# Mobility Control and Its Applications in Mobile Ad Hoc Networks *

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## Abstract

*Most existing localized protocols in mobile ad hoc networks (MANETs), such as data communication and topology control, use local information for decentralized decision among nodes to achieve certain global objectives. These objectives include determining a small connected dominating set (CDS) for virtual backbone and topology control by adjusting transmission ranges of nodes. Because of asynchronous sampling of local information at each node, delays at different stages of protocol handshake, and movement of mobile nodes, local view captured at different nodes may be* inconsistent *and/or* outdated *and may not reflect the actual network situation. The former may cause "bad" decisions that fail to keep the given global constraint such as global domination and connectivity, and the latter may incur "broken" links which in turn will ultimately cause the failure of the constraint. In this paper, we review some techniques that handle inconsistent and outdated local views. These techniques are illustrated using several well-known protocols in data communication and topology control.*

**Keywords**: *Connectivity, connected dominating set (CDS), mobile ad hoc networks (MANETs), mobility management, simulation, topology control.*

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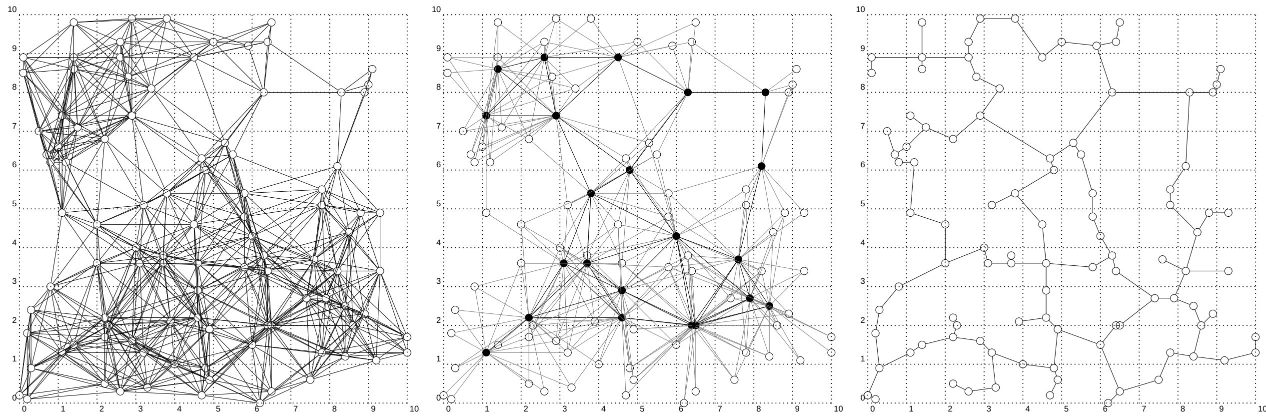
## 1 Introduction

In mobile ad hoc networks (MANETs), all nodes cooperate to achieve a global task, such as data gathering, communication, and area monitoring. MANETs are characterized by unit disk graphs where two nodes are connected only if their geographical distance is within a given transmission range (as shown in Figure 1 (a) where the transmission range is 2.5). To design protocols that are simple and quick to converge, many protocols in MANETs rely on *localized algorithms*. The localized algorithm running at each node makes its local decision based on local information within 1 or 2 hops. Collectively, nodes running the localized algorithm achieve some desirable global objectives. Two widely-used applications of the localized algorithm are (1) determining a connected dominating set (CDS) for efficient routing [1, 3, 5, 10], and (2) selecting an appropriate transmission range of each node for topology control [2, 4, 6, 7].

A connected dominating set (CDS) is a subset such that each node in the system is either in the set or the neighbor of a node in the set. The CDS has been used widely to support the notion of *virtual backbone* in MANETs. Another application of CDS is in broadcasting, where nodes and only nodes in the CDS forward the broadcast message to reduce message collision. However, finding a minimum CDS is NP-complete. Most practical approaches in MANETs use localized algorithms to find a small CDS. In a typical localized CDS protocol, each node uses local information to determine its status, *dominator* or *dominatee*. Figure 1 (b) shows a CDS constructed via a localized algorithm [1]. In this diagram the connections between dominatees are not shown. As dominators (black nodes) form a backbone of the MANET, any dominatee (white node) can switch to the sleep mode for energy saving without causing network partition. Most localized CDS algorithms rely on 2-hop information of the current node $v$, which includes information of $v$'s neighbors and neighbors of $v$'s neighbors.

In MANETs, in order to reduce energy consumption and signal interference, it is important to select an appropriate transmission power for each node, also called *topology control*, while still satisfying certain global constraints, including connectivity and other reliability and throughput related measures. In localized topology control, each node uses local information to select a subset of physical neighbors, called *logical neighbors*, and its transmission range is reduced to reaching only as far as the farthest logical neighbor. Figure 1 (c) shows the result of a localized topology control algorithm [2], where both the average number of neighbors and transmission range are reduced significantly, while the network is still connected. Localized topology control algorithms usually rely on 1-hop location information of the current node $v$, which includes information of $v$'s neighbors and their location information. Some algorithms require less information where distance or angle of arrival information of neighbors is sufficient.

Compared with their centralized counterparts, localized algorithms are lightweight, fast to converge, and resilient to node movement. However, without a mobility control mechanism, global domination and connectivity may still be compromised by node movement. In most existing localized algorithms, each node in a MANET emits a periodic "Hello" message to advertise its presence and its position (if needed) at a fixed interval $\Delta$. "Hello" intervals at different nodes are asynchronous to reduce message collision. Each node uses received "Hello" messages as samples to construct a local view of its 1- or 2-hop neighborhood. In a




(a) The original network

(b) Connected dominating set

(c) Topology control

**Figure 1. Virtual networks constructed via localized algorithms. The original MANET has 100 nodes and a transmission range of 2.5.**

MANET with mobile nodes, the limited sample frequency, asynchronous "Hello" intervals, and delays at different stages of protocol handshake will cause a mismatch between the *virtual network* constructed from the collection of local views sampled at different nodes and the *actual network*. This mismatch will cause the *link availability* issue, where a neighbor in a virtual network is no longer a neighbor in the actual network, because the virtual network is constructed from *outdated* information. Therefore, special mechanisms are needed to address the following issue:

- *Delay and mobility management*: How protocols deal with imprecise neighborhood information caused by node mobility and various delays introduced at different stages of protocol handshake.

One solution in [8], as will be discussed later in detail, uses two transmission ranges to address the link availability issue. First, a transmission range $r$ is determined based on the selected protocol. This transmission range is either the same as the "Hello" message range $r^{'}$ as in the CDS protocol or shorter than $r^{'}$ as in the topology control protocol. The actual transmission uses a long transmission range set to $r + l$. The difference, $l$, between these two ranges is based on the update frequency and the speed of node movement.

The mismatch between the virtual network and actual network will cause a more serious problem: *inconsistent local views*. Inconsistent local views may cause "bad" decisions that fail to keep the the global constraint such as global domination and connectivity. Again, special mechanisms are needed to address the following issue:

- *Node synchronization and consistent local view*: How each node knows when to sample its local view. How each node collects and uses the local information in a consistent way.

We will examine two different approaches that address the consistency issue: enforcing consistent views and making conservative decisions. The first approach was initially proposed in [9] to construct consistent 1-hop information for topology control. This approach can also be extended to support the construction of 2-hop information. The second approach was originally proposed in [8] for CDS formation. But the same principle can be used in topology control.

The main objective of this paper is to expose to the reader the challenging issue related to mobility control. Through discussion on the effect of mobile nodes on several important protocols, we present some problems, provide possible solutions, and discuss several open issues. By this, we hope to stimulate more research in this important area.

## 2 Link availability issue and solution

In MANETs, because of asynchronous "Hello" messages and various protocol handshake delays, neighborhood information and/or position used in decision making may be outdated. For example, a previously sampled neighbor can move out of transmission range during the actual transmission. In order to apply existing protocols without having to redesign them, the notion of *buffer zone* is used in [8], where two circles with radii $r$ and $r + l$ are used. $r$ corresponds to the transmission range determined by a selected protocol, whereas $r + l$ corresponds to the actual transmission range used. $l = d \times 2t$ is defined as a buffered range depending on the moving speed $t$ of mobile nodes and the maximum time delay $d$. To simplify the discussion, both "Hello" intervals and moving patterns/speeds are homogeneous, and hence, $l$ is uniform for each node.

The above requirement of buffered range guarantees link availability in the worst case situation. However, probabilistic study in [8] reveals that the worst case rarely happens. In MANETs with very high moving speed ($t$), it is either impossible or too expensive to use such a large $l$. Both probabilistic analysis and simulation results in [8] show that link availability is preserved in most cases with a buffered range much smaller than $d \times 2t$. There is a wide range of potential trade-offs between efficiency and connectivity.

Specifically, suppose $r^{'}$ is the normal "Hello" message range. A typical CDS protocol works as follows:

1. Select $r = r^{'}$ for neighborhood information exchange.

2. Apply the selected localized CDS protocol to determine the status of each node.

3. Use $r + l$ for each dominator in the actual transmission.

Step 2 of the above process varies from protocol to protocol. Here we use Wu and Li's marking process and Rules 1 and 2 [10] to illustrate:

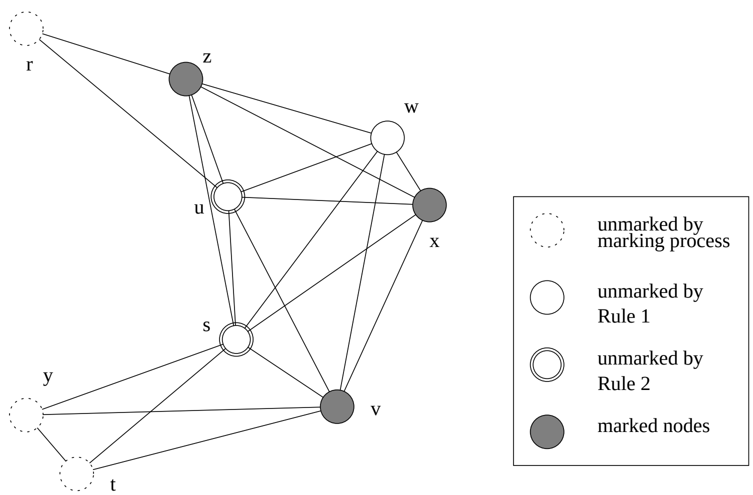



**Figure 2. Wu and Li's CDS algorithm. Black nodes are marked (i.e., in the CDS).**

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At each node $u$:

- Marking Process: $u$ is marked true (i.e., becomes a dominator) if there are two unconnected neighbors.
- Rule 1: $u$ is unmarked (i.e., becomes a dominatee) if its neighbor set is covered by another node with a higher id.
- Rule 2: $u$ is unmarked if its neighbor set is covered jointly by two connected nodes with higher id's.

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In Rules 1 and 2, we say $u$'s neighbor set, $N(u)$, is *covered* by one or two *covering* nodes, if every node $w$ in $N(u)$ is either a covering node or a neighbor of a covering node. Figure 2 shows a sample ad hoc network with 9 nodes. Node $r$ is unmarked by the marking process because its neighbors $u$ and $z$ are directly connected. Node $w$ is unmarked by Rule 1 because its neighbor set is covered by node $x$. Here node id $x$ is higher than $w$ according to the alphabetical order. Node $u$ is unmarked by Rule 2 because its neighbor set is covered by two connected nodes $x$ and $z$. Clearly, the marked nodes $v$, $x$, and $z$ form a CDS of the sample network.

Originally, Rules 1 and 2 use only marked nodes as covering nodes, and involve overhead in communicating dominating set status. Stojmenovic et al [5] showed that unmarked nodes can also be covering nodes, and there is no need to exchange dominating set status. Dai and Wu's [1] proposed a generalized rule (called Rule $k$) to construct a smaller CDS. Based on the generalized rule, $u$ is unmarked if its neighbor set is covered by several connected nodes with higher id's. The number of the covering nodes is allowed to be more than two.

When the network is static or local views are consistent (say, all nodes see only solid line) in Figure 3, both nodes $u$ and $v$ are marked after the marking process. $u$ will be unmarked using Rule 1.

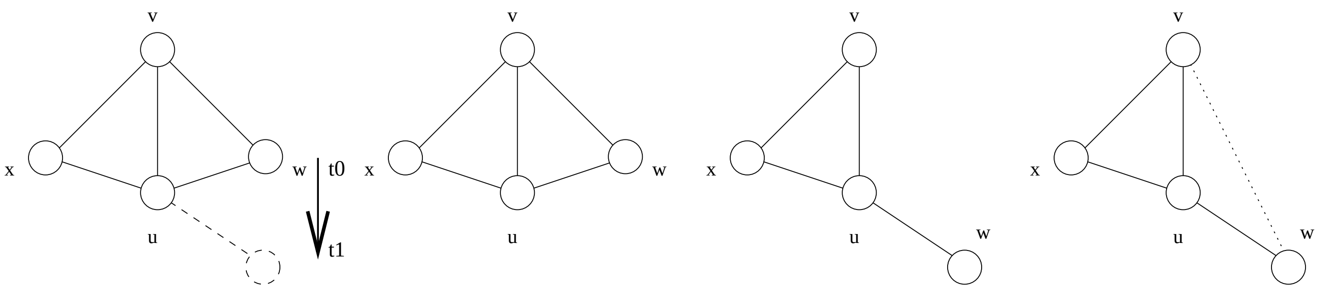


**Figure 3. As node $w$ moves away from node $v$ (a), both nodes $u$ and $v$ are unmarked due to inconsistent local views sampled at nodes $u$ and $v$ (b,c). Based on the conservative view, node $v$ is still marked for a little while after it detected the broken link $(v, w)$. The dotted line represents a virtual link in $v$'s view.**

A typical topology control protocol works as follows:

1. Select $r'$ to collect neighborhood information.
2. Apply a selected localized topology control protocol to select $r(u)$, $r(u) \leq r'$, for node $u$ to cover its farthest logical neighbor.
3. Use $r(u) + l$ for the actual transmission.

We use Li, Hou, and Sha's topology control algorithm based on local minimum spanning tree (MST) [2] to illustrate step 2 of the above process.

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At each node $u$:

1. Build a local MST using Prim's algorithm based on 1-hop location information. The resultant MST covers all 1-hop neighbors of $u$.
2. Select neighbors in MST as logical neighbors of $u$.
3. Set the transmission range of $u$ to the distance to the farthest logical neighbor.

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When the network is static or local views are consistent (say, all nodes see only solid line) in Figure 4 (a), the MST includes two links $(u, v)$ and $(w, v)$. Node $u$ has one logical neighbor $v$ and sets its range to $4$. Node $w$ has one logical neighbor $v$ and sets its range to $5$. Node $v$ has two logical neighbors $u$ and $w$ and sets its range to $5$ to reach the farthest node $w$.

When the network contains mobile nodes, such as node $w$ in Figure 4, the transmission range of each node is increased to maintain the link availability. For example, if it is known that the maximum relative

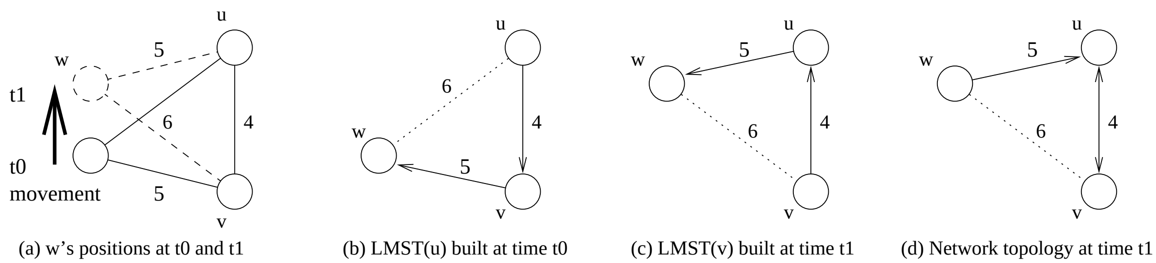



**Figure 4. Node $w$ becomes unreachable from nodes $u$ and $v$ due to inconsistent local views sampled at nodes $u$ and $v$.**

movement between two nodes during one "Hello" interval is $l = 2$, then the actual transmission range of nodes $u$, $v$, and $w$ are adjusted to 8, 7, and 8, respectively. Therefore, link $(v, w)$ is still available even if node $w$ moves upward and the distance between $v$ and $w$ becomes 6. It is also observed in [8] that the buffer zone width $l = 2$ is conservative and not always necessary. The probability is high that all links can be maintained with a smaller $l$.

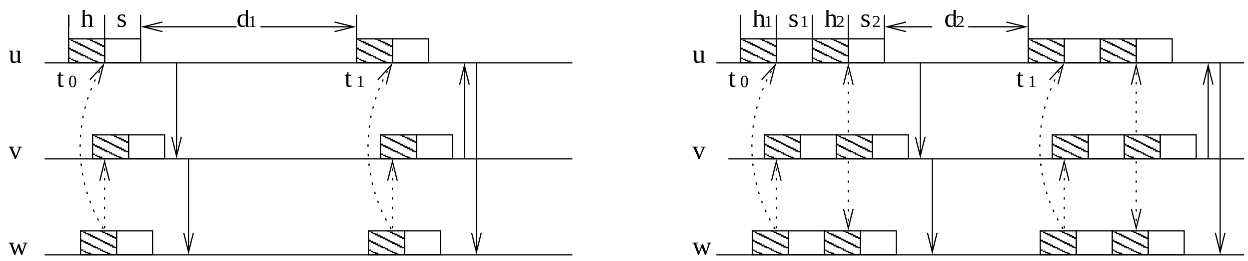
## 3 View consistency issue

Again, we use two localized algorithms as examples to demonstrate how inconsistent local views cause "bad" decisions in MANETs: Wu and Li's marking process [10] for CDS construction, and Li, Hou, and Sha's topology control algorithm based on local MST [2].

In the CDS construction example (as shown in Figure 3), we assume that node $w$ moves southward. Link $(v, w)$ exists at time $t_0$ and is broken at time $t_1$. We also assume $t_0$ and $t_1$ belong to two intervals. Since link $(v, w)$ is two hops away from node $u$, when node $u$ decides its status, it uses the outdated information (lagging by one interval) that link $(v, w)$ still exists. The local view $u$ is shown in Figure 3 (b). Based on Rule 1, node $u$ is unmarked because its neighbor set is covered by node $v$. However, when node $v$ decides its status, it has the fresh information that link $(w, v)$ is broken since it is adjacent to the link (as shown in Figure 3 (c)). Based on the marking process, the only two neighbors of $v$, $x$ and $u$, are connected, so node $v$ is also marked false. As a consequence, none of the nodes in the network are marked!

In the topology control example (as shown in Figure 4), assume node $u$'s view reflects the topology at $t_0$ (as shown in Figure 4 (b)) whereas node $v$'s view corresponds to the topology at $t_1$ (as shown in Figure 4 (c)). This happens when the recent "Hello" message from $w$ is sent at $t$, where $t_0 < t < t_1$. In this case, $u$ has only one logical neighbor $v$, and $v$ has only one logical neighbor $u$. Based on the protocol, a link is selected only if both end nodes select each other. As a result, only one link $(u, v)$ exists after the topology control (as shown in Figure 4 (d)). A network partition occurs!

In the above examples, individual nodes make "bad" decisions based on inconsistent local views. Two views are inconsistent if their common parts do not match. In the CDS example, link $(v, w)$ exists in node




(a) consistent 1−hop information

(b) consistent 2−hop information

**Figure 5. Build consistent local views at the beginning of each "Hello" interval. Dotted lines represent "Hello" messages. Solid lines represent data packets.**

$u$'s view but not in node $v$'s view. In the topology control example, $w$ is closer to $v$ in $u$'s view but closer to $u$ in $v$'s view. There are two solutions to this problem: (1) enforcing consistent local views, or (2) making conservative decisions that maintain the global property, as will be discussed in the next two sections.

## 4 Consistent local view

We first consider 1-hop (location) information used in topology control. Originally, each node receives "Hello" messages from its 1-hop neighbors, and updates its local view upon the arrival of every "Hello" message. If all nodes have synchronized clocks, this scheme actually works. In the topology control example, if both nodes $u$ and $v$ make their decisions at $t_0$, they will agree that $v$ is closer to $w$; at $t_1$, they will agree that $u$ is closer. Here we omit the propagation delay and assume that a "Hello" message is received by all neighbors at the same time. However, it is impossible to have totally synchronized clocks in a MANET without centralized control. If $u$ makes its decision slightly earlier than $v$, and $w$'s "Hello" message arrives after $u$'s decision and before $v$'s decision, then the two nodes have inconsistent views. This inconsistency cannot be avoided no matter how small the asynchrony is.

The traditional solution for this problem is to build local views only once at the beginning of each "Hello" interval. As shown in Figure 5 (a), each "Hello" interval is divided into three time periods $\Delta = h + s + d_1$. Because of asynchronous clocks, different nodes may start their "Hello" intervals at different times. That is, some nodes have "faster" clocks than other nodes. However, we assume the difference between two clocks is bounded by $s$. In the construction of consistent views, each node sends its "Hello" message during period $h$, waits for a period $s$, and conducts normal activities (e.g., sending data packets) in period $d_1$. As the $h$ period of the "slowest" node ends before the $s$ period of the "fastest" node, every node receives all "Hello" messages before the end of its $s$ period. Local views built in the end of $s$ are consistent. It is safe to route data packets in period $d_1$ based on these local views.

This scheme can be extended to build 2-hop information. As shown in Figure 5 (b), each "Hello" interval is divided into five periods $\Delta = h_1 + s_1 + h_2 + s_2 + d_2$. Normally $h_1 = h_2$ and $s_1 = s_2$. Again, we assume the clock difference is bounded by both $s_1$ and $s_2$. Each node first advertises its 0-hop information (i.e., its id and/or location) in period $h_1$, builds 1-hop information at the end of period $s_1$, and then advertises the newly constructed 1-hop information in period $h_2$. At the end of period $s_2$, every node constructs its consistent local view, which is ready for use in period $d_2$. The drawback of this scheme is that two "Hello" messages are sent during each interval $\Delta$, and the effective communication period $d_2$ is further reduced.

The traditional solution relies on the assumption that the maximal difference among local clocks, $s$, is predictable and $s \leq \Delta$. In a totally asynchronous system, $s = \Delta$ and the above simple approach cannot be applied. Note that even if $s < \Delta$ at a particular network, delays accumulate unless some clock synchronization protocol is applied. Although various solutions exist to adjust clock values, frequent clock synchronization is costly. When maintaining (partially) synchronous "Hello" interval becomes too expensive or impossible, we propose using timestamped asynchronous "Hello" messages to enforce application specific consistent local views.

The basic idea is to maintain a sequence number $i_v$ at each node $v$, and attach the sequence number to each "Hello" message from this node. The sequence number serves as a timestamp. Consistent local views are obtained from "Hello" messages with the same timestamps. This can be done by carrying a timestamp in each data packet (including control packets from a higher level protocol). The timestamp is chosen by the originator of the data packet, and all nodes relaying this packet must determine their logical neighbors based on information of the same version (i.e., with the same timestamp). In this scheme, each node keeps several local views, each local view corresponding to a recently used timestamp. Similarly, several logic topologies co-exist in the same network. Each logic topology corresponds to a timestamp and is connected. The logic time (i.e., the timestamp of the latest local view) of the originator of the data packet is used as a selector. It indicates in which logical topology this data packet is travelling. This approach can tolerate a larger "time skew" among different local views and, therefore, involves less synchronization overhead.

In Figure 4, suppose the first "Hello" message from node $w$ has timestamp 0, and the second one has timestamp 1. When the above method is applied, two parallel logic topologies exist. The logical topology corresponding to timestamp 0 includes two bidirectional links $(u, v)$ and $(v, w)$. The logic topology corresponding to timestamp 1 includes $(u, v)$ and $(u, w)$. When a data packet $p$ is sent from $u$ to $w$, the source node $u$ selects a recent timestamp and forwards $p$ on the corresponding logical topology. If $p$ has timestamp 0, it is first forwarded to $v$. Based on $v$'s local view with timestamp 0, $w$ is a logical neighbor of $v$, and $p$ is forwarded along the logical link $(v, w)$. If $p$ has timestamp 1, it is sent to $w$ directly via logical link $(u, w)$. In both cases, $p$ arrives safely at its destination.

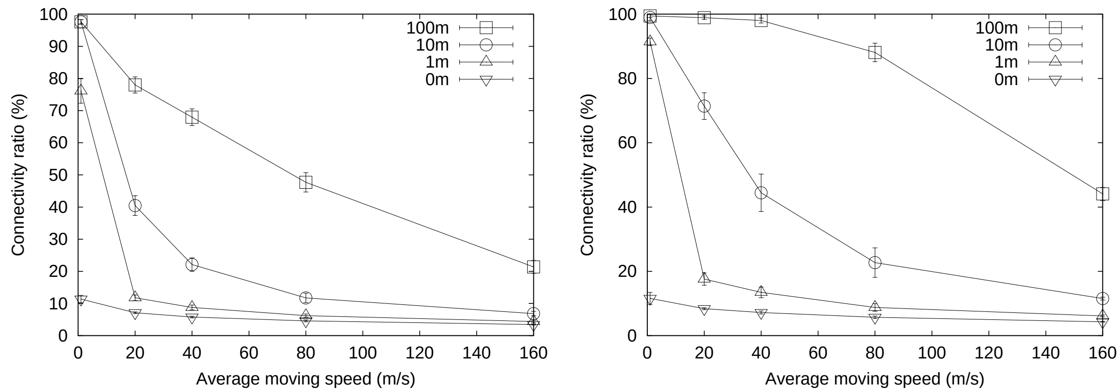
## 5 Conservative local view

Both solutions for enforcing consistent local views require a certain degree of internode synchronization, which introduces extra overhead. When maintaining consistent local views becomes too expensive or impossible, another approach called *conservative local view* [9] can be applied, which makes conservative decisions based on inconsistent views. No synchronization is necessary. A conservative decision is one that maintains the global property with the penalty of lower efficiency. That means selecting more logical neighbors in a topology control algorithm, which in turn generates a larger average transmission range, and marks more nodes as dominators in a CDS formation process. We use Wu and Li's marking process as an example to illustrate the conservative approach.

In Wu and Li's marking process, a node $v$ may be unmarked incorrectly if (1) $v$ no longer views a node $w$ as its neighbor, and (2) another node $u$ still views $w$ as $v$'s neighbor and unmarks itself based on this view. As the broken link $(v, w)$ is first detected by $v$ and then propagated to $u$ via periodical "Hello" messages, local views of nodes $u$ and $v$ are inconsistent for a short period. During that period, $u$ and $v$ may be unmarked simultaneously, and the CDS is temporarily compromised. In order to prevent conditions (1) and (2) from happening together, each node must use a conservative local view, instead of its most recent local view, to make conservative decisions. In this case, the conservative local view $View_c(v)$ of node $v$ is constructed from $k$ most recent local view $View_1(v), View_2(v), \ldots, View_k(v)$ based on the following rule: a link $(u, w)$ exists in $View_c(v)$ if and only if (1) $(u, w)$ exists in the most recent local views $View_1(v)$, or (2) $u = v$ and $(u, v)$ exists in at least one recent local view $View_i(v)$ for $1 \leq i \leq k$. That is, a broken link is preserved longer in the conservative views of its two end nodes than in those of all other nodes.

As shown in Figure 3 (d), after node $v$ detects a broken link $(v, w)$, it will keep a virtual link corresponding to the broken link in its local view for a short time period. Based on this conservative view, $v$ is still a dominator. Note that the virtual link $(v, w)$ is still available during this time period, if $v$ uses a large actual transmission range to create a buffer zone, as discussed in Section 2. The virtual link stays in $v$'s view until all other nodes have removed this link from their views. When 2-hop information is used, link $(v, w)$ exists in local views of $v$'s 1-hop neighbors and $w$'s 1-hop neighbors, which will remove link $(v, w)$ from their local views after receiving a "Hello" message from $v$ or $w$. Node $v$ will send its next "Hello" message within a "Hello" interval ($\Delta$). Node $w$ may detect the broken link and send its "Hello" message later than $v$, but the difference is bounded by $\Delta$. Therefore, it is safe to remove the virtual link $(v, w)$ for $v$'s local view after $2\Delta$.

This approach can also be applied to other localized CDS and topology control algorithms. However, the conservative decisions are different from algorithm to algorithm, and the construction of conservative views depends on the specific algorithm. For example, in Li, Hou, and Sha's local MST algorithm, a conservative view of node $v$ can be defined as follows: given $k$ most recent local views $View_1(v), View_2(v), \ldots, View_k(v)$, which contain distance values $d_i(u, w)$ ($1 \leq i \leq k$) between any two nodes $u$ and $w$ within $v$'s transmission range (including $v$), their distance in the conservative view is (1) $\max_i d_i(u, w)$, if $u \neq v$ and $w \neq v$, and (2) $\min_i d_i(u, w)$ otherwise. That is, the virtual distance between $v$ and a neighbor $w$ in its conservative view may be smaller than the actual distance, and the virtual distance between two neighbors may be larger than the actual distance. When conservative local views are used in Figure 4, both nodes $u$ and $v$ select $w$ as a logical neighbor, and the network connectivity is preserved.




(a) With inconsistent local views (b) With consistent local views

**Figure 6. Connectivity ratio of a topology control algorithm under different buffered ranges.**

## 6 Simulation Results

We illustrate sample results from simulations of the mobility control mechanisms. For more results, the readers can refer to [8, 9]. All simulations are conducted using $ns$-2, with 100 nodes, a $900 \times 900m^2$ deployment area, normal transmission range $r' = 250m$, $1s$ "Hello" interval, and a random waypoint mobility model. The network connectivity is measured in terms of the connectivity ratio, which is defined as the ratio of pairs of connected nodes to the total number of pairs. In the original Dai and Wu's CDS algorithm [1], the connectivity ratio drops rapidly as the average moving speed increases. When a small ($20m$) buffer zone is used to tolerate broken links, the delivery ratio improves significantly under low ($1m/s$) to moderate ($40m/s$) mobility. With a $100m$ buffer zone, the algorithm has almost $100\%$ connectivity ratio under very high ($160m/s$) mobility.

Figure 6 (a) shows the connectivity ratio of Li, Hou, and Sha's topology control algorithm [2]. When there is no buffer zone ($0m$), the connectivity ratio is very low ($10\%$) under an average moving speed of $1m/s$. The connectivity ratio increases significantly after a very small ($1m$) buffer zone is used. On the other hand, $100\%$ connectivity ratio is not achieved under low mobility. Moderate and high mobility causes low connectivity ratio. Figure 6 (b) shows the effect of using consistent views. When using a $20m$ buffer zone in MANETs with a $10m/s$ average moving speed, the connectivity ratio is $40\%$ without consistent views, and $70\%$ with consistent views. When using a $100m$ buffer zone under a $40m/s$ average moving speed, the connectivity ratio reaches $98\%$ with consistent views, while the original connectivity ratio without consistent views is only $70\%$.

Overall, simulation results confirm that the global connectivity can be compromised by both link availability and view consistency issues. Both issues can be overcome with mobility control mechanisms, and the global property can be preserved with high probability and relatively small overhead.

## 7 Conclusion

We have addressed issues related to mobility control in mobile ad hoc networks. To illustrate the importance of the negative impact of mobile nodes on various protocols, we focus on two types of protocols, one for CDS construction and the other for topology control. It has been shown that most existing protocols on CDS construction and topology control will generate incorrect results in the presence of mobile nodes. We discuss two major problems caused by mobility control: link availability and view consistency, and provide several solutions. Mobility control in MANETs is still in its infancy. Many open issues exist:

- How does mobility affect protocols at other layers?
- Can approaches for view consistency in distributed systems be applied in mobile ad hoc networks?
- How should various kinds of cost and efficiency trade-off be done?

More efforts are needed to address these issues before various protocols can be applied in MANETs with mobile nodes.

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