# Design and Analysis of an MST-Based Topology Control Algorithm

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***Abstract*—In this paper, we present a minimum spanning tree (MST)-based algorithm, called local minimum spanning tree (LMST), for topology control in wireless multihop networks. In this algorithm, each node builds its LMST independently and only keeps on-tree nodes that are one-hop away as its neighbors in the final topology. We analytically prove several important properties of LMST: 1) the topology derived under LMST preserves the network connectivity; 2) the node degree of any node in the resulting topology is bounded by 6; and 3) the topology can be transformed into one with bidirectional links (without impairing the network connectivity) after removal of all unidirectional links. Simulation results show that LMST can increase the network capacity as well as reduce the energy consumption.**

***Index Terms*—Graph theory, spatial reuse, topology control.**

## I. Introduction

ENERGY efficiency [2] and network capacity are perhaps two of the most important issues in wireless ad hoc networks and sensor networks. Topology control algorithms have been proposed to maintain network connectivity while reducing energy consumption and improving network capacity. The key idea to topology control is that, instead of transmitting with the maximal power, nodes in a wireless multihop network collaboratively determine their transmission power and define the network topology by forming the proper neighbor relation under certain criteria. This is in contrast to the "traditional" network in which each node transmits with its maximal transmission power and the topology is built implicitly by routing protocols (that update their routing caches as timely as possible) [3] without considering the power issue. Not until recently has the issue of topology/power control attracted much attention.

The importance of topology control lies in the fact that it critically affects the system performance in several ways. For one, as shown in [4], it affects network spatial reuse and, hence, the traffic carrying capacity. Choosing too large a power level results in excessive interference, while choosing too small a power level may result in a disconnected network. Topology control also affects energy usage of communication, and thus impacts on the battery life, a critical resource in many mobile applications. In addition, topology control also impacts on contention for the medium. Collisions can be mitigated as much as possible by choosing the smallest transmission power subject to maintaining network connectivity [5], [6].

Several topology control algorithms [5], [7]–[10] have been proposed to create a power-efficient network topology in wireless multihop networks with limited mobility, among which the relay-region based approach (R&M) [10], CBTC($\alpha$) [7], COMPOW [5] and CLUSTERPOW [8], and CONNECT [9] may have received the most attention. We will summarize existing work in Section II. Some of the algorithms require explicit propagation channel models (e.g., [10]), while others incur significant message exchanges (e.g., [5]). Their ability to maintain the topology in the case of mobility is also rather limited.

In this paper, we propose a minimum spanning tree (MST)-based topology control algorithm, called local minimum spanning tree (LMST), for multihop wireless networks with limited mobility. The topology is constructed by having each node build its local MST independently (with the use of information locally collected) and keep only one-hop on-tree nodes as neighbors. There are several salient features of LMST: 1) the topology constructed under LMST preserves the network connectivity; 2) the degree of any node in the resulting topology is bounded by 6; and 3) the resulting topology can be converted into one with only bidirectional links (after removal of unidirectional links). Feature 2) is desirable because a small node degree reduces the MAC-level contention and interference. The capability of forming a topology that consists of only bidirectional links is important for link level acknowledgments and packet transmissions/retransmissions over the unreliable wireless medium. Bidirectional links are also important for floor acquisition mechanisms such as RTS/CTS in IEEE 802.11.

Simulation results indicate that compared with the other known topology control algorithms, LMST has smaller average node degree (both logical and physical) and smaller average link length. The former reduces the MAC-level contention, while the latter implies that only small transmission power is needed to maintain connectivity. LMST also outperforms the other algorithms in terms of the total amount of data delivered (in bytes), the energy efficiency (in bytes/Joule), and the end-to-end delay.

The rest of the paper is organized as follows. We first summarize related work in Section II. Then we present the LMST algorithm in Section III and prove several of its desirable properties: preservation of network connectivity, bound on the node degree,

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and construction of topology with only bidirectional links, in Section IV. The frequency to update the topology in case of limited mobility is determined using a probabilistic model in Section IV-C. Finally, we present the performance study in Section V, and conclude the paper in Section VI.

## II. Related Work

In this section, we summarize several topology control algorithms that have been proposed in the literature: relay-region based approach (R&M) [10], CBTC($\alpha$) [7], COMPOW [5] and CLUSTERPOW [8], and CONNECT [9].

Rodoplu and Meng [10] (denoted *R&M*) introduced the notion of *relay region* and *enclosure* for the purpose of power control. For any node $i$ that intends to transmit to node $j$, node $j$ is said to lie in the *relay region* of a third node $r$, if node $i$ will consume less power when it chooses to relay through node $r$ instead of transmitting directly to node $j$. The *enclosure* of node $i$ is then defined as the union of the complement of relay regions of all the nodes that node $i$ can reach by using its maximal transmission power. A two-phase distributed protocol was then devised to find the minimum power topology for a static network. In the first phase, each node $i$ executes local search to find the enclosure graph. This is done by examining neighbor nodes which a node can reach by using its maximal power and keeping only those do not lie in the relay regions of previously found nodes. In the second phase, each node runs the distributed Bellman-Ford shortest path algorithm upon the enclosure graph, using the power consumption as the cost metric. It is shown that the network is strongly connected if every node maintains links with the nodes in its enclosure and the resulting topology is a minimum power topology. To deal with limited mobility, each node periodically executes the distributed protocol to find the enclosure graph. This algorithm assumes that there is only one data sink (destination) in the network, which may not hold in practice. Also, an explicit propagation channel model is needed to compute the relay region.

Ramanathan and Rosales-Hain [9] presented two centralized algorithms, *CONNECT* and *BICONNAUGMENT*, to minimize the maximal power used per node while maintaining the (bi)connectivity of the network. Both are simple greedy algorithms that iteratively merges different components until only one remains. They also introduced two distributed heuristics for mobile networks. In *LINT*, each node is configured with three parameters—the "desired" node degree $d_d$, a high threshold $d_h$ on the node degree, and a low threshold $d_l$. Every node will periodically check the number of active neighbors and change its power level accordingly, so that the node degree is kept within the thresholds. *LILT* further improves *LINT* by overriding the high threshold when the topology change indicated by the routing update results in undesirable connectivity. Both centralized algorithms require global information, thus cannot be directly deployed in the case of mobility and the proposed distributed heuristics may not preserve the network connectivity.

*COMPOW* [5] and *CLUSTERPOW* [8] are approaches implemented in the network layer. Both hinge on the idea that if each node uses the smallest common power required to maintain network connectivity, the traffic carrying capacity of the entire network is maximized, the battery life is extended, and the MAC-level contention is mitigated. Each node runs several routing daemons in parallel, one for each power level. Each routing daemon maintains its own routing table by exchanging control messages at the specified power level. By comparing the entries in different routing tables, each node can determine the smallest common power that ensures the maximal number of nodes are connected. The major drawback of these two approaches is their significant message overhead, since every node has to run multiple routing daemons, each of which has to exchange link state information with the counterparts at other nodes.

CBTC($\alpha$) [7] is a two-phase algorithm in which each node finds the minimal power $p$ such that transmitting with the power $p$ ensures that the node can reach some node in every cone of degree $\alpha$. The algorithm has been proved to preserve network connectivity if $\alpha < 5\pi/6$. Several optimization methods (that are applied after the topology is derived under the base algorithm) are also discussed to further reduce the transmitting power. An event-driven strategy is proposed to reconfigure the network topology in the case of mobility. Each node is notified when any neighbor leaves/joins the neighborhood and/or the angle changes. The mechanism used to realize this requires state to be kept at, and message exchanges among, neighboring nodes. The node then determines whether it needs to rerun the topology control algorithm.

Instead of adjusting the transmission power of individual devices, there also exist other approaches to generate power-efficient topology. By following a probabilistic approach, Santi *et al.* derived the suitable common transmission range which preserves network connectivity, and established the lower and upper bounds on the probability of connectedness [6]. In [11], a "backbone protocol" is proposed to manage large wireless ad hoc networks, in which a small subset of nodes is selected to construct the backbone. In [12], a method of calculating the power-aware connected dominating sets was proposed to establish an underlying topology for the network.

## III. MST-Based Topology Control Algorithm

In this section, we first outline a set of guidelines for devising topology control algorithms. Then we present the localized topology control algorithm, LMST.

### A. Design Guidelines

The following guidelines are essential to effective topology control algorithms.

1) The network connectivity should be preserved with the use of minimal possible power. This is the most important objective of topology control.
2) The algorithm should be distributed. This is due to the fact that there is, in general, no central authority in a wireless multihop network, and thus each node has to make its decision based on the information collected from the network.
3) To be less susceptible to the impact of mobility, the algorithm should depend only on the information collected

locally, e.g., within one hop. Algorithms that depend only on local information also incur less message overhead/delay in the process of collecting information.

4) It is desirable that in the topology derived under the algorithm, all links are bidirectional. As mentioned in Section I, bidirectional links ensure existence of reverse paths [5] and facilitate link-level acknowledgment and proper operation of the RTS/CTS mechanism.
5) It is also desirable that the node degree in the derived topology is small. A small node degree helps to mitigate the well known hidden and exposed terminal problems,[1] as there will be fewer nodes that have to be silenced in a communication activity.

### B. LMST Algorithm

To facilitate discussion of the proposed algorithm, we first define the following terms. We denote the network topology constructed under the common transmission range $d_{\max}$ as an undirected simple graph $G = (V, E)$ in the plane, where $V$ is the set of nodes in the network and $E = \{(u,v) : d(u,v) \leq d_{\max}, u, v \in V\}$ is the edge set of $G$. A unique $id$ (such as an IP/MAC address) is assigned to each node. For notational simplicity, we denote $id(v_i) = i$. We also define the *Visible Neighborhood* $NV_u(G)$ of node $u$ as follows.

*Definition 1 (Visible Neighborhood):* The visible neighborhood $NV_u(G)$ is the set of nodes that node $u$ can reach by using the maximal transmission power, i.e., $NV_u(G) = \{v \in V(G) : d(u,v) \leq d_{\max}\}$. For each node $u \in V(G)$, let $G_u = (V_u, E_u)$ be the induced subgraph of $G$ such that $V_u = NV_u$.

The proposed algorithm is composed of the following three phases: *information collection, topology construction, determination of transmission power*, and an optional optimization phase: *construction of topology with only bidirectional edges*. We assume that the propagation channel is symmetric and obstacle-free, and each node is equipped with the ability to gather its location information via, for example, several lightweight localization techniques for wireless networks (see [13] for a summary), GPS for outdoor applications and pseudolite [14] for indoor applications.

*1) Information Collection:* The information needed by each node $u$ in the topology construction process is the information of all nodes in $NV_u(G)$. This can be obtained by having each node broadcast periodically a `Hello` message using its maximal transmission power. The information contained in a `Hello` message should at least include the node id and the position of the node. Those periodic messages can be sent either in the data channel or in a separate control channel. The `Hello` messages can be combined with those already employed in most ad hoc routing protocols. In addition, each node can piggy-back its location information in data packets to reduce the number of `Hello` exchanges. The time interval between two broadcasts of `Hello` messages depends on the level of node mobility, and will be determined by the probabilistic model to be introduced in Section IV-C.

*2) Topology Construction:* After obtaining the information of the visible neighborhood $NV_u(G)$, each node $u$ builds its local MST $T_u = (V(T_u), E(T_u))$ of $G_u$ which spans all the nodes within its neighborhood. The time complexity varies from $O(e \log v)$ (the original Prim's algorithm [15]) to almost linear of $e$ (the optimal algorithm [16]), where $e$ is the number of edges and $v$ is the number of vertices.

Two points are worth mentioning here. First, to build a power efficient MST, the weight of an edge should be the transmission power between the two nodes. As power consumption is, in general, of the form $c \cdot d^r, r \geq 2$, i.e., a strictly increasing function of the Euclidean distance, it suffices to use the Euclidean distance as the weight function. The same MST will result. Second, the MST may not be unique if there exist multiple edges with the same weight. As the uniqueness is necessary for the proof of connectivity, we refine the weight function as follows:

*Definition 2 (Weight Function):* Given two edges $(u_1, v_1)$ and $(u_2, v_2)$, the weight function $d'$: $E \mapsto R$ is defined as

$$\begin{aligned} d'(u_1,v_1) > d'(u_2,v_2) &\Leftrightarrow d(u_1,v_1) > d(u_2,v_2) \\ \text{or} \quad & (d(u_1,v_1) = d(u_2,v_2) \\ & \quad \&\& \max\{id(u_1), id(v_1)\} > \max\{id(u_2), id(v_2)\}) \\ \text{or} \quad & (d(u_1,v_1) = d(u_2,v_2) \\ & \quad \&\& \max\{id(u_1), id(v_1)\} = \max\{id(u_2), id(v_2)\} \\ & \quad \&\& \min\{id(u_1), id(v_1)\} > \min\{id(u_2), id(v_2)\}). \end{aligned}$$

The weight function $d'$ guarantees the local MST $T_u$ constructed by node $u$ is unique. After node $u$ builds the MST, it will determine its neighbors. To facilitate discussion, we define the *Neighbor Relation* and the *Neighbor Set*:

*Definition 3 (Neighbor Relation and Neighbor Set):* Node $v$ is a neighbor of node $u$'s, denoted $u \rightarrow v$, if and only if $(u, v) \in E(T_u)$. $u \leftrightarrow v$ if and only if $u \rightarrow v$ and $v \rightarrow u$. That is, node $v$ is a neighbor of node $u$'s if and only if node $v$ is on node $u$'s local MST, $T_u$, and is "one-hop" away from node $u$. The *neighbor set* $N(u)$ of node $u$ is $N(u) = \{v \in V(G_u) : u \rightarrow v\}$.

The neighbor relation defined above is not symmetric, i.e., $u \rightarrow v$ does not necessarily imply $v \rightarrow u$. Fig. 1 gives such an example. There are altogether 6 nodes, $V = \{u, v, w_1, w_2, w_3, w_4\}$, where $d(u,v) = d < d_{\max}$, $d(u, w_4) < d_{\max}$, $d(u, w_i) > d_{\max}$, $i = 12, 3,$, and $d(v, w_j) < d_{\max}$, $j = 1, 2, 3, 4$. Since $NV_u = \{u, v, w_4\}$, it can be obtained from $T_u$ that $u \rightarrow v$ and $u \rightarrow w_4$. Also $VN_v = \{u, v, w_1, w_2, w_3, w_4\}$ and, hence, $v \rightarrow w_1$. Here we have $u \rightarrow v$ but $v \nrightarrow u$.

The network topology under LMST is all the nodes in $V$ and their individually perceived neighbor relations. Note that the topology is *not* a simple superposition of all local MST's.

*Definition 4 (Topology $G_0$):* The topology, $G_0$, derived under LMST is a directed graph $G_0 = (V_0, E_0)$, where $V_0 = V, E_0 = \{(u,v) : u \rightarrow v, u, v \in V(G)\}$.

*3) Determination of Transmission Power:* Assume that the maximal transmission power is known and is the same to all nodes. By measuring the receiving power of `Hello` messages, each node can determine the specific power levels it needs to

[1]The hidden terminal problem refers to the situation in which a station is hidden when it is within the transmission range of the intended receiver node of the packet but out of the range of the sender node, while the exposed terminal problem refers to the situation in which a station is exposed when it is within the transmission range of the sender node, but out of the range of the receiver.

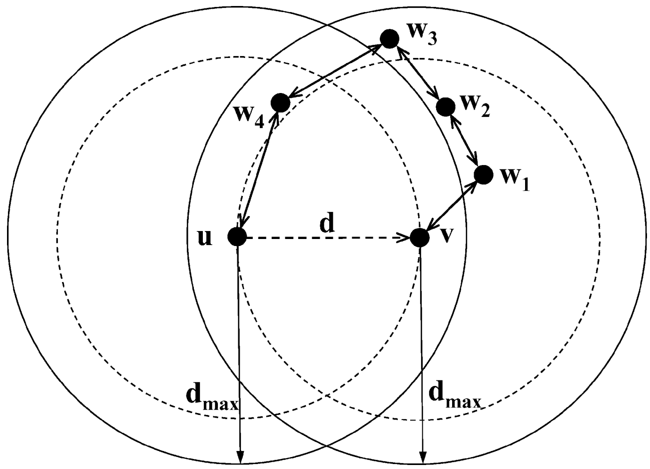



Fig. 1. An example that links in the topology derived under LMST may be unidirectional

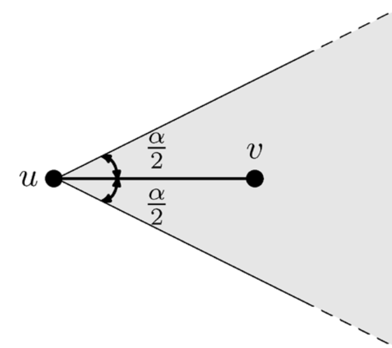



Fig. 2. Definition of $cone(u, \alpha, v)$.

reach each of its neighbors. In what follows, we first describe two commonly-used propagation models, and then elaborate on how we determine the transmission power. Note that this approach can be applied to any propagation channel model.

In the *Free Space* propagation model, the relation between the power used to transmit packets, $P_t$ and the power received, $P_r$ can be characterized as $P_r = P_t G_t G_r \lambda^2 / (4\pi d)^2 L$, where $G_t$ is the antenna gain of the transmitter, $G_r$ is the antenna gain of the receiver, $\lambda$ is the wave length, $d$ is the distance between the antenna of the transmitter and that of the receiver, and $L$ is the system loss.

In the *Two-Ray Ground* propagation model, the relation between $P_t$ and $P_r$ is $P_r = P_t G_t G_r h_t^2 h_r^2 / d^4 L$, where $G_t$ is the antenna gain of the transmitter, $G_r$ is the antenna gain of the receiver, $h_t$ is the antenna height of the transmitter, $h_r$ is the antenna height of the receiver, $d$ is the distance between the antenna of the transmitter and that of the receiver, and $L$ is the system loss.

In general, the relation between $P_t$ and $P_r$ is of the form $P_r = P_t \cdot G$, where $G$ is a function of $G_t$, $G_r$, $h_t$, $h_r$, $\lambda$, $d$, $\alpha$, $L$ and is time-invariant if all the above parameters are time-invariant. At the information collection stage, each node broadcasts its position using the maximal transmission power $P_{\max}$. When node $A$ receives the position information from node $B$, it measures the receiving power $P_r$ and obtains $G = P_r / P_{\max}$. Henceforth node $A$ needs to transmit using at least $P_{\text{th}} \cdot G = P_{\text{th}} P_r / P_{\max}$ so that node $B$ can receive messages, where $P_{\text{th}}$ is the power threshold to correctly receive the message. A broadcast to all neighbors requires a power level that can reach the farthest neighbor. Here we introduce the notion of *Radius*:

*Definition 5 (Radius of Node $u$):* The radius, $r_u$, of node $u$ is defined as the Euclidean distance between node $u$ and its farthest neighbor, i.e, $r_u = \max\{d(u, v) : v \in N(u)\}$.

*4) Construction of Topology With Only Bidirectional Edges:* As illustrated in Fig. 1, some links in $G_0$ may be unidirectional. As mentioned in Section III-A, it is desirable to obtain network topologies consisting of only bidirectional edges. There are two possible solutions: 1) to enforce all the unidirectional links in $G_0$ to become bidirectional; or 2) to delete all the unidirectional links in $G_0$. We term the two new topologies $G_0^+$ and $G_0^-$, respectively. Specifically,

*Definition 6 (Topology $G_0^+$):* The topology, $G_0^+$, is a undirected graph $G_0^+ = (V_0^+, E_0^+)$, where $V_0^+ = V_0$, $E_0^+ = \{(u, v) : (u, v) \in E(G_0) \text{ or } (v, u) \in E(G_0)\}$.

*Definition 7 (Topology $G_0^-$):* The topology, $G_0^-$, is a undirected graph $G_0^- = (V_0^-, E_0^-)$, where $V_0^- = V_0$, $E_0^- = \{(u, v) : (u, v) \in E(G_0) \text{ and } (v, u) \in E(G_0)\}$.

To convert $G_0$ into either $G_0^+$ or $G_0^-$, every node $u$ may probe each of its neighbors in the neighbor set $N(u)$ to find out whether or not the corresponding edge is unidirectional, and in the case of a unidirectional edge, either deletes the edge ($G_0^-$) or notifies its neighbor to add the reverse edge ($G_0^+$). In Section IV, we will prove that both new topologies preserve the desirable properties of $G_0$. There exists a tradeoff between the two choices: the latter gives a comparatively simpler topology and, hence, is more efficient in terms of spatial reuse, while the former allows more routing redundancy.

## IV. Theoretical Base of LMST

In this section, we state and prove several desirable properties of the network topology derived by LMST. We also determine, with the use of a probabilistic model, how often the neighborhood information should be exchanged and the topology should be updated.

### A. Properties of LMST

*Definition 8 (Cone):* A $cone(u, \alpha, v)$ is the unbounded shaded region shown in Fig. 2.

*1) Degree Bound:* It has been observed that any MST of a finite set of points in the plane has a maximum node degree of six [17]. We prove this property (which will serve as the base for the proof of Theorem 3) independently for LMST.

*Lemma 1:* Given three nodes $u, v, w \in V(G_0)$ satisfying $d'(u, v) > d'(u, w)$ and $d'(u, v) > d'(v, w)$, then $u \nrightarrow v$.

*Proof:* We only need to consider the case when $d(u, v) \le d_{\max}$ since $d(u, v) > d_{\max}$ would imply $u \nrightarrow v$. Assume $u \rightarrow v$. Since $d(u, w) \le d(u, v) \le d_{\max}$, there exists a unique path $p = (v_0 = u, v_1, v_2, \cdots, v_{m-1}, v_m = w)$ on $T_u$ from node $u$ to node $w$, where $(v_i, v_{i+1}) \in E(T_u)$, $i = 0, 1, \cdots, m-1$. If $v$ is on the path $p$, replacing edge $(u, v)$ with edge $(u, w)$ and keeping all other edges unchanged in $T_u$ will result in a spanning tree of $G_u$ with a less weight. If $v$ is not on $p$, replacing edge $(u, v)$ with edge $(v, w)$ and keeping all other edges unchanged in $T_u$ will result in a spanning tree of $G_u$ with a less weight. Both scenarios contradict with the fact that $T_u$ is the unique MST of $G_u$. ■

*Theorem 1 (Degree Bound):* Define the degree of a node as the number of neighbors. The degree of any node in $G_0$ is bounded by 6, i.e., $deg(u) \leq 6, \forall u \in V(G_0)$.

*Proof:* Consider any node $u \in V(G_0)$. Put the nodes in $N(u)$ (except $u$ itself) in order such that for the $i^{\text{th}}$ node $w_i$ and the $j^{\text{th}}$ node $w_j$ $(j > i)$, $d'(u, w_j) > d'(u, w_i)$. By Lemma 1, we have $d'(u, w_j) \leq d'(w_i, w_j)$ (otherwise $u \nrightarrow w_j$). Thus, $\angle w_i u w_j \geq \pi/3$, i.e., node $w_j$ cannot reside inside $Cone(u, 2\pi/3, w_i)$. Therefore, node $u$ cannot have neighbors other than node $w_i$ inside $Cone(u, 2\pi/3, w_i)$. By induction on the rank of nodes in $N(u)$, the maximal number of neighbors that $u$ can have is no greater than 6, i.e., $deg(u) \leq 6$. ■

Note that what has been discussed so far is actually the *logical* node degree, i.e., the number of neighbors. In practice, it is more important to consider the *physical* node degree, i.e., the number of nodes within the transmission radius. For an arbitrary topology, the physical degree cannot be bounded if all nodes use omni-directional antennas. However, with the help of directional antennas, we will be able to bound the physical degree given that the logical degree is bounded under LMST (except for some extreme cases, e.g., a large number of nodes are of the same distance from one node). When transmitting to a specific neighbor, node $u$ adjusts its direction and limits the transmission power so that no other nodes will be affected.

As a smaller node degree usually implies less contention and interference in wireless multihop networks, the degree bound obtained in Theorem 1 can be used to better design medium access algorithms. For example, several TDMA-based scheduling algorithms have been proposed to maximize the spatial reuse and minimize frame length [18], [19], most of which require that the maximum node degree be bounded.

*2) Network Connectivity:* We prove that the topology, $G_0$, derived under LMST preserves the network connectivity of $G$. For any two nodes $u, v \in V(G_0)$, node $u$ is said to be *connected to* node $v$ (denoted $u \Leftrightarrow v$) if there exists a path $(w_0 = u, w_1, \ldots w_{m-1}, w_m = v)$ such that $w_j \leftrightarrow w_{j+1}$, $j = 0, 1, \cdots, m-1$, where $w_k \in V(G_0)$, $k = 0, 1, \cdots, m$. It follows that $u \Leftrightarrow w$ if $u \Leftrightarrow v$ and $v \Leftrightarrow w$. To facilitate the derivation in this section, we assume $G$ is connected.

*Lemma 2:* For any node pair $[u, v]$, $u, v \in V(G_0)$, if $d(u, v) \leq d_{\max}$ then $u \Leftrightarrow v$.

*Proof:* For all the node pairs $[u, v]$ satisfying $d(u, v) \leq d_{\max}$ and $u, v \in V(G_0)$, sort them in ascending order of $d'(u, v)$, i.e., $d'(u_1, v_1) < d'(u_2, v_2) < \cdots < d'(u_l, v_l)$. We prove by induction on the rank of the node pairs in the ordering.

1) *Basis*: $k = 1$, the first pair $[u_1, v_1]$ satisfies $d'(u_1, v_1) = \min_{u,v \in V(G_0)}\{d'(u, v)\}$ and $d(u_1, v_1) \leq d_{\max}$. Thus, $u_1 \leftrightarrow v_1$, which means $u_1 \Leftrightarrow v_1$.

2) *Induction*: Assume Lemma 2 holds for all pairs $[u_i, v_i]$, $i = 1, 2, \cdots, k-1$. Now we prove Lemma 2 also holds for the node pair $[u_k, v_k]$. We consider two cases:

- *Case 1*: $u_k \leftrightarrow v_k$, which implies $u_k \Leftrightarrow v_k$.
- *Case 2*: Either $u_k \nrightarrow v_k$ or $v_k \nrightarrow u_k$, or both. Without loss of generality, assume $u_k \nrightarrow v_k$. Since $v_k \in NV_{u_k}$, there exists a unique path $p = (w_0 = u_k, w_1, w_2, \cdots, w_{m-1}, w_m = v_k)$ from node $u_k$ to node $v_k$, where $(w_i, w_{i+1}) \in E(T_{u_k})$, $i = 0, 1, \cdots, m-1$. Since $T_{u_k}$ is the unique MST of $G_{u_k}$, we have $d'(w_i, w_{i+1}) < d'(u_k, v_k)$, otherwise we can construct another spanning tree with a less weight, by replacing edge $(w_i, w_{i+1})$ with $(u_k, v_k)$ and keeping all the other edges in $T_{u_k}$ unchanged. Applying the induction hypothesis to each pair $[w_i, w_{i+1}]$, $i = 0, 1, \cdots, m-1$, we have $w_i \Leftrightarrow w_{i+1}$, thus $u_k \Leftrightarrow v_k$. ■

*Theorem 2:* $G_0$ preserves the connectivity of $G$, i.e., $G_0$ is connected if $G$ is connected.

*Proof:* Suppose $G$ is connected. For any two nodes $u, v \in V(G)$, there exists at least one path $p = (w_0 = u, w_1, w_2, \cdots, w_{m-1}, w_m = v)$ from $u$ to $v$, where $(w_i, w_{i+1}) \in E(G)$, $i = 0, 1, \cdots, m-1$, and $d(w_i, w_{i+1}) \leq d_{\max}$. Since $w_i \Leftrightarrow w_{i+1}$ by Lemma 2, we have $u \Leftrightarrow v$. ■

*3) $G_0^+$ and $G_0^-$ Preserve Properties of $G_0$:* $G_0^+$ is an undirected graph, thus all the edges are bidirectional. Since all the links in $G_0$ are preserved in $G_0^+$, it follows that $G_0^+$ preserves the connectivity of $G_0$. Now we prove that the degree of any node in $G_0^+$ is also bounded by 6. Notice that this is not a simple property of the MST because $G_0^+$ may no longer be an MST due to those edges added.

*Theorem 3:* The degree of any node in $G_0^+$ is bounded by 6, i.e., $deg(u) \leq 6, \forall u \in V(G_0^+)$.

*Proof:* For any node $u \in V(G_0^+)$, denote $N^+(u) = \{v \in V(G_u) : (u, v) \in E(G_0^+)\}$. First we prove by contradiction that if $v \in N^+(u)$ in $G_0^+$, there does not exist any other node $w \in N^+(u)$ that lies inside $Cone(u, 2\pi/3, v)$. Assume that such a node $w \in N^+(u)$ exists, then $\angle wuv < \pi/3$. If $d'(u, w) > d'(u, v)$, then $d'(u, w) > d'(v, w)$, which implies $w \nrightarrow u$ and $u \nrightarrow w$ by Lemma 1. Otherwise if $d'(u, w) < d'(u, v)$, then $d'(u, v) > d'(v, w)$, which implies $u \nrightarrow v$ and $u \nrightarrow v$ by Lemma 1. Both scenarios contradict with the assumption that $v, w \in N^+(u)$.

Now we have proved that there does not exist any neighbor other than $v$ that lies inside $Cone(u, 2\pi/3, v)$ in $G_0^+$. Using the same arguments as in Theorem 1, it is easy to see that the maximal number of neighbors that $u$ can have is no greater than 6, i.e., $deg(u) \leq 6$. ■

Since $G_0^-$ is derived from $G_0$ by removing all unidirectional links, it is obvious that the degree of any node in $G_0^-$ is also bounded by 6. We now prove that $G_0^-$ preserves the connectivity.

*Theorem 4:* $G_0^-$ preserves the connectivity of $G$, i.e., $G_0^-$ is connected if $G$ is connected.

*Proof:* If a node pair $[u, v]$, $u, v \in V(G_0)$ satisfies $d(u, v) \leq d_{\max}$, by Lemma 2, there exists a path $p = (w_0 = u, w_1, w_2, \ldots, w_{m-1}, w_m = v)$ such that $w_j \leftrightarrow w_{j+1}$, $j = 0, 1, \cdots, m-1$, where $w_k \in V(G_0)$, $k = 0, 1, \cdots, m$. The same result holds for $G_0^-$ since all links in $p$ are bidirectional and the removal of unidirectional links does not affect the existence of such a path. Following the same line of argument as presented in Theorem 2, we can prove that $G_0^-$ preserves the connectivity of $G$. ■

### B. Relaxation of Assumptions

Although the assumptions in Section III-B are widely used in existing topology control algorithms, some of them are made for the ease of analysis and may not be practical. In this section, we discuss how to relax some of these assumptions.

*1) Relaxing the Requirement of Position Information:* It is assumed in Section III-B that each node is equipped with the capability of gathering its own location information. This requirement can be relaxed.

In the topology construction phase in Section III-B-2, the information needed by LMST is all the existing edges in the network. If each node knows its own position, either by special hardware or localization service provided by the network, it will be fairly easy to gather the knowledge of existing edges. However, LMST can still operate if position information is not available. In particular, our solution involves an extra round of information dissemination. First, each node periodically broadcasts, using its maximal transmission power, a very short `Hi` message which includes only its node $id$ and transmission power. Upon receiving such a message from a neighbor node $v$, each node $u$ estimates the length of the edge $(u, v)$ based on the attenuation incurred in the transmission. Denote the set of edges incident to $u$ as $E_u^T = \{(u, v) : v \in NV_u(G)\}$. After $u$ has collected the information of $E_u^T$, $u$ can then broadcast this information in an `Edge` message. Based on the `Edge` messages received from all of its neighbors, each node $u$ will be able to construct the edge set for its visible neighborhood, $E(NV_u)$, which is sufficient for $u$ to construct its local MST $T_u$.

Although this solution may incur more communication and computation overhead, and make LMST less "localized", it eliminates the need for the position information, and thus is better suited for wireless sensor networks where the cost and the energy consumption should be kept as low as possible.

*2) Relaxing the Requirement of Obstacle-Free Channel:* We assume in Section III-B an obstaclefree channel. This assumption can be readily dismissed.

As mentioned in Section IV-B1, what is required by LMST is the information of all existing edges in the network. An edge that was not formed in the network, either because the two endpoints of the edge are not within the transmission range of each other or because there exists a obstacle in between, does not have any impact on the results of LMST. In addition, from the point of view of a node $u$, it only knows whether or not there exists a link between itself and another node $v$, but has no way to differentiate between the following two possible scenarios: a) the two nodes are not within transmission range of each other; or b) the obstacle between the two nodes blocks the communication. As long as the original topology (which has taken into consideration the obstacles in the network) is connected, LMST can be applied to preserve the connectivity. Therefore, the assumption of obstacle-free wireless channel can be dismissed without any modification on LMST.

### C. Estimation of Information Exchange Period

We now estimate the time interval between two information exchanges (i.e., two broadcasts of `Hello` messages) under a probabilistic model with the following assumptions.

i) Initially all nodes are uniformly distributed within a disk of area $S_0$ and $N$, the total number of nodes in $G$, is known or can be estimated.

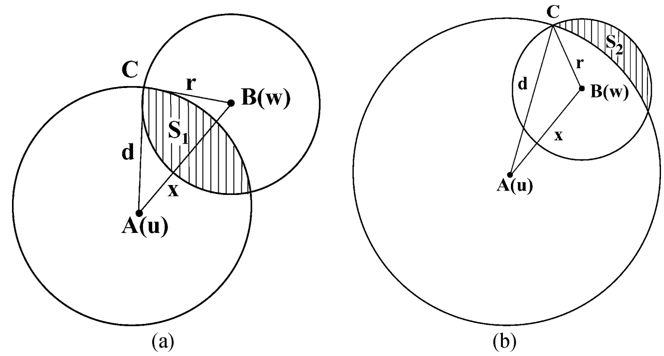



Fig. 3. Calculation of the probabilities that a new neighbor moves into the transmission range of a node and that an existing neighbor moves out of the transmission range, within a time interval of $t$.

ii) After a short time interval of length $t$, the location of a node $u$ will be randomly distributed inside a disk centered at its current location, with a radius of $v_{\max} \cdot t$, where $v_{\max}$ is the maximum speed of $u$. This is a Brownian-like mobility model that preserves the uniform node distribution [20].

Since $S_0$ is relatively large and $t$ is relatively short, the border effect can be ignored. Also, the above assumptions are made based on the notion of randomness, and may not necessarily represent the node distribution and mobility model in the real world. However, due to the fact that appropriate statistical models that characterize these distributions of interest are lacking, the above assumptions may serve to give rough estimates of information exchange periods.

Let $d$ be the maximum transmission range of any node. Denote $D(u, d)$ as the disk of radius $d$ centered at node $u$. We fix the reference frame on any node $u$ and calculate the probabilities that a new neighbor moves into the transmission range of $u$ and that an existing neighbor moves out of the transmission range of node $u$, within a time interval of $t$.

*1) Probability That Node $w$ Moves Into the Disk $D(u, d)$:* As shown in Fig. 3(a), suppose node $u$ is located in position $A$, with its neighbor $w$ in position $B$. The maximum transmission range of node $u$ is $AC = d$, and the distance between nodes $u$ and $w$ is $x(> d)$. Let $BC = r = 2v_{\max} \cdot t$. The probability that node $w$ moves into the transmission range of node $u$ within time $t$ is the probability that node $w$ moves into the disk $D(u, d)$ (i.e., the shaded area in Fig. 3(a)) within time $t$. This probability can be calculated by considering the following two cases.

- *Case I*: $0 < r < 2d$. The probability, $p_{\text{join}}$, that node $w$ moves into $D(u, d)$ within time $t$ is

$$p_{\text{join}} = \int_d^{d+r} \frac{2\pi x}{S_0} \frac{S_1}{\pi r^2} dx = \int_d^{d+r} \frac{2xS_1}{S_0 r^2} dx$$

where

$$\begin{aligned} S_1 &= \alpha_1 d^2 + \alpha_2 r^2 - xr \sin \alpha_2, \\ \alpha_1 &= \angle CAB = \arccos \frac{x^2 + d^2 - r^2}{2xd} \\ \alpha_2 &= \angle CBA = \arccos \frac{x^2 + r^2 - d^2}{2xr}. \end{aligned}$$

- *Case II*: $r \geq 2d$. The probability of interest is

$$\begin{aligned} p_{\text{join}} &= \int_{d}^{r-d} \frac{2\pi x}{S_0} \frac{\pi d^2}{\pi r^2} dx + \int_{r-d}^{r+d} \frac{2\pi x}{S_0} \frac{S_1}{\pi r^2} dx \\ &= \int_{d}^{r-d} \frac{2\pi x}{S_0} \frac{d^2}{r^2} dx + \int_{r-d}^{r+d} \frac{2x S_1}{S_0 r^2} dx \\ &= \frac{\pi d^2}{S_0 r^2} \left[ (r-d)^2 - d^2 \right] + \int_{r-d}^{r+d} \frac{2x S_1}{S_0 r^2} dx \\ &= \frac{\pi d^2 (r-2d)}{S_0 r} + \int_{r-d}^{r+d} \frac{2x S_1}{S_0 r^2} dx. \end{aligned}$$

*2) Probability That Node $w$ Moves Out of the Disk $D(u,d)$:* The probability that an existing neighbor $w$ moves out of the transmission range of node $u$ within time $t$ is the probability that $w$ moves out of the disk $D(u,d)$ [i.e., into the shaded area in Fig. 3(b)] in time $t$. We consider three cases.

- *Case I*: $0 < r < d$. The probability, $p_{\text{leave}}$, that node $w$ moves out of $D(u,d)$ in time $t$ is

$$p_{\text{leave}} = \int_{d-r}^{d} \frac{2\pi x}{S_0} \frac{S_2}{\pi r^2} dx = \int_{d-r}^{d} \frac{2x S_2}{S_0 r^2} dx,$$

where

$$\begin{aligned} S_2 &= (\pi - \alpha_2) r^2 - (\alpha_1 d^2 - x r \sin \alpha_2), \\ \alpha_1 &= \angle CAB = \arccos \frac{x^2 + d^2 - r^2}{2xd}, \\ \alpha_2 &= \angle CBA = \arccos \frac{x^2 + r^2 - d^2}{2xr}. \end{aligned}$$

- *Case II*: $d \leq r < 2d$. The probability of interest can be expressed as

$$\begin{aligned} p_{\text{leave}} &= \int_{0}^{r-d} \frac{2\pi x}{S_0} \frac{\pi (r^2 - d^2)}{\pi r^2} dx + \int_{r-d}^{d} \frac{2\pi x}{S_0} \frac{S_2}{\pi r^2} dx \\ &= \int_{0}^{r-d} \frac{2\pi x}{S_0} \frac{(r^2 - d^2)}{r^2} dx + \int_{r-d}^{d} \frac{2x S_2}{S_0 r^2} dx \\ &= \frac{\pi (r+d)}{S_0 r^2} (r-d)^3 + \int_{r-d}^{d} \frac{2x S_2}{S_0 r^2} dx. \end{aligned}$$

- *Case III*: $r \leq 2d$. The probability of interest can be expressed as

$$p_{\text{leave}} = \int_{0}^{d} \frac{2\pi x}{S_0} \frac{\pi (r^2 - d^2)}{\pi r^2} dx = \frac{\pi (r^2 - d^2) d^2}{S_0 r^2}.$$

*3) Estimation of Information Exchange Periods:* Given that node $u$ has $n$ neighbors and the total number of nodes is $N$, the probability that no new neighbor enters the visible neighborhood of node $u$ is $p_1 = (1 - p_{\text{join}})^{N-n-1}$, and the probability that no neighbor leaves the visible neighborhood of node $u$ is $p_2 = (1 - p_{\text{leave}})^n$. Thus, the probability that the visible neighborhood of node $u$ changes is $p_{\text{change}} = 1 - p_1 p_2$. Given a predetermined probability threshold $p_{\text{th}}$, we can determine the topology update interval $t$ such that $p_{\text{change}} < p_{\text{th}}$.

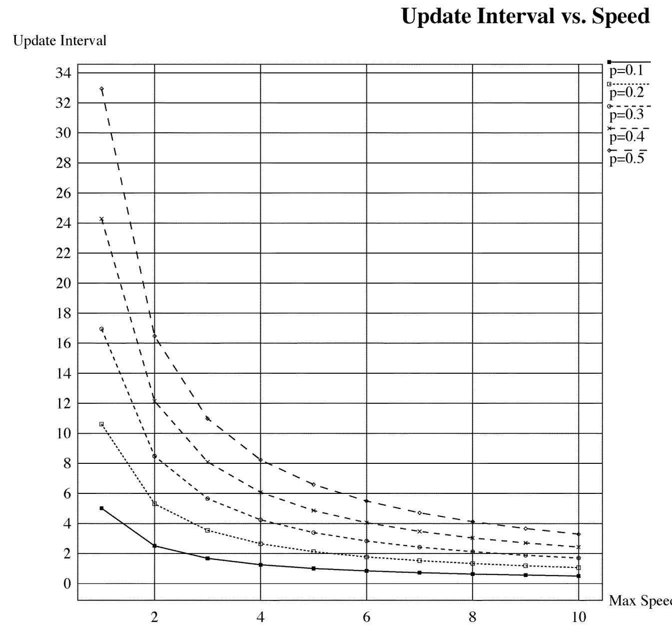



Fig. 4. Information update period versus the maximum speed with respect to different values of $p_{\text{th}}$.

Note that this estimate only serves as a guideline on how to choose the interval of information exchange. To demonstrate how it is affected by the maximum speed $v_{\max}$ and the probability threshold $p_{\text{th}}$, we consider a scenario in which 100 nodes are randomly distributed inside a disk of radius 1000 m. The transmission range is $d_{\max} = 250$ m. The number of neighbors is set to 25. Fig. 4 gives the curve of the information update period versus the maximum speed with respect to different values of $p_{\text{th}}$. For example, to ensure that the probability of visible neighborhood change is kept below 0.2, the information update period decreases from 10.6 to 1.06 s when the maximum speed increases from 1 to 10 m/s.

## V. Performance Evaluation

In this section, we present several sets of simulation results to evaluate the effectiveness of LMST. As R&M and CBTC come closest to our work, we compare them with LMST in the simulation study. We also use the topology derived using the maximal transmission power as a baseline. The reasons we do not compare LMST against *CONNECT* and *COMPOW/CLUSTERPOW* are two-fold: a) *CONNECT* and its extension are centralized algorithms that require global information, while LMST is a localized algorithm that derives the network topology based on local information; and b) *COMPOW/CLUSTERPOW* are implemented at the network layer and incur significant message overhead, while LMST is implemented below the network.

We will evaluate the performance of these topology control algorithms with respect to two categories of performance metrics: traffic-independent and traffic-dependent. The traffic-independent performance metrics used in the study are listed as follows.

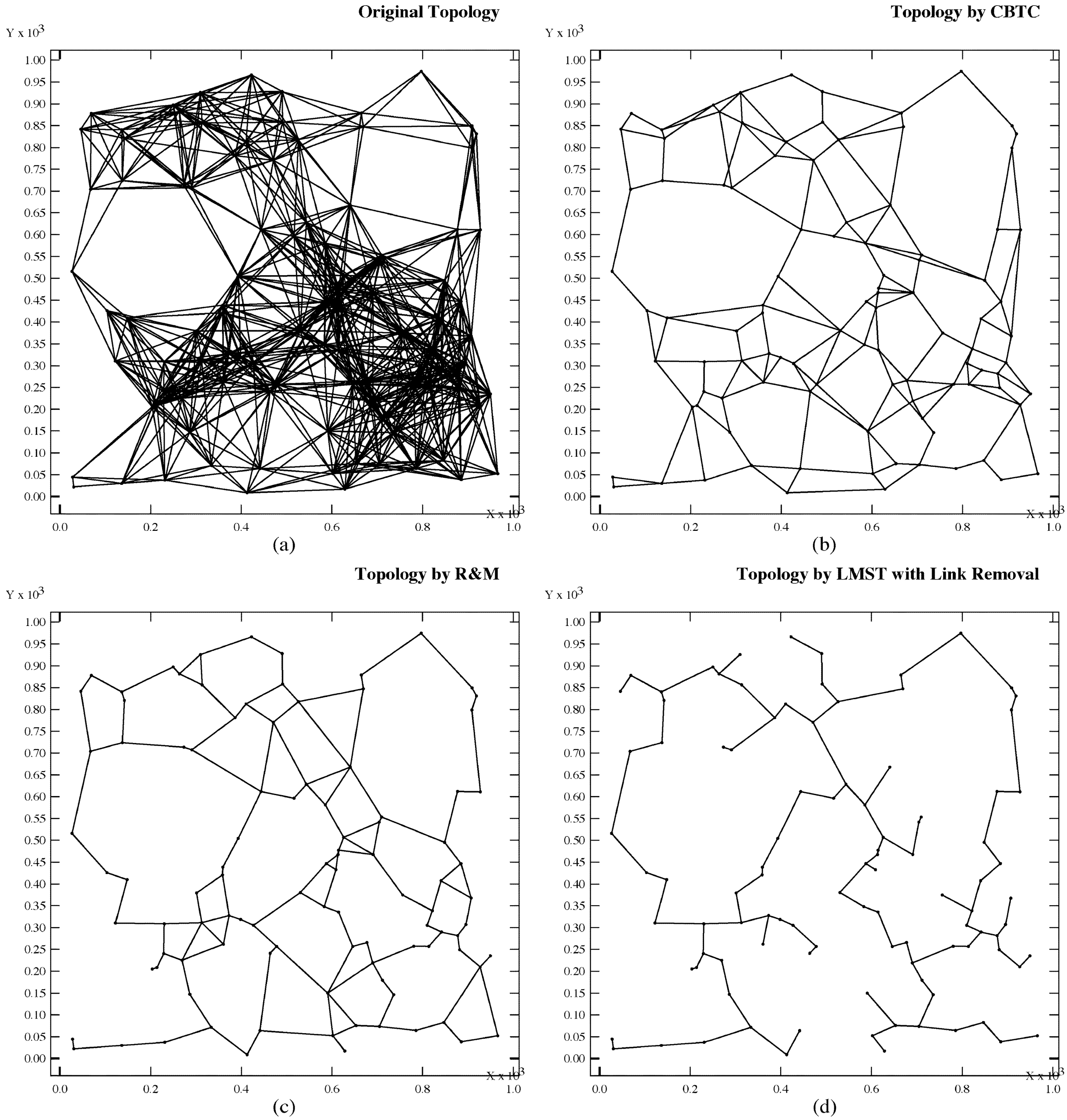



Fig. 5. Network topologies derived under different algorithms. (a) Topology derived using maximal transmission power. (b) Topology derived under CBTC. (c) Topology derived under R&M. (d) Topology derived under LMST with link removal.

1) Logical/physical node degree: A smaller average node degree usually implies less contention and interference, and better spatial reuse.
2) Radius: As each node $u$ sets its transmission range to be the radius $r_u$, a smaller value of $r_u$ implies less power consumption.
3) Average link length.

The traffic-dependent performance metrics are listed as follows.

1) Total data delivered (end-to-end). This serves as a good indicator of the network capacity achieved.
2) Energy efficiency (bytes/Joule): Energy efficiency is defined as the total data delivered (in bytes) divided by the total energy consumption (in Joules).
3) Average number of transmissions for each packet delivered: This can be interpreted as the number of times a packet has to be transmitted, hop by hop, on the way from its source to destination, and is loosely related to the average packet delay.

Note that traffic-dependent performance metrics are affected by, in addition to the quality of topology control, several other factors, such as the spatial distribution of wireless devices, MAC level contention/interference, and routes selected by routing protocols.

### *A. Performance With Respect to Traffic-Independent Performance Metrics*

All simulations in this section were carried out in *J-Sim*, a component-based, compositional network simulator written in

Java.[2] Nodes are randomly distributed in a $1000 \times 1000$ m$^2$ region. The transmission range of each node is $d_{\max} = 250$ m.

For a network of 100 nodes, the topology derived using the maximal transmission power, R&M (under the two-ray ground model), CBTC, and LMST with link removal are shown in Fig. 5. The corresponding maximal, minimum, and average node degrees are given below at the bottom of the page. R&M, CBTC and LMST all dramatically reduce the average node degree while maintaining network connectivity. Moreover, LMST outperforms both R&M and CBTC.

In the next simulation, we vary the number of nodes in the region from 50 to 250. Each data point is the average of 100 simulation runs. The average logical and physical node degrees for the topologies generated by R&M, CBTC, and LMST are shown in Fig. 6. Both the average logical and physical node degrees derived under R&M and CBTC increase with the increase of spatial density, while that under LMST actually decreases slightly. Also, we measure the average logical node degree for topologies derived under LMST, LMST with link addition, and LMST with link removal and have the following observations: i) the average node degree under LMST and its two variations does not differ much, and decreases as the node density increases. This is in contrast with the observation that the average node degree of the topology derived using the maximal transmission power increases almost linearly; and ii) the average node degree under LMST is very close to that of a global spanning tree, which is known to have the least average node degree ($2 - (2/n) \rightarrow 2$, as $n \rightarrow \infty$) among all the spanning subgraphs. Due to the space limit, the figures that give the above observation are not shown here, but instead can be found in [21]. The average radius and the average link length for the topologies derived using the maximal transmission power, R&M, CBTC, and LMST with link removal are shown, respectively, in Fig. 7(a) and (b). LMST outperforms others in both cases.

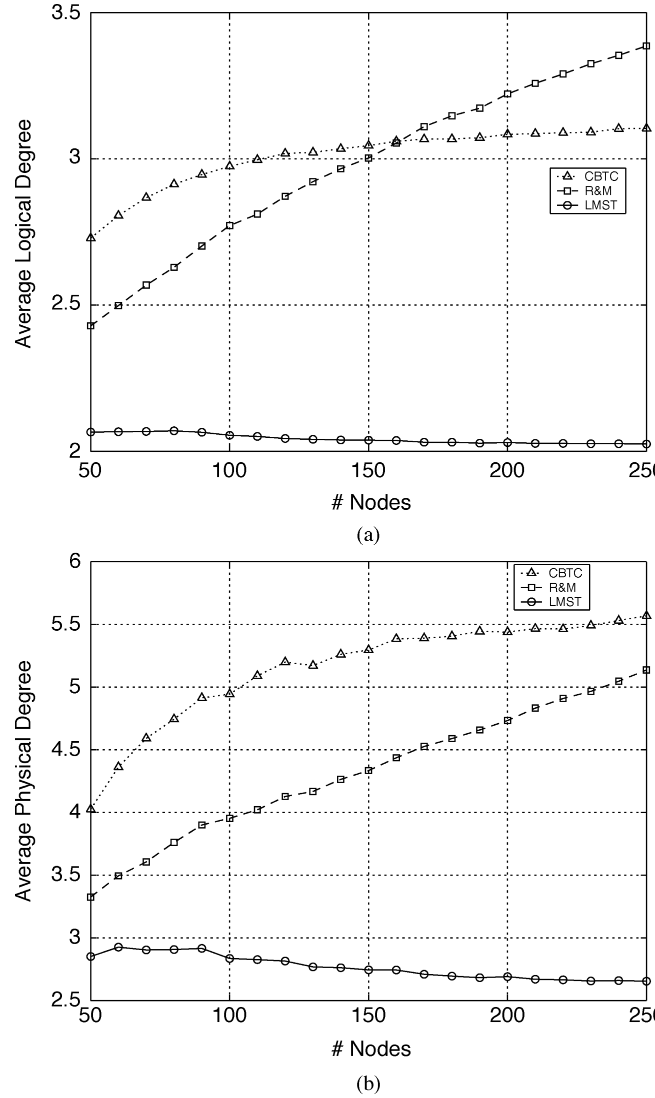



Fig. 6. Performance comparisons (w.r.t. degree, radius, and average length of links) among different algorithms. (a) Average logical degree. (b) Average physical degree.

### B. Performance With Respect to Traffic-Dependent Performance Metrics

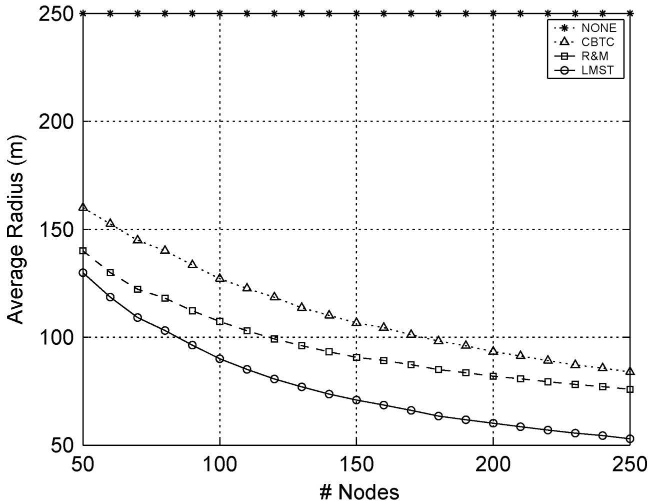
All simulations in this section were carried out in *ns*-2.[3] A total of $n$ nodes are randomly distributed in a $1500 \times 200$ m$^2$ region, with half of them being sources and the other half being destinations. To observe the effect of spatial reuse, the deployment region should be large enough as compared with the transmission/interference range. To reduce the number of nodes and to expedite simulation, we use a rectangular region, rather than a square region.

Each simulation run lasts for 200 s, and each data point in the figures is the average of ten simulation runs. The number of nodes in the network, $n$, is varied from 40 to 150. The propagation model is the two-ray ground model, the MAC protocol is IEEE 802.11 (2 Mb/s bandwidth), and the routing protocol is AODV. We use the energy model in *ns*-2, i.e., it takes 660, 395, and 35 mW for a node to transmit, receive and stay idle, respectively. The traffic sources are CBR and TCP with bulk FTP. The start time of each connection is chosen randomly from [25 s, 50 s].

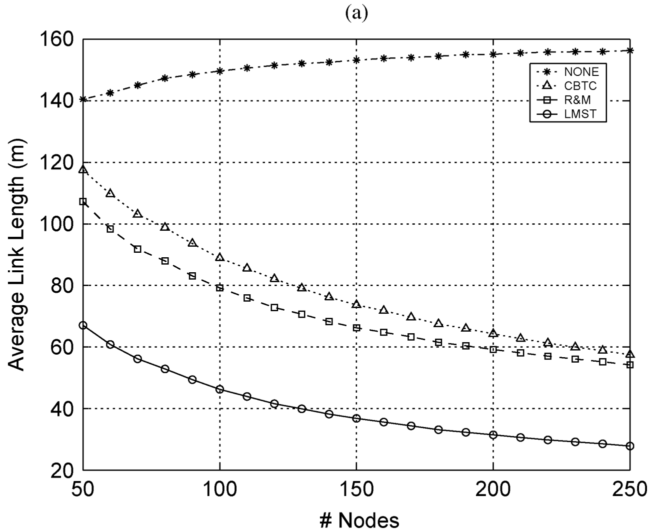
[2][Online] Available: http://www.j-sim.org

[3][Online] Available: http://www.isi.edu/nsnam/ns/

| Algorithm | Maximum degree | Minimum degree | Average degree |
|---|---|---|---|
| Max trans. power | 28 | 4 | 16.48 |
| CBTC($5\pi/6$) | 5 | 1 | 2.97 |
| R&M (Two − ray ground model) | 5 | 1 | 2.64 |
| LMST | 3 | 1 | 2.06 |
| LMST with link removal | 3 | 1 | 2.04 |

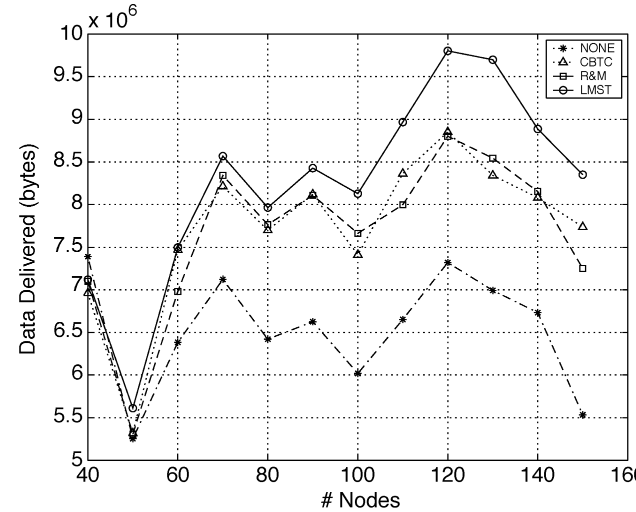



(a)

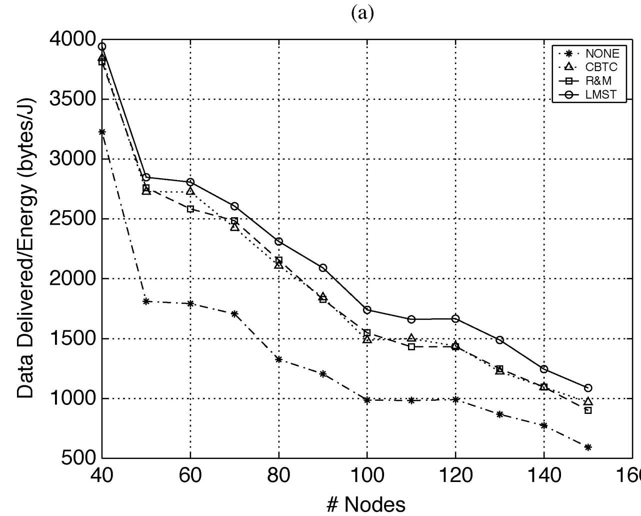



(b)

Fig. 7. Performance comparisons (w.r.t. radius, and average length of links) among different algorithms (NONE indicates the case where no topology control is employed). (a) Average radius. (b) Average link length.




(a)




(b)

Fig. 8. Total amount of data delivered (in bytes)and the energy efficiency (bytes/Joule) under CBR traffic. (a) Total throughput (bytes). (b) Energy efficiency (bytes/Joule).

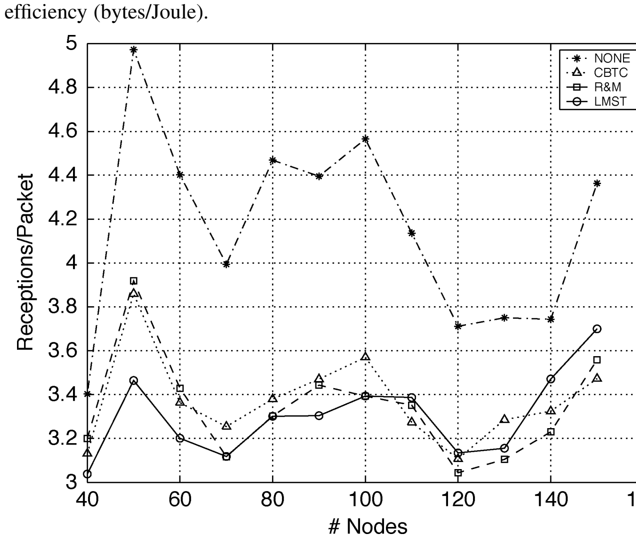



Fig. 9. Total number of transmissions for each packet delivered under CBR traffic.

In what follows, due to the space limit we only report results for the CBR traffic. Results for TCP traffic with bulk FTP exhibit similar trends and can be found in [21].

*Performance with respect to energy efficiency*: We now study the impact of topology control on energy efficiency (in bytes/Joule), where the energy efficiency is defined to be the total end-to-end data delivery divided by the total energy consumption across the network. Fig. 8 depicts the total data delivered and the energy efficiency for CBR traffic. LMST delivers the most amount of data, while the other three do not differ significantly in the amount of data delivered. Moreover, LMST outperforms the other algorithms in energy efficiency as shown in Fig. 8(b).

*Performance with respect to #transmissions each packet incurs*: Fig. 9 shows the average number of transmissions for each packet delivered. As mentioned previously, this can be interpreted as the number of times each packet has to be transmitted, hop by hop, on its way from the source to the destination. As a topology control algorithm constrains a node from transmitting using the maximal transmission power, it is usually believed that packets traverse more hops (and, hence, incurs more number of transmissions) on the topology derived under a topology control algorithm. As shown in Fig. 9, this conjecture is invalidated to some extent—topology control does not necessarily introduce more numbers of transmissions. This is especially true in the case of CBR traffic, where all three topology control algorithms outperform NONE. In the case of TCP traffic, LMST incurs the least number of hops among all three topology control algorithms and performs slightly worse than NONE. We believe this is because with topology control, the medium is shared in a more efficient manner so that data packets do not encounter excessive medium contention/collision and can be delivered more quickly.

## VI. Conclusion

In this paper, we present a localized MST-based topology control algorithm (LMST) for wireless multihop networks with limited mobility. As each node builds its local MST independently using locally collected information, the algorithm incurs less message overhead/delay in deriving the topology. Local repair can be easily made in the case of mobility. We also prove that the algorithm exhibits several desirable properties: 1) the topology derived preserves the network connectivity; 2) the degree of any node in the topology is bounded by 6; and 3) the topology can be transformed into one with bidirectional links (without impairing the network connectivity) after removal of all unidirectional links.

In the simulation study, we show that the topology derived under LMST achieves a small average node degree (which is very close to the theoretical bound), and a small average radius. The former reduces the MAC-level contention, while the latter implies that only small transmission power is needed to maintain connectivity. Simulation results also indicate that LMST outperforms the other known topology control algorithms in the total amount of data delivered (in bytes), the energy efficiency (in bytes/Joule), and the end-to-end delay. In particular, the simulation results invalidate the common belief that as packets traverse more hops on the topology derived under a topology control algorithm, the number of transmissions for each packet delivered is also larger.

Note that LMST attempts to minimize MAC-level interference and maximize spatial reuse and network capacity by enabling each node to construct an MST locally. The downside is that it eliminates redundant paths between sources and destinations. In the case that a node fails (due to power depletion and/or malicious destruction) or moves away, the network may be temporarily disconnected (note, however, that the network will regain its connectivity, if possible, in the next information exchange period (Section III-B1)). There exists a tradeoff between route redundancy and the other performance aspects (power consumption, spatial reuse, MAC level interference, and network capacity), and we will explore into the problem of striking a balance between the two contradictory set of performance metrics.

Another interesting research direction is to relax several assumptions made in the paper and consider more general cases. For example, the assumption of homogeneous nodes does not always hold in practice. Most existing algorithms cannot be directly applied to heterogeneous wireless multihop networks where nodes have different maximal transmission power. In one of our companion papers [22], we have devised two localized topology control algorithms for heterogeneous networks, directed relative neighborhood graph (DRNG) and directed local spanning subgraph (DLSS). We are also working on relaxing other assumptions.

Finally, an efficient topology control algorithm should enable each node to take into account the dynamics of the traffic load in its neighborhood and adjust the transmission power accordingly. This requires that each node obtains traffic information in the neighborhood and executes a more complex procedure. We will further investigate along this direction.

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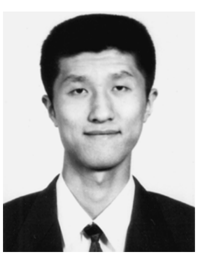

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