An Energy Efficient Localized Topology Control Algorithm for Wireless Multihop Networks

Dezhong Shang, Baoxian Zhang, Zheng Yao, and Cheng Li

Abstract: **Localized topology control is attractive for obtaining reduced network graphs with desirable features such as sparser connectivity and reduced transmit powers. In this paper, we focus on studying how to prolong network lifetime in the context of localized topology control for wireless multi-hop networks. For this purpose, we propose an energy efficient localized topology control algorithm. In our algorithm, each node is required to maintain its one-hop neighborhood topology. In order to achieve long network lifetime, we introduce a new metric for characterizing the energy criticality status of each link in the network. Each node independently builds a local energy-efficient spanning tree for finding a reduced neighbor set while maximally avoiding using energy-critical links in its neighborhood for the local spanning tree construction. We present the detailed design description of our algorithm. The computational complexity of the proposed algorithm is deduced to be $O(m \log n)$, where m and n represent the number of links and nodes in a node's one-hop neighborhood, respectively. Simulation results show that our algorithm significantly outperforms existing work in terms of network lifetime.**

Index Terms: **Energy criticality, energy efficient routing, localized topology control, wireless multi-hop networks.**

I. INTRODUCTION

The topology of a multihop wireless network (e.g., wireless ad hoc network, wireless sensor network, etc.) has great impact on the network performance [1]–[5]. In many cases, nodes in a wireless multihop network are often battery operated. When the battery of a node runs out of energy, a node cannot work any longer. The goal of topology control is to achieve sparse connectivity, decreased energy consumption and radio interface, controlled transmission power, and prolonged network lifetime. Recently, design of efficient topology control algorithms has attracted a lot of attention and much work has been carried out.

Existing topology control algorithms focus mainly on the allocation of low transmit powers at network nodes while preserving global connectivity. Based on the required network state information to be kept at nodes, existing algorithms can work with either global network state information (e.g., [5], [6]) or local network state information (e.g., [7]–[9]). The former can usually assign very low transmit powers at node while the latter has high scalability with certain sacrifice (i.e., increase) in node transmit powers. However, all the above algorithms overemphasize too much on the sparseness of created networks after topology control and lack of consideration of the energy criticality status of nodes and links in the network. Their generated topologies may keep using the links between energy critical nodes continuously for packet relaying while removing those links between energy abundant nodes or links under the name of generating sparser topologies, which can in return hurt the network lifetime performance. Considering the energy-criticality of nodes / links into topology control is important for achieving prolonged network lifetime. In [10], Liu *et al.* designed an enhanced algorithm to the local minimum spanning tree (LMST) algorithm (E-LMST) by considering the energy-criticality of nodes when building local minimal spanning tree by forcing those energy-critical nodes (if any) to be leaf nodes on the tree. Simulation results show that E-LMST outperforms LMST in terms of network lifetime. However, the ability of E-LMST for prolonging network lifetime is still considered to be limited. How to design energy-efficient localized topology control algorithms for prolonged network lifetime by fully utilizing the limited routing information at network node is still an interesting topic to explore.

In this paper, a localized energy-efficient topology control algorithm is proposed to achieve prolonged network lifetime via energy-draining balancing among nodes. To characterize the energy status of each link in the network, a new metric is introduced for localized topology control. In our proposed algorithm, those links between energy abundant nodes are more likely to be used when generating each node's neighbor set in order to build a sparser network with long lifetime. It requires each node to keep its one-hop neighborhood knowledge including the topology as well as the energy status (after granulation) of each link in the one-hop neighborhood. The computational complexity of our proposed algorithm is derived to be $O(m \log n)$, where m and n represent the number of links and nodes in a node's one-hop neighborhood. Simulation results show that the proposed algorithm can achieve significantly prolonged network lifetime as compared with existing algorithms.

The rest of this paper is organized as follows. In Section II, we briefly review related work. In Section III, we model the network under study. In Section IV, we propose the localized topology control algorithm and derive its computational complexity. In Section V, we conduct extensive simulations to evaluate the performance of the proposed algorithm by comparing it with existing work. In Section VI, we conclude this paper.

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D. Shang, B. Zhang, and Z. Yao are with the Research Center of Ubiquitous Sensor Networks, University of Chinese Academy of Sciences, China, email: shangdezhong12@mails.ucas.ac.cn, {bxzhang, yaozheng}@ucas.ac.cn.

C. Li is with the Faculty of Engineering and Applied Science, Memorial University, Canada, email: licheng@mun.ca.

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II. RELATED WORK

Topology control has great impact on the performance of wireless networks. In the literature, a lot of topology control algorithms have been proposed. Based on the network state information to be kept, existing topology control algorithms can be classified into two categories: Algorithms using global network state information and algorithms requiring local network state information to be kept at each node (e.g., one-hop or two-hop neighborhood knowledge). The latter type of algorithms is often referred to as localized algorithms. In a topology control algorithm belonging to the former type, global network state information is needed for generating reduced graphs. Therefore, their implementations are expensive in practice due to the high overhead for collecting and storing such information. In contrast, localized algorithms can enable each network node to independently control its local topology by using its local neighborhood information while keeping the connectivity of the network (e.g., LMST [7], LSPT [8]) or connected with high probability (e.g., k-NEIGH protocol [11]). In general, localized algorithms have higher scalability than that using global information. On the other hand, algorithms using global network state information can provide better topology control performance (e.g., in terms of reducing nodal transmit powers) and exhibit better performance in small-scale networks. Next, we shall respectively introduce typical algorithms belonging to either type.

Some typical topology control algorithms using global network state information are introduced as follows. In [5], Ramanathan *et al.* presented two algorithms respectively called CONNECT and BICONNAUGMENT, which are greedy algorithms minimizing the maximal power used per node. These two algorithms work to merge different network components iteratively until only one remains (provided that the original graph is connected). The COMPOW protocol, proposed by Narayanaswamy *et al.* in [6], tries to maintain the global connectivity of the entire network with the minimal but sufficiently high common transmission power. In COMPOW, each node is assumed to be able to work at multiple discrete power levels. COMPOW requires each node to run several distance vector routing daemons in parallel, one for each power level. Each routing daemon converges independently in the network. However, its high communication overhead is a drawback in large-scale networks. In [12], Kawadia *et al.* extended the COMPOW protocol to work in networks with non-uniform node distribution in order to achieve reduced power consumption for end-to-end packet delivery.

Many localized topology control algorithms have been proposed in recent years. Relative neighborhood graphs (RNG) and Gabriel graphs (GG) are well known localized topology control algorithms [13]. The RNG has an edge between two nodes u and v, if there is no node w such that $\max\{d(u,w), d(v,w)\} < d(u,v)$, where $d(x,y)$ represents the Euclidean distance between x and y. The GG has an edge between two nodes u and v if and only if there is no node w such that $d^2(u,w) + d^2(v,w) \leq d^2(u,v)$. Both RNG and GG are easy to compute using a local algorithm. The directed RNG (DRNG) [14] is aimed to enhancing RNG to work with heterogeneous nodes and in irregular radio environment and it removes those long links which can be replaced by other shorter bypassing links. DRNG requires two-hop topology information to be kept at nodes. In [9], Rodoplu and Meng proposed the concept of relay region and enclosure graph, with which each node builds a local closure graph and maintains only a set of neighbors with which direct communication is power-efficient than the case that an intermediate node is introduced. In [8], Dijkstra's algorithm is applied to the one-hop local topology at each node to build sparse connectivity such that each node independently builds a local shortest path spanning tree (LSPT) on top of its one-hop neighborhood and then maintains only those one-hop on-tree neighbors as its new neighbors. In [7], a localized topology control algorithm based on the LMST is proposed. In this algorithm, each node builds its own minimum spanning tree independently according to the information on its one-hop neighborhood, and only keeps one-hop nodes on the tree as its neighbors in the final topology graph. The simulation results in [7] show that LMST is able to reduce transmission power of nodes and is proved in the literature that the degree of any node in the topology-control graph is bounded by 6. However, all the above localized topology algorithms fail to consider the energy criticality of nodes. In this case, some energy-critical nodes may be overused until these nodes run out of power. In particular, for static networks, their generated topologies are invariable during the network lifetime if link powers do not change with time.

Recently, some lifetime-prolonging localized topology control algorithms have been proposed. In [10], E-LMST enhances LMST for prolonged network lifetime. For this purpose, E-LMST introduces an energy-draining balancing strategy and tries to avoid using those energy-critical nodes to forward packets, if possible. E-LMST requires each node to know whether it belongs to energy-critical nodes among all nodes in the entire network. With that knowledge, each node builds a local minimum spanning tree but forcing energy-critical nodes to be leaf nodes. Like LMST, E-LMST keeps the one-hop neighbor nodes on the tree as neighbor nodes in the final topology. In [15], two lifetime-extended dynamic topology control algorithms based on cooperative communication technology (LDTCC) were proposed. Cooperative communications allows relay nodes to help the source node forward the same information simultaneously so as to reduce the power consumption. The algorithms consider both the overall energy cost of maintaining links and current available energy of nodes. However, the implementations of these two algorithms need to support cooperative communications at the physical layer.

III. NETWORK MODEL AND ROUTING INFORMATION

In this paper, we study a multi-hop wireless network, which can be modeled by $G(V,E)$, where *V* is the set of nodes and *E* is the set of links connecting the nodes in *G*. The set of nodes and links in G are accordingly represented by $V(G)$ and $E(G)$, respectively. A link $(u,v) \in E(G)$ means node u and v can communicate with each other directly. Specifically, if $d(u,v) \leq R$, then a link exists between node u and node v, where $d(u,v)$ represents the geometrical distance between u and v, and R represents the maximum uniform transmission range of nodes in the network. In order to successfully communicate with a neigh-

boring node, each node in the network can adaptively adjust its transmit power. We assume that each node is equipped with an omnidirectional antenna.

Let e_{uv} represent the (minimal) power required for a node u to successfully transmit an information unit to another node v, which is $d(u,v), d(u,v) \leq R$, far away from node u. In this paper, the power consumption model in [5]–[7] is used to calculate the power consumed for the transmission.

$$e_{uv} = d(u,v)^{\alpha} + c \tag{1}$$

where α and c are constants for specific wireless systems and propagation environments (usually $2 \leq \alpha \leq 4$). In (1), c stands for the overhead due to signal processing and minimal energy required for successful reception. In (1), a simplified interference model is adopted, in which the interference level is independent of network traffic and the same at all nodes. Moreover, e_{uv} is set to be infinite ($e_{uv} = \infty$) if $d(u,v) > R$. For a given path *p* connecting a pair of nodes, the overall power consumed for sending an information unit along path *p* is the sum of the link powers of its constituent links as follows.

$$e(p) = \sum_{(u,v) \in p} e_{uv}. \tag{2}$$

In this paper, it is assumed that all nodes are aware of its location information, which can be obtained via certain localization techniques or devices, for example, GPS receivers. Further, each node keeps the location information of all its one-hop neighbor nodes. Such location information can be obtained via exchanging of hello messages among one-hop neighbor nodes when the network is initially deployed. If nodes can move, periodical exchanging of such hello messages is needed. Let $N(u)$ represent the one-hop neighborhood set of node $u \in V(G)$, then $N(u) = \{v | v \in V(G), (u,v) \in E(G)\} + \{u\}$. Let $NE(u)$ represent the set of the edges between two nodes in $N(u)$, then $NE(u) = \{(x,y) \,|\, (x,y) \in E(G) \wedge x, y \in N(u)\}$.

IV. PROPOSED ALGORITHM

In this section, we propose an energy-efficient localized topology control algorithm, which is aimed to achieve the following design objectives: (1) Reduce the transmission power of the network nodes, (2) prolong the network lifetime. In order to achieve these two goals simultaneously, we consider how to maximally avoid overusing those links between energy-critical nodes to undertake the task of relaying packets, if possible.

The proposed algorithm is designed to enhance the LMST algorithm, which creates sparser graph via minimizing the transmission powers of nodes. To ease the presentation, our algorithm is referred to as X-LMST. X-LMST takes the energy-criticality of links into consideration when building local MST via localized topology control. However, it should be noted that our algorithm design in this paper can also co-work well with other localized topology control algorithms (e.g., LSPT [8], R&M [9], etc.).

One key issue in X-LMST is how to determine the energy criticality of a link in the network. To achieve this goal, a new metric is introduced. Specifically, in order to determine whether a link is energy-critical, the energy status of the two endpoint nodes of the link needs to be inspected. An intuition is that if one of them has extremely low energy, no matter how high the residual energy the other node is, the link should be considered energy-critical. The detail about the calculation of the energy cost of each link in the network will be presented in subsection IV-A.

In X-LMST, each node $u \in V(G)$ builds a local energy-efficient minimal spanning tree covering all the nodes in its one-hop neighborhood. In this process, those energy-critical links are maximally avoided to be used for prolonging the network lifetime. Specifically, if there are energy-critical links in u's one-hop neighborhood, u will remove all of them and apply the LMST algorithm to the remaining graph to generate a minimal spanning tree. If the calculated graph fails to make all nodes $\in N(u)$ be connected, node u will recover those previously-removed links and in the decreasing order of residual-energy-based link cost (which is relevant to the residual energy of two endpoints of each of the links, see (3) and related explanation for details), until a spanning tree covering all the nodes in its one-hop neighborhood is built. After building the tree, node u chooses its one-hop neighbors on the calculated tree as its new neighbors under localized topology control. The final graph resulted by X-LMST is the union of the individual topologies created by different nodes.

The X-LMST algorithm in this paper is to some extent similar to E-LMST[10] in terms of energy-criticality avoidance. However, E-LMST focuses on energy-critical node avoidance while X-LMST focuses on energy critical link avoidance by defining a new link cost function to characterize the energy status of each link, which is expected to achieve further prolonged network lifetime.

A. Energy Critical Link Determination

In this subsection, we describe how each node determines whether a link in its one-hop neighborhood is energy critical or not. Let $E_{\max}$ denote the full energy amount of a node and E_x denote the residual energy of a node x, $x \in V(G)$. The full energy space of $E_{\max}$ is divided into L ($L > 1$) equal intervals. L is a network parameter. The energy level of a node x is denoted by L_x, where $L_x = \lceil L \times E_x / E_{\max} \rceil$.

For a link $(x,y) \in E(G)$, a new metric is defined (denoted by ERG_{xy}) to characterize the energy status of the link as follows.

$$ERG_{xy} = \ln(L_x \times L_y). \tag{3}$$

This new metric has the following salient properties: (1) it is symmetrical, i.e., $ERG_{xy} = ERG_{yx}$; (2) The metric monotonically increases with E_x or E_y; (3) The first order partial derivative of the metric monotonically decreases. Because of these properties, ERG_{xy} is expected to properly reflect the energy starvation situation of link (x,y). As mentioned above, the energy status of the two end nodes of a link decides whether the link is energy critical or not. Meanwhile, because of the above third property, a change due to a lower energy level can cause a greater change in ERG_{xy} than that due to a higher energy level, which makes the dropping of low energy level cause big change in the link energy criticality metric than that by a high energy level.

We define an energy-critical ratio *K* (e.g., $K = 20$), which means *K* percent of the links in the neighborhood of a node with the lowest ERG_{xy} are considered to be energy-critical. The energy-critical value associated with a node $u \in V(G)$, denoted by ERG_u^C, is the threshold for u such that those links in $NE(u)$ with an ERG_{xy} smaller than ERG_u^C are said to be energy-critical links. Each node $x \in V(G)$, has its own ERG_x^C, which is the energy level of the link hitting the energy-critical ratio among the links in the node's one-hop topology.

Algorithm 1 A node u uses X-LMST to calculate its local spanning tree

Input: Node u, energy threshold ERG_u^C, graph G_u;
Output: T_u, NS_u

1: Let $G_u = (V_u, E_u)$, where $V_u = N(u)$, $E_u = \{(x,y) \,|\, (x,y) \in NE(u), ERG_{xy} > ERG_u^C\}$
2: $E_u^R = \{(x,y) \,|\, (x,y) \in NE(u), ERG_{xy} \leq ERG_u^C\}$
3: $A \leftarrow \emptyset$ //An empty tree is created
4: **for** each vertex $x \in V_u$ **do**
5: MAKE-SET(x)
//Create $|V_u|$ individual trees, where $|V_u|$ means the number of nodes in V_u
6: **end for**
7: Sort the links in E_u in the *non-decreasing* order by link power
8: **for** each link $(x,y) \in E_u$ **do**
9: **if** FIND-SET(x)$\neq$ FIND-SET(y) **then**
//Check whether u and v are the same tree
10: $A \leftarrow A \cup \{(x,y)\}$
11: UNION(*x*,*y*)
//Merge the two trees to which u and v belong
12: **end if**
13: **end for**
14: Sort the links in E_u^R in the *non-increasing* order by the ERG-based link cost in (3).
15: **for** each link $(x,y) \in E_u^R$ **do**
16: **if** FIND-SET(x)$\neq$ FIND-SET(y) **then**
17: $A \leftarrow A \cup \{(x,y)\}$
18: UNION(*x*,*y*)
19: **end if**
20: **end for**
21: Build T_u based on *A*
22: $NS_u \leftarrow$ The set of one-hop neighboring nodes on T_u

B. Algorithm Design

After determining the value of ERG_u^C in X-LMST, a node $u \in V(G)$ can build its one-hop topology, $G_u = (V_u, E_u)$, where $V_u = N(u)$, $E_u = \{(x,y) \,|\, (x,y) \in NE(u), ERG_{xy} > ERG_u^C\}$. Then, node u builds the minimal spanning tree (MST) T_u of G_u. The cost of a link $(x,y) \in E_u$ is the link power associated with the link. Algorithm 1 shows the pseudo codes for X-LMST. In Algorithm 1, line 1 is to prepare u's one-hop topology using those non-energy-critical links and line 2 is to keep the set of energy-critical links. Lines 3–13 are to build the MST (in terms of link power) using those non-energy-critical links. The codes between lines 3–13 are almost verbatim to that for Kruskal's algorithm [16]. Lines 14–20 are to continue the MST construction (if the resulting tree structure by lines 3–13 has not covered all nodes in V_u). However, in this process, links with abundant energy have priority to be used (see lines 14–15) instead of low link power as done in the process between lines 9–12). Line 21 builds an MST T_u for node u and line 22 returns the new neighbor set for u.

To maintain a correct neighbor set in dynamic networks, each node can adaptively update its neighbor set as its neighboring nodes move or the costs of link(s) in its one-hop neighborhood change. After implementation of X-LMST, the individual local graph at a node u is $G_u^1 = (V_u^1, E_u^1)$, where $V_u^1 = NS_u + \{u\}$ and $E_u^1 = \{(x,u) \in E(G) \,|\, x \in NS_u\}$. The final graph resulted by X-LMST is the union of the individual local topologies created by different nodes in the network.

Fig. 1 shows an example illustrating how X-LMST and LMST work, respectively, for the central node *o* to compute its local

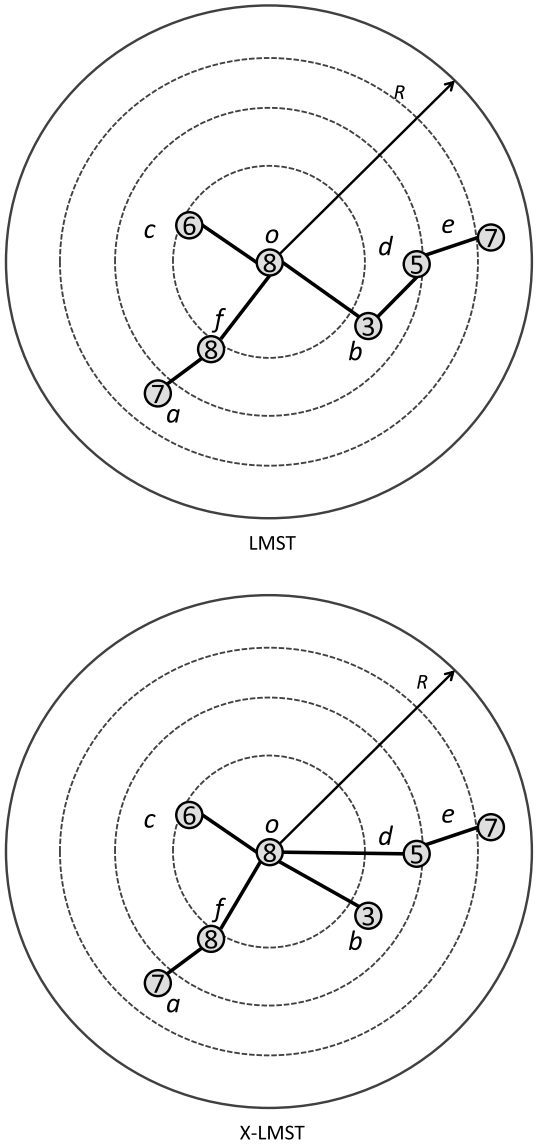

Fig. 1. An example illustrating how LMST and X-LMST work, respectively.

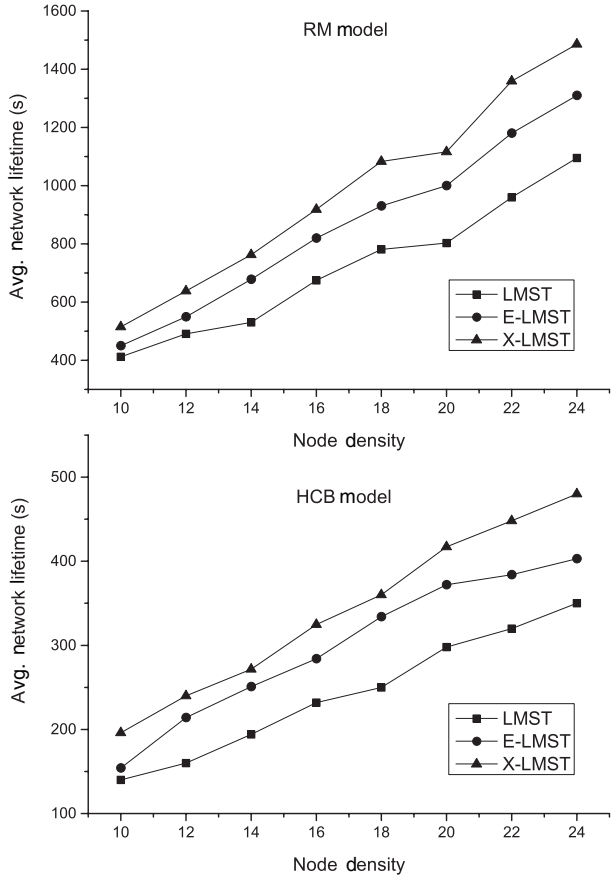

Fig. 2. Comparison of average network lifetime versus node density.

spanning tree on its one-hop neighborhood. In the figure, the number in a circle for each node represents the energy level of the node. In this example, node *o* builds the localized spanning tree T_o using LMST and X-LMST, respectively. In this example, node b is considered to be energy-critical because it has the lowest energy level in *o*'s one-hop neighborhood. For LMST, node *o* builds an MST using link power as the link cost. In this case, node b will have to undertake the forwarding task between *o* and {*d*,*e*}, so LMST is not energy-efficient. In contrast, X-LMST provides a better choice than LMST. Link (d, b) is considered energy-critical because nodes d and b have relatively low energy level. Thus, link (d, b) is ignored in the process of tree construction. Link (o, d) has relatively high ERG_{od} and is thus selected to build T_o. As a result, X-LMST shows better capability in avoiding using energy-critical nodes and balancing the energy draining.

The computational complexity of X-LMST can be deduced as follows. Lines 1–3 take $O(1)$ time. Lines 4–6 take $O(n)$ time, where n represents the number of neighbor nodes of u in *G*. Lines 7 and 14 take $O(m \log m)$ time in total, where m represents the number of links in u's one-hop neighborhood in *G*. The "for" loop between lines 8–13 and that between lines 15–20 take $O(m)$ time in total. Lines 21–22 take $O(1)$ time. Therefore, the overall computational complexity by X-LMST is $O(m \log m)$. Since $m < n^2$, we have $\log m = O(\log n)$. Thus, the overall computational complexity of X-LMST is thus $O(m \log n)$.

C. Add Reverse Edge

X-LMST may create graphs containing unidirectional edge(s) like E-LMST and LMST. In [7], it is proved that either deleting the unidirectional edge or add the reverse edge will not affect the network connectivity. Here, we choose to add reverse edge if unidirectional edge occurs, in order to provide more routing redundancy for the upper-layer energy-efficient routing protocol. Although adding reverse edge(s) will result in greater node degree, we believe that those added reverse edges can offer more routing redundancy/opportunity to the routing layer and therefore improve the network lifetime performance and also load balancing capability.

V. SIMULATION RESULTS

In this section, we conduct extensive simulations for performance evaluation. We simulated the following three algorithms: X-LMST, E-LMST [10], and LMST [7]. On top of the topologies resulted by different algorithms, min-hop routing was used for route discovery for each communication request. Min-hop routing returns a path, which connects a pair of source and destination node and contains the least number of nodes. Actually, the maximum residual energy routing protocol, which returns the path with the highest residual energy, was also implemented for route discovery, and no obvious difference in network lifetime performance was observed. Note that a path's residual energy is determined by the node with the least residual energy on the path. In the simulations, the following three measures were compared: Network lifetime, which is defined as the time when the first node in the network runs out of its energy; average transmit radius; and average node degree. Our event-driven simulator was developed using C++.

In the simulations, we used the energy model, which was also used in [9], [10], [17], according to which the power consumed between two neighbor nodes is $d^\alpha + c$, where d is the distance between the communicating nodes, and α and c are constants. In [9], Rodoplu and Meng adopted the model with $d^4 + 2 \times 10^8$ (referred to as the RM model). For this model, the maximum transmission range R is 250 m. Reference [17] adopted the model with $d^2 + 500$ (referred to as the HCB model). For this model, $R = 50$ m. In this paper, we shall use the above settings of α and c in our simulations.

In the simulations, nodes are randomly distributed in a square area. The number of the nodes in a network is always 300, and the size of the square area where the nodes are deployed is calculated to meet desirable node density (from 8 to 24 nodes per communication zone). Each link is associated with a power value normalized over the maximum link transmission power. Each node is initially allocated a randomly selected of energy from the normalized range of [4,000, 8,000]. In our simulations, only those connected graphs are considered.

There are always 10 connections being routed at any time. Each connection has one source and one destination, which are selected randomly. We assume that the MAC layer is ideal, which can guarantee that packets can always be delivered without loss. Each connection lasts for a random period of time in the range of [5, 16] s. The packet arrival rate per connection is four packets per second.

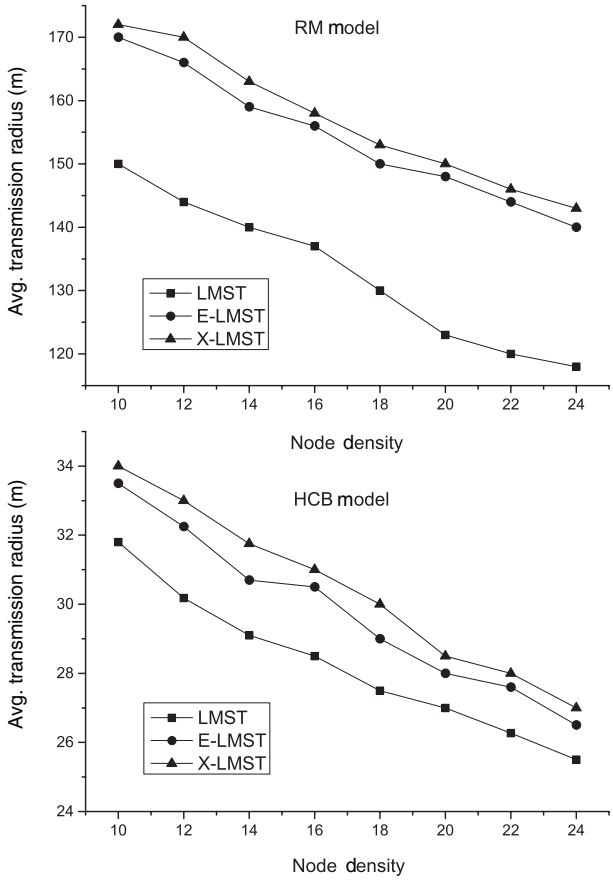

Fig. 3. Comparison of average transmit radius versus node density.

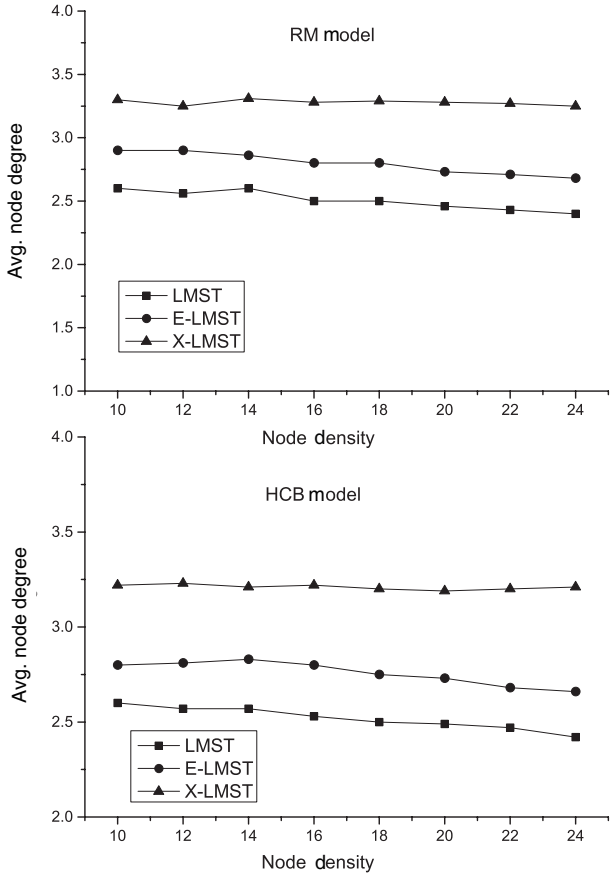

Fig. 4. Comparison of average node degree versus node density.

In the simulations, the full energy space is divided into 20 equal intervals (i.e., $L = 20$) and 18% of links with the lowest link costs in the neighborhood of a node are consider to be energy critical. These parameters were decided after a serial of simulations as follows. First, 15% of the links in a node's one-hop neighborhood were fixed to be energy critical, then we tried different values of energy-dividing interval ($L = 5$, 10, 15, 20, and 25) in the simulations. We found that when the full energy space is divided into 20 intervals, X-LMST has the best performance. After the best value of energy-dividing level L was determined, we chose different energy critical ratios (10%, 11%, 12%,$\cdots$,30%) in the simulations. The results show that when energy critical ratio is set to 18%, X-LMST performs the best.

Fig. 2 compares the average network lifetime performance by different algorithms with varying node densities. In Fig. 2, it is seen that X-LMST performs the best in terms of average network lifetime among the three algorithms. The simulation results shows that (1) X-LMST can prolong the network lifetime over 40% as compared with LMST; (2) X-LMST outperforms E-LMST (up to 10%) in terms of average network lifetime. In general, the average network lifetime by each of the three algorithms increases with node density. This is reasonable because the number of equal-cost min-hop paths connecting a node pair increases with node density, which can lead to increased load balancing and energy draining capability in the network and thus prolonged network lifetime. In addition, the advantage of X-LMST also increases with node density. This is because more choices can be provided to avoid overusing the energy-critical links in the network as node density increases. It should be noted that the network lifetime performance by E-LMST is slightly inferior to that reported in [10] because our implementation of E-LMST in this paper considers the control overhead for energy criticality threshold calculation, which causes a lot of network-wide dissemination of nodal energy level signaling messages (triggered as node energy level change).

Fig. 3 compares the average transmit radius by different algorithms versus node density. The transmit radius is defined as the distance between a node u and its farthest neighbor in its neighbor set NS_u. The average transmit radius is the sum of the transmit radiuses (by different algorithms) of all nodes in the network over the number of nodes. Fig. 3 shows that LMST has the lowest average transmit radius; X-LMST is the highest; E-LMST is in between. This meets our expectation since X-LMST allows nodes to keep some long links while removing some short but energy critical links to achieve energy-draining balancing in the network.

Fig. 4 compares the performance of different algorithms in terms of average node degree versus node density. LMST has the smallest average node degree because it does not consider the remaining energy of nodes. In contrast, X-LMST has the largest average node degree among the three algorithms.

In summary, X-LMST performs the best in terms of average network lifetime as compared with E-LMST and LMST at cer-

tain penalty in average transmit radius and average node degree performance.

VI. CONCLUSION

In this paper, we have proposed a new localized energy efficient topology control algorithm X-LMST for wireless multihop networks. It tries to avoid overusing those energy-critical links in building a reduced network topology graph at each node. In this way, energy-critical nodes/links are discouraged from being overused and the network lifetime is thus prolonged. Simulation results show that X-LMST can greatly prolong the network lifetime as compared with existing work. X-LMST is simple, efficient, localized in nature, and is thus to be practical to be used for wireless multi-hop networks.

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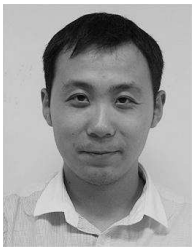
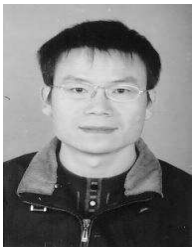


Dezhong Shang received his B.S. degree in 2012 from Fudan University, and is currently pursuing his Master degree in Computer Science at Research Center of Ubiquitous Sensor Networks at University of Chinese Academy of Sciences, Beijing, China. His main research interests include routing and topology control algorithm design in wireless sensor networks, ad hoc networks, and delay tolerant networks.



Baoxian Zhang is currently a Full Professor with the Research Center of Ubiquitous Sensor Networks at the University of Chinese Academy of Sciences (UCAS), Beijing, China. He received his Ph.D degree from Northern Jiaotong University, China, in 2000. Prior joining UCAS, he was a Research Scientist with School of Information Technology and Engineering, University of Ottawa, Canada. He has served as Guest Editors of special issues including IEEE Journal on Selected Areas in Communications, ACM Mobile Networks and Applications, Wiley Wireless Communications and Mobile Computing, and Elsevier Ad Hoc Networks. He has served on technical program committees for many international conferences and symposia such as IEEE GLOBECOM and ICC. He has coauthored a book in Wireless Sensor Networks and published over 100 refereed technical papers in archival journals and conference proceedings. His research interests cover network protocol and algorithm design, wireless ad hoc and sensor networks. Dr. Zhang is a Senior Member of the IEEE.

Zheng Yao received his B.S. degree in Computer Science and Engineering from Xi'an Jiaotong University in 1991, and received his M.S. and Ph.D. degrees in Computer Application from Harbin Institute of Technology, China, in 1994 and 1997, respectively. He is currently a Full Professor with the University of Chinese Academy of Sciences. He has published over 20 papers in journals and conference proceedings. His research interests covers software engineering, open source software, wireless sensor networks, and Internet of things.

Cheng Li received the B. Eng. and M. Eng. degrees from Harbin Institute of Technology, Harbin, P. R. China, in 1992 and 1995, respectively, and the Ph.D. degree in Electrical and Computer Engineering from Memorial University, St. John's, Canada, in 2004. He is currently a Professor at the Faculty of Engineering and Applied Science of Memorial University, St. John's, Canada. His research interests include mobile ad hoc and wireless sensor networks, wireless communications and mobile computing, switching and routing, and broadband communication networks. He is an Editorial Board Member of Wiley Wireless Communications and Mobile Computing and Journal of Networks, and an Associate Editor of Wiley Security and Communication Networks. He has served a technical program committee (TPC) Co-Chair for the IEEE WiMob'11 and QBSC'10. He has served as a Co-Chair for various technical symposia of many international conferences, including the IEEE GLOBECOM and ICC. He has served as the TPC Member for many international conferences, including the IEEE ICC, GLOBECOM, and WCNC. Dr. Li is a Registered Professional Engineer (P. Eng.) in Canada and is a Senior Member of the IEEE and a Member of the IEEE Communication Society, Computer Society, Vehicular Technology Society, and Ocean Engineering Society.