Fully Localized Energy-efficient Multicast in Large-Scale Wireless Ad Hoc Networks

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***Abstract*—Most of the proposed distributed energy-efficient multicasting algorithms are using the local search technology to refine a multicast tree iteratively. They use MST or SPT as the initial solution and improve the total power consumption by switching some tree nodes from their respective parent nodes to new corresponding parent nodes. These algorithms are not scalable because the refinement operations require heavy message exchange flows. In this paper, we propose the algorithm Localized Energy-efficient Multicast with Grouping (LEMG) features doing local search in a fully localized fashion. The mechanism Grouping exploits a novel idea to evaluate the power consumption cost of every node and limit the message passing within a adjustable constant hop. Our simulation shows LEMG is energy-efficient comparable to DMEM, and the refinement can be done in only limited hops of message passing regardless of the network size and the number of destinations.**

***Index Terms*—Energy efficiency, routing protocols, wireless ad hoc network, localized algorithm**

I. Introduction

With the popularity of wireless network, ad hoc network is getting more and more attractive due to their potential applications. Without infrastructure, wireless ad hoc networks are formed by wireless devices in a self-organized and decentralized manner. It is flexible and can be deployed easily in any environment. A node in these networks is equipped with an antenna powered by batteries. When the battery of a node is depleted, it may lead to network disconnection. In order to prolong the network lifetime, the energy-aware routing of ad hoc wireless networks has received significant attention.

In the survey [7], there are two main metrics for energy-aware multicast/broadcast routing. Both the two direction receive much attention. For one is energy-efficient routing [18] [2] [3] [11] [10] [12] [6] [16] [5] [13] which wants to minimizing the total power consumption of all nodes in the multicast/broadcast session, the other is maximum lifetime routing [4] [15] [14] [8] which target to maximize the operation time until the battery depletion of the first node in the multicast/broadcast session. Some of existing solutions are centralized which may lead to extreme communication overhead for ad hoc network. The others are in a distributed manner; however, knowledge of whole network energy saving information is indispensable to make decision. The amount of messages increases dramatically with the network size. Accordingly, It may cause unacceptable execution time in large-scale networks. Hence, an ideal algorithm or protocol for ad hoc networks should be localized which is defined by that each node can decide its own behavior based only on the information from neighboring nodes within a constant hop distance [2].

In this work, we focus on source initiated energy-

efficient routing in multicast which is more predominant communication primitives than unicast and broadcast. It allows some source node to send data to any number of destination nodes in the network. We assume that the measurement of the energy consumption when transmitting a unit message depends on the range of the emitter. Thereby, an energy-efficient multicast tree can be constructed by intelligently adjusting the transmission range of every node in the network.

The main contribution of our work is that we propose a refinement based algorithm: LEMG (Localized Energy-efficient Multicast with Grouping) that all the information exchange only within a constat hops while existing solutions need a global coordinator or must operate one by one to overcome the conflict. What is more, by adjusting the setting of the two parameters: group size limit **m** and execution round demand **x**, we can control the number of control messages in the network and the refinement time. Due to the localized property of LEMG, the refinement time with the same setting is nearly constant regardless of the network size and the number of destination. Therefore, LEMG is scalable to large- scale ad-hoc networks.

The rest of this paper is organized as follows: We give a literature review in Section 2. Then, Section 3 describes the system model used. We propose localize refinemet based algorithm LEMG in Section 4. Section 5 provides performance evaluation result of LEMG. We finally summarize this work in Section 6.

II. Related Work

Wieselthier et al. presented the energy-efficient broadcasting/multicast problem in [18]. They proposed the concept of *wireless multicast advantage* which indicates that the total power required for a node to reach a set of other neighboring nodes is simply the maximum required to reach any of them individually. They also proposed a centralized heuristic BIP and MIP for constructing the energy-efficient broadcast/multicast tree, which becomes a benchmark for lots of later proposed solutions. The problem of constructing the optimal energy-efficient broadcast tree is NP-hard [1], so as multicast tree. Therefore, several approaches and heuristic algorithms have been proposed.

In the pruning approach [18] [16], the energy-efficient multicast problem is studied in the same approach of energy-efficient broadcast. It constructs a broadcast tree first, then prunes the nodes that are not needed to reach the destinations. Therefore, every solution for broadcasting can be transferred to multicasting by such approach. In the scenario which we only want to access few destinations in the network, the routing tree which pruning from broadcasting tree may cause an energy- consuming long path. Accordingly, This approach performs well only when the number of destinations is relative large. In the refinement approach [8] [6] [16], they construct an initial multicast tree first, then refine the multicast tree iteratively to improve the solution. In S-REMiT [16], it uses MST or SPT as an initial multicast tree and makes refinement by switching the parent of some nodes to new ones such that power consumption can be reduced. This distributed algorithm is not scalable because the time required for refinement phase is influenced by network size due to the decision of refinement is made one by one in DFS order. Another refinement based algorithm DMEM [6] has shown that it providing better performance than MIP[18] and MIDP[5]. It proposed several localized operations to discover energy conservation in which each node requires only the knowledge of all its neighbors. After the energy conservation was discovered localized of each node, it needs to pass all the requests to the source node to make final decision. Such a source-decision mechanism may cause more radio interference near the source node, and the indefinite time of requests gathering. Moreover, due to there is no limitation on distance (hops) of message passing, the refinement time of these operations would be influenced by network size. It leads to indefinite refinement time and hardly to be applied on large-scale networks.

III. System Model

In this section, we firstly present the **Network Model**, which include the notation and terminology we emploied to represent a network. Secondly, we show how to evaluate power consumption of wireless medium with **Power Consumption Model**. Lastly, the effect of control messages is discussed.

A. Network Model

A wireless ad hoc network can be modeled by a simple graph $G = (V, E)$. Where V is the set of nodes, and $E \subseteqq V^2$ is the set of wireless communication links between pairs of nodes. We assume each node is equipped with an omnidirectional antenna which has a maximum transmission range R. Edge $(u, v) \in E$ means that **v** is a neighbor of **u**, or **v** is within the maximum transmission range of **u**, therefore **u** can directly send messages to **v**.

We focus on a source-initiated multicast session in ad hoc network. Any node in the network can be a source node which starts a multicast session and sends some data to any number of specific destination nodes. Each multicast group consists of the source and the destination nodes. The nodes which are not in the multicast group may support transmission as relays to provide connectivity or to reduce total power consumption. The multicast group, relay nodes and transmission link form a multicast tree $T = (V_T, E_T)$. We define Neighbor(u) is the set of neighboring tree nodes of u as follows:

$$Neighbor(u) = \{v \mid (u, v) \in E_T\} \tag{1}$$

B. Power Consumption Model

We assume that each node can adjust its transmission power p where $0 \leqq p \leqq p_{max}$. The wireless signal of a transmitter can be correctly received by all nodes within its radio coverage range with enough receiving signal strength. As shown in Fig. 1, nodes v, w, x can receive signal from transmitter **u**. The transmission power of **u** is defined as $P_{u,(v,w,x)} = max\{P_{u,v}, P_{u,w}, P_{u,x}\} = P_{u,v}$. Which is considered as *Wireless Multicast Advantage*[18]. It is different compared to wired network which every single transmission is over a dedicate cable link connecting two nodes, so the power consumption of a node in a wired network is the sum of power consumed in each transmission link. On the other hand, in wireless medium, the power required is merely the transmission link to the furthest node. The power consumption of a node **u** for sending a unit data in wireless medium can be formulated as follows:

$$P(u) = K \times r_u^{\alpha} + c \tag{2}$$

where r_u is the Euclidean distance between **u** and the furthest node in the transmission. $\alpha \in (2, 4]$ is a constant which represents the power attenuation in the medium, depending on the condition of environment. c is a distance independent constant for the overhead due to signal processing. K is the transmission-quality parameter satisfying $K \geq 1$. Its value is determined by the antenna designs.

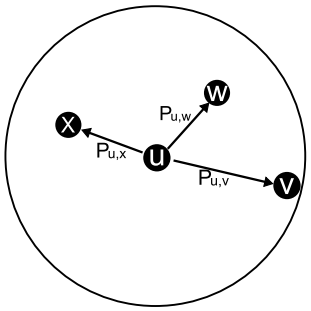


Fig. 1: wireless multicast advantage:$P_{u,(v,w)} = max\{P_{u,v}, P_{u,w}\}$

In a network G, given a source node and any number of specific destination nodes, we want to construct a multicast tree T, in which the total power consumption of sending a unit data from source to all the destination nodes is minimized while the number of messages and time for the construction and the refinement are as low as possible. The total power consumption mentioned is simply the sum of the energy expended at each node in multicast tree T, defined as follows:

$$P(T) = \sum_{u \in V_T} P_T(u) \tag{3}$$

Where $P_T(u)$ is the power consumption of a node **u** in processing a unit data in multicast tree T given by:

$$P_T(u) = \begin{cases} P(u), & \text{if u is the source} \\ P(u) + P_{recv}, & \text{if u is a relay node} \\ P_{recv}, & \text{if u is a leaf node.} \end{cases}$$

P_{recv} is the energy needed in receiving a unit data. The goal of energy-efficient multicasting is to minimize $P(T)$. Besides, for adapting to any network size, the message overhead and time required for algorithm should be independent of network size and the number of destination.

C. Control Messages

Many proposed approaches for the energy-efficient multicasting problem use local search technology to iteratively improve an initial feasible solution. The refinement operation requires exchange of control messages between nodes. The more the transmission of control message, the severer the RF interference and packet collision at the MAC layer, resulting in longer delay or stale information because of the mobility of nodes. To keep the message complexity in control, the hops of message passing should be limited and each refinement decision should be made based solely on knowledge of nodes within constant hops.

IV. Proposed Algorithm

A. Overview

Our focus in this paper is to establish minimum energy multicast trees using fully localized algorithms called Localized Energy-efficient Multicast with Grouping(LEMG). The basic idea of LEMG is similar to the approaches using the local search technology[6][8][16]. We firstly construct an initial multicast tree and then try to refine the initial solution by switching a tree node's parent to another node. The LEMG algorithm, on the other hand, requires only local information and without resorting to global decision-making. To keep the connectivity of the multicast tree after parent-switching refinement, LEMG applies the *Numbering Principle*. In addition, LEMG uses the *Grouping* operation to organize the tree nodes into groups, by which the hops of message passing can be restricted. Also, within the groups, each node can derive an important information, *Cost*. The details of LEMG will be discussed in later this section.

B. Multicast Tree Construction

Once a node wants to initialize a multicast session. We construct an initial multicast tree SPT on top of ESPT first. ESPT[17] is a localized topology control algorithm proposed by Wang, Wei, and Kuo featuring all the SPT being a subgraph of its regardless of the source node and destination nodes. Furthermore, ESPT can be constructed with only few message exchanges and has been demonstrated that its total power consumption is lower than that of the best known algorithms.

A SPT can be created by performing a network-wide flood. But all nodes propagate messages with the maximum transmission power. We can perform a network-wide broadcast on ESPT to construct SPT. Therefore, the power emitting of every node can be constrained in an appropriate radius. We assume an underlying topology is first derived using ESPT for the purpose of broadcasting messages like publication of services or route discovery.

Algorithm 1 Multicast Tree Construction

1: **if** source **s** want to initiate a multicast session S to send data to nodes in D **then**
2: Create an entry (s,S) at s
3: $\beta[s] \leftarrow 0$ // accumulative power consumption
4: $\pi[s] \leftarrow NIL$ // predecessor
5: broadcast CONST_REQ $< s, S, D, \beta[s] >$
6: **end if**
7: **for** a nodes **v** other than **s do**
8: **if v** receives CONST_REQ $< s, S, D, \beta[u] >$ from **u then**
9: **if** no entry is indexed by (s,S) at v **then**
10: Create an entry (s,S) at **v**;
11: $\beta[v] \leftarrow \infty$
12: $\pi[v] \leftarrow NIL$
13: $Number[v] \leftarrow 0$ // Relation Number
14: **end if**
15: **if** $\beta[u] + P_{u,v} < \beta[v]$ **then**
16: $\beta[v] \leftarrow \beta[u] + P_{u,v}$
17: $\pi[v] \leftarrow u$
18: broadcast CONST_REQ$< s, S, D, \beta[v] >$
19: **end if**
20: **if** v is a destination **then**
21: $\# \leftarrow 1$
22: send CONST_REP$< s, S, \# >$ back to **u**
23: **end if**
24: **end if**
25: **if v** receives CONST_REP $< s, S, \# >$ from **u then**
26: $\# \leftarrow \# + 1$
27: **if** $\# > Number[v]$ **then**
28: $Number[v] \leftarrow \#$
29: **end if**
30: establish the link (v,u)
31: send CONST_REP$< s, S, \# >$ to $\pi[v]$
32: **end if**
33: **end for**

The algorithm of initial multicast tree construction is shown in Algorithm 1. When a node s wants to send data to nodes in D, it initiates *Multicast Tree Construction Request* (CONST_REQ) and broadcasts the request (Line 1-6). The packet

CONST_REQ $< s, S, D, \beta[v] >$ carries the source node ID s, the session number S, the destination set D, and the accumulative power consumption β which records the power expense for sending this packet since the source. When a node **v** receives a new CONST_REQ from **u**, an entry is created by setting the initial value of $\beta[v], \pi[v]$, and $Number[v]$ (Line 9-13) where $\pi[v]$ is for storing the parentID and Number[v] is used to record a *Relation Number* for assuring connectivity in the refinement step discussed in later subsection. If the accumulative power consumption from the source to **v** via **u** (i.e. $\beta[u] + P_{u,v}$) is smaller than $\beta[v]$, node **u** is regarded as a better predecessor of **v**. We update $\beta[v]$ and record **u** as the parent of **v** (Line 15-19). Additionally, if **v** is a destination, it would unicast a *Multicast Tree Construction Reply* (CONST_REP) back to source along the same path (Line 20-23). The reply packet records the number of hop counts $\#$ traveled since **v**. When an intermediate node **v** receives CONST_REP from **u**, it would establish the link (v,u) by making edge $(v, u) \in E_T$, and records the largest number of hop count $\#$ received from its children nodes as its *Relation Number*. Then, it relays CONST_REP toward source (Line 25-32).

After source receives all the CONST_REP from every destinations, an initial multicast tree T has been constructed. And all the node $u \in V_T$ have been assigned a *Relation Number*. Now we would propose two mechanisms: Numbering and Grouping.

1) Numbering: We assure the multicast tree T will remain connected after switch operations by the following lemma given in [16]

Lemma 1: When switching the parent of node **u** from node **v** to node **w**, If node **w** is not a descendant of node **u** in tree **T**, then the tree will remain connected after switch.

The *Relation Number* of a node in fact records the number of hops between the node and its furthest descendant when the tree is constructed. In other words, the main principle of this numbering operation is that *every non-leaf node **u** in the tree has larger* Relation Number *than its descendants*. It means, once the *Relation Number* of a node **u** is greater than node **v**, node **u** can never be a descendant of node **v**. We can make use of this *Relation Number* and lemma 1 to guarantee the switch we made can keep the connectivity of T by always picking a new parent with greater *Relation Number*.

2) Grouping: Next, after the initial multicast tree is constructed, we now evaluate the *Cost* of every nodes in the tree by organizing the nodes in the tree into groups (the shade region in Fig. 2). The purpose of *Grouping* is that in the multicast tree, some nodes are *essential nodes* (e.g. destinations or branch nodes as in Fig. 2) must be reached, and others serve as relays. We group each *essential node* with relays on the path to the source until the next essential node. If node **v** switches its parent from node **w** to node **u**, the links(t,h),(h,w) and (w,v) can be pruned without influence on the connectivity of the multicast tree. We define the cost of node **v** as the gain of energy conservation after the pruning operation which can be calculated as:

$$cost(v) = \begin{cases} P_{hw} + P_{wv}, & \text{if h is not the furthest child of t} \\ P_{hw} + P_{wv} + (P_{th} - P_2(t)), & \text{otherwise} \end{cases}$$

Where $P_2(t)$ is the transmitted power required to support a link between t and the second furthest child of t.

Algorithm 2 Grouping

1: **if** $v \in T$ receives ON_REQ $< s, S, m, x, \sigma, c >$ from a neighbor **u then**
2: $c \leftarrow c + 1$
3: **if** $c = 1$ **then**
4: $status[v] \leftarrow$ head node
5: **if** **v** is the furthest child of **u** **then**
6: $cost(v) \leftarrow P(u) - P_2(u)$
7: **else**
8: $cost(v) \leftarrow 0$
9: **end if**
10: **else**
11: $\sigma \leftarrow \sigma + P(u)$
12: $cost(v) = \sigma$
13: **end if**
14: **if** (**v** is a (destination $\vee$ branch node)) $\vee$ (c = m) **then**
15: $status[v] \leftarrow tailnode$
16: $\sigma \leftarrow 0$
17: $c \leftarrow 0$
18: **end if**
19: Send ON_REQ $< s, S, m, x, \sigma, c >$ to neighbors other than **u** in tree
20: **end if**

The algorithm of *Grouping* is shown in Algorithm

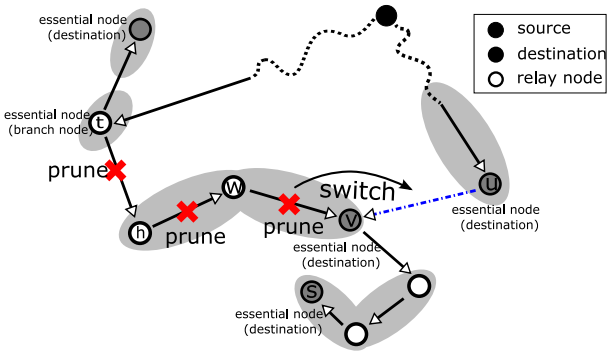


Fig. 2: Switch operation:
Node **v** switches its parent from node **w** to node **u**. And the relays which is no longer required after switching are pruned.

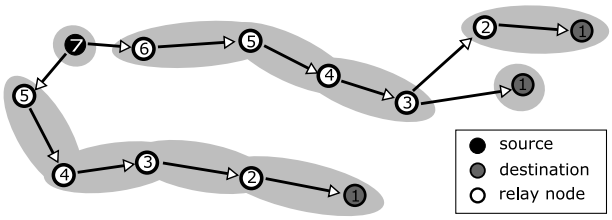


Fig. 3: group size limit=∞

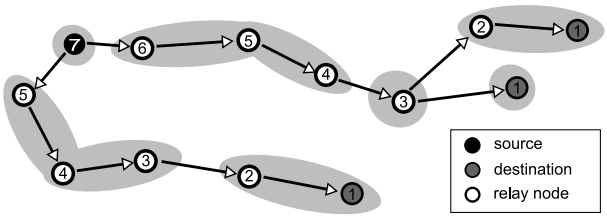


Fig. 4: group size limit=3

2. After receiving all the CONST_REP from every destinations, source then broadcasts *Organize Nodes Request* (ON_REQ). An ON_REQ message can be presented as a tuple $< s, S, m, x, \sigma, c >$ consisted of the source node s, the multicast session S, the group size limit m, the execution round demand x, the accumulative power consumption in current group σ and the number of nodes in current group c.

When a node **v** $\in V_T$ receives an ON_REQ from **u**, it updates c immediately (line 2), and evaluates its cost (line 3-13), then checks whether it is the final node of the current group (line 14-18). Finally, it sends the request to neighbors other than **u** in the tree (line 19). We divide the tree into many groups by destinations and branch nodes. That is when node **v** is a destination in the multicast session or a branch node in the tree ,it will be the last node (tail node) in the current group (Fig. 3). There is another case that if we set the group size limit $m \in N$ to bound the maximum group size, the group will also end at the node with c reach the group size limit m. The node also will be the tail node in the current group (Fig. 4). It then initialize σ and c to start a new group (line 15-17).

We evaluate the cost of nodes by accumulating power consumption of relays in the same group (line 11-12), but when the node is a starter (head node) of a group, the cost evaluation is different. The cost of such nodes is the power saved in the parent node when the node has been removed, as shown in line 5-8 of Algorithm 2.

C. Refinement Step

After grouping, we had evaluated the cost of every node $u \in V_T$. Then we can start the refinement step. The refinement step is in a full localized fashion and can be organized as follow: every group has a token which is passed to nodes one by one in *Relation Number* order. The token passing from the *tail node* to the *head node* of a given group is called a round. A head node passes the token directly to the tail node in the same group to start a new round. This token can be regarded as a permission to do operations such as sending requests or initiating the refinement. Each group counts the number of round executed until it reaches the execution round demand **x**.

1) Token Passing: We initialize the refinement step by passing token from the tail node of the group. The algorithm of token passing is shown in Algorithm 3. Once a node **v** receives a token. It computes the *Gain* of all the node $u \in Neighbor(v)$ with $Number(u) \geq Number(v)$(Line 2-4). *Gain(u)* is given by $Cost(v) - Increase(u)$. Here, $Cost(v)$ had been evaluated during grouping, which can be seen as the accumulative power consumption required to sent data to node **v**. $Increase(u)$ is the additional power needed at node **u** by adding a new child **v**, which is given in line 3. So the *Gain* is the amount of reduced power by switching the parent of node **v** to node **u**.

If the *Relation Number* of node **u** with highest

Algorithm 3 Token passing

1: **if v** receives token **then**
2: **for all u** such that $u \in Neighbor(v) \wedge Number(u) \geq Number(v)$ **do**
3: $Increase(u) = max\{P_{u,v}, P(u)\} - P(u)$
4: $Gain(u) = Cost(v) - Increase(u)$
5: **end for**
6: **if** $\max_{\forall u} \{Gain(u)\} > 0 \wedge Number(u) = Number(v)$ **then**
7: send INR_REQ to **u** and wait for reply
8: **end if**
9: **if** $\max_{\forall u} \{Gain(u)\} > 0 \wedge Number(u) > Number(v)$ **then**
10: send JOIN_REQ$< u, Gain(u), v >$ to **u**
11: **if v** is the head node of the group **then**
12: send LEAVE_REQ$< parent(v), v >$ to parent(v)
13: **end if**
14: Wait for reply
15: **end if**
16: Pass the token to next node
17: **end if**

positive *Gain* is the same as node **v**, we send an *Increase Number Request* (INR_REQ) first and wait for reply (line 6-8). The request will make node **u** increase its *Relation Number* under numbering principle, so node **v** can request node **u** to be its new parent. The details will be discussed later this section.

When the *Relation Number* of node **u** with highest positive *Gain* is bigger then v. It can send the *Join Request* (JOIN_REQ) to the node **u** to invite it to be its new parent(line 10). And if node **v** is the head node of its group, it also have to send a *Leave Request* (LEAVE_REQ) to its parent (line 11-13). Then wait the reply for the request sent (line 14). Finally, after **v** receives all the reply, or there is no any node with positive *Gain*, it passes the token to the next node (line 16).

2) Request Handling: Now, we address how would a node respond to the received request. Due to the possibility of decision conflict, not all the switch refinement can be done immediately. To deal with the problem, every node should send a request and wait for acceptance before doing any switching operation.

The reply to the request under different situation is shown in Algorithm 4. When a node **v** receives a JOIN_REQ. If **v** had received the token this round, it is in a stable state. Which means this node won't be pruned or decrease its emitting radius in this round. Accordingly, any node joining **v** won't cause a conflict, and it can reply *Join Request Acceptance* (JOIN_ACP) immediately (line 3-4).

But if **v** hasn't received the token, we can't assure whether **v** will be pruned in this round. So we hold the request by sending *Join Request Hold* (JOIN_HOLD) back to **u** (line 6). Meanwhile, node **v** forwards the JOIN_REQ along the tree path to the token node. The token node keeps track of the JOIN_REQ with the largest *Gain*, JOIN_REQ*. If the token node happens to be the originator of JOIN_REQ*, a JOIN_ACP will be transmitted. Otherwise, it transmits a JOIN_RJT. Finally, the token is passed to the next node. The node receiving JOIN_HOLD will hold the token until it also receiving JOIN_ACP, or *Join Request Reject* JOIN_RJT.

When a node **v** receives a LEAVE_REQ. Because the JOIN_ACP and LEAVE_ACP cause a conflict. If it had sent any JOIN_ACP in this round, it replies *Leave Request Reject* (LEAVE_RJT), else it replies *Leave Request Acceptance* (LEAVE_ACP) (line 22-28).

3) Non-tree Node Operation: A node not in the tree can also contribute to energy saving by connecting two neighboring tree nodes through it. Unfortunately, limitation of space forbids full treatment of the subject. For more details, please consult our full paper[9].

4) Increase Number Request: Increase Number Request (INR_REQ) is a special request, which is used to increase the number of a node in a reasonable range so that we can choose a new parent with the same *Relation Number* by sending INR_REQ first.

After the computation of a token node **v**, if the Relation Number of the node **u** with largest *Gain* is as same as the token node **v**, we can send INR_REQ to node **u** first to ask for increasing *Relation Number* under *Numbering* principle. When the node u receives the request, it can change its *Relation Number* to the average of current *Relation Number* and the upper bound of *Relation Number*. That is $Number(u) = (Number(u) +$ *upper_bound_of_* $Number(u))/2$. Where the *upper_bound_of_*$Number(u) =$

Algorithm 4 Request Handling

```
for a tree node v do
    if v receives a JOIN_REQ< v, Gain, u > then
        if v has gotten token in this round then
            reply JOIN_ACP back to u
        else
            reply JOIN_HOLD back to u
            send JOIN_REQ< v, Gain, u > to the token node
        end if
    end if
    if v holds the token then
        record the JOIN_REQ with the largest Gain as JOIN_REQ*
        if JOIN_REQ< v, Gain, u > then
            if JOIN_REQ< v, Gain, u >= JOIN_REQ* then
                reply JOIN_ACP back to u
            else
                reply JOIN_RJT back to u
            end if
        else
            pass the token to the next node
        end if
    end if
    if v receives a LEAVE_REQ< v, u > then
        if v doesn't send any JOIN_ACP in this round then
            reply LEAVE_ACP back to u
        else
            reply LEAVE_RJT back to u
        end if
    end if
end for
```

$min\{Number(parent(u)), Number(\textit{the node u requested if any})\}$. After node **u** changes its *Relation Number*, it then broadcasts the update message to all the neighbor, and sends a *Increase Number Reply* (INR_REP) to node **v**. Accordingly, node **v** can request node **u** to be its new parent without violating numbering principle.

5) Refinement: If a head node receives both JOIN_ACP and LEAVE_ACP or a non-head node receives JOIN_ACP. It can firstly perform the refinement by switching to new parent node **u**. Then it sends *Disorganize Nodes Confirm* (DON_CONF) to group members with bigger *Relation Number*. The node receives the message would regard itself as a non-tree node and relay DON_CONF message to the next node until the message reaches a destination or a branch node. The former simply drops the message and tags itself as a tail node. The later would send an ON_REQ message to its child node to form a new group if it is no longer a branch node or drop the DON_CONF message otherwise. If the pruned node had sent a JOIN_HOLD before, it needs to send *Join Request Reject* (JOIN_RJT) to cancel the hold. On the other hand, if the new parent **u** becomes a branch node, it turns itself into a tail node and all its children become head nodes of the corresponding groups. As a result, the switching and pruning operations retains a multicast tree structure.

V. Performance Evaluation

In this section, we evaluate the performance of LEMG through detailed simulation in static ad-hoc networks with our implemented c++ simulator. We assume the MAC layer is ideal and the radio transmission radius of a node is fixed to 250 meters.

We use the energy model proposed by Ingelrest et al. [3], that is the power consumption of a emitter **u** with a radius r_u is given by

$$P_T(u) = \begin{cases} r_u^4 + 10^8, & \text{if u is the source} \\ r_u^4 + 10^8 + \frac{1}{3}(100)^4, & \text{if u is a relay node} \\ \frac{1}{3}(100)^4, & \text{if u is a leaf node.} \end{cases}$$

In each experiment, the ratio of number of the multicast group nodes to total nodes varies from 10% to 100% for every 10% increment, and we do 1000 simulation runs for each setting. The nodes in the network is uniformly distributed inside a square region and the network connectivity is assured. Besides, the nodes in the multicast group are chosen randomly as well as the source node.

The experiments can be divided into two stages. In the first stage, we investigate the influence of two important settings of LEMG: group size limit **m** and execution round demand **x**. In the second stage, we compare LEMG with other protocols to evaluate the performance.

A. Performance Metrics

In each experiment, we look into the following metrics for evaluating the performance of LEMG with respect to other representative algorithms.

1) **Total power consumption (TPC)**: The total tree power required using a heuristic algorithm. It is the average of the sum of the energy consumed in every tree node for one

unit of transmission out of 1000 simulation runs.

2) **Relative TPC**: The ratio of the TPC of LEMG to that of the initial multicast tree SPT.
3) **Normalized TPC**: The ratio of TPC to the average of the best tree powers obtained from heuristic algorithms in the set H = {MIP,DMEM,LEMG}. That is, Normalized $TPC = \frac{TPC_{alg}}{TPC_{best}}$, where $TPC_{best} = avg \min\{TPC_{alg}\}$ and $alg \in H$.
4) **Total control messages (TCM)**: The number of control messages for refinement over the whole course of simulation. The metric can be used to evaluate the message complexity of heuristic algorithms.
5) **Total time periods (TTP)**: The total time periods required for a simulation run of a heuristic algorithm. A time period is defined as the processing time and transmission time of a node. The metric can be viewed as a measure of execution time of the corresponding algorithm in an ideal environment with collisionless MAC layer.

B. Experiments Result in different settings

In the first stage of experiments, an ad-hoc network with 400 nodes in a physical area of 2000 meters $\times$ 2000 meters is simulated. All curves are averages over 1000 independent simulation runs.

1) Execution Round Demand: At first, the influence of execution round demand **x** is studied. The group size limit **m** is set to 400 which means no restriction on group size. Generally speaking, more refinement could possibly be discovered with larger **x**. As shown in Fig. 5a, the relative power consumption decreases with the increase of **x**. However, the relative power consumption when **x**=10 is similar to that when **x**=5. In Fig. 5b, the TCM are similar under **x**=10 and **x**=5 which represents the number of refinement can be done is very limited after five rounds of execution in each group. But, as we can see in Fig.5c, the TTP when **x**=10 is approximately twice of that when **x**=5. Consequently, we adopt the setting **x**=5 in all the following experiments.

2) Group Size Limit: Next, we analyze the impact of group size **m**. It imposes a restriction on the maximal hops of message passing for one refinement operation. Consider the *Grouping* mechanism, more redundant relay nodes and links in between could be removed with larger **m**, resulting in better energy conservation. On the other hand, a large group size can cause the increase in the communication overhead and thus the time complexity of the algorithm. Our focus is to find an appropriate setting for **m** through extensive simulations.

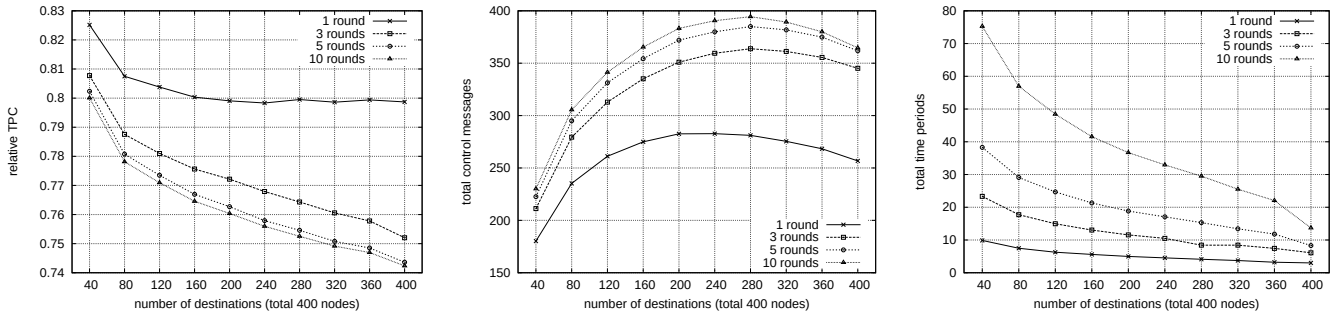
Fig. 6a shows the relative power consumption of multicast trees constructed by our LEMG with different setting of **m**. Each curve is characterized by the multicast group size. We can observe that the larger the **m**, the lower the power consumed. Meanwhile, no more improvement can be made when **m** is larger than ten. Fig. 6b and Fig. 6c also show the TCM and the TTP are nearly the same when **m**=10 and **m**=400(i.e. no restriction on group size). Therefore, we set **m**=10 in all the following experiments.

C. Performance Result

After the values of x and m have been decided, we compare our LEMG with MIP and DMEM. MIP is perhaps the most well-known centralized multicast algorithm and has been often used as a baseline algorithm for comparison. DMEM, to the best of our knowledge, is the latest distributed tree-based multicast algorithm that attempts to explore the energy conservation by the use of several localized operations.

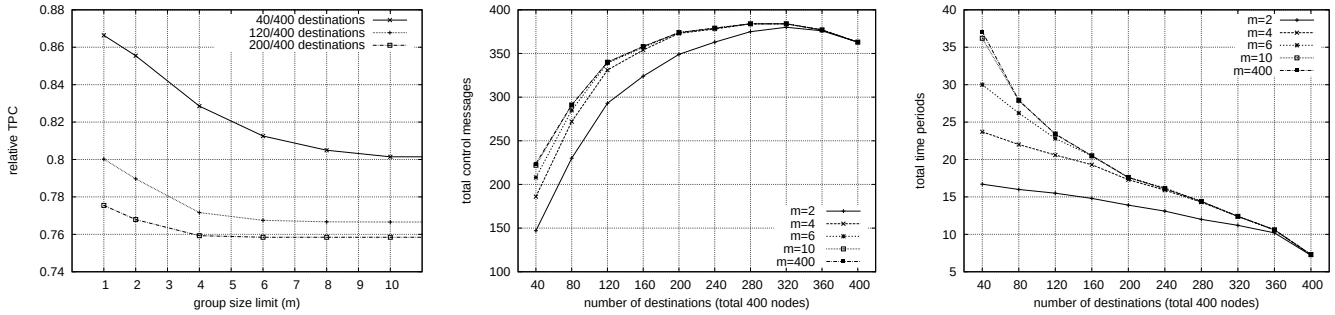
The performance is evaluated on two different network scenarios. For one is the standard scenario where 100 nodes are randomly generated in a square area of size 1000 meters $\times$ 1000 meters. The other is the large-scale scenario, there are 400 nodes in the square region of 2000 meters $\times$ 2000 meters. Fig. 7a and Fig. 7b show the normalized power consumption with respect to various multicast group sizes for the standard scenario and the large-scale scenario respectively. LEMG performs almost as good as DMEM and better than MIP when the multicast group size is small. As the multicast group size increases, LEMG is less energy efficient. This is because the average group size in a LEMG tree decreases with the growth of multicast group size. However, it is only $5\% - 6\%$ worse than DMEM at most.

Fig. 8a and Fig. 8b depict the comparison of total control messages (TCM) which is shown on the



(a) (b) (c)

Fig. 5: Execution rounds experiment (a) Relative power consumption (b) Total control messages (c) Total time periods



(a) (b) (c)

Fig. 6: Group sizes experiment (a) Relative power consumption (b) Total control messages (c) Total time periods

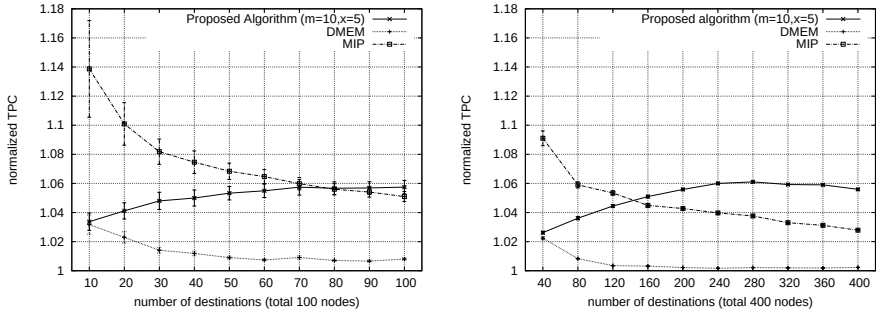
vertical axis in log scale for LEMG and DMEM. We can observe that the message complexity of DMEM grows dramatically with the multicast group size and the network size. This is due all the local energy savings information has to be sent to the source and the final decision will be send back to the node with the maximum energy savings. On the contrary, LEMG has much lower TCM and it grows linearly with network sizes.

The comparison of the total time periods (TTP) of LEMG and DMEM under different network scenarios are shown on Fig. 9a and Fig. 9b. The x-axis represents various multicast group sizes and the TTP is shown on the y-axis in log scale. We can see that in DMEM, the TTP increases with multicast group sizes, while that of LEMG decreases in contrast. It is due to larger multicast group results in smaller groups in the LEMG tree and the execution time is therefore reduced. Furthermore, the TTP is almost invariant to network sizes, while in DMEM, the TTP increases dramatically with network sizes.

In summarize, although LEMG is slightly inferior to DMEM in energy conservation under large multicast group size, its superiority on TCM and TTP over DMEM is obvious. When considering node mobility and varying link condition in wireless ad-hoc networks, timeliness of the algorithm is important. Otherwise, the energy savings information may not be valid anymore. From the simulation results, LEMG is more suitable to be applied in a large-scale ad-hoc wireless network.

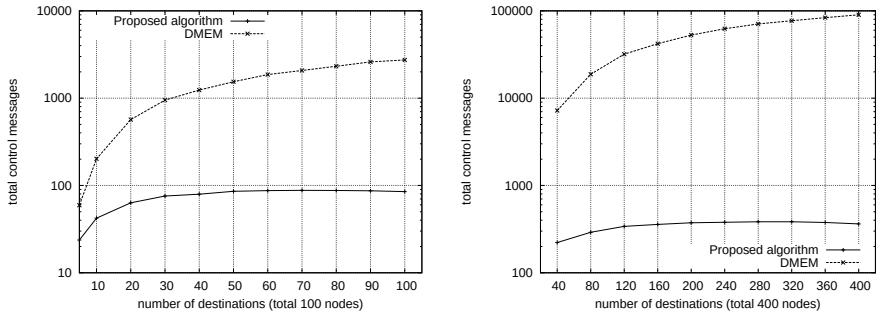
VI. Conclusion and Future Work

In this work, we proposed a fully localized refinement based algorithm for building energy-efficient multicast tree in wireless ad hoc network. We started with the construction of a SPT on top of ESPT. With Grouping mechanism, we make the cost evaluation



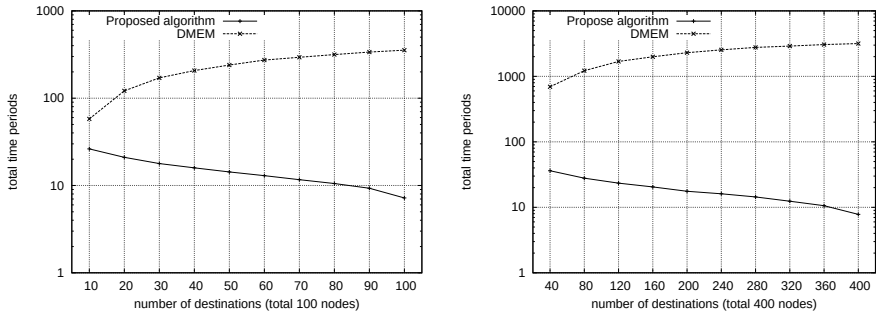
(a) (b)

Fig. 7: Normalized power consumption comparison of MIP, DMEM and LEMG (a) Standard scenario (b) Large-scale scenario



(a) (b)

Fig. 8: Total control messages comparison of DMEM and LEMG (a) Standard scenario (b) Large-scale scenario



(a) (b)

Fig. 9: Total time periods comparison of DMEM and LEMG (a) Standard scenario (b) Large-scale scenario

and limit the hop count of message passing in the refinement step. Two adjustable parameters: group size limit **m** and execution round demand **x** control the time required for refinement and the efficiency of LEMG. Besides, All the message passing is within a constant hop count which is decided by **m**.

The simulation results show the average total power consumption of LEMG is colse to DMDM with only 5% difference while all the message passing in proposed algorithm is limit to **m** hops. Besides, the refinement of LEMG can be done in only limited hops of message passing and nearly constant regardless of the network size and the number of destinations in the same setting. What is more, the total control message in the refinement

grows only linearly with network size, so the average control message per node is also not affected by network size. Consequently, the algorithm we proposed can achieve energy-efficient comparable solution to others in only few hops message passing, and can be adapted well in any size of network due to the localized property.

Most energy-efficient multicast algorithm only consider an ideal MAC layer. For future work, we shall implement the performance evaluation in network simulator to study a more realistic MAC layer. We shall also evaluate the influence of mobility and directional antenna on LEMG for a more piratical scenario.

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