View Consistency for Reliable Topology Control in Mobile Ad Hoc Networks

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***Abstract*— In localized topology control protocols for mobile ad hoc networks (MANETs), each node selects a few logical neighbors from its 1-hop neighbors based on its local view, constructed by exchanging periodical "Hello" messages among neighbors, and uses a small transmission range to cover those logical neighbors. Transmission range reduction conserves energy and bandwidth consumption, while still maintaining the network connectivity. However, our recent study showed that the majority of localized topology control protocols are unable to maintain connectivity in MANETs, due to network dynamics such as node mobility. One challenging problem involved is to construct consistent local views for the selection of a correct set of logical neighbors. All existing methods that enforce consistent local views require a certain degree of global synchronization. In this paper, we propose a new mobility management mechanism called *weak consistency* to address this problem. Compared with previous consistency schemes, this new mechanism requires no inter-nodal coordination and incurs no extra overhead. We show that a wide range of localized topology control protocols can be enhanced to ensure correct decisions based on local views that are weakly consistent. It is also proved that two recent "Hello" messages from each node are sufficient to construct weakly consistent local views, when each node updates its local views instantaneously, and three recent "Hello" messages are enough when each node updates its local view once per "Hello" interval.**[1]

I. INTRODUCTION

In mobile ad hoc networks (MANETs), it is important to select an appropriate transmission power for each node, called *topology control*, to reduce energy consumption and signal interference while still maintaining network connectivity. Most existing topology control protocols use the localized approach [1], [2], [3], [4], [5], [6], [7]: Each node collects its 1-hop information through periodic, asynchronous "Hello" messages, which forms its *local view*. Each node selects a few logical neighbors from its 1-hop neighbors based on its local view. The collection of logical links (i.e., links between logical neighbors) forms the *logical topology*. The logical topology is connected as long as the original network is connected under a (long) normal transmission range, and all nodes use consistent local views. Each node then sets its (short) actual transmission range to be the distance to the farthest logical neighbor.

The majority of existing localized topology control protocols assume a static network without mobility. Our recent study on mobility-sensitive topology control [8] showed that these protocols cannot maintain connectivity in MANETs, either because insufficient actual transmission ranges are computed based on outdated location information, or because insufficient logical neighbors are selected due to inconsistent local views. In [8], the problem of outdated location information was solved by slightly increasing the actual transmission range. The problem of view inconsistency is more challenging. It was proposed in [8] to enforce consistent local views using (loosely) synchronized "Hello" messages. The basic idea is to force all local views to use the same version of "Hello" messages from each node. The major drawback of this (strong) consistency mechanism is the extra overhead. In order to orchestrate "Hello" messages to construct consistent local views, a certain degree of global synchronization is required, which becomes costly in large scale networks.

To erase the above difficulty, we propose a new mechanism, called *weak consistency*, to preserve connectivity. In weakly consistent local views, several most-recent "Hello" messages from each node are maintained, and no inter-nodal synchronization is required. The original topology control protocols are enhanced to make the correct decisions based on this (possibly conflicting) history information. This method maintains connectivity by slightly increasing the number at logical neighbors. In this paper, we review several popular localized topology control schemes using a general framework, formally define the notion of view consistency, and prove topology connectivity guaranteed by consistent views. We divide localized topology control schemes into two categories: those using only link cost in their decision making (called *cost-based schemes*), and those using node location information and properties of 2-D geometric graphs (called *location-based schemes*). For each category, we give a formal definition of weak consistency and enhanced topology control schemes that guarantee connectivity. A simple method has been introduced to construct weakly consistent views using multiple "Hello" messages from each node. We prove that two or three recent "Hello" messages are sufficient under normal circumstances.

II. LOCALIZED TOPOLOGY CONTROL

In a localized topology control protocol, each node advertises its ID and location in periodic "Hello" messages. We

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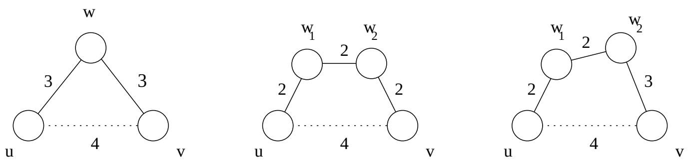
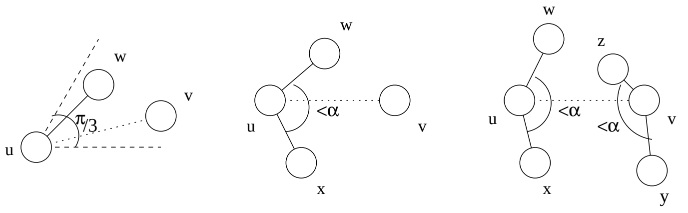


(a) RNG (b) LSPT (c) LMST

Fig. 1. Cost-based link removal. Numbers are link distances. Dotted links can be removed by applying corresponding link removal conditions.



(a) Yao Graph (b) CBTC, α=2π/3 (c) CBTC, α=5π/6

Fig. 2. Location-based link removal conditions. Dotted links can be removed by applying corresponding link removal conditions.

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 are asynchronous. 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 $[t - \Delta, t]$. 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 detected via “Hello” exchanges. We assume the network is sufficiently dense, such that the original topology is always connected.

Each node constructs its local view of its 1-hop neighbors in the original topology, and runs the topology control algorithm to determine its logical neighbor set. Given an original topology G, all topology control algorithms can be viewed as a 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. A link (u, v) can be removed only by its end nodes u and v, when a certain link removal condition is satisfied; otherwise, nodes u and v are logical neighbors.

A. Cost-based link removal

In cost-based link removal conditions [2], [3], [4], [5], each link (u, v) is given a cost $c_{u,v}$, which is a function of the geographical distance $d_{u,v}$ between nodes u and v.

The relative neighborhood graph (RNG) condition [5] has been used in several topology control protocols [9], [10]. In Figure 1 (a), link (u, v) can be removed by the RNG condition, because $c_{u,v} > \max\{c_{u,w}, c_{w,v}\}$.

RNG condition: A link (u, v) can be removed if a path (u, w, v) exists such that $c_{u,v} > \max\{c_{u,w}, c_{w,v}\}$.

The minimal energy topology control protocols [2], [4] preserve all shortest paths using transmission power as link cost, i.e., $c_{u,v} = d^{\alpha}_{u,v} + c$. The link removal process is equivalent to constructing a local shortest path tree and removing all non-SPT links from the original topology. Figure 1 (b) shows an example of the LSPT condition with $\alpha = 2$ and $c = 0$.

LSPT condition: A link (u, v) can be removed if a path $(u, w_1, w_2, \ldots, w_k, v)$ exists such that $c_{u,v} > c_{u,w_1} + c_{w_1,w_2} + \ldots + c_{w_k,v}$.

In the local minimal spanning tree (LMST) protocol [3], each node builds an LMST and removes all non-MST links. As shown in Figure 1 (c), when nodes u and v are connected via an alternative path (u, w_1, w_2, v) with $c_{u,v} > \max\{c_{u,w_1}, c_{w_1,w_2}, c_{w_2,v}\}$, link (u, v) is a non-MST link and can be removed.

LMST condition: A link (u, v) can be removed if a path $(u, w_1, w_2, \ldots, w_k, v)$ exists such that $c_{u,v} > \max\{c_{u,w_1}, c_{w_1,w_2}, \ldots, c_{w_k,v}\}$.

B. Location-based link removal

Location-based conditions [1], [6], [7] use both distance information and the direction dir_v of each neighbor v. As geometrical properties are used to prove the correctness of these protocols, the distance and direction information must be consistent with a node placement scheme in order to preserve connectivity.

In Yao graph [6], a disk centered at node u is evenly divided into K sectors with width $2\pi/K$. In each sector, only one node, which is the closest to u in this sector, is selected as a logical neighbor. Here $\lfloor \frac{dir_v}{\pi/3} \rfloor$ is the sector ID of node v. In Figure 2 (a), link (u, v) is removed because nodes v and w are in the same $\pi/3$ sector, and w is closer to u.

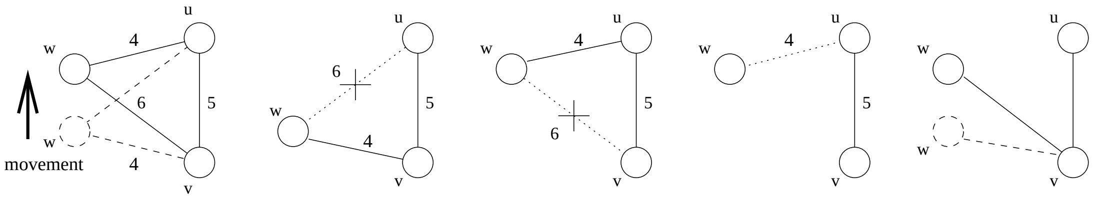
Yao condition: A link (u, v) can be removed if a node w exists such that $\lfloor \frac{dir_v}{\pi/3} \rfloor = \lfloor \frac{dir_w}{\pi/3} \rfloor$ and $d_{u,v} > d_{u,w}$.

In cone-based topology control (CBTC) [1], [7], each node u selects its logical neighbor set $\{w_1, w_2, \ldots, w_k\}$ such that the following condition holds: If a disk centered at u is divided into k cones by lines uw_i $(1 \le i \le k)$, the angle of the maximal cone is less than α. In addition, the logical neighbor set is *self-inclusive*: If v is a logical neighbor of u, all nodes w with distance $d_{u,w} \le d_{u,v}$ are also logical neighbors of u. There are two variations of CBTC. In the first variation, called CBTC($2\pi/3$), $\alpha = 2\pi/3$ and a link (u, v) can be removed by one end node u. Link (u, v) in Figure 2 (b) can be removed in CBTC($2\pi/3$), because v is within a cone $\angle wux \le 2\pi/3$.

CBTC($2\pi/3$) condition: A link (u, v) can be removed if two nodes w and x exist such that $dir_w \ge dir_v \ge dir_x$, $dir_w - dir_x < 2\pi/3$, and $d_{u,v} > \max\{d_{u,w}, d_{u,x}\}$.

In the second variation, CBTC($5\pi/6$), $\alpha = 5\pi/6$ and a link (u, v) cannot be removed by a single end node, but must be removed jointly by both end nodes u and v. Link (u, v) in Figure 2 (c) can be removed based in CBTC($5\pi/6$), because both end nodes u and v consider it removable.

CBTC($5\pi/6$) condition: A link (u, v) can be removed if (1) two nodes w and x exist in u's local view such that $dir_w \ge dir_v \ge dir_x$, $dir_w - dir_x < 5\pi/6$, and $d_{u,v} > \max\{d_{u,w}, d_{u,x}\}$, and (2) two nodes y and z exist in v's local view such that $dir_y \ge dir_u \ge dir_z$, $dir_y - dir_z < 5\pi/6$, and $d_{v,u} > \max\{d_{v,y}, d_{v,z}\}$.



(a) w's positions at t1 and t2 (b) u's local view before t2 (c) v's local view after t2 (d) logical topology at t' (e) using consistent views

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

III. STRONG VIEW CONSISTENCY

A. Inconsistent views and network partition

At each moment t, "Hello" messages sent and received during time period $[t - \Delta, t]$ form the *local view*. In Figure 4 (a), three nodes sample their local views at different times (represented by black dots). Note that local times at different nodes $(t_0, t_1, t_2, \ldots)$ are asynchronous. All nodes use the latest "Hello" messages (represented by white dots) to construct their local views. The corresponding local views of node u and v are shown in Figures 3 (b) and (c).

Our objective is to maintain connectivity for a given *observation period* $[t, t+d]$: if an external observer visits each node at a randomly selected time during the observation period and collects it adjacent logical links, all these logical links form a connected topology. If the routing process of a data packet is no longer than d, then the above definition guarantees a persistant path from the source to the destination. Local views of all nodes, used to select their logical neighbors, form a global state of a distributed computation (i.e., a cut [11]). Due to the lack of globally synchronous clocks, local views in the same cut are sampled at different times. We define the *maximal cut width* δ as the maximal difference between sampling times of two local views in the same cut. Depending on the sampling strategy, δ may be larger than d.

In a MANET, any non-zero δ may cause inconsistent local views. We use the RNG condition to illustrate the partition problem caused by inconsistent views. Suppose node w in Figure 3 (a) moves upward and advertises its location twice at time t_1 and t_2 (local times of w), respectively. When node u applies the RNG condition before t_2, link (u, w) is removed because $c_{u,w} > \max\{c_{u,v}, c_{v,w}\}$ in u's local view (Figure 3 (b)). After t_2, node v removes link (v, w) because $c_{v,w} > \max\{c_{u,v}, c_{u,w}\}$ in its local view (Figure 3 (c)). The corresponding logical topology at $t' > t_2$ is disconnected (Figure 3 (d)).

B. Strong view consistency

For a given local view of node u, a subgraph $G_u = (V_u, E_u)$ of the original topology can be constructed, where V_u contains u and its 1-hop neighbors under the normal transmission range r, and E_u consisting of links (v, w) for all $v, w \in V_u$ with $d_{v,w} \leq r$. We define strong view consistency as follows.

Definition 1: Local views in a cut are (strongly) consistent if, for each node u, the same location of u is observed in local views of all u's neighbors.

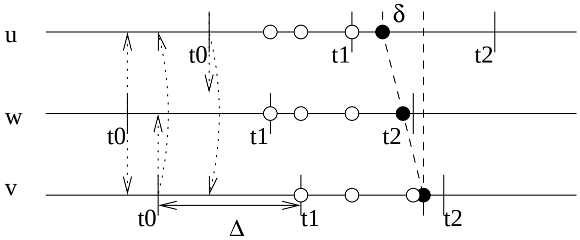


Fig. 4. Time-space view of the example in Figure 3 (a). Short vertical bars mark transmission times of "Hello" messages at each node. Dashed arrows illustrate the first round of "Hello" exchanges among neighbors.

When local views in a cut are strongly consistent, the corresponding logical topology is connected. As shown in Figure 3 (e), when both u and v get w's location from the older "Hello" message sent at t_1 (marked by the dashed circle), only link (u, w) will be removed and the logical topology is connected. The proof of the following theorem is omitted due to lack of space.

Theorem 1: Applying a link removal condition based on consistent local views preserves connectivity.

In Figure 4, local views of u and v are inconsistent because the cut "crosses" one of w's "Hello" messages. Local views sampled before this "Hello" message contain the former location of w, while local views sampled after this message contain the latter location of w.

IV. WEAK VIEW CONSISTENCY

Several methods were discussed in [8] which avoid a cut crossing a "Hello" message in order to maintain strong view consistency. However, all these methods require a certain degree of global synchronization, which may cause a performance penalty in large scale networks. We propose to maintain *weak consistency* for making conservative decisions based on totally asynchronous local views. In this section, we give a systematic scheme 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.

A. Weak consistency in cost-based algorithms

When enforcing weak consistency among local views, each local view contains k recent "Hello" messages of each neighbor. The value of k depends on the "Hello" interval Δ and maximal cut width δ. Figure 5 shows an example where the

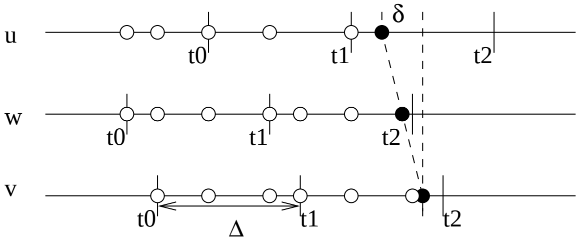


Fig. 5. Constructing weakly consistent local views.

local view of each node contains two recent "Hello" messages sent by itself and each 1-hop neighbor. We propose enhanced link removal conditions that exploit this history information to preserve connectivity. For clarity, this subsection discusses only cost-based conditions. Location-based conditions will be discussed in the next subsection.

When applying cost-based conditions, the cost $c_{u,v}$ of each link (u, v) is computed from the locations of nodes u and v. With multiple locations for each node stored in different "Hello" messages, several costs will be computed for each link. 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 and c_e^{Min} the minimal cost in C_e. Then we enhance the original link removal conditions as follows.

Enhanced cost-based link removal conditions: A link (u, v) can be removed only if

- (**RNG**) a path (u, w, v) exists such that $c_{u,v}^{Min} > \max\{c_{u,w}^{Max}, c_{w,v}^{Max}\}$,
- (**LSPT**) a path $(u, w_1, w_2, \ldots, w_k, v)$ exists such that $c_{u,v}^{Min} > c_{u,w_1}^{Max} + c_{w_1,w_2}^{Max} + \ldots + c_{w_k,v}^{Max}$, or
- (**LMST**) a path $(u, w_1, w_2, \ldots, w_k, v)$ exists such that $c_{u,v}^{Min} > \max\{c_{u,w_1}^{Max}, c_{w_1,w_2}^{Max}, \ldots, c_{w_k,v}^{Max}\}$.

Consider the case when the enhanced RNG is applied to the MANET in Figure 3 (a). Each node builds its local view based on two recent "Hello" messages from each node, as shown in Figure 5. In u's local view sampled before t_2, $C_{u,w} = \{6\}$, $C_{u,v} = \{5\}$, and $C_{v,w} = \{4\}$. Link (u, w) is removed because $c_{u,w}^{Min} > \max\{c_{u,v}^{Max}, c_{v,w}^{Max}\}$. In v's local view sampled after time t_2, $C_{u,w} = \{4, 6\}$, $C_{u,v} = \{5\}$, and $C_{v,w} = \{4, 6\}$. Link (v, w) is preserved because $c_{v,w}^{Min} < c_{u,w}^{Max}$. The final logical topology consisting of link (u, v) and (u, w) is connected.

Let c_e^{MinMax} be the minimal c_e^{Max} and c_e^{MaxMin} be the maximal c_e^{Min} in local views of all nodes, the following definition gives a sufficient condition for preserving logical topology connectivity in the above enhanced cost-based link removal conditions.

Definition 2: Local views of the original topology $G = (V, E)$ are weakly consistent with respect to enhanced cost-based link removal conditions 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 $\{4, 6\}$ in v's local view, $c_e^{MaxMin} = 4$, $c_e^{MinMax} = 3$, and the two local views are weakly inconsistent. Note that strongly consistent local views are always weakly consistent.

Theorem 2: Applying enhanced cost-based link removal conditions based on weakly consistent local views preserves connectivity.

Proof: Let E_R be 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 links have larger maximal minimal costs than $c_{u,v}^{MaxMin}$, no link of P has been removed yet. Therefore, nodes u and v are still connected via path P, which contradicts the assumption that removing (u, v) causes a partition. ■

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 the number of "Hello" messages from each node that is needed to build weakly consistent local views with respect to cost-based link removal conditions is $k = \lceil \frac{\delta}{\Delta} \rceil + 1$.

Proof: Let t be the starting time of a cut; that is, the first local view is sampled at time t. The last local view is sampled at time $t + \delta$. For any 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, we have $k = \lceil \frac{\delta}{\Delta} \rceil + 1$. ■

We consider two view updating strategies. When using the *instantaneous updating strategy*, each node updates its local view (and hence recomputes its set of logical neighbors) whenever it receives a new "Hello" message. In this case, the maximal cut width $\delta = d$, where $d \ll \Delta$ is the maximal end-to-end routing delay (the observation period). When using the *periodical updating strategy*, each node updates its local view once per "Hello" interval, and $\delta = \Delta + d < 2\Delta$. The following corollary holds, assuming reliable "Hello" message delivery. 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.

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.

B. Weak consistency for location-based algorithms

The weak consistency definition for cost-based conditions is not sufficient for a location-based scheme, because both link distance and relative node direction are involved in selecting logical neighbors. As each node may have multiple locations in each local view, multiple distances may be computed for each link, and multiple directions for each neighbor in each local view. Again, in each local view, we define $d_{u,v}^{Max}$ ($d_{u,v}^{Min}$) as the maximal (minimal) distance between nodes u and v, and dir_u^{Max} (dir_u^{Min}) the maximal (minimal) relative direction of a neighbor u. Using these notations, we enhance location-based link removal conditions to preserve connectivity, and provide the corresponding definition of weak consistency.

Enhanced location-based link removal conditions: A link (u, v) can be removed only if

- (**Yao condition**) for each sector $i \in [\lfloor \frac{dir_v^{Min}}{\pi/3} \rfloor, \lfloor \frac{dir_v^{Max}}{\pi/3} \rfloor]$, there exists a node w_i such that $\lfloor \frac{dir_w^{Max}}{\pi/3} \rfloor = \lfloor \frac{dir_w^{Min}}{\pi/3} \rfloor = i$ and $d_{u,v}^{Min} > d_{u,w_i}^{Max}$.
- (**CBTC($2\pi/3$) condition**) two nodes w and x exist such that $dir_w^{Min} \geq dir_v^{Max}$, $dir_v^{Min} \geq dir_x^{Max}$, $dir_w^{Min} - dir_x^{Max} < 2\pi/3$, and $d_{u,v}^{Min} > \max\{d_{u,w}^{Max}, d_{u,x}^{Max}\}$.
- (**CBTC($5\pi/6$) condition**) (1) two nodes w and x exist in u's local view such that $dir_w^{Min} \geq dir_v^{Max}$, $dir_v^{Min} \geq dir_x^{Max}$, $dir_w^{Min} - dir_x^{Max} < 5\pi/6$, and $d_{u,v}^{Min} > \max\{d_{u,w}^{Max}, d_{u,x}^{Max}\}$, and (2) two nodes y and z exist in v's local view such that $dir_y^{Min} \geq dir_u^{Max}$, $dir_u^{Min} \geq dir_z^{Max}$, $dir_y^{Min} - dir_z^{Max} < 5\pi/6$, and $d_{v,u}^{Min} > \max\{d_{v,y}^{Max}, d_{v,z}^{Max}\}$.

Definition 3: Local views of the original topology $G = (V, E)$ are weakly consistent with respect to enhanced location-based link removal conditions if for each $u \in V$, at least one common location of u appears in local views of all u's neighbors.

Compared with the cost-based definition, the above location-based definition of weak consistency requires the exact locations of neighboring nodes. This is because location-based link removal conditions depend on the properties of 2-D geometric graphs, especially those regarding the angles and edge lengths of a triangle. The previously used maximal/minimal concepts are insufficient to ensure connectivity in these conditions. The following theorem uses a stronger definition of connected original topology: if we construct a virtual network by arbitrarily selecting a location for each node, which is one of the multiple locations advertised within a cut, the resultant network is always connected. This is a reasonable assumption in a dense network with a relatively small cut width. The proof is omitted due to the lack of space.

Theorem 4: Applying enhanced location-based link removal conditions based on weakly consistent local views preserves connectivity.

Note that Theorem 4 also guarantees the connectivity of logical topology in cost-based schemes. However, this theorem does not render Theorem 2 useless. Theorem 2 guarantees connectivity based on a weaker assumption, which provides more flexibility in the implementation of those schemes.

Theorem 5: The number of "Hello" messages required from each node to build weakly consistent local views with respect to location-based link removal conditions is $k = \lceil \frac{\delta}{\Delta} \rceil + 1$.

Obviously, Corollary 1 also applies to location-based topology control schemes. That is, weak consistency is guaranteed when there are two or three recent "Hello" messages for local view construction.

V. CONCLUSION

This paper introduces a new mechanism called weak consistency that preserves connectivity in localized topology control protocols, where each node makes independent decisions based on its local view to select a small set of logical neighbors and adjust its transmission range accordingly. Compared to previous view consistency mechanisms in [8], constructing weakly consistent local views require no global synchronization and has very low overhead. We also show that a wide range of existing topology control protocols can be enhanced to make conservative decisions based on asynchronous "Hello" messages, 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 in most scenarios.

REFERENCES

[1] L. Li, J. Y. Halpern, V. Bahl, Y. M. Wang, and R. Wattenhofer, "Analysis of a cone-based distributed topology control algorithm for wireless multi-hop networks," in *Proc. of PODC*, Aug. 2001, pp. 264–273.

[2] L. Li and J. Y. Halpern, "Minimum energy mobile wireless networks revisited," in *Proc. of ICC*, June 2001, pp. 278–283.

[3] N. Li, J. C. Hou, and L. Sha, "Design and analysis of an MST-based topology control algorithm," in *Proc. of INFOCOM*, Mar./Apr. 2003, vol. 3, pp. 1702–1712.

[4] V. Rodoplu and T. H. Meng, "Minimum energy mobile wireless networks," *IEEE Journal of Selected Areas in Communications*, vol. 17, no. 8, pp. 1333–1344, Aug. 1999.

[5] G. Toussaint, "The relative neighborhood graph of finite planar set," *Pattern Recognition*, vol. 12, no. 4, pp. 261–268, 1980.

[6] Y. Wang, X. Li, P. Wan, and O. Frider, "Distributed spanners with bounded degree for wireless ad hoc networks," *International Journal of Foundations of Computer Science*, vol. 14, no. 2, pp. 183–200, 2003.

[7] R. Wattenhofer, L. Li, V. Bahl, and Y. M. Wang, "Distributed topology control for power efficient operation in multihop wireless ad hoc networks," in *Proc. INFOCOM*, Apr. 2001, pp. 1388–1397.

[8] J. Wu and F. Dai, "Mobility-sensitive topology control in mobile ad hoc networks," in *Proc. of IPDPS*, Apr. 2004, pp. 502–509.

[9] J. Cartigny, D. Simplot, and I. Stojmenović, "Localized minimum-energy broadcasting in ad-hoc networks," in *Proc. of INFOCOM*, Mar./Apr. 2003, vol. 3, pp. 2210 –2217.

[10] M. Seddigh, J. Solano, and I. Stojmenović, "RNG and internal node based broadcasting in one-to-one wireless networks," *ACM Mobile Computing and Communications Review*, vol. 5, no. 2, pp. 37–44, Apr. 2001.

[11] M. Singhal and N. G. Shivaratri, *Advanced concepts in operating systems, Distributed, database, and multiprocessor operating systems*, McGraw-Hill, Inc., 1994.