Energy Efficient Multicast Routing in Mobile Ad Hoc Networks

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Abstract. In this paper, we address the problem of multicast routing in mobile ad-hoc networks from the viewpoint of energy efficiency. In an ad-hoc wireless network, each node runs on a local energy source which has a limited energy life span. Thus, energy conservation is a critical issue in mobile ad-hoc networks. One approach for energy conservation is to establish routes that require lowest total energy consumption. This optimization problem is referred as the minimum-energy multicast routing problem (MEMRP). In this paper, propose new efficient heuristic algorithms for the construction of energy-efficient multicast routes in mobile ad-hoc networks. These algorithms exploit the broadcast nature of the wireless channel, and address the need for energy-efficient operations. Empirical studies show that our algorithms are able to achieve better performance than algorithms that have been developed for MEMRP.

1 Introduction

Mobile ad-hoc networks are multi-hop wireless networks where nodes cooperatively maintain network connectivity. Unlike wired networks or cellular networks, no wired backbone infrastructure is installed in ad-hoc wireless networks. Such networks have been receiving increasing attention in recent years due to their potential applications in the establishment of dynamic communications for emergency/rescue operations, disaster relief efforts, military networks, etc [1].

In an ad-hoc wireless network, a link between any pair of nodes is considered to exist, if each has enough resources (such as the number of transceivers) available for this purpose and that the signal-to-noise ratio at the receiving node is sufficiently high. Thus, unlike the case of wired networks, the set of wireless network links and their capacities are not determined a priori, but depend on factors such as distance between nodes, transmitted power, users' interference, etc.

Each node in an ad-hoc wireless network is battery operated and thus runs on a local energy source. When a node runs out of energy it must be turned off to replace or recharge its battery. During that time the node cannot be used in the network. Thus, it is important to establish routes with low energy consumption to maximize the energy life of each node in the network.

Consequently, if the destination nodes are in the immediate communication vicinity of a transmitting node, a single transmission suffices for reaching all these

receivers. We assume that the power level of a transmission can be chosen within a given range of values. Hence, there is an incentive to route using maximum power (and thus maximum communication range). However, doing so may result in increased energy usage. Due to the nonlinear attenuation of the received signal power with distance, a transmission over multiple short hops may require less power than a transmission over a single direct link.

In this paper, we address the problem of constructing minimum energy routes for source-initiated multicast (one-to-many) traffic. The objective here is to construct a minimum energy tree, rooted at the source that reaches all of the desired destinations. This problem is referred to as the *minimum energy multicast routing problem (MEMRP)* and it has been addressed in the pioneering work by Wieselthier et. al. in [1,2]. This problem has also been shown to be NP-hard [3,4].

MEMRP involves the designation of which nodes are to transmit and the power levels at which they are to do so. The construction of minimum energy multicast trees will depend on various factors which include node mobility, network resources (such as number of transceivers and number of frequency bands), transmitted power level, etc. In order to assess these complex trade-offs one at a time, we assume that there is no mobility (as in [1,2]). Nevertheless, as argued in [1,2], the impact of mobility can be incorporated into this static model because transmitter power can be adjusted to accommodate the new locations of the nodes, as necessary. In addition, we also assume that there are sufficient network resources. Under these assumptions, we will propose new efficient heuristic algorithms for MEMRP. Extensive empirical studies are carried out to evaluate the performance of our proposed algorithms and to compare them with existing heuristic algorithms.

2 Wireless Communication Model

We consider a network consisting of a set of nodes randomly deployed over a given area. Connectivity of the network depends on the Euclidean distance between nodes, the maximum transmission power level (or maximum transmission range) and the minimum signal power that is required at the receiving node. The received signal power varies as $r^{-\alpha}$, where r is the Euclidean distance and α is a parameter that typically takes on a value between 2 and 4, depending on the characteristics of the communication medium. Based on this model the transmitted power required to support a link between two nodes separated by distance r is proportional to r^α . Without loss of generality, we set the normalizing constant equal to 1, resulting in:

$$P_{ij} = \text{power needed to support connection between node } i \text{ and node } j \\ = r_{ij}^\alpha \quad \text{where } r_{ij} \text{ is the Euclidean distance between node } i \text{ and node } j.$$

We assume that omni directional antennas are used by all nodes in a mobile ad-hoc network to transmit and receive signals. Due to the *broadcast nature* of these antennas, all nodes within the communication range of a transmitting node can receive its transmission. Consider the example shown in Figure 2.1, in which node S is the source node (transmitting node) and nodes $D1$ and $D2$ are the destination nodes. The power required to reach node $D1$ from node S is $P1$; the power required to reach node $D2$ from node $D1$ is $P2$; the power required to reach node $D2$ from node S is $P3$.

A single transmission at power $P = \max \{P1, P3\}$ by node S is sufficient to reach both nodes $D1$ and $D2$, based on the assumption of omni directional antennas. So the total cost (energy consumption) for wireless applications for the above example is equal to P . This situation is fundamentally different from wired applications, in which the cost of node S 's transmission to nodes $D1$ and $D2$ would be the sum of the costs to individual nodes (sum of the link cost). The ability to exploit this property of wireless communication, which is referred to as the “*wireless multicast advantage*” in [1,2], makes multicasting an excellent setting to study the potential benefits of energy-efficient protocols.

Fig. 2.1. Wireless Multicast Advantage

In wired models, any two nodes can communicate as long as there is a link connecting them. The cost of transmission from a source node to a set of nodes D_r that are within distance r from the source node would be the sum of the cost of individual links that are used in the routes from the source to this set of nodes. The situation in wireless network is different, however, due to its wireless broadcast property. Let v be a node in D_r that is furthest away from the source node and let the distance between them be denoted by r_{max} . In this case, a transmission at power r_{max}^α by the source node will be received by all nodes in the set D_r without additional expenditure of power from this set of nodes. Thus wired networks can be viewed as *link-based* in contrast to the case of wireless networks which are viewed as *node-based*.

We next consider the example as shown in Figure 2.1 again to determine an appropriate transmission strategy that will result in lower energy consumption. Without loss of generality, we assume node $D2$ is further away from node S than node $D1$; so $P3$ is greater than $P1$. Two alternative strategies can be used to transmit data from node S to nodes $D1$ and $D2$:

- Node S transmits at $P1$ to reach node $D1$, then node $D1$ transmits at $P2$ to reach node $D2$; total power required is $P1+P2$
- Node S transmits at $P3$ to reach both nodes $D1$ and $D2$; total power required is $P3$

We would like to choose the alternative that results in lower total energy consumption. So if $P3$ is greater than $P1+P2$, strategy (a) should be used; otherwise choose strategy (b) (illustrated in Figure 2.2).

Fig. 2.2. Choices for transmission strategy.

3 Problem Formulation

We consider source-initiated, circuit-switched multicast sessions. We assume that the network nodes are given as a finite point set V in a two-dimensional plane. Any node in the network is permitted to initiate a multicast session. For each node $u \in V$, let P_u denotes the power level at which node u is transmitting. We assume that each node u may transmit at any power level $P_u \leq P_{max}$. Thus, given the value of P_{max} , we can determine the communication range of all nodes and the connectivity of the network. In each multicast session, the transmission from a source node $s \in V$ is to reach all nodes in D , where $D \subseteq V - \{s\}$; the nodes in D are called *destination nodes*. A set of nodes $U \subseteq V - \{s\}$ may be needed as *relays* to provide connectivity to other nodes in the session. This set of nodes is referred to as the set of *transmitting nodes*. A *path* from node v_0 to node v_{k+1} is comprised of a sequence of vertices $v_0, v_1, v_2, \dots, v_k, v_{k+1}$ such that

- (i) a transmission from node v_0 will reach v_1 but not v_j where $2 \leq j \leq k+1$
- (ii) a transmission from v_i will reach v_{i+1} but not v_j where $i \in \{1, 2, \dots, k-1\}$ and $i+2 \leq j \leq k+1$
- (iii) a transmission from v_k will reach node v_{k+1} .

A *multicast (broadcast) tree* T is comprised the source node s , the set of transmitting nodes U , and the set of non-transmitting nodes W . The source node s is the *root* of the multicast(broadcast) tree T . The set of non-transmitting nodes W form the *leaf nodes* of the multicast (broadcast) tree. Note that all leaf nodes are destination nodes, i.e. $W \subseteq D$; otherwise these nodes can be deleted from the tree resulting in lower energy consumption.

The total energy required to maintain the multicast (broadcast) tree is simply the sum of the energy expended by the source node and each of the transmitting nodes in the tree; leaf nodes (which do not transmit) do not contribute to this quantity. The problem of building a minimum energy multicast (broadcast) tree for a given network is called the *Minimum Energy Multicast (Broadcast) Routing Problem*. Due to the wireless broadcast advantage property of mobile ad-hoc networks (as mentioned in section 2), MEBRP is different from the broadcast routing problem in wired network which can be formulated as the minimum cost spanning tree (MST) problem. While the MST problem is solvable in polynomial time, MEBRP is known to be NP-hard. Thus heuristic algorithms are likely to be the only viable approach for this problem.

4 Previous Work

Subbarao [5] proposed a dynamic power-conscious unicast routing scheme (minimum power routing – MPR) that incorporates physical layer and link layer statistics to conserve power, while compensating for the propagation path losses, shadowing and fading effects, and interference environment at the intended receiver. The main idea of MPR is to select a path between a given source and destination (using Bellman-Ford algorithm - shortest path algorithm) that will require the least amount of total power expended, while still maintaining an acceptable signal-to-noise ratio at each receiver.

Chang et. al. [6] proposed an energy conserving routing algorithm for wireless ad-hoc networks by maximizing the lifetime of the system. In particular, the algorithm select routes and the corresponding power levels such that the time until a node's energy source (battery) drains out, is maximized. However, this algorithm does not attempt to minimize the overall energy required to maintain the routing tree. Other existing work in [7], [8], [9] addressed the problem of energy efficient unicast routing (rather than multicasting) for wireless ad-hoc network.

Both MEBRP and MEMRP have been addressed by Wieselthier et. al. in [1,2]. In particular, the works in [1,2] jointly address the issues of transmitting power levels (and hence network connectivity, a Physical layer function) and multicast (broadcast) tree formation (a routing function, associated with the Network layer) in order to achieve energy-efficient communication. Heuristic algorithms that have been proposed to address the issue of constructing energy-efficient broadcast and multicast routing trees include the *Broadcast Incremental Power (BIP)* heuristic, *Multicast Incremental Power (MIP)* heuristic [1,2] and the *Node-Based Spanning Tree (NST)* heuristic [1].

4.1 Broadcast Incremental Power (BIP) Algorithm

BIP is similar to the Prim's Algorithm for constructing minimum spanning tree (MST); new nodes are added to the tree one at a time until all nodes are included into the tree. The cost of adding a new node to the current partial tree is equal to the additional amount of energy that needs to be consumed when the new node is added to the current partial tree.

The fundamental difference between BIP and Prim's algorithm is as follows. The inputs to Prim's algorithm are the link costs, which remain unchanged throughout the execution of the algorithm. However, BIP dynamically update the costs at each step (after the addition of a new node to the partial tree) to reflect the fact that the cost of adding a new node v (which is adjacent to some node u in the partial tree) to T . In particular, the dynamic computation of cost is carried out as follows. Let P_{uv} denotes the power level that node u has to transmit to reach node v and let $P(u)$ denotes the power level at which node u is transmitting (prior to the addition of node v); if node u is currently a leaf node, $P(u) = 0$. The incremental cost (energy consumption) P'_{uv} incurred in the addition of node v into the partial tree is computed as follows: $P'_{uv} = P_{uv} - P(u)$. BIP has a complexity of $O(|V|^3)$.

4.2 Multicast Incremental Power (MIP) Algorithm

A broadcast tree is initially constructed using the BIP algorithm. To obtain a multicast tree, the broadcast tree is pruned by eliminating all transmissions that are not needed to reach the members of the multicast group. In particular, nodes with no downstream destinations will not need to transmit, and some nodes will be able to reduce their transmitted power if their distant downstream neighbors are pruned from the tree.

4.3 Node-Based Spanning Tree Algorithm (NBST)

This heuristic is based on the notion of the metric n/p , where n is number of “new” nodes (i.e. nodes not in the partial tree) that can be added to a current partial tree by using an additional p units of power:

$$\frac{n}{p} = \frac{\text{number of new nodes reached}}{\text{total power required to reach them}}$$

Hence, the physical meaning of n/p can be interpreted as the number of “new” nodes that can be reached per unit of additional power. The idea of this heuristic is to try to maximize the value of n/p in each iteration of the algorithm. Given a partial tree T , let V_T denotes the set of nodes in T and $\bar{V}_T$ denotes the set of nodes that are not in T , i.e. $\bar{V}_T = V - V_T$. Construction of the spanning tree begins at the source node, i.e. $V_T = \{s\}$ and $\bar{V}_T = V - \{s\}$. The transmission power of the source node is chosen to maximize the n/p metric. Nodes within its communication range will be included into the partial tree, V_T and $\bar{V}_T$ are both updated to reflect this fact. In the next iteration, each node that is currently in the partial tree (i.e. V_T) will evaluate their respective n/p metric. The node which has the maximum n/p value will then transmit at the power level which maximizes the n/p metric and all nodes within its communication range will next be included into the partial tree. This process continues until all nodes are in the tree. Next, the broadcast tree is pruned to eliminate all unnecessary transmissions. This heuristic has a time complexity of $O(|V|^3)$.

5 New Proposed Algorithms

In this section, we propose two new heuristic algorithms, namely the *Look-ahead Node-to-Power Ratio (LANPR) Algorithm* and the *Least Incremental-Power-Path (LIP) Algorithm*, for MEMRP. LANPR is also based on the notion of the n/p metric. However, it differs from the NBST algorithm (described in section 4.3) in that it is designed to address a drawback of NBST, which will be described next.

5.1 A Drawback of the NBST Heuristic

Consider the network in Figure 2.1, where $P3 > P1$. The power required to reach node $D1$ from node S is $P1$; the power required to reach node $D2$ from node $D1$ is $P2$; the power required to reach node $D2$ from node S is $P3$. The two alternative strategies for transmitting data from the source node S to nodes $D1$ and $D2$ has been discussed in section 2 and is illustrated in Figure 2.2.

Using NBST, we will use strategy (a) if $(1/P1) > (2/P3)$ and if $(1/P2) > (1/(P3 - P1))$; in this case the source node will first transmit to node $D1$ using power level $P1$ and next node $D1$ will transmit to node $D2$ using power level $P2$; the total power consumed is thus $P1 + P2$. Strategy (b) will be applied if $(1/P1) < (2/P3)$; in this case the source node will transmit to both nodes $D1$ and $D2$ using power level $P3$. We note that

$$(i) \quad \frac{1}{P1} - \frac{2}{P3} = \frac{P3-2P1}{P1 \times P3} \Rightarrow \begin{cases} \frac{1}{P1} > \frac{2}{P3} & \text{if } P3 > 2P1 \\ \frac{1}{P1} < \frac{2}{P3} & \text{if } P3 < 2P1 \end{cases}$$

$$(ii) \quad \frac{1}{P2} - \frac{1}{P3-P1} = \frac{(P3-P1)-P2}{P2(P3-P1)}$$

$$\text{If } P3 > 2P1 \text{ and } P1 > P2, \text{ then } (P3-P1)-P2 > P3-2P1 > 0 \Rightarrow \frac{1}{P2} - \frac{1}{P3-P1} > 0$$

Hence under the assumption of $P3 > P1 > P2$,

$$\begin{cases} \text{use strategy (a) if } P3 > 2P1 \\ \text{use strategy (b) if } P3 < 2P1 \end{cases}$$

The choice of transmission strategies under the above assumption is illustrated in Figure 5.1.

Fig. 5.1. Strategy Selection Range for NBST Algorithm

Based on the selection strategies illustrated in Figure 5.1, a non-optimal decision will be made by NBST if the value of $P3$ lies between the value of $(P1+P2)$ and $(P1+P1)$. In particular, it is easy to see that strategy (a) should be used in this case, as it will result in lower power consumption (since $P3 > P1+P2$). But NBST will opt to use strategy (b) instead, which will result in higher power consumption. This scenario is illustrated in Figure 5.2.

Fig. 5.2. Error Range in Strategy Selection for NBST Algorithm

5.2 Look-Ahead Node-to-Power Ratio (LANPR) Algorithm

In this section, we propose a new heuristic algorithm, called the *Look-ahead Node-to-Power Ratio (LANPR) Algorithm*, that is capable of addressing a deficiency (mentioned in section 5.1) of NBST. Construction of the spanning tree begins at the

source node. Given a partial tree T , let V_T denotes the set of nodes in T and $\bar{V}_T$ denotes the set of nodes that are not in T . In each iteration of LANPR, we determine a node v such that this node has the maximum n/p value among all nodes that are currently in the partial tree. Having found the node v , let $(n/p)_v$ denote its maximum n/p value, S_v denote the set of nodes in $\bar{V}_T$ that are within the communication range of node v when it transmits at the power level, say P_v , which is dictated by $(n/p)_v$. If $|S_v| = 1$, then node v will transmit at power level P_v to reach the node in S_v . If $|S_v| > 1$, we will attempt to **look-ahead** (predict) to determine if it would be more efficient (in terms of energy consumption) to first transmit to only one of the nodes in S_v , say w . The node w is selected to be the nearest node to node v . Let the maximum n/p value that corresponds to the transmission of node w to other nodes that are not in the tree be denoted by $(n/p)_w$. If $(n/p)_w > (n/p)_v$ then, the algorithm will choose to transmit from node v to node w . Otherwise, node v will transmit all nodes in S_v using power level P_v . This process continues until all nodes are included into the tree. Next, the broadcast tree is pruned to eliminate all unnecessary transmissions.

The ability of LANRP to address the drawback (described in section 5.1) of NBST can be explained as follows. We again consider the network in Figure 2.1, where $P3 > P1$. As discussed earlier, NBST will make a “wrong” choice of transmission strategy when the value of $P3$ falls within the error range ($P1+P2 < P3 < 2P1$) as shown in Figure 5.2. We will next show how LANRP will be able to address this problem. LANRP will first compute the maximum n/p value that node s should transmit. Since $2/P3 > 1/P1$, node s may choose to transmit to both nodes, $D1$ and $D2$, simultaneously at power level $P3$ (this corresponds to strategy (b)). However, prior to doing so, it will first attempt to “look-ahead” to determine if it would be more energy efficient to first transmit to its nearest neighbor, namely $D1$, and subsequently may use the latter to transmit to $D2$ (strategy (a)). The decision to use either of these strategies by LANRP is determined by the values of $1/P2$ and $2/P3$. In particular, strategy (a) will be used if $(1/P2) > (2/P3)$; otherwise strategy (b) will be chosen.

$$\text{We note that } \frac{1}{P2} - \frac{2}{P3} = \frac{P3 - 2P2}{P2 \times P3} \Rightarrow \begin{cases} > 0 & \text{if } P3 > 2P2 \\ < 0 & \text{if } P3 < 2P2 \end{cases}$$

Hence, we can deduce from Figure 5.3 that if the value of $P3$ lies between $P1+P2$ and $2P1$, then $P3 > 2P2$ (as $P1 > P2$); this in turns implies that $1/P2 > 2/P3$ and thus LANPR will adopt strategy (a). Hence, the drawback of NBST can be circumvented in this case (illustrated in Figure 5.3). The pseudocode of LANPR is given in Figure 5.4.

Fig. 5.3. Strategy Selection Range in LANPR Algorithm

Lemma 1. The time complexity of LANPR is $O(|V|^3)$.

Proof. The **while loop** in step 1 has at most $|V|$ iterations. The same is true for each of the **for** loops in steps 2 and 3. Hence steps 1 to 3 can be done in $O(|V|^3)$. Step 4 can be completed in $O(|V|)$. Pruning of the tree in Step 5 can be done in $O(|V|)$. Thus, the worst case time complexity of LANPR is $O(|V|^3)$.

While LANPR has the same worst case time complexity as the MIP algorithm, it potentially requires fewer steps to build a multicast tree than MIP algorithm in general. In the worst case, it adds in one node at one time, and takes $|V|-1$ steps to build a tree for a network with $|V|$ nodes, which is the same as the number of steps required by MIP algorithm. We also note that LANPR is based on similar paradigm as MIP in the sense that a broadcast tree is first constructed using these algorithms and the tree is subsequently pruned to eliminate all unnecessary transmissions. We will next propose another algorithm, called the *Least Incremental-Power Path Algorithm (LIP)*, that is based on the paradigm to constructing a multicast tree directly (thus eliminating the need to prune the resultant tree).

5.3 Least Incremental-Power Path Algorithm (LIP)

Given a pair of nodes $u, v \in V$, we define the *shortest path* SP_{uv} from u to v to be a path that requires the least total energy consumption for a transmission from node u to reach node v . The energy consumption of path SP_{uv} , say $E_{SP_{uv}}$, is equal to the sum of the power level at which each node in SP_{uv} has to transmit.

Given a source node $s \in V$ and a set of destination nodes $D \subseteq V - \{s\}$, let $P_{su} = r_{su}^\alpha$, where r_{su} denotes the Euclidean distance between s and u , for each $u \in D$. Let w be a node in D such that

$$P_{sw} = \max_{u \in D} \{P_{su}\}.$$

It is clear that if the source node transmits at power level P_{sw} , each node in D will be able to receive the transmission from s . Hence the total energy required to maintain the multicast tree is bounded from above by P_{sw} . Next, we note that the total energy consumption of shortest path from s to w (which may include some other destination nodes) is also no more than P_{sw} , i.e. $E_{SP_{sw}} \leq P_{sw}$.

Procedure LANPR

$V_T = \{s\}; \bar{V}_T = V - \{s\};$

while ($|V_T| < \text{total number of nodes}$) {

for (every node $i \in V_T$) {

for (every node $j \in \bar{V}_T$) {

 compute n_{ij}/p_{ij}

 }

/* step 1 */

/* step 2 */

/* step 3 */

```

     $(n/p)_{(i)} = \max_{j \in \bar{V}_T} \frac{n_{ij}}{P_{ij}}$ 
}
Let  $(n/p)_v = \max_{i \in V_T} \{(n/p)_i\}$ 

Let  $S_v$  denotes the set of nodes from  $\bar{V}_T$  that are able to receive
the transmission from node  $v$ .

if  $|S_v| = 1$  {
     $S'_v = S_v$ 
} else {
    Let node  $w \in S_v$ , which is nearest to node  $v$ 

     $\bar{V}'_T = \bar{V}_T - \{w\}$ 

    for (every node  $y \in \bar{V}'_T$ ) { /* step 4 */
        compute  $n_{wy}/p_{wy}$ 
    }

     $(n/p)_{(w)} = \max_{y \in \bar{V}'_T} \frac{n_{wy}}{p_{wy}}$ 

    if  $((n/p)_w > (n/p)_v)$  {
        Let  $S'_v = \{w\}$ 
    } else {
         $S'_v = S_v$ 
    }
}
}

 $\bar{V}_T = \bar{V}_T - S'_v$ 
 $V_T = V_T + S'_v$ 
}

eliminate all unnecessary transmissions from set  $V_T$ ; /* step 5 */

```

Fig. 5.4. LANPR Algorithm

The basic idea of the Least Incremental-Power Path Algorithm (LIP) is as follows. The algorithm first compute a shortest path from the source node s to a node w in D , where $P_{sw} = \max_{u \in D} \{P_{su}\}$. All nodes in this path are included in the set V' . Next, the

algorithm builds a multicast tree by adding nodes from the multicast group $D-V'$ to V' one at a time, and stops when V' contains all elements from D . In each iteration, a node from $D-V'$ is selected for inclusion into the partial tree as follows. Given a pair of nodes $a \in V'$ and $b \in D-V'$, let IP_{ab} denotes a path from a to b , where each node in

this path, except for a , belongs to $V-V'$. Let $P(a)$ denotes that power level at which node a is currently transmitting in the partial tree. Let q be the node that is adjacent to node a in the path IP_{ab} . The incremental power P'_{aq} that node a has to utilize for its transmission to reach node q is equal to $P'_{aq} - P(a)$. Hence the energy consumption of path IP_{ab} , say $E_{IP_{ab}}$, is equal to the sum of $P'_{aq} - P(a)$ and the power levels at which each of the other nodes in IP_{ab} has to transmit. Let LIP_{uv} denotes a path from a node $u \in V'$ and $v \in D-V'$ such that $E_{LIP_{uv}} = \min_{a \in V', b \in D-V'} \{E_{IP_{ab}}\}$. We call LIP_{uv} a *least incremental-*

power path from V' to $D-V'$. Hence, in each iteration, the algorithm attempts to find a least incremental-power path from V' to $D-V'$. The nodes on this path will be included into the partial tree if the total energy requirement of the resultant tree is less P_{sw} ; otherwise the source will choose to transmit at power level P_{sw} to reach all destination nodes and the algorithm will terminate.

Lemma 2. The time complexity of LIP is $O(|V|^3)$.

Proof. The shortest path in step 1 can be found in $O(|V|^2)$. Each iteration of step 2 is of order $O(|V|^2)$. Since there are at most $|V|$ iterations of step 2, this step can be completed in $O(|V|^3)$. Thus, the worst case time complexity of LIP is $O(|V|^3)$.

Procedure LIP;

Input: $V, s \in V, D \subseteq V$;

Output: multicast tree $T=(s, U \cup W)$;

begin

set $V'=\phi$; $D'=\phi$, $A=\phi$, $dest=1$; $E=0$;

find shortest path SP_{sw} from s to w ;

/* **step 1**; $w \in D$ &

$P_{sw} = \max_{u \in D} \{P_{su}\}$ */

$V'=V' \cup \{\text{all nodes in } SP_{sw}\}$;

$D'=D' \cup \{\text{all destination nodes in } SP_{sw}\}$;

$E=E_{SP_{sw}}$;

while $(|D'| < |D|)$

/* **step 2** */

find a path LIP_{uv} where $u \in V'$, $v \in D-V'$, such that

$E_{LIP_{uv}} = \min_{a \in V', b \in D-V'} \{E_{IP_{ab}}\}$;

/* **step 3** */

if $E + E_{LIP_{uv}} < P_{sw}$ **then**

$V'=V' \cup \{\text{all nodes in } LIP_{uv} \text{ except } u\}$;

$D'=D' \cup \{\text{all destination nodes in } LIP_{uv} \text{ except } u\}$;

else

$V' = \{s, w\}$;

/* s will transmit using power level P_{sw} to all destination nodes */

```

         $D' = D;$ 
    end while;
     $U \cup W = V' - \{s\}$ 
end; (Procedure LIP)

```

Fig. 5.5. Algorithm LIP

6 Simulation Results

Let $ALG = \{MIP, NBST, LANPR, LIP\}$ denotes the set of algorithms to be evaluated. In our empirical study, the performance of each algorithm from the set ALG is evaluated for various networks. Each network with a specified number of nodes is randomly generated within a 10×10 square region. One of the nodes is randomly chosen to be the source and the some of the nodes are chosen to be the destinations. The value of α (characteristics of the attenuation of communication medium) is chosen to be 2. The performance metric is the total power required to maintain a multicast tree by the respective algorithms. For each algorithm q from the set ALG , let

$Pow_q(m)$ = total power of the multicast tree for network m generated by algorithm q .

$Pow_{opt}(m)$ = total power of the **minimum energy** multicast tree for network m generated using exhaustive search

We define the normalized power associated with algorithm q (against exhaustive search) for network m to be $Pow_q^{opt}(m) = \frac{Pow_q(m)}{Pow_{opt}(m)}$.

Table 6.1 summarizes the performance of all the algorithms whose solutions are normalized against the corresponding optimal solutions that are found using exhaustive search. Only small network sizes (ranging from 10 to 20) are used in this set of results, as it is computationally expensive to apply exhaustive search to large networks. For each network size, 100 networks are randomly generated, and the following performance indicators are computed for each algorithm: (i) mean value of the normalized power (ii) variance of the normalized power and (iii) 90% confidence interval of the normalized power obtained by each algorithm.

As the number of nodes increases, the performance of all algorithms deviates further away from the optimal solution. We observe that NBST has the worst performance among all the algorithms; one possible reason for this phenomenon is given in section 5.1. Both LANPR and LIP consistently perform better than MIP (in terms of mean power) but we observe that the gain in performance of LANPR and LIP over MIP reduces as the number of destination nodes increase. Similarly, LIP performs better than LANPR for networks with no more than 50% of nodes being destination nodes. The results also indicate that LANPR will potentially perform better than LIP for networks with large number of destination nodes (as could be seen from Table 6.1(b)).

Table 6.1. Total Power Required for Multicasting (Normalized against Optimal Solution)

V	MIP		NBST		LANPR		LIP	
	Mean	Var	Mean	Var	Mean	Var	Mean	Var
10	1.1754	0.1615	1.2751	0.1455	1.1729	0.1087	1.0343	0.0085
15	1.2303	0.0924	1.3633	0.0974	1.1970	0.0370	1.0794	0.0172
20	1.3050	0.2660	1.4372	0.1146	1.2757	0.0892	1.0942	0.0161

(a) 25% of nodes are destination

V	MIP		NBST		LANPR		LIP	
	Mean	Var	Mean	Var	Mean	Var	Mean	Var
10	1.0991	0.0202	1.1493	0.0267	1.0745	0.0141	1.0753	0.0126
15	1.1443	0.0214	1.1887	0.0247	1.0845	0.0088	1.0904	0.0098
20	1.1506	0.0151	1.2429	0.0338	1.1326	0.0141	1.1373	0.0140

(b) 75% of nodes are destination

Table 6.2. Total Power Required for Multicasting (Normalized against MIP)

V	MIP		NBST		LANPR		LIP	
	Mean	Var	Mean	Var	Mean	Var	Mean	Var
25	1.0000	0.0000	1.1425	0.0768	1.0131	0.0405	0.9129	0.0211
50	1.0000	0.0000	1.1508	0.0495	1.0021	0.0174	0.9369	0.0127
75	1.0000	0.0000	1.1567	0.0302	1.0052	0.0140	0.9491	0.0109
100	1.0000	0.0000	1.1654	0.0297	1.0042	0.0111	0.9652	0.0082

(a) 25% of nodes are destination

V	MIP		NBST		LANPR		LIP	
	Mean	Var	Mean	Var	Mean	Var	Mean	Var
25	1.0000	0.0000	1.0583	0.0370	0.9639	0.0112	0.9862	0.0095
50	1.0000	0.0000	1.0635	0.0247	0.9713	0.0084	1.0060	0.0050
75	1.0000	0.0000	1.0670	0.0170	0.9725	0.0046	1.0175	0.0036
100	1.0000	0.0000	1.0648	0.0135	0.9693	0.0037	1.0262	0.0029

(b) 75% of nodes are destination

Table 6.2 summarizes performance for all algorithms whose solutions are normalized against those obtained using the MIP algorithm. Network sizes ranging from 25 to 100 are used in this study and 1000 networks are randomly generated for

each of them. As could be seen from the results, LIP performs the best for networks with small number of destination nodes (Table 6.2(a)). In contrast, LANPR performs better than the other algorithms for networks with a larger number of destination nodes (Table 6.2(b)). Again, we observe that NBST does not perform as well as the other algorithms in all cases.

7 Conclusion

In this paper, we proposed new heuristic algorithms to address some of the fundamental issues associated with energy-efficient multicasting in wireless ad-hoc network. Empirical study shows that our proposed algorithms are able to achieve better performance (in terms of energy consumption) than existing multicast algorithms for ad-hoc wireless networks. In particular, our proposed algorithms (LANPR and LIP) not only exploit the wireless multicast advantage of ad-hoc networks, but also take a broad view of the network's node location before making routing decision. This in turn gives our proposed algorithm an edge over existing algorithms in generating low energy multicast trees.

Our empirical results show that LIP performs best for networks with small number of destination nodes. This implies that pruning a broadcast tree to form a multicast tree is not an effective way of building multicast tree for such networks; i.e. building multicast tree directly would lead to a more energy efficient multicast tree for these networks.

We note however that our proposed algorithms assume complete knowledge of the network topology which in turns limit their scalability. Hence further research is needed to develop distributed algorithms that provide the benefits that have been demonstrated in this paper. Furthermore, it is important to study the impact of limited bandwidth and transceiver resources on MEMRP, as well as to develop mechanisms to cope with node mobility.

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