Mobility-Sensitive Topology Control in Mobile Ad Hoc Networks *

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Abstract

In most existing localized topology control protocols for mobile ad hoc networks (MANETs), each node selects a few logical neighbors *based on location information, and uses a small transmission range to cover those logical neighbors. Transmission range reduction conserves energy and bandwidth consumption, while still maintaining network connectivity. However, the majority of these approaches assume a static network without mobility. In a mobile environment network connectivity can be compromised by two types of "bad" location information:* inconsistent information*, which makes a node select too few logical neighbors, and* outdated information*, which makes a node use too small a transmission range. In this paper, we first show some issues in existing topology control. Then we propose a mobility-sensitive topology control method that extends many existing mobility-insensitive protocols. Two mechanisms are introduced: consistent local views that avoid inconsistent information, and delay and mobility management that tolerate outdated information. The effectiveness of the proposed approach is confirmed through an extensive simulation study.*

Keywords: Connectivity, mobile ad hoc networks (MANETs), mobility management, simulation, topology control, view consistency.

*This work was supported in part by NSF grants CCR 0329741, CNS 0434533, CNS 0422762, and EIA 0130806. A preliminary version of this paper has been published in Proceedings of the 18th International Parallel and Distributed Processing Symposium (IPDPS 2004). Contact address: jie@cse.fau.edu

1 Introduction

In mobile ad hoc networks (MANETs), all nodes cooperate to achieve certain global tasks, such as area monitoring and data gathering/communication. To reduce energy consumption and signal interference, it is important to select an appropriate transmission power for each node, a process called *topology control*, while still satisfying certain global constraints. Most existing topology control protocols in MANETs use localized approaches to find a small transmission range subject to some global constraints, including connectivity and other reliability and throughput related measures [13, 14, 16, 24, 29, 31, 32]. The majority of these approaches assume a static network without mobility. However, the majority of these approaches assume a static network without mobility. In a typical localized approach, each node collects neighborhood information through periodic, asynchronous "Hello" messages. We refer to neighborhood information collected at each node as the *local view* at a particular time.

Consider the example in Figure 1. Assume u's local view is sampled at t while v's local view is done at $t + \Delta$. The initial transmission ranges of stationary nodes u and v are 4.5, and the distance between u and v is 10. At t (Figure 1 (a)), mobile node w is 4 and 6 away from nodes u and v, respectively, and at $t + \Delta$ (Figure 1 (b)), w is 6 and 4 away from nodes u and v. The *global view* (Figure 1 (c)) derived by a simple collection of u and v's local views does not correspond to the actual network at any moment. Most existing localized topology control protocols will assign a transmission range of 4 to u and v, resulting in a disconnected network!

In most existing localized topology control protocols, it is assumed that the network is connected at all times under a (large) normal transmission range. Each node selects a few *logical neighbors* from its 1-hop neighbors within the normal transmission range. The selection of logical neighbors is usually based on 1-hop information (i.e., location information of all 1-hop neighbors), although some protocols use only partial 1-hop information such as the direction or location information of nodes within a search region that is smaller than the normal transmission range [13, 14]. The (short) actual transmission range of each node is set to be the distance to its farthest logical neighbor. The union of the logical neighbor sets of all nodes forms a *logical topology*. The logical topology is required to be connected. Such connectivity is ensured under all localized topology control protocols when the network is static. However, since the location information of logical neighbors is collected at different times and nodes move around, there is no guarantee that a logical neighbor is within the actual transmission range at a particular time. In this case, some logical neighbors are no longer reachable while others are still reachable (and reachable neighbors are called *effective neighbors*). The union of the effective neighbor sets of all nodes forms an *effective topology*.

In the example of Figure 1, the logical topology is connected (assuming u and v are selected by w as

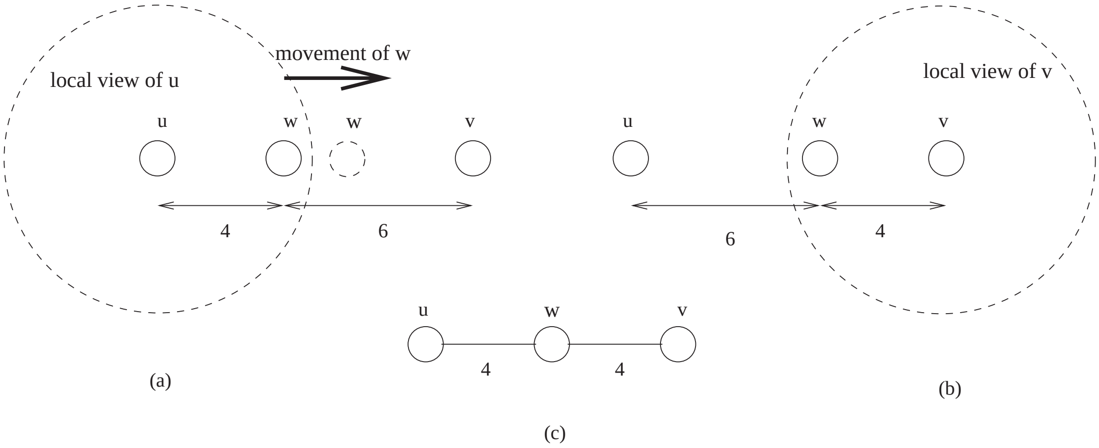


Figure 1. (a) local view of u at t, (b) local view of v at $t + \Delta$, and (c) global view.

logical neighbors), whereas the effective topology is not connected under the uniform transmission range of 4.5 at any particular time. It is assumed that each node refreshes the logical neighbor information periodically. In the above example, u refreshes its view at time t, and v refreshes its view at time $t + \Delta$. Both nodes select a transmission range of 4, which causes a partition. Due to inconsistent views of a particular node in terms of its location (u's view of w and v's view of w in the above example), a more serious problem might occur – a disconnected logical topology as a result of inconsistent local views, as will be shown later. The above discussion leads to two related issues in topology control:

- *Connected logical topology*: Given that the original network is connected (under the normal transmission range), how to ensure that the logical topology generated from a topology control protocol is connected.

- *Connected effective topology*: Given that the corresponding logical topology is connected, how to ensure that the effective topology is connected.

This paper attempts to address the above issues with a focus on mechanisms used to relax the strict conditions often used in research on topology control, rather than proposing a new topology control protocol. The advantage of this approach is obvious – our approach can be applied to a large group of protocols by relaxing their assumptions. The proposed approach, called *mobility-sensitive topology control*, extends many existing mobility-insensitive protocols. Specifically, two mechanisms are proposed to address the above issues:

- *Consistent local views for connected logical topology*: Consistent local views are enforced using either synchronous or asynchronous "Hello" messages. If all nodes use the same version of location information to select their logical neighbors, the resultant logical topology is guaranteed to be connected. Imprecise location information can still cause a partition in the effective topology, but not in the logical topology.

- *Delay and mobility management for connected effective topology*: To deal with imprecise location information caused by node mobility and various delays introduced at different stages of protocol handshakes, each node increases its actual transmission range to cover its logical neighbors. Such coverage (and a connected effective topology) is guaranteed under a moderate mobility level.

The effectiveness of the proposed approach is also confirmed through an extensive simulation study. To our best knowledge, although topology control has been studied extensively in MANETs, our approach is the first attempt ever to systematically extend a large body of localized topology control protocols to the mobile environment without changing the original protocols.

The major contributions of this paper are as follows:

1. A general framework for mobility-sensitive topology control in MANETs.

2. Two synchronization-based methods to enforce consistent local views, which guarantee a connected logical topology in existing topology control schemes without modification.

3. A weak consistency scheme without synchronization overhead, which guarantees a connected logical topology in many existing schemes after minor modifications.

4. A "buffer zone" mechanism that guarantees (under low mobility) or enhances (under high mobility) the connectivity of the effective topology.

5. An extensive simulation study to reveal the connectivity problem caused by mobility and to evaluate the proposed mobility management schemes.

The remainder of the paper is organized as follows: Section 2 overviews existing topology control protocols and mobility management schemes. In Section 3, a formal framework is designed to unify several popular topology control protocols and explain the connectivity issues caused by node movement. In Section 4, we propose our solutions to two connectivity issues and show these solutions can be integrated into those topology control protocols that fit in the proposed formal framework. Simulation results on various topology control protocols are presented in Section 5. The paper concludes in Section 6 with some ideas for future research.

2 Related Work

This section first briefly reviews existing topology control schemes, especially localized schemes. Then several fault tolerant and mobility aware routing mechanisms are discussed.

2.1 Topology Control

Most existing topology control protocols select a less-than-normal transmission range (also called the actual transmission range) while maintaining network connectivity. Centralized protocols [21, 23, 33] construct optimized solutions based on global information and, therefore, are not suitable in MANETs. Probabilistic protocols [2, 20, 23] adjust transmission range to maintain an optimal number of neighbors, which balances energy consumption, contention level, and connectivity. However, they do not provide hard guarantees on network connectivity. In a few special cases [22], topology control is integrated into routing protocols to provide a minimal uniform actual transmission range. Most localized topology control protocols use non-uniform actual transmission ranges computed from 1-hop information (under the normal transmission range). The following is a list of well-known localized topology control protocols that can be enhanced by the mobility management scheme proposed in this paper.

RNG-based protocols. The relative neighborhood graph (RNG) [29] is a geometrical graph used to remove edges (i.e., reduce the number of neighbors) while maintaining network connectivity. An edge (u, v) is removed if there exists a third node w such that $d(u, v) > d(u, w)$ and $d(u, v) > d(v, w)$, where $d(u, v)$ is the Euclidean distance between u and v. In localized topology control protocols [6, 25], each node determines its logical neighbor set based on the location information of 1-hop neighbors. Two nodes u and v are logical neighbors if and only if edge (u, v) exists in RNG. The Gabriel graph [10] is a special case of RNG, where the third node w is restricted to the disk with diameter uv.

Minimum-energy protocols. Rodoplu and Meng [24] proposed another method of reducing the number of edges while maintaining network connectivity and, in addition, preserving all minimum-energy paths. A minimum-energy path between two nodes u and v is defined as the shortest path between u and v, using transmission power as edge cost. An edge (u, v) can be removed if there exists another node w, such that 2-hop path (u, w, v) consumes less energy than direct transmission. Li and Halpern [13] extended this scheme by using k-hop ($k \geq 2$) paths to remove more edges, and at the same time to reduce the computation overhead.

In both protocols in [13] and [24], instead of selecting logical neighbors from the normal 1-hop neighbor set, each node collects the location information of nodes within a small *search region* to conserve control message overhead. The radius of the search region is iteratively enlarged until logical neighbors in the search region can cover the entire normal 1-hop neighborhood; that is, each position outside of the search region can be reached via a k-hop path through a selected logical neighbor, and the k-hop path is more energy-efficient than direct transmission. If the search region is the entire 1-hop neighborhood, the Li and Halpern's algorithm is equivalent to constructing a local shortest path tree (SPT) and considering only neighbors of the root in the SPT as logical neighbors.

Cone-based protocols. In cone-based topology control (CBTC) [14, 32], the logical neighbor set $\{w_1, w_2, \ldots, w_k\}$ of node v is selected to satisfy the following condition: if a disk centered at v is divided into k cones by lines vw_i ($1 \leq i \leq k$), the angle of the maximal cone is no more than α. It was proved in [14] that, when $\alpha \leq 5\pi/6$, CBTC preserves connectivity, and, when $\alpha \leq 2\pi/3$, the corresponding symmetric subgraph (a subgraph after removing all unidirectional edges) is connected. Several optimizations are also proposed in [14] to further reduce the number of logical neighbors and transmission range. Bahramgiri et al [1] extended CBTC to provide k-connectivity with $\alpha \leq 2\pi/3k$. Similar to the minimum-energy protocols, CBTC uses dynamic search regions to reduce control overhead. Furthermore, CBTC requires only direction information instead of accurate location information.

A similar but separate scheme is based on Yao graph [31], where a disk centered at node v is evenly divided into k cones, and a logical neighbor is selected from each cone. It was proved that Yao graph is connected with $k \geq 6$. Yao graph with $k = 6$ can be viewed as a special case of CBTC with $\alpha = 2\pi/3$, but not vice versa.

MST-based protocol. Li et al [16] proposed to build a local minimal spanning tree (MST) at each node to include its 1-hop neighbors only based on location information. This scheme guarantees connectivity, is easy to implement, and has a constant upper bound (six) on the number of logical neighbors of each node.

The above schemes can be combined or enhanced to achieve multiple desirable properties such as low message cost, constant stretch ratio [28], low weight [19], and minimal interference [3].

2.2 Mobility Management

There are two different mobility managements in MANETs, both are related to routing protocols. The first one, called *mobility-assisted management*, is to exploit node movement and achieve eventual delivery. In this case, the network may be temporarily partitioned and a store-and-relay [7] routing strategy must be used, which has a relatively long delay. The second, called *mobility-tolerant management*, is to overcome the node movement and maintain a connected topology at every moment. In this case, a normal routing protocol can be used and a short delay can be expected.

Mobility-assisted management. Solutions to the first problem have been proposed by exploiting both random [9, 11, 26, 27, 30] and controlled [4, 17, 36, 37] node movement. In epidemic routing [30], a data packet is propagated to neighbors with a certain probability. It is expected that the random node movement will eventually bring this packet to its destination. A similar scheme was proposed in [11], with a constraint that the packet will be relayed only once before it reaches its destination. The focus here is on reducing bandwidth consumption. In the Infostation [9] and Data MULEs [26] models, only a few nodes collect and carry data to other nodes. In SWIM [27], the epidemic and Infostation models are combined to reduce delay. The delay and overhead can be reduced using controlled node movement. Li and Rus [17] proposed to recruit mobile nodes as intermediate nodes, which modify their trajectories in order to relay data packets. In message ferrying [36, 37], a few mobile nodes serve as ferries to carry packets from the sources to destinations. In MV routing [4], the movement of autonomous agents is scheduled for the agents to meet with their peers and exchange the carried packets.

Mobility-tolerant management. This paper focuses this approach: to maintain a connected effective topology in spite of random node movement. All localized topology control protocols discussed in Section 2.1 depend on accurate location or direction information to guarantee connectivity. In MANETs, neighborhood information is updated via periodical exchanges of control messages. As will be shown in Section 3, no matter how small the exchange period, connectivity can always be compromised by inconsistent views at different nodes. Various fault tolerant schemes [1, 15, 18] have been proposed to construct a K-connected topology in static networks. Unfortunately, these approaches can only reduce but not eliminate network partition.

It was shown in [20] that connectivity in probabilistic topology control protocols is barely affected by mobility. Blough et al [2] showed that connectivity is preserved with high probability (95%) if every node keeps nine neighbors. In our approach, the logical neighbor set and transmission range are first computed from the neighborhood information of each individual node, and then they are adjusted to balance the mobility. Compared with the uniform optimal node degree in probabilistic protocols, our approach requires fewer neighbors on average. Although the node degree in [2] can be further reduced, it is not clear whether the resultant topology is still resilient to mobility after optimization.

Wu and Dai [35] proposed a mobility management scheme to guarantee a connected dominating set (CDS) in a MANET. In order to guarantee link availability in the CDS, only links with relatively small distance values are considered in the formation of the CDS. Asynchronous local views of each node are also considered in this scheme. However, local views in CDS formation consist of connection information only. The technique used to overcome view inconsistency in [35] does not apply in topology control, where accurate location information is needed.

3 A Formal Framework

In this section, we first put existing topology control protocols into a formal framework. The problem of disconnected logical/effective topology caused by node movement is then demonstrated within this framework. In the next section, we will introduce several methods to solve this problem and prove their correctness using the same framework. For the sake of clarity, we consider only topology control protocols using normal 1-hop information for logical neighbor selection.

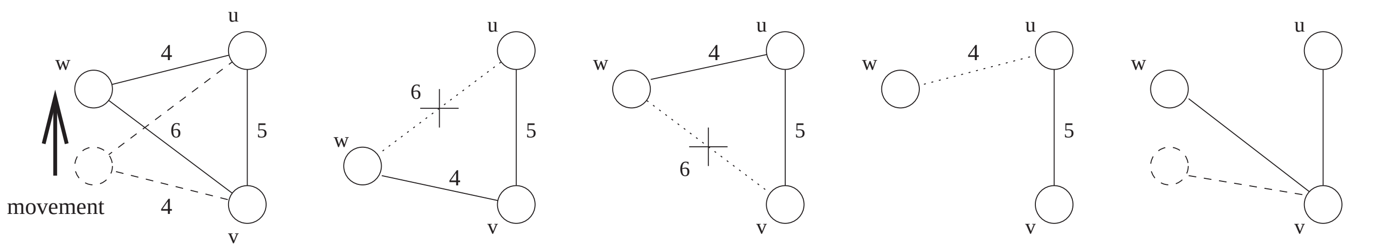
3.1 Logical Topology

In topology control protocols based on 1-hop information, each node advertises its ID and location through periodic "Hello" messages with the normal transmission range. We assume a fixed "Hello" interval; that is, the period between two "Hello" messages from the same node is a constant Δ. However, due to the inaccuracy of local clocks in individual nodes, "Hello" messages from different nodes may be asynchronous. We define the *original topology* as a dynamic graph $G = (V, E)$, where V is the set of nodes, and E is the set of *bidirectional links*. At a given time t, a bidirectional link $(u, v) \in E$ implies that both nodes u and v have received a "Hello" message from each other during time period $[t - \Delta, t]$. Due to the node mobility and packet collision, some bidirectional links may not be detected. We assume the network is *sufficiently dense*, such that the original topology is always connected with the normal transmission range after removing those undetected links. This is a reasonable assumption, as topology control techniques are applied to dense networks.

Given an original topology G, a topology control algorithm can be viewed as the process of removing links from E to produce a *logical topology* $G' = (V, E')$, where E' is the set of *logical links* after link removal. Specifically, each link (u, v) in the original topology is given a cost $c_{u,v}$ computed from the physical distance $d_{u,v}$ between u and v. In RNG-based and MST-based protocols, $c_{u,v} = d_{u,v}$. In the SPT-based protocol (i.e., the minimal energy protocol based on 1-hop information), $c_{u,v} = d_{u,v}^{\alpha} + c$ with constants α and c. We assume that each link cost is unique and forms a total order of E. If two links have the same cost, ID's of end nodes can be used to break a tie. For the successful removal of a link (u, v), one of the following conditions must hold:

Link removal conditions: A link (u, v) will be removed from the original topology

1. in a RNG-based protocol, if a path (u, w, v) exists such that $c_{u,v} > \max\{c_{u,w}, c_{w,v}\}$.
2. in a SPT-based protocol, if a path $(u, w_1, w_2, \dots, w_k, v)$ exists such that $c_{u,v} > c_{u,w_1} + c_{w_1,w_2} + \dots + c_{w_k,v}$.



(a) w's positions at t_0 and t_1 (b) u's local view before t_1 (c) v's local view after t_1 (d) logical topology at t' (e) using consistent views

Figure 2. Partition in a 3-node network. Dotted lines represent links removed based on local views.

3. in a MST-based protocol, if a path $(u, w_1, w_2, \ldots, w_k, v)$ exists such that $c_{u,v} > \max\{c_{u,w_1}, c_{w_1,w_2}, \ldots, c_{w_k,v}\}$.

It has been proved in [16] that the MST-based protocol preserves connectivity. That is, the logical topology derived from link removal condition 3 is connected, as long as the original topology is connected. Since both conditions 1 and 2 are stronger than condition 3, RNG- and SPT-based protocols also preserve connectivity. At each moment t, "Hello" messages sent and received during time period $[t - \Delta, t]$ form the *local view* of each node, which includes ID's and locations of itself and its 1-hop neighbors. A subgraph G_v of the original topology can be constructed from those "Hello" messages, where the cost of each link is computed based on the locations of end nodes.

3.2 View Consistency

Due to the lack of synchronous clocks, local views at different nodes may be asynchronous and inconsistent. We define consistent views as follows.

Definition 1 *Local views of the original topology $G = (V, E)$ are consistent, if for each link $(u, v) \in E$, the same $c_{u,v}$ appears in all local views containing (u, v).*

In Figure 2 (a), when node w moves upwards and sends two "Hello" messages from different locations, node u's local view based on the former "Hello" message from w (Figure 2 (b)) and node v's local view based on the latter "Hello" message (Figure 2 (c)) are inconsistent.

In localized topology control protocols, each node selects *logical neighbors* periodically based on its local view. During the selection process, each node removes its adjacent links by applying condition 1, 2, or 3 in Section 3.1. Here we assume that each link (u, v) exists in the local views of end nodes u and v, and can only be removed by its end nodes. After this process completes, the end nodes of remaining links become logical neighbors. Figure 3 shows a time-space view of the example in Figure 2, where

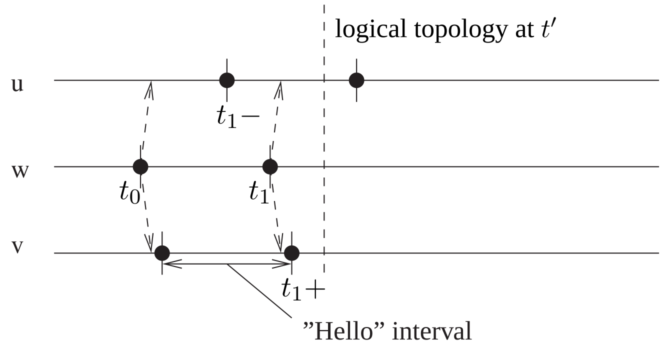


Figure 3. Time-space view of the example in Figure 2.

each node makes its decision right after it sends a "Hello" message. For example, w sends two "Hello" messages at t_0 and $t_1 = t_0 + \Delta$, u makes its decision before t_1, and v makes its decision after t_1. The resultant logical topology in Figure 2 (d) is observed at $t^{'} > t_1$. The following theorem shows that localized protocols preserve connectivity as long as all nodes have consistent views.

Theorem 1 *If the original topology is connected, then the resultant logical topology, derived by applying link removal condition 1, 2, or 3 at each node based on consistent local views, is still connected.*

Proof: By contradiction, suppose $G = (V, E)$ is connected but $G^{'} = (V, E^{'})$ is disconnected. Let $E_R = E - E^{'}$ be the set of removed links. Since each link has the same cost in all local views, we can sort E_R into a sequence $e_1, e_2, \ldots, e_{|E_R|}$ by the descending order of c_{e_i}, and remove those links from E in this order. Let e_l be the first link that causes the partition; that is, the topology $G^{l-1} = (V, E - \{e_1, e_2, \ldots, e_{l-1}\})$ is connected, while $G^l = (V, E - \{e_1, e_2, \ldots, e_l\})$ is disconnected. We show that is impossible. Without loss of generality, let u be the node that removes $e_l = (u, v)$. No matter which link removal condition is used, there must be a path $P = (u, w_1, w_2, \ldots, w_k, v)$ in u's local view, with the cost of each link smaller than $c_{u,v}$. Since all previously removed links have larger costs than $c_{u,v}$, every link in P remains in G^l. Therefore, nodes u and v are still connected via path P, which contradicts the early assumption that the removal of (u, v) disconnects G^l. $\square$

In static networks, local views are static and thus consistent. In MANETs, local views are dynamic and may be inconsistent. In this case, a total order of link cost no longer exists, and simultaneous link removals may yield a disconnected logical topology. We use the MST-based protocol [16] as an example to illustrate the inconsistent views and disconnected logical topology caused by node movement. Suppose node w in Figure 2 (a) moves upward, and advertises its locations twice at time t_0 and t_1, respectively. When node u applies condition 3 at $t_1 - \delta$, link (u, w) is removed because $c_{u,w} > \max\{c_{u,v}, c_{v,w}\}$ in u's local view (Figure 2 (b)). At $t_1 + \delta$, node v removes link (v, w) because $c_{v,w} > \max\{c_{u,v}, c_{u,w}\}$ in

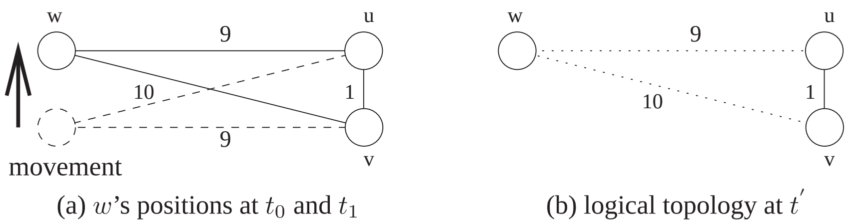


Figure 4. Disconnection cannot be avoided by enabling physical neighbors.

its local view (Figure 2 (c)). The corresponding logical topology at $t' > t_1 + \delta$ is disconnected (Figure 2 (d)). Note that the local views of nodes u and w are inconsistent no matter how small δ is. This problem cannot be solved by reducing the "Hello" interval Δ. A feasible solution is to force u and v to use the same version of w's location information. As shown in Figure 2 (e), when both u and v get w's location from the older "Hello" message sent at t_0 (marked by the dashed circle), only link (u, w) will be removed and the logical topology is connected. Detailed synchronization operations that enforce view consistency will be discussed in the next section.

3.3 Effective Topology

Once a set of logical neighbors is determined, each node u adjusts its actual transmission range r_u to $d_{u,v}$, the distance to the farthest logical neighbor v. All nodes within the actual transmission range are called *physical neighbors*. Usually, non-logical physical neighbors are disabled; any data packet received from a non-logical neighbor will be discarded. In some topology control protocols, non-logical physical neighbors are *enabled*; all incoming packets will be reported to the upper level protocol. In Figure 2 (d), node u has only one logical neighbor v. Its actual transmission range r_u is set to $d_{u,v} = 5$. Since $d_{u,w} = 4 < d_{u,v}$, w is still a physical neighbor of u. One may argue that the resultant topology is still connected after enabling all physical neighbors. Unfortunately, enabling physical neighbors and slightly increasing actual transmission range cannot preserve connectivity. As shown in Figure 4, when $d_{u,v} \ll d_{u,w}$, r_u needs to be increased dramatically in order to reach w. This is impractical in a topology control protocol, which is supposed to reduce the actual transmission range.

After each node determines its actual transmission range, an *effective topology* $G'' = (V, E'')$ is formed from all *effective links*. An effective link $(u, v) \in E''$ is a logical link in E' if $r_u \geq d_{u,v}$ and $r_v \geq d_{u,v}$. The corresponding end nodes u and v are called *effective neighbors*. In static networks, each node knows its accurate distance to each logical neighbor. The actual transmission range is large enough to cover all logical neighbors. That is, $E'' = E'$, and the effective topology is connected as long as the logical topology is connected. In MANETs, however, link distance is a function of time, which may exceed the actual transmission range computed from outdated 1-hop information. A mobility management scheme is required to preserve the connectivity of the effective topology, which will also be discussed in the next section.

4 Proposed Method

Our mobility-sensitive topology control scheme preserves connectivity in two steps. First, the connectivity of the logical topology is guaranteed by building and using consistent local views. We discuss different schemes to enforce strong view consistency as required in Definition 1 and thus preserve connectivity as proved in Theorem 1. Then we relax the strong consistency requirement in Definition 1 and propose a *weak consistency* model. This model, when applied to several existing topology control protocols, guarantees a connected logical topology while avoiding the synchronization overhead of strong consistency.

The second step is to ensure the connectivity of the effective topology. Each node uses a larger-than-actual transmission range (called an *extended transmission range*) to create a "buffer zone" that preserves all logical links in the effective topology. The size of the buffer depends on the maximal moving speed and "Hello" interval.

4.1 Strong View Consistency

Consider all "Hello" messages sent by a node v: $m(v,1), m(v,2), \ldots, m(v,l)$. We give each message a *version* $1, 2, \ldots, l$, where 1 is the version of the first message, and l the version of the most recent message. Due to the message propagation delay and asynchronous clock at each node, different "Hello" messages with different versions may be used by different nodes in local view construction. At any time t, let $M(t,v) = \{m(v,i_1), m(v,i_2), \ldots, m(v,i_k)\}$ be the set of v's "Hello" messages used in at least one local views. Our view consistency schemes are based on the following theorem.

Theorem 2 *Local views of the original topology $G = (V, E)$ are consistent at time t, if $|M(t,v)| = 1, \forall v \in V$.*

Proof: Consider any link $(u,v) \in E$ and its costs $c^{w_1}_{u,v}, c^{w_2}_{u,v}, \ldots, c^{w_m}_{u,v}$ in local views of nodes $w_1, w_2, \ldots, w_m$ that include this link. Since all nodes use the same "Hello" message from u and the same "Hello" message from v, the distance $d^{w_i}_{u,v}$ is the same is local views of all nodes w_i ($1 \leq i \leq m$). Because the cost $c^{w_i}_{u,v}$ depends on the distance $d^{w_i}_{u,v}$ only, we have $c^{w_1}_{u,v} = c^{w_2}_{u,v} = \ldots = c^{w_m}_{u,v}$. □

We consider two methods that enforce $M(t,v) = 1$ at any time t. One method uses asynchronous and timestamped "Hello" messages to achieve connectivity in the routing of each packet. Unlike epidemic routing [30] and message ferrying [36, 37] schemes, our method does not cause significant increase of end-to-end delay or memory consumption. The other method uses synchronized “Hello” messages to enhance connectivity during each “Hello” interval.

The first method (called the *proactive approach*) is applied to the routing process of each packet, during which the source and all relaying nodes use the same version of “Hello” messages to form local views. In the proactive approach, each “Hello” message is associated with a timestamp (i.e., the version number). Each node keeps several local view versions, each version corresponding to a recently used timestamp. In addition, each data packet carries the latest timestamp of the source, and uses this timestamp to select local views at relaying nodes. Note that a certain clock synchronization mechanism is required such that the time skew between two “Hello” messages with the same version number is constrained by the *synchronous delay* Δ', where Δ' equals to the “Hello” interval Δ plus a small physical clock skew.

Note that when a node receives a data packet with timestamp s, it may or may not have sent its “Hello” messages with timestamp s. As a consequence, each node may or may not receive all neighborhood information with timestamp s. In MANETs with a dynamic neighbor relationship, it is difficult for a node to determine if it has received “Hello” messages from all 1-hop neighbors. A solution is to wait a large time period (e.g., $\Delta^{'}$) before it migrates to the next local view.

In the second method (called the *reactive approach*), node synchronization, topology control initialization, and “Hello” message are combined into a simple flood message. In this approach, the initiator (and synchronizer) sends out its timestamped “Hello” message. Each node in the network will send out its “Hello” message with the same timestamp the first time it receives the initiation message. Each node then waits for a period (bounded by the broadcast delay) to make its decision using only neighbors’ “Hello” messages with the same timestamp.

Although the reactive approach looks much simpler than the proactive approach, it will generate significant traffic during the initiation period. (1) The initiation process is a “flooding” process instead of a broadcast process. In general, a broadcast process can be efficiently implemented by selecting a small forward node set [34] (as in Figure 2 where only node v acts as the forwarding node), whereas in a flooding process, each node needs to forward once. (2) In this flooding process, although each node only needs to respond to the first-received message by sending out its “Hello” message, it still cannot ignore the subsequent message, because these messages are “Hello” messages from other neighbors.

4.2 Weak View Consistency

Both solutions for enforcing consistent local views require a certain degree of synchronization, which introduces extra overhead. When maintaining consistent local views becomes too expensive or impossible, we propose to maintain weak consistency for making conservative decisions based on asynchronous and inconsistent local views. In this subsection, we give a systematical method for making "conservative" decisions in topology control, i.e., slightly increasing the number of logical neighbors, and prove that this method preserves logical topology connectivity.

As in the proactive scheme for view consistency, each node stores several recent "Hello" messages for each 1-hop neighbor in its local view. But the way of using those "Hello" messages is different. Since each node in v's local view has several positions in multiple "Hello" messages, each link has several costs computed from different locations of the two end nodes. Let C_e be the set of costs of link e in the local view of a given node. We use c_e^{Max} to denote the maximal cost c_e^{Min} the minimal cost in C_e. Let c_e^{MinMax} be the minimal c_e^{Max} and c_e^{MaxMin} be the maximal c_e^{Min} in all local views, we define *weak view consistency* for localized topology control as follows:

Definition 2 *Local views of the original topology $G = (V, E)$ are weakly consistent if $c_e^{MinMax} \geq c_e^{MaxMin}, \forall e \in E$.*

For example, if C_e is $\{1, 3, 5\}$ in u's local view and $\{2, 4, 6\}$ in v's local view, then $c_e^{MaxMin} = 2$ and $c_e^{MinMax} = 5$. Local views of u and v are weakly consistent because $c_e^{MinMax} \geq c_e^{MaxMin}$. If, however, the set of c_e is $\{1, 3\}$ in u's local view and $\{4, 5\}$ in v's local view, then then $c_e^{MaxMin} = 4$ and $c_e^{MinMax} = 3$ and the two local views are weakly inconsistent. The following theorem shows that two or three recent "Hello" messages from each node is sufficient for constructing weakly consistent local views.

Theorem 3 *If the difference between sampling times of any two local views is bounded by δ, and all nodes use a fixed "Hello" interval Δ, then storing k recent "Hello" messages at each node preserves weak consistency, where $k = \lceil \frac{\delta}{\Delta} \rceil + 1$.*

Proof: Let $[t, t + \delta]$ be the time period that all nodes sample their local views. For each link (u, v), $c_{u,v}^{MinMax} \geq c_{u,v}^{MaxMin}$ is guaranteed if a common $c_{u,v}$ exists in all local views containing this link, which, in turn, is guaranteed if a common location of u and a common location of v appears in all these local views. When all nodes collect k recent versions of "Hello" messages, all "Hello" messages issued within time period $[t+\delta-k\Delta, t]$ will be used to build local views of neighboring nodes. If the length of this time period is no less than Δ, every node will have at least one "Hello" message received by all neighboring nodes, which carries the common location to build weakly consistent local views. That is, $k\Delta - \delta \geq \Delta$ and $k \geq \frac{\delta}{\Delta} + 1$. Since k is an integer number, we have $k = \lceil \frac{\delta}{\Delta} \rceil + 1$. □

There are two sampling strategies. In *instantaneous updating*, a local view is sampled and logical neighbors are selected whenever a new “Hello” message has been transmitted or received. In this case, $\delta = d$, where $d \ll \Delta$ is the maximal end-to-end routing delay. In *periodical updating*, each node samples its local view and determines its logical neighbors once per “Hello” interval. As a result, $\delta = \Delta + d < 2\Delta$. We assume all “Hello” messages have been received successfully.

Corollary 1 *When $d \leq \Delta$, weakly consistent local views can be constructed from at most two recent “Hello” messages using the instantaneous updating strategy, and three recent “Hello” messages using the periodical updating strategy.*

In practical networks, “Hello” messages may be lost due to collision and mobility. In this case, storing more “Hello” messages from each sender can enhance the probability of building weakly consistent local views. In a MANET with weakly consistent local views, the original link removal conditions can be enhanced to preserve connectivity.

Enhanced link removal conditions: A link (u, v) will be removed

1. in a RNG-based protocol, if a path (u, w, v) exists such that $c_{u,v}^{Min} > \max\{c_{u,w}^{Max}, c_{w,v}^{Max}\}$.
2. in a SPT-based protocol, if a path $(u, w_1, w_2, \ldots, w_k, v)$ exists such that $c_{u,v}^{Min} > c_{u,w_1}^{Max} + c_{w_1,w_2}^{Max} + \ldots + c_{w_k,v}^{Max}$.
3. in a MST-based protocol, if a path $(u, w_1, w_2, \ldots, w_k, v)$ exists such that $c_{u,v}^{Min} > \max\{c_{u,w_1}^{Max}, c_{w_1,w_2}^{Max}, \ldots, c_{w_k,v}^{Max}\}$.

Theorem 4 *If the original topology is connected, then the resultant logical topology, derived by applying enhanced link removal condition 1, 2, or 3 at each node based on weakly consistent local views, is also connected.*

Proof: Similar to that of Theorem 1, suppose E_R is the set of removed links and the logical topology is disconnected. We can remove links $e_1, e_2, \ldots, e_{|E_R|}$ from E_R in the descending order of $c_{e_i}^{MaxMin}$. Let $e_l = (u, v)$ be the first link that causes the partition and u be node that removes e_l. There must be a path $P : u, w_1, w_2, \ldots, w_k, v$ in u's local view, with $c_{u,v}^{MaxMin} \geq c_{u,v}^{Min} > \max\{c_{u,w_1}^{Max}, c_{w_1,w_2}^{Max}, \ldots, c_{w_k,v}^{Max}\} \geq \max\{c_{u,w_1}^{MinMax}, c_{w_1,w_2}^{MinMax}, \ldots, c_{w_k,v}^{MinMax}\} \geq \max\{c_{u,w_1}^{MaxMin}, c_{w_1,w_2}^{MaxMin}, \ldots, c_{w_k,v}^{MaxMin}\}$. Since all previously removed link has larger maximal minimal costs than $c_{u,v}^{MaxMin}$, all links of P have not been removed yet.

Therefore, nodes u and v are still connected via path P, which contradicts the assumption that removing (u, v) causes partition. □

We use the same example in Figure 2 to illustrate this approach. Suppose all nodes keeps two recent "Hello" messages. In u's local view at time $t_1 - \delta$, $C_{u,w} = \{6\}$, $C_{u,v} = \{5\}$, and $C_{v,w} = \{4\}$. Link (u, w) is removed because $c_{u,w}^{Min} < c_{u,v}^{Max} < c_{v,w}^{Max}$. In v's local view at time $t_1 + \delta$, $C_{u,w} = \{4, 6\}$, $C_{u,v} = \{5\}$, and $C_{v,w} = \{4, 6\}$. Link (v, w) is preserved because $c_{v,w}^{Min} < c_{u,w}^{Max}$. The final effective topology consisting of links (u, v) and (u, w) is connected.

4.3 Delay and Mobility Management

Although under the above models each node obtains a consistent local view, views of different nodes are taken from different physical times. In other words, the node information shows node positions at different times. In order to apply existing topology control protocols without having to re-design them, we use the notion of *buffer zone*, where two circles with radii r and $r + l$ are used (see Figure 5). r corresponds to the actual transmission range determined by a topology control protocol. $r+l$ corresponds to the extended transmission range used, where l is defined as a buffer zone width depending on the maximal moving speed v of mobile nodes and the maximum time delay Δ''.

The maximal time delay Δ'' is defined as the age of the oldest "Hello" message included by a current local view. In the proactive approach, a local view taken at time t may depend on the "Hello" message sent at $t - \Delta'$ and may be used until $t + \Delta'$. Therefore, $\Delta'' = 2\Delta'$. In the reactive approach, all "Hello" messages are sent at the beginning of the current "Hello" interval. Therefore, Δ'' is bounded by Δ plus the propagation delay (including the short backoff delays at intermediate nodes) of the flooding process. When the weak consistency is used, Δ'' is bounded by $(k+1)\Delta$, where k is the number of recent "Hello" messages stored at each node.

Using the buffer zone concept, each node transmits with an increased power to cover the extended transmission range. The following theorem shows that such a scheme avoids link failures and preserves a connected effective topology.

Theorem 5 *If the logical topology is connected and each node uses an buffer zone width $l = 2\Delta''v$, then the resultant effective topology is also connected.*

Proof: Consider any link (u, v) in the logical topology. Suppose node u computes the distance $d_{u,v}$ based on location information in two "Hello" messages sent by u and v at t_u and t_v seconds ago, respectively. Here $0 \leq t_u, t_v \leq \Delta''$. In the topology control process, u's actual transmission range is set to $r > d_{u,v}$. The maximal moving distance of nodes u and v are $t_u v$ and $t_v v$, respectively. Their current distance

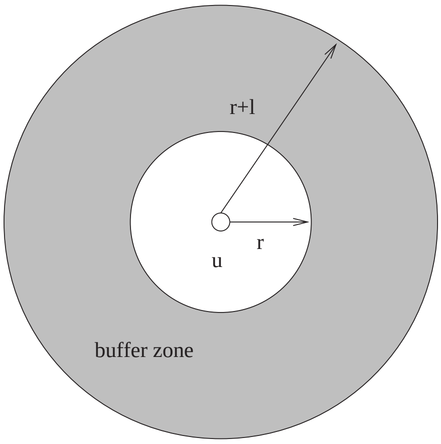


Figure 5. The notion of buffer zone with different transmission ranges.

is $d'_{u,v} \leq d_{u,v} + t_u v + t_v v \leq r + 2\Delta'' = r + l$. That is, v is within u's extended transmission range. Similarly, we can prove that u is also within v's extended transmission range. Since all logical links are effective links, the effective topology is connected. □

When this approach is applied to address the problem of disconnected effective topology (such as the one in Figure 1), the extended transmission range is properly set based on the "Hello" interval and node moving pattern and its speed. In the example of Figure 2 (e), the transmission power of each node is enlarged to create a buffer zone that guarantees the existence of a effective link even if the distance between v and w has been changed due to the movement.

In MANETs with high moving speed and long time delay, using a buffer zone width of $2\Delta'' v$ becomes expensive. However, Wu and Dai [35] showed that an effective link can be maintained with high probability with even with a much narrower buffer zone. Several optimization methods can be used to have a good estimate of l at each node. For example, the "timeliness" of each "Hello" message can be measured by latency between the (physical) time it is received and the time it is used in a local decision. The network connectivity is also affected by the redundancy of a topology control protocol. In a protocol with low redundancy (such as the MST-based protocol), a few link failures will causes a network partition. In protocols with higher redundancy (such as RNG- and SPT-based protocols), the effective topology can survive several link failures due to the existence of multiple alternative paths.

5 Simulation

In the simulation study, the proposed scheme has been applied to several existing localized topology control protocols, including the RNG-, SPT-, and MST-based protocols. Our simulation results confirm that node movement will cause partitions in both logical and effective topologies, and these problems can be solved by the proposed view consistency and mobility and delay management schemes.

5.1 Implementation

We evaluate topology control protocols under $ns2$ [8] and its CMU wireless and mobility extension [12] with a similar setting to that in [16]. 100 nodes are randomly placed in a $900 \times 900m^2$ area. The normal transmission range is $250m$, which yields an average node degree of 18 without topology control. The mobility pattern is generated based on the random waypoint model [5] with zero pause time and the average moving speed varying from 1 to $160m/s$. Note that the typical moving speed in a MANET ranges from $1m/s$ (walking) to $20m/s$ (driving). This study uses a much wider speed range to emulate the situation in dense networks that use a much short transmission ranges. For example, when the transmission range is $33.375m$, the impact of a speed of $20m/s$ is equivalent to that of $160m/s$ in a MANET with a transmission range of $250m/s$. In order to isolate the effects of mobility from other factors, all simulations use an ideal MAC layer without collision and contention. Each simulation lasts $100s$ and is repeated 20 times. All data are sampled 10 times per second and 1000 times per simulation. Each result is associated with the 95% confidence interval.

In our implementations of baseline protocols, each node advertises its location via asynchronous "Hello" messages. Although MAC layer collision is not simulated, the "Hello" interval of each node is randomly selected from $1 \pm 0.25s$ to avoid the collision in the real world. "Hello" messages are transmitted with the normal transmission power. Each node selects its logical neighbors based on the complete 1-hop information. Three baseline protocols are implemented: RNG-based protocol, MST-based protocol, and minimum-energy (SPT-based) protocol. The minimum-energy protocol builds local SPTs based on the energy function $E = d^\alpha$, where E is the required transmission power, and d is the length of a link. We use two choices of α: (1) $\alpha = 2$ as in the free space model, and (2) $\alpha = 4$ as in the two-way ground reflection model.

In all protocols, each node updates its logical neighbor set whenever it sends a "Hello" message, and adjusts its transmission power to the minimal power that reaches the farthest logical neighbor. The logical neighbor set is attached in the header of every outgoing packet. The receiver will drop the packet if it is not in the sender's logical neighbor set. Unidirectional links are neither removed nor converted into bidirectional edges. We have not simulated the cone-based protocol, as we are still in search of an implementation of CBTC with all its optimizations in [14].

Two connectivity models can be defined in MANETs: *strict connectivity* and *weak connectivity*. A MANET is strictly connected if its snapshot (i.e., the effective topology at a particular time) taken at every moment is connected. However, in a MANET with mobile nodes, it is difficult to capture network topology under a snapshot (although we can do so in simulations via assuming an omniscient "god"). Weak connectivity, which is application dependant, is more appropriate. In this model, the connectivity is defined in terms of capability of completing a connectivity-related task, such as global flooding, measured in terms of the percentage of nodes that receive the message. Note that a weakly connected network may not be strictly connected under a particular snapshot (or even any snapshot). In Figure 1, a broadcast initiated at u at time t and forwarded by w at time $t + \Delta$ ensures a full coverage. However, the network is not connected under any snapshot. Note that weak connectivity is exploited only in special routing schemes such as Infostation variations [27] and epidemic routing [30], where end-to-end delay is traded for eventual delivery. In a flooding that completes in a small ($< 0.01s$) time period, weak connectivity is a rather accurate approximation of the strict connectivity.

Against the baseline protocols, we evaluate three mechanisms that enhance the connectivity in MANETs.

- *Buffer zone*: If the logical topology is connected, then using a buffer zone can tolerate the inaccurate location information caused by mobility. In the worst case, the age of the location information is twice the maximal "Hello" interval, i.e., $2.5s$, and the relative speed between two neighbors is two times the maximal moving speed and four times the average moving speed. Therefore, to tolerate an average moving speed of $10m/s$, the width of the buffer zone shall be $100m$. However, as shown in [35], the same level of mobility can be tolerated by a much thinner buffer zone with high probability.

- *View synchronization*: The connectivity of the logical topology cannot be guaranteed based on inconsistent local views. We use a simplified mechanism to provide almost consistent views on-the-fly. Whenever a node sends a packet, it updates its logical neighbor set based on the current view, i.e., the location information advertised in latest "Hello" messages from 1-hop neighbors. If the packet travels fast enough, nodes visited by the same packet will probably have consistent local views. Note that each node must use its previous location advertised in the last "Hello" message, instead of its current location, in its calculation. The weak view consistency mechanism is not simulated.

- *Physical neighbor*: The network connectivity can be enhanced by allowing non-logical neighbors to relay packets instead of dropping them. This mechanism works better with a large buffer zone, where more physical neighbors form multiple paths that tolerate higher mobility levels.

The baseline protocols and different enhancements are compared in terms of the following metrics.

- *Connectivity ratio*: i.e., the ratio of connected node pairs to the total number of node pairs. We compute the connectivity ratio as the average delivery ratio of broadcast packets originated from

Algorithm	Trans. range (m)	Node degree
MST	65.09 ± 1.61	2.09 ± 0.01
RNG	78.95 ± 2.65	2.44 ± 0.03
SPT ($\alpha = 4$)	75.04 ± 2.00	2.51 ± 0.05
SPT ($\alpha = 2$)	100.10 ± 2.75	3.46 ± 0.10

Table 1. Average transmission range and node degree of baseline protocols.

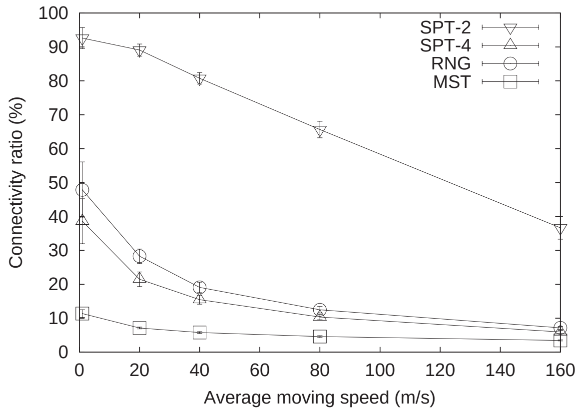


Figure 6. Connectivity ratio of baseline protocols.

random sources. The broadcast frequency is 10 packets per second and 1000 packets per simulation.

- *Transmission range*: The average transmission range serves as an indicator of the average transmission power. We avoid using transmission power directly, because the diversity of the energy models may cause unnecessary ambiguity. The transmission range is also a good indicator of the channel reuse ratio.

- *Node degree*: One common goal of topology control protocols is to reduce the network density, which can be represented by the average node degree. Here we consider only the number of logical neighbors, except in the third enhancement, where physical neighbors also count.

5.2 Results

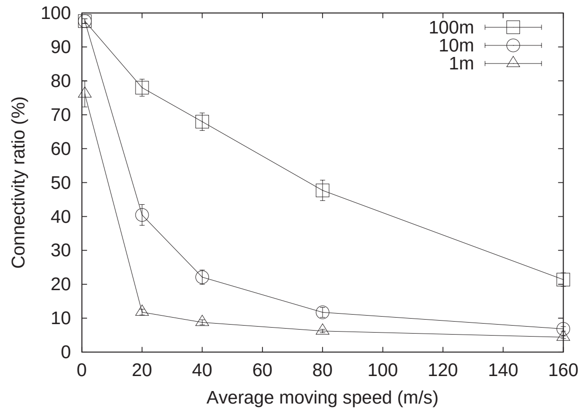
Baseline protocols. Table 1 shows the effectiveness of each baseline protocol in reducing the transmission range and number of logical neighbors. The MST-based protocol (MST) has the smallest transmission range and node degree. The average node degree of 2.09 implies that the logical topology is close to tree, which has the average node degree of $2(n-1)/n = 1.98$. A tree is the most efficient way to maintain a connected logical topology. However, it is also the most vulnerable. The SPT-based protocol with $\alpha = 2$ (SPT-2) has the largest transmission range ($100m$) and node degree (3.46). Compared with the normal transmission range ($250m$) and original node degree (18), SPT-2 still saves significantly in energy and bandwidth consumption. The RNG-based protocol (RNG) and SPT-based protocol with $\alpha = 4$ (SPT-4) have similar transmission range and node degrees, which lie between MST and SPT-2. RNG has slightly larger transmission range and smaller node degree than SPT-2, suggesting that RNG has more physical neighbors than SPT-2.

Figure 6 shows the connectivity ratio of baseline protocols in MANETs. The mobility level varies from very low ($1m/s$) to moderate (20-40m/s) and extremely high (80-160m/s). Our objective is to find methods that maintain high connectivity ratio ($\geq 90\%$) under low and moderate mobility. Extremely high mobility is unlikely in MANETs and is used to benchmark the resilience of each protocol to mobility. As shown in Figure 6, all baseline protocols are vulnerable to mobility. The best protocol, SPT-2, can tolerate only very slow mobility. Other protocols have only 50% (RNG), 40% (SPT-4) and 10% (MST) connectivity ratio under very low mobility. MST is the most vulnerable, because in a tree-like topology, the probability of partition is very high. In most scenarios, a single link failure is enough to disconnect the entire network.

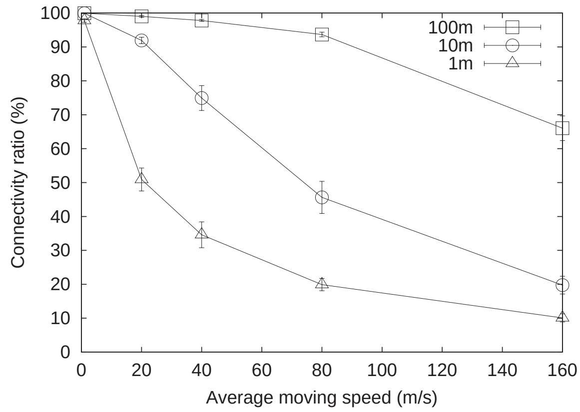
Buffer zone. We first handle link failures caused by logical neighbors moving out of the actual transmission range. The goal is to find the minimal buffer zone width that tolerates moderate mobility, that is, maintains 90% delivery ratio when the average moving speed is below or equal to $40m/s$. Our finding is that using buffer zone alone does not eliminate the problem in most protocols. As shown in Figure 7, MST tolerates $1m/s$ mobility with a $10m$ buffer zone. However, it cannot tolerate $20m/s$ or higher mobility. Both RNG and SPT-4 can tolerate moderate mobility with a $100m$ buffer zone, but cannot do so with a $10m$ buffer zone. The only exception is SPT-2, which tolerates moderate mobility with a $10m$ buffer zone.

Algorithms using a buffer zone have the same average node degree in their logical topologies. They do, however, have larger transmission ranges. Figure 8 (a) shows that, when a $100m$ buffer zone is used to tolerate moderate mobility, the average transmission ranges of RNG and SPT-4 are above $160m$. On the other hand, the same job is done in SPT-2 with a $10m$ buffer zone and $120m$ average transmission range. The suggestion is that a certain level of redundancy may be necessary for saving energy in MANETs.

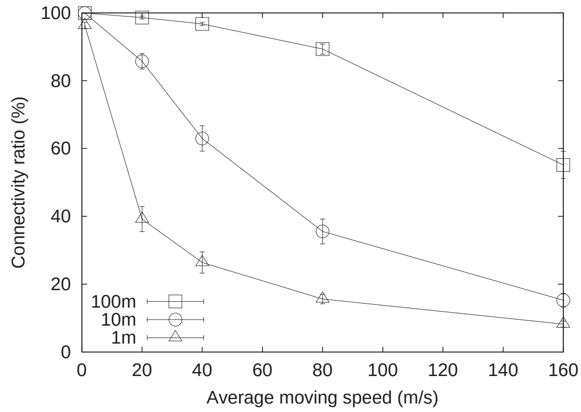
View synchronization. We consider the partitioned logical topology caused by inconsistent local views. When the simple view synchronization mechanism is used together with buffer zones, all pro-



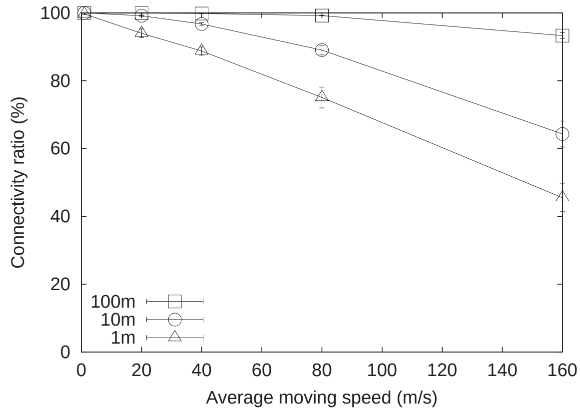
(a) MST



(b) RNG

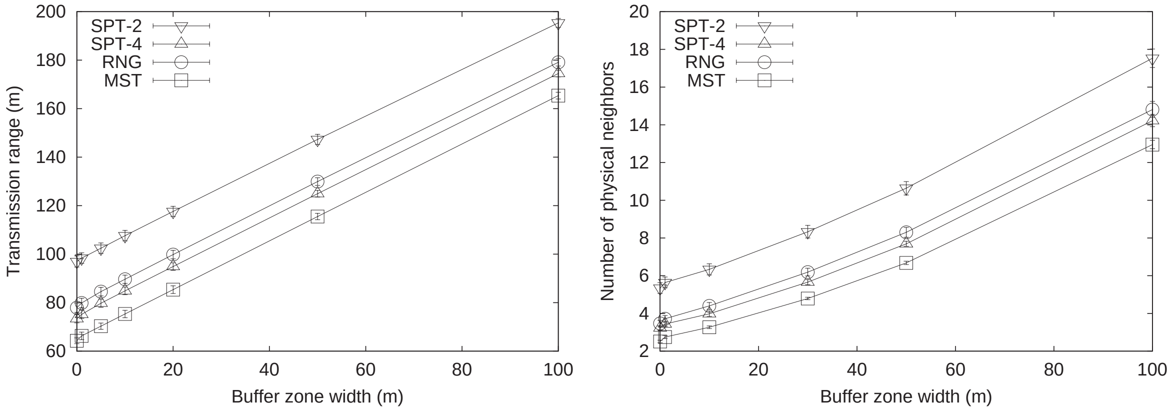


(c) SPT ($\alpha = 4$)



(d) SPT ($\alpha = 2$)

Figure 7. Connectivity ratio with different buffer zone widths.



(a) (b)

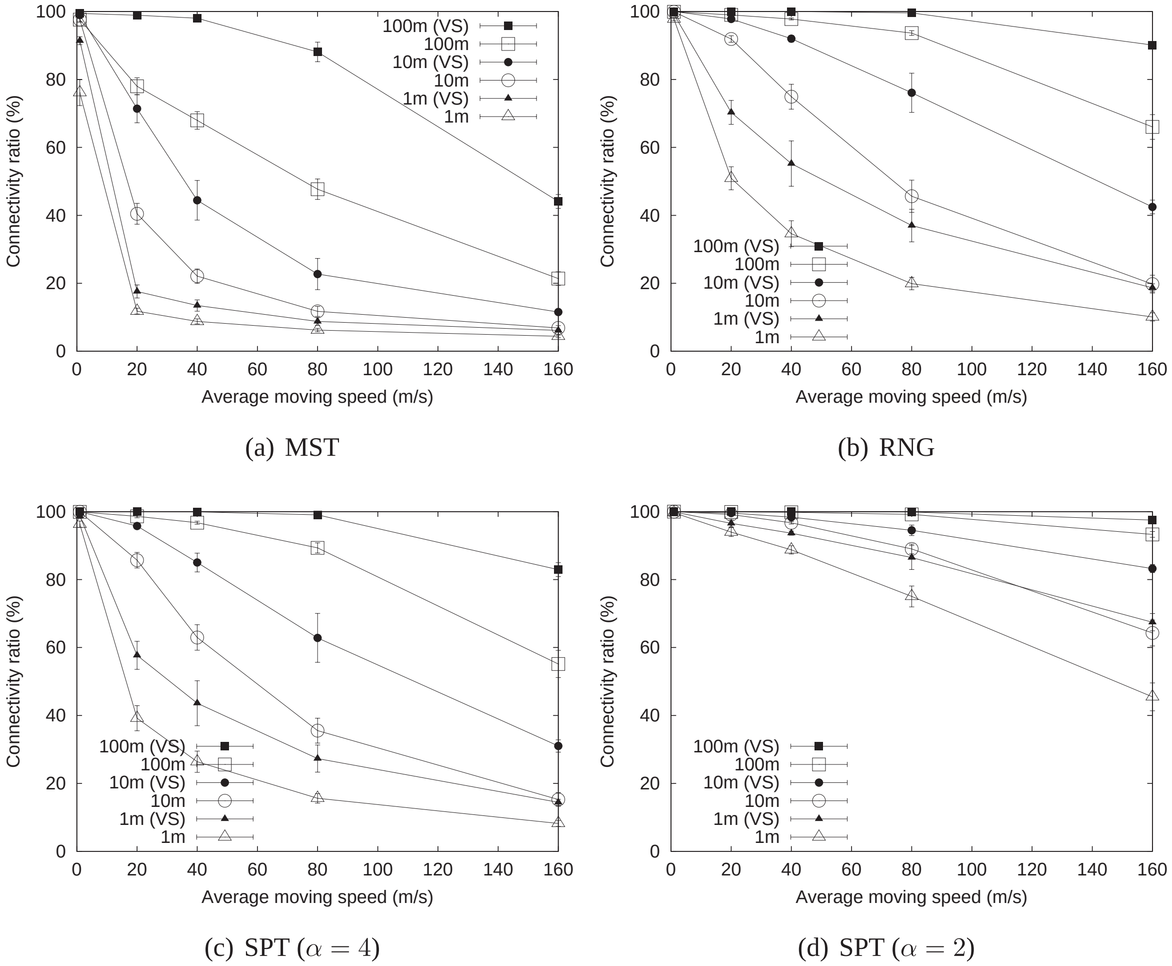
Figure 8. Average transmission range (a) and number of physical neighbors (b) versus buffer zone width.

tocols show solid improvement in connectivity ratios. Figure 9 compares different connectivity ratios achieved with and without view synchronization. With view synchronization (VS), MST can tolerate moderate mobility with a $100m$ buffer zone. RNG can do so with a $10m$ buffer zone. SPT-4 can tolerate $20m/s$ mobility with a $10m$ buffer zone, but still needs a $100m$ buffer zone to tolerate $40m/s$ mobility. SPT-2 can tolerate $40m/s$ mobility with a $1m$ buffer zone, $80m/s$ mobility with a $10m$ buffer zone, and $160m/s$ with a $100m$ buffer zone.

Algorithms using view synchronization have the same average transmission range and node degree as protocols not using this mechanism. RNG is our favorite in this case: it tolerates moderate mobility with $10m$ buffer zone, which corresponds to an average transmission range of $88m$, as shown in Figure 8. Meanwhile, the $1m$ buffer zone width used in SPT-2 corresponds to an average transmission range of $98m$.

Physical neighbor. The connectivity ratio can be improved via relatively high redundancy, i.e., a large neighbor set. An effective method that increases redundancy is to treat all physical neighbors as logical neighbors. That is, the topology control protocol will pass to the upper layer every packet it receives, instead of dropping packets from non-logical neighbors. Asynchronous views are now tolerable, because the resultant logical neighbor sets are only references in computing a small transmission range that maintains connectivity with a high probability. The idea is similar to that in the K-Neigh [2] protocol. The difference is that, in K-Neigh, a uniform optimal number of neighbors is used to decide the transmission power at each node.

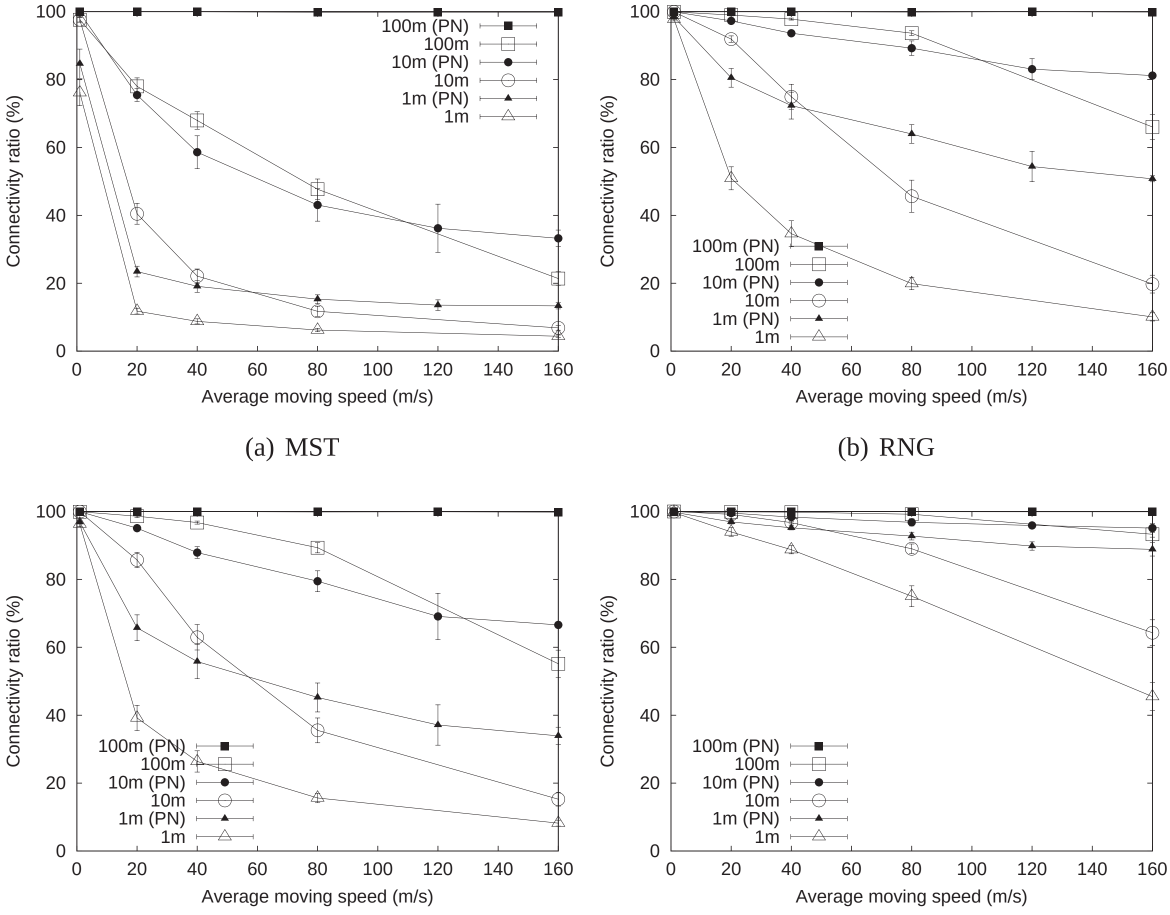
Figure 10 shows the effect of using physical neighbors (PN). The result is similar to the effect of



(a) MST (b) RNG

(c) SPT ($\alpha = 4$) (d) SPT ($\alpha = 2$)

Figure 9. Connectivity ratio with and without view synchronization.



(a) MST (b) RNG

(c) SPT ($\alpha = 4$) (d) SPT ($\alpha = 2$)

Figure 10. Connectivity ratio before and after using physical neighbors.

view synchronization. SPT-2 can tolerate moderate mobility with a $1m$ buffer zone, RNG and SPT-4 can with a $10m$ buffer zone, and MST with a $100m$ buffer zone. Note that, when $100m$ buffer zones are used, every protocol has a perfect connectivity ratio (100%) under extremely high mobility ($160m/s$). Actually, MST achieves 93% connectivity ratio with a $30m$ buffer zone in our simulation. Figure 8 (b) illustrates the increased redundancy. The average node degree that tolerates moderate mobility is 4.7 for MST ($30m$), 4.2 for RNG ($10m$), 3.8 for SPT-4 ($10ms$), and 5.4 for SPT-2 ($1m$). These results are smaller than the optimal node degree in K-Neigh.

Simulation results can be summarized as follows:

1. Many localized topology control protocols suffer from low connectivity ratio in MANETs.

2. The low connectivity ratio is caused by both link failures caused by outdated location information and disconnected logical topology caused by inconsistent local views of neighboring nodes.

3. When a simple view synchronization mechanism is used, RNG and SPT can tolerate moderate mobility ($\leq 40m/s$) with small buffer zones ($\leq 10m$).

4. If all physical neighbors are allowed to forward packets, all protocols can tolerate moderate mobility with average node degrees from 3.8 to 5.4.

6 Conclusion

We have proposed a mobility-sensitive topology control method that extends many mobility-insensitive protocols. This method is based on two mechanisms: local view consistency based on (partially) synchronous and asynchronous "Hello" messages, and buffer zone created by slightly increasing the actual transmission range. These two mechanisms ensure the connectivity of both logical topology and effective topology, two notions proposed in this paper for topology control in dynamic networks. Extensive simulation confirmed the effectiveness of these two mechanisms in maintaining network connectivity under slow and moderate mobility.

In this paper, we are especially interested in maintaining consistent local views that guarantee a connected logical topology. A local view consists of locations of 1-hop neighbors within a normal transmission range. It is collected via exchanging "Hello" messages among neighbors and used to select logical neighbors at each node. We first define strong view consistency based on a formal framework of topology control protocols, and prove that strongly consistent local views guarantee the global connectivity. Two view consistency mechanisms are then proposed to ensure strong view consistency using synchronous and timestamped "Hello" messages. To reduce the maintenance cost, we further introduce the concept of weak view consistency, which can be achieved without any synchronization among neighbors. We show that a wide range of existing topology control protocols can be enhanced to make conservative decisions based on weakly consistent local views, and prove that, using the information carried by two or three recent "Hello" messages from each node, these conservative decisions guarantee a connected logical topology.

Our future work includes exploring other mobility management schemes for a wider spectrum of topology control protocols. For example, it would be interesting to combine mobility-assisted management and mobility-tolerant management to achieve a weak form of connectivity: the snapshot of an effective topology is not connected at every moment, but a message can be delivered within a bounded period of time. We also intend to apply the proposed mobility management scheme to topology control protocols using a dynamic search region [13, 14, 24, 32], where only partial 1-hop information, including direction and distance information of nodes within the current search region, is available. Our simulation study have not considered the effect of message collision. In the future, we plan to obtain more accurate results using a realistic power control MAC layer.

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