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On Minimizing the Impact of Mobility on Topology Control in Mobile Ad Hoc Networks

Hiroki Nishiyama, *Member, IEEE,* Thuan Ngo, Nirwan Ansari, *Fellow, IEEE,* and Nei Kato, *Senior Member, IEEE*

***Abstract*—Although topology control has received much attention in stationary sensor networks by effectively minimizing energy consumption, reducing interference, and shortening end-to-end delay, the transience of mobile nodes in Mobile Ad hoc Networks (MANETs) renders topology control a great challenge. To circumvent the transitory nature of mobile nodes, k-edge connected topology control algorithms have been proposed to construct robust topologies for mobile networks. However, uniformly using the value of k for localized topology control algorithms in any local graph is not effective because nodes move at different speeds. Moreover, the existing k-edge connected topology control algorithms need to determine the value of k *a priori*, but moving speeds of nodes are unpredictable, and therefore, these algorithms are not practical in MANETs. A dynamic method is proposed in this paper to effectively employ k-edge connected topology control algorithms in MANETs. The proposed method automatically determines the appropriate value of k for each local graph based on local information while ensuring the required connectivity ratio of the whole network. The results show that the dynamic method can enhance the practicality and scalability of existing k-edge connected topology control algorithms while guaranteeing the network connectivity.**

***Index Terms*—Mobile ad hoc network, topology control, k-edge connectivity, mobility.**

I. INTRODUCTION

In stationary ad hoc networks, owing to the limitation of network resources (i.e., bandwidth, sensor energy, and so forth), topology control has been considered as a state-of-the-art approach to provision broadcasting with moderate energy costs, low interference, and short end-to-end delay [1], [2]. Moreover, localized versions of topology control algorithms, which avoid the use of central node supervision, have been employed in constructing network topologies with reduced cost, and have thus been tailored for Mobile Ad hoc Networks (MANETs).

The primary latency of mobile networks is attributed to unpredictable topology changes owing to mobility. As a result, topology control algorithms that can only guarantee 1-edge connectivity, such as Local Minimum Spanning Tree (LMST) [3], Relative Neighborhood Graph (RNG) [4], and Local Shortest Path Tree (LSPT) [5], may no longer be applicable in MANETs because the network might be disconnected even when only a single link is broken. Accordingly, more reliable topology control algorithms such as Fault-tolerant Local Spanning Subgraph (FLSS) [6] and Local Tree-based Reliable Topology (LTRT) [7] are considered for MANETs. They can preserve k-edge connectivity, i.e., network connectivity cannot be lost if the number of broken links are smaller than k, and are referred to as k-edge connected algorithms in this paper. The drawback of these algorithms is that the value of k, referred to as the level of redundancy, is uniformly set for all local graphs regardless of the different moving speeds of nodes. Thus, in order to guarantee network connectivity, they need to use a high value of k to mitigate the case where some nodes move too fast. This might lead to a redundant topology, because some areas in the network may have slow moving nodes and do not need a high value of k.

This paper proposes a dynamic method for k-edge connected algorithms that determines the value of k for each local graph based on local movements while maintaining the required connectivity. Each node periodically broadcasts a “hello” message within its maximum transmission range, which contains information about its position and current moving speed. The “hello” message sending interval is referred to as the *topology update interval*. Afterward, each node collects information about positions and speeds of its neighboring nodes and builds its own local graph. The node uses a k-edge connected algorithm with k-value decided based on the moving speeds of itself and its neighbors. After applying a topology control algorithm, each node finds its logical neighbors and calculates a new transmission range to cover them. It should be noted that our main focus is in topology control, i.e., how to determine the transmission range of each node in order to maintain network connectivity. Although flow control algorithms (which mitigate radio interference) [8], routing techniques (which establish multiple paths) [9], [10], and security technologies [11], [12] have an important role in improving the reliability of mobile ad hoc networks, these issues are beyond the scope of this paper.

In order to find an appropriate value of k corresponding to nodes’ moving speeds, we introduce an analysis about the relationship between network connectivity and the value of k. Li *et al.* [3] calculated the probability that a node moves out of another node’s transmission range. We adopt this result to measure the connectivity of topology constructed by using k-edge connected algorithms and calculate the probability that the network is disconnected. We incorporate our proposed dynamic method into LTRT, and refer to it as Dynamic LTRT (DLTRT). Simulation results show that LMST, RNG and LSPT, and also FLSS and LTRT with small values of k

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are significantly sensitive to mobility. They also demonstrate that DLTRT is practical in MANETs by ensuring the required connectivity ratio of the network.

The remainder of this paper is organized as follows. We first summarize some related works on localized topology control algorithms in Section II. Then, we analyze and evaluate the effects of mobility on network connectivity and the advantage of using k-edge connected algorithms in Section III. In Section IV, we calculate the lower bound of the network connectivity ratio corresponding to different values of k with given node moving speeds. DLTRT is also described in this section. The performance evaluation is presented in Section V. Finally, Section VI concludes this paper.

II. RELATED WORKS

In wireless ad hoc and sensor networks, most topology control algorithms are based on Minimum Spanning Tree (MST) and/or RNG. The common idea of MST-based algorithms is to find the minimum spanning tree of a graph that connects all vertices and has the minimum total link weight. Li *et al.* [3] proposed LMST which can be considered as the most typical MST-based topology control algorithm. As a prominent localized algorithm, LMST, which is used in the local graph of each node, can be constructed by using the information of its 1-hop neighbors. In graph theory, the degree of a node is the number of connections it has to other nodes, and it is often used as an evaluation metric of network topology. By using MST to find the logical neighbors of each node, LMST is able to guarantee the network connectivity with a small average node degree. The time complexity of LMST is $O(m + n \log n)$ when Fibonacci heap and Prim's algorithms are used [13], where m and n denote the number of edges and number of vertices, respectively. Li *et al.* [14] proposed a family of structures called k-localized minimum spanning tree (LMST$_k$) and proved that the node degree of the structure LMST$_k$ is bounded by 6. They also proposed a lower weighted structure, namely, Incident MST and RNG Graph (IMRG) which uses both MST and RNG.

RNG was first proposed by Toussaint [4] with the objective to remove redundant edges while preserving the network connectivity. An edge (u, v) is considered redundant if there exists a node w such that the distances from w to u and v are respectively shorter than the length of edge (u, v). The resulting graph after eliminating all such redundant edges is the topology constructed by RNG. Cartigny *et al.* [15] showed that LMST generates a topology that is a sub-graph of RNG's topology when both algorithms are applied for the same graph. K. J. Supowit [16] proved that RNG can be constructed efficiently with a computational cost of $O(n \log n)$. RNG can be easily used for local graphs because each node only needs the distances to its neighbors to decide whether an edge is redundant. Therefore, Razafindralambo and Simplot-Ryl [17] used RNG for their algorithm to guarantee connectivity during the deployment of sensor networks.

Another spanning tree algorithm used for topology control is the Shortest Path Tree (SPT). Rodoplu and Meng [18] proposed a topology control algorithm by using the idea of SPT that an edge connecting two nodes should be redundant if there is a 2-hop path connecting them with a smaller weight than the edge. Li and Halpern [5] extended the algorithm from 2-hop paths to k-hop paths by adopting Dijkstra's algorithm [19]. The weight function used for the graph is d^α, where d and α are the length of the edge and the path loss exponent dependent on the radio propagation model, respectively. The localized version of this algorithm called LSPT has the complexity $O(m + n \log n)$ by using Fibonacci heap.

Although LMST, RNG, and LSPT are considered simple and applicable topology control algorithms in wireless sensor networks, the resulting topologies are only 1-edge connected. As a consequence, the network connectivity can be dropped even when only one link is broken. Therefore, some other researches focus on fault-tolerant strategies. Bahramgiri *et al.* [20] proposed a distributed topology control algorithm to preserve k-edge connectivity. The algorithm is based on the Cone-Based Topology Control (CBTC) algorithm, CBTC(α), proposed by Li *et al.* [21]. The original algorithm attempts to calculate the minimum transmission power for each node u such that there exists a node in every cone of degree α around u that can be reached by u within its transmission range. They proved that when $(\alpha < 5\pi/6)$, network connectivity is preserved [21], and when $(\alpha < 2\pi/3k)$, the algorithm guarantees k-edge connectivity. However, evaluation results showed that CBTC(α) with $(\alpha < 2\pi/3k)$ will generate topologies that are much more redundant than other k-edge connected algorithms [7]. With the same objective in preserving k-edge connectivity, Li and Hou [6] proposed FLSS. The idea of FLSS is based on repeatedly adding the lowest weighted edge in the set of edges until the resulting topology is k-edge connected. They proved that in terms of minimizing the transmission power, FLSS is min-max optimal among strictly localized algorithms which preserve k-edge connectivity. However, the disadvantage of FLSS is its high complexity, $O(m(m + n))$.

LTRT, recently proposed by Miyao *et al.* [7], is a reliable topology control algorithm that guarantees k-edge connectivity with low complexity, $O(k(m + n \log n))$. Moreover, LTRT is proved to be nearly optimal and is superior to FLSS in terms of applicability. LTRT can be considered as a localized version of Tree-based Reliable Topology (TRT) proposed by Ansari *et al.* [22].

III. TOPOLOGY CONTROL IN MANETS

In this section, we evaluate the performance of five algorithms including three 1-edge connected algorithms, i.e, LMST, RNG, and LSPT, and two k-edge connected algorithms, namely, FLSS and LTRT, for topology control in MANETs. The complexity of each algorithm is summarized in Table I.

A. Effects of mobility on topology control

In principle, topology control attempts to decide for each node the minimum transmission power that adequately guarantees connectivity of the node. In static networks, it is enough to preserve network connectivity because the node movement is not taken into consideration. However, in MANETs, network

TABLE I
COMPUTATION TIME OF THE CONSIDERED ALGORITHMS.

Algorithm	Complexity
LMST	$O(m + n \log n)$
RNG	$O(n \log n)$
LSPT	$O(m + n \log n)$
FLSS	$O(m(m + n))$
LTRT	$O(k(m + n \log n))$

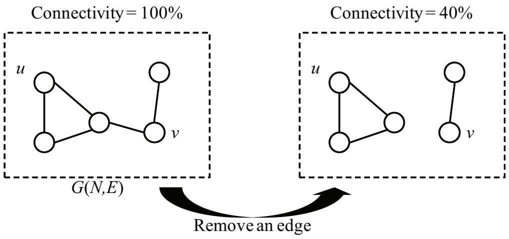

Fig. 1. Change of network connectivity ratio by removing an edge.

topology varies and fluctuates owing to mobility, and thus, it may not be able to preserve the network connectivity. This is a well-known problem, but is yet to be solved efficiently.

It is worthy to present a discourse on the importance of topology control in mobile networks. Therefore, one of our contributions is providing a performance evaluation of topology control algorithms in MANETs. Although the influence of mobility on topology control in MANETs is obvious, an adequate evaluation of this influence is essential.

B. Considered performance metric

In order to evaluate the performance of topology control algorithms in MANETs, we introduce a performance metric, namely, *connectivity ratio*, which measures the network connectivity. After constructing the topology, each node is aware of its neighbors, and before the next update, it will try to communicate with those nodes. However, owing to mobility in MANETs, some of its neighbors may move out of its transmission range, thus resulting in disruption before the next topology construction.

Each node constructs a graph by using the information about its neighboring nodes and their node positions periodically. Connectivity ratio demonstrates the connectivity of this graph and is calculated as the percentage of connected node pairs out of the total number of node pairs in the network. A node pair (u, v) is considered connected if and only if there exists a path from u to v, and vice versa. Denote C as the connectivity ratio of a given network topology, $G(N, E)$, where N is the set of nodes and E is the set of links; C can be computed as follows:

$$C = \frac{\sum_{u,v \in N} c_{uv}}{|N|(|N| - 1)} \tag{1}$$

where

$$c_{uv} = \begin{cases} 1, & \text{if } u \neq v \text{ and } (u, v) \text{ is connected,} \\ 0, & \text{otherwise.} \end{cases}$$

By using this metric, the network connectivity can be evaluated without data transmission. Moreover, by choosing the time of taking a snapshot, the metric can be used to measure the relationship between network topology and topology update interval. Fig. 1 shows the change in network connectivity ratio before and after removing an edge.

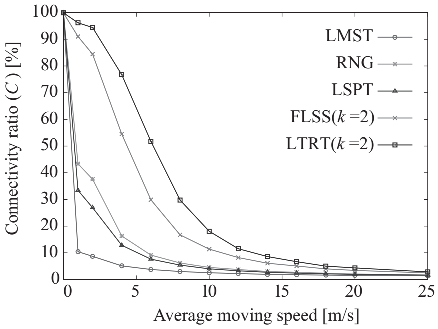

Fig. 2. Effect of moving speed on network connectivity.

C. Evaluation of mobility effect

According to the evaluation of mobility effect on topology control algorithms in MANETs conducted in [23], the topologies constructed by topology control algorithms are quite sensitive to mobility in terms of connectivity ratio. As demonstrated in Fig. 2, when the moving speed increases, the connectivity ratio of each of the considered algorithms decreases significantly.

We also discussed some methods to improve the connectivity of resulting topologies when we use topology control algorithms. The simplest method is to frequently update the network topology by shortening the topology update interval. This method obviously improves the network connectivity because every node has the updated information of its neighbors and is able to decide the needed transmission power. However, frequent updating also leads to the huge cost of constructing topology. Another method is using k-edge connected algorithms with an appropriate value of k in order to achieve redundant edges that helps the topology to become more fault-tolerant. The primary challenge for this method is to tolerate the trade-off between topology control and the reliability of the network. We propose a method for k-edge connected algorithms to resolve this problem in the next section.

IV. PROPOSED METHOD FOR k-EDGE CONNECTED ALGORITHMS

In the previous section, we discussed about the influence of mobility on topology control algorithms in MANETs. Although the simulation results show that current topology control algorithms are sensitive to mobility, the k-edge connected algorithms still exhibit superiority to the others in terms of scalability in MANETs. However, some improvements are still needed. In this section, we propose a method to help the k-edge connected algorithms to be more readily applicable in mobile networks. We also provide some analyses about network connectivity and its relationship with the value of k. By using these analyses, we can set up a network with the desirable connectivity level.

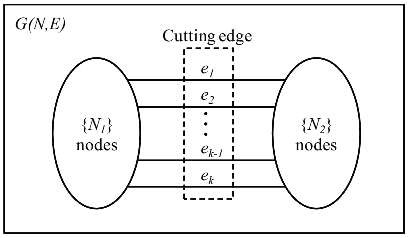

Fig. 3. A cutting edge of $G(N, E)$

A. Motivation

Before discussing about the latency of k-edge connected algorithms, we clarify the definition of a k-edge connected graph.

Definition: A graph is k-edge connected if the removal of any $(k-1)$ edges does not partition the graph.

Another illustration of k-edge graphs is depicted in Fig. 3. Here, the graph $G(N, E)$ can be seen as a combination of two sub-graphs including two sets of nodes $\{N_1\}$ and $\{N_2\}$, respectively, where $\{N_1\} \cup \{N_2\} = \{N\}$. The two sub-graphs are connected together by the set of edges $\{e_1, e_2, ..., e_k\}$, referred to as a cutting edge of $G(N, E)$. A graph is k-edge connected if any cutting edge of the graph has at least k edges. A cutting edge of a graph is a set of edges that will partition the graph if all edges in the set are removed.

Although k-edge connected topology control algorithms, which generate k-edge connected topologies, are proved to be more fault-tolerant in MANETs, they still have some shortcomings in terms of effectiveness and applicability.

Effectiveness: The original k-edge connected algorithms are applied by using the same value of k for every local graph in the network. However, the nodes generally move with different speeds in MANETs. There may be some low and fast moving speed zones. In low moving speed areas, it is not necessary to use a large value of k because it leads to unnecessary redundancy. On the other hand, in high moving speed areas, if we use very small value of k, we cannot construct a robust network. Therefore, using the same value of k, i.e., generating the same redundancy for every local graph, may not be effective.

Applicability: Generally, we are not able to predict the moving speeds of all network nodes correctly in MANETs. However, in order to apply k-edge connected algorithms, the value of k must be chosen *a priori*. If we choose a small value of k while moving speeds are high, the connectivity might not be preserved. On the other hand, if moving speeds are low but we choose a large value of k *a priori*, the redundancy will be high. Therefore, choosing an appropriate value of k for the whole network is still not applicable.

To address the above issues, we propose a dynamic method that uses a k-edge connected algorithm, but attempts to choose an appropriate value of k for each local graph. The method is effective because it is based on moving speeds of nodes in each local graph to choose an appropriate value of k. On the other hand, each node only needs to estimate the moving speeds of the nodes in its local graph, and thus, it is more practical than the original algorithms. Like other localized mechanisms which are applied to local graphs, our proposed method has to overcome a quite difficult problem, i.e., to guarantee the global network connectivity while each node only has the knowledge about its local graph. To find an effective solution to this problem, we first use an assumption that the network will be disconnected if and only if there exists a node such that all the links connected to its neighbors are broken. Theoretically, the proposal can be an extension of any k-edge connected algorithms. However, because LTRT shows its superiority over other current k-edge algorithms in terms of scalability, we apply the proposed method to LTRT to evaluate our proposal.

B. Estimate the network connectivity

We first provide an analysis about network connectivity. This analysis is accomplished to estimate the lower bound of the network connectivity ratio when the network is disconnected. We then derive an expression of the relationship between the network connectivity ratio and the probability that the network is partitioned.

We prove that if a graph is separated into sub-graphs, the connectivity ratio of the whole graph will be the smallest when the number of nodes in all sub-graphs is the same (see Appendix). The smallest value is considered as the lower bound of the network connectivity ratio when an n-node connected graph is separated into m sub-graphs, and it is calculated by the following equation.

$$\begin{aligned} C_{Lower}(m) &= \frac{\lfloor n/m \rfloor (\lfloor n/m \rfloor - 1)\{m - (n - m\lfloor n/m \rfloor)\}}{n(n-1)} \\ &\quad + \frac{\lfloor n/m \rfloor (\lfloor n/m \rfloor + 1)(n - m\lfloor n/m \rfloor)}{n(n-1)} \\ &= \frac{(2n-m)\lfloor n/m \rfloor - m\lfloor n/m \rfloor^2}{n(n-1)}. \end{aligned} \tag{2}$$

By using probability, we can calculate the average lower bound of the network connectivity ratio when the network is separated as follows.

$$C_{AvgSepLower} = \frac{\sum_{m=2}^{n} \left\{ \binom{n-1}{m-1} \times C_{Lower}(m) \right\}}{2^{n-1} - 1}. \tag{3}$$

Given ρ_{global} as the probability that a network is disconnected due to mobility, the average lower bound of network connectivity is calculated as follows.

$$\begin{aligned} C_{LowerBound} &= (1 - \rho_{global}) \times 1.0 \\ &\quad + \rho_{global} \times C_{AvgSepLower}. \end{aligned} \tag{4}$$

By using the result shown in Eq. (4), after deciding the required connectivity ratio of the network, (e.g., maintaining at least 80%), we can determine ρ_{global} that limits the probability that the network is partitioned. In order to find the relationship of ρ_{global} with the appropriate value of k, we provide some further analyses next.

C. Relationship between network connectivity and node moving speed

We start from determining the relationship between the node moving speed and the disconnection of a link. After

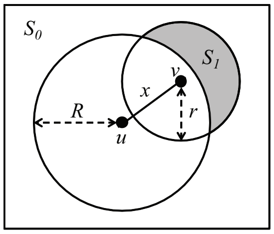

Fig. 4. Calculation of the probability that node v moves out of disk $D(u, R)$

calculating the probability that a link is broken, we evaluate the disconnection of a local graph referred to as the probability that a node disconnects from all its neighbors. We then determine the relationship between the disconnections of a local graph and the whole network.

1) Moving speeds and link disconnection: We use the probability that a node moves out of the transmission range of another node, ρ, as an indication of link disconnection. Fortunately, the value of ρ has been studied in [3] by Li *et. al.* with the assumptions that nodes are uniformly distributed and their movements follow a Brownian-like mobility model which preserves the uniform node distribution. Here, we review the main result of their analyses, i.e., three formulas, and omit their derivation procedure. According to their studies, ρ can be defined as the probability that node v moves out of the disk $D(u, R)$ (as shown in Fig. 4). Here, the disk $D(v, r)$ is the area that node v can move during the topology update interval, Δt. If v_{max} is the maximum speed of nodes, then $r = 2v_{max} \times \Delta t$. The nodes are supposed to move randomly in an area S_0. The probability is calculated for three different cases:

if $0 < r < R$:

$$\rho = \int_{R-r}^{R} \frac{2xS_1}{S_0 r^2} dx, \tag{5}$$

if $R < r < 2R$:

$$\rho = \frac{\pi(r+R)}{S_0 r^2}(r-R)^3 + \int_{r-R}^{R} \frac{2xS_1}{S_0 r^2} dx, \tag{6}$$

if $r > 2R$:

$$\rho = \frac{\pi(r^2 - R^2)R^2}{S_0 r^2}. \tag{7}$$

Herein, we only consider the case that a node moves out of the transmission range of another node, while some nodes may enter the transmission range of the same node. This is because the node is not aware of its new neighbors until receiving their "hello" messages, which are sent only one time during the period. Therefore, only nodes moving out of the transmission range are taken into account in our model.

2) The disconnection probability of a k-edge connected local graph: In k-edge connected topologies, each node has at least k neighbors. On the other hand, because ρ is calculated with the assumption that the nodes move with the maximum moving speed v_{max}, the probability that this node disconnects from an arbitrary neighbor is not greater than ρ. Therefore, the probability that a node disconnects from its all neighbors, called ρ_{local}, may not exceed ρ^k. The more the number of neighbors is, the more fault-tolerant the topology will be because $\rho^k \leq \rho$.

3) The disconnection of local and global graphs: In order to establish the relationship between ρ_{local} and ρ_{global}, we need to obtain the global view of the entire network. However, such information is not available in mobile ad hoc networks, especially in large-scale networks. In practice, each node only knows its local information. Therefore, in our model, we use the alternative derivation of ρ_{global} from ρ_{local} with the assumption that the network will be disconnected if and only if there exists a node which loses all links connecting to its neighbors. In this case, the following relationship between ρ_{local} and ρ_{global} is established.

$$\rho_{global} = 1 - (1 - \rho_{local})^n. \tag{8}$$

After calculating ρ_{global} by using Eq. (4), we can use the result shown in Eq. (8) to compute ρ_{local}. Then, we can estimate the value of k for each local graph by finding the smallest value of k satisfying:

$$\rho^k \leq \rho_{local}. \tag{9}$$

D. Dynamic Method for k-edge Connected Algorithms

Our proposed method includes two main phases: *preliminary*, which attempts to find the value of ρ_{local}, and *dynamic topology control*, which assigns the appropriate value of k for each local graph. In the *preliminary* phase, by using Eq. (4), we first calculate ρ_{global} which satisfies the requirement on the network connectivity determined according to the aim of network and/or service providers. For example, if we need to guarantee that whenever a node broadcasts a message, there are at least 80% of nodes receiving the message, i.e., expecting responses from more than 80% of nodes, the required connectivity ratio can be set to 80%. After getting the value of ρ_{global}, the value of ρ_{local} can be derived by using Eq. (8). The *preliminary* phase will be executed only one time at the initial phase.

In the *dynamic topology control* phase, each node performs the procedure shown in Procedure 1. Each node keeps its own moving history, and periodically broadcasts a "hello" message within its maximum transmission range containing its node ID, position, and moving speed. Also, each node stores such information whenever it receives "hello" messages sent from its neighbors. This information is used for building the local graph in each node. The maximum moving speed among the speeds of its neighbors is utilized for the computation of the value of ρ in the local graph. The reason is that our proposal considers the worst case where every neighbor moves at the highest moving speed observed. This allows the theoretical network connectivity ratio to be higher than the lower bound. After calculating ρ, the smallest number satisfying the condition represented by Eq. (9) is determined as the optimal value of k. Finally, the node's transmission range is adjusted by running a k-edge connected algorithm with the optimal value of k, and is maintained until the next topology update.

Procedure 1 Dynamic topology control in each node

```
loop
    Calculate the current moving speed.
    Broadcast a “hello” message.
    Build the local graph similar to Fig 4.
    Calculate $\rho$ based on the local graph by using one of Eqs. (5) to (7).
    Determine the optimal value of $k$ by using Eq. (9) with the calculated value of $\rho$.
    Run a $k$-edge connected algorithm with the optimal value of $k$.
    Keep the determined transmission range during the period of topology update.
end loop
```

V. PERFORMANCE EVALUATION

In this section, we evaluate the performance of our proposed method in terms of the connectivity ratio, node degree, and transmission range. Although the proposal can be applied for any k-edge connected algorithms, we apply it to LTRT which is considered scalable and has low complexity. In order to compare the performance of LTRT after applying the proposed method and that of the original LTRT, we first calculate the “expected results” of the original LTRT by simulating a large number of possible network scenarios. The expected results are calculated by manually choosing an appropriate value of k for each kind of scenarios, i.e., for each node’s average moving speed. If the performance of the proposed method is equivalent to the expected results, the proposed method can be considered superior to the original LTRT. The performance evaluation is conducted by using Network Simulator 2 (NS-2).

A. *Deriving the expected results of LTRT*

As discussed earlier, not only LTRT but also the other k-edge algorithms exhibit two main shortcomings. They use the same value of k for all local graphs. In addition, they need to estimate the moving speeds of all nodes beforehand. Because the estimation cannot be made correctly, LTRT cannot achieve the best performance in simulations. Instead, we attempt to find the expected results of LTRT, i.e., the results that would be obtained if we could have correctly estimated the moving speeds of all nodes beforehand.

1) Evaluation settings: We generate the network scenarios by using the random way point mobility model to simulate the original LTRT and our proposed method in MANETs. In this model, mobile nodes change moving speeds and directions after a pause time. In each change, a destination is chosen randomly, and the moving speed is limited to a specific range. Each node maintains its direction and speed until arriving at the chosen destination. The settings of this evaluation are presented in Table II. In this evaluation, 100 nodes are placed randomly and uniformly in an area of 1000m×1000m in each scenario. The default maximum transmission range is set to 250m. Average moving speeds of nodes vary from 0 to 25m/s, and the topology update interval is set to 10 seconds. We choose 80% as a lower bound of the connectivity ratio that the resulting topologies need to preserve regardless of the speeds of nodes. We first run LTRT with many values of k varying from 1 to 7. Our objective is to choose the smallest value of k corresponding to each average moving speed while guaranteeing the connectivity ratio of at least 80%.

TABLE II
EVALUATION SETTINGS TO FIND THE EXPECTED RESULTS OF LTRT

Simulation Parameter	Value
Simulation area	1000m×1000m
Maximum transmission range	250m
Number of nodes	100
Number of scenarios	2600
Topology update interval	10s
Average moving speed	$0 \sim 25$m/s
Number of edge connectivity (k)	$1 \sim 7$
Required connectivity ratio	80%

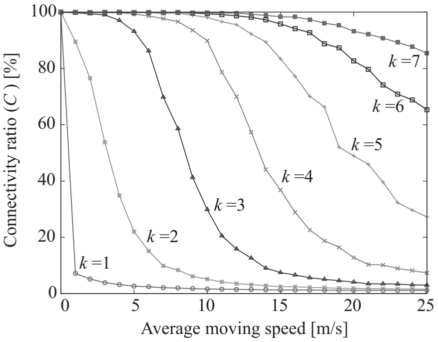

Fig. 5. Connectivity ratio of the topology constructed by LTRT with the value of k varying from 1 to 7

2) The expected results of LTRT: After executing LTRT with many values of k, we achieve the results as shown in Fig. 5. The figure demonstrates that the higher value of k is, the better the connectivity ratio will be. With the average moving speeds of nodes from 0 to 25m/s and the topology update interval of 10 seconds, Fig. 5 shows that with $k = 7$, LTRT always guarantees a connectivity ratio higher than the required connectivity ratio (80%) regardless of the node’s moving speed. However, as we discussed before, a high value of k also leads to a high transmission range, which is related to energy consumption and interference. Therefore, we aim to use the smallest possible value of k that still guarantees the required connectivity ratio.

We now choose an appropriate value of k for each average moving speed. In order to do that, with each average moving speed, we choose from the curve of the lowest value of k until the curve at that speed is lower than 80%. With the results shown in Fig. 5, we can choose $k = 1$ when the average moving speed is 0m/s, choose $k = 2$ when the average moving speed is 1m/s or 2/ms, and so on.

B. *Performance evaluation of the proposed method*

In order to evaluate the performance of our proposed method, we apply the method to LTRT that can generate k-edge connected topologies with the superiority over other k-edge connected topology control algorithms in terms of complexity.

TABLE III
CHOOSING AN APPROPRIATE VALUE OF ρ_{local}

ρ_{local}	ρ_{global}	Lower bound of connectivity ratio
0.0001	0.0099	99.01%
0.0010	0.0952	90.55%
0.0022	0.1977	80.39%
0.0035	0.2957	70.65%
0.0051	0.4002	60.28%
0.0069	0.4996	50.42%

1) *Simulation environments:*

a) Preliminary phase: Before conducting the simulation, we carry out the *preliminary phase* of the proposed method. We calculate the appropriate value of ρ_{local} by using the results shown in Eqs. (4) and (8). Table III lists some examples of ρ_{local}, the corresponding ρ_{global}, and the lower bound of network connectivity ratio that we can achieve if we use that value of ρ_{local}. The table shows that $\rho_{local} = 0.0022$ can help to satisfy the required connectivity ratio of 80%. Therefore, the value $\rho_{local} = 0.0022$ is a good choice for use in the next phase.

b) Dynamic topology control phase: In this simulation, we use the same scenarios as the ones we used to evaluate the original LTRT. Because the number of edge connectivity, k, is chosen dynamically in each local graph, we do not have to assign the value beforehand. In each local graph of node u, after u knows the moving speeds and positions of its neighbors, it calculates ρ by using Eqs. (5), (6), and (7). The value of k in each local graph will be calculated by choosing the smallest integer k which satisfies $\rho^k \leq \rho_{local}$. Here, ρ_{local} is set to 0.0022 to satisfy the required connectivity ratio.

2) Simulation results: Three performance metrics are considered, namely, connectivity ratio, transmission range, and node degree, which are described below.

a) Connectivity ratio: Fig. 6 illustrates the performance of the proposed method in terms of the connectivity ratio. It satisfies the requirement of maintaining the connectivity ratio of at least 80%. When the average moving speed is smaller than 5m/s, the connectivity ratio of dynamic topology control is almost the same as that of the original LTRT which uses the same value of k for all local graphs. This is because when the average moving speed is small, the difference between nodes in terms of moving speeds is not large, and thus, the chosen value of k in every local graph in the proposed method may be the same. However, when the moving speed is higher, the connectivity ratios of the expected results obtained by the original LTRT and the proposed method are different. When the average moving speed is varied from 5m/s to 15m/s, they can be considered comparable in the whole range. When the moving speed is higher, from 16m/s to 25m/s, the connectivity ratio of our proposal is slightly lower than the expected result, but is still higher than 80%.

b) Transmission range: Among the metrics used to evaluate the performance of topology control algorithms, the transmission range is one of the most important ones because it reflects the energy consumption and the interference of the network. Therefore, an important objective of topology control algorithms is to minimize the transmission ranges of nodes. Fig. 7 demonstrates the transmission range corresponding to each average moving speed of our proposed method and the expected result of the original LTRT. It shows that even when the average moving speed is 25m/s, the transmission range is still lower than 200m. Note that the default maximum transmission range is set to 250m. The results show that our proposal is able to save from 20% to 60% of the maximum transmission range. The performance of our proposed method in terms of average transmission range is demonstrated and comparable to the expected result. While the expected result looks like a step function, the transmission range of our proposal gradually increases following the average moving speed. Therefore, our proposal can be considered to be more desirable than the original LTRT.

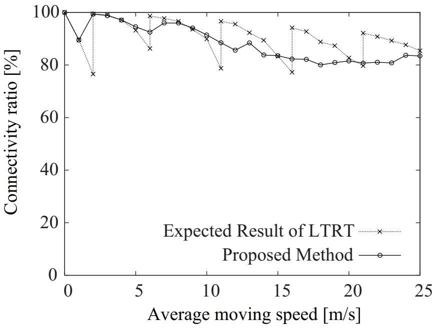

Fig. 6. Connectivity ratio of the proposed method in contrast with the expected result of the original LTRT

c) Node degree: Node degree is another important metric to evaluate the performance of topology control algorithms. The higher the node degree is, the higher the collision will be. Node degree also reflects the redundancy of topologies. Therefore, all topology control algorithms attempt to achieve a small average node degree. The result of our proposal in terms of node degree is shown in Fig. 8. The figure demonstrates that the proposed method is as good as the expected result of the original LTRT in terms of the average node degree. It is even more preferable because unlike the expected result, the average node degree gradually increases when the average moving speed increases. When the average moving speed increases, from 16m/s to 25m/s, the node degree of our proposal is slightly lower than the expected result. The trade-off here is shown clearly because we also achieve a lower connectivity ratio when the average moving speed is high in this range.

The performance of our proposed method in terms of the connectivity ratio, average transmission range, and average node degree has demonstrated the effectiveness of our proposal. Our proposed method not only achieves results comparable to the expected results of the original algorithm, but is also more practical and scalable. Therefore, the proposal should be an effective and practical method for k-edge connected algorithms in MANETs.

VI. CONCLUSION

In this paper, we have considered the influence of mobility on topology control in MANETs. Owing to the presence of mobility, it is necessary to use scalable topology control algorithms to compromise the trade-off between topology control

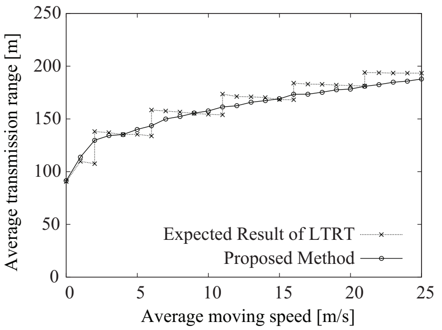

Fig. 7. Transmission range of the proposed method in contrast with the expected result of the original LTRT

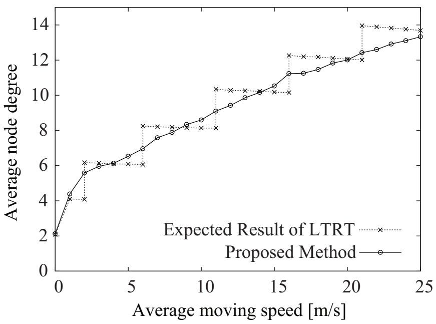

Fig. 8. Node degree of the proposed method in contrast with the expected result of the original LTRT

and reliability. Therefore, we have focused on using k-edge connected algorithms, which are proven to be applicable in MANETs. However, effectiveness and applicability are the two primary issues for existing k-edge connected algorithms. Thus, we have proposed a dynamic method for k-edge connected algorithms that attempts to choose an appropriate value of k for each local graph based on local movements. Another challenge for this method is to guarantee the global network connectivity while each node possesses only the information of its local graph. We use probability to choose an appropriate value of k for each local graph based on the premise that the network will be partitioned if and only if there exists a node disconnected from the remaining network. The simulation results have demonstrated that the proposed method, DLTRT, achieves the performance that is nearly the same as the expected results of the original LTRT. Therefore, the proposed method should be considered as a good extension that makes k-edge connected algorithms more practical and scalable in MANETs.

APPENDIX

Lemma 1. If an n-node connected graph is separated into two connected sub-graphs, the whole graph will have the smallest connectivity ratio when the numbers of nodes in the two sub-graphs are the same (when n is even) or differ by 1 (when n is odd).

Proof. If n is even. When both the sub-graphs have $n/2$ nodes, the connectivity ratio of the whole graph is:

$$C_0 = \frac{(n/2-1)\cdot n/2 + (n/2-1)\cdot n/2}{(n-1)n} = \frac{n/2-1}{n-1}$$

When the two sub-graphs have different number of nodes, those numbers can be expressed by $(n/2+i)$ and $(n/2-i)$ with $i > 0$. In this case, the connectivity of the whole graph is:

$$\begin{aligned} C_i &= \frac{(n/2+i-1)(n/2+i)+(n/2-i-1)(n/2-i)}{(n-1)n} \\ &= \frac{n/2-1}{n-1} + \frac{2i^2}{(n-1)n} \end{aligned}$$

Since $C_i > C_0$ for any $i > 0$, Lemma 1 is true when n is even. Lemma 1 can also be similarly proven to be true when n is odd.

Lemma 2. If an n-node connected graph is separated into m connected sub-graphs, the whole graph will have the smallest connectivity ratio when the number of nodes in any sub-graph is $\lfloor n/m \rfloor$ or $(\lfloor n/m \rfloor - 1)$.

Proof. Consider two sub-graphs with the difference of the numbers of nodes of respective sub-graphs greater than 1. Following Lemma 1, the total connectivity ratio of the two sub-graphs will be smaller if we move some nodes from the bigger sub-graph to the smaller one until the difference is not greater than 1. If we repeat this process until we cannot find two such sub-graphs, the connectivity of the whole graph will be the smallest and the number of nodes in any sub-graph is $\lfloor n/m \rfloor$ or $(\lfloor n/m \rfloor - 1)$.

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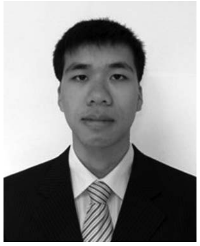

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