modified cost function that enabled us to extend network lifetime significantly by a factor of two if the tree is updated every second. Finally, we introduced statistical measure in our proposed metric to damp route oscillations and showed that the oscillation can be cut down by half at a small cost of network lifetime.

Current trend of research in multicast routing protocols seems to be leaning toward mesh-based approach mainly because of superior performance of ODMRP. However, our results suggest that the tree-based protocols should also be further pursued because of their energy efficiency. Some of our planned future work involves finding a spanning tree with globally minimum total power, better metrics for lifetime extension and stability, and protocol design of this algorithm to conduct packet level simulation including node mobility.

8. References

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