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The Impacts of Spatial Topology Redundancy on Proactive MANET Routing Performance

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Abstract— **The nodes of proactive MANET routing protocols maintain routing information via periodic (link) state advertisements in the presence of frequent topology dynamics. However, the overhead introduced by the state advertisements may lead to performance degradation and consume battery power. Therefore, the unique characteristics of MANETs call for a comprehensive and quantitative analysis of the performance of proactive routing protocols. In this study, we present a quantitative study to investigate the impact of spatial topology redundancy on OLSR's performance. In particular, three options for link state advertisements are studied: the directed MPR subgraph option, the undirected MPR subgraph option and the full graph option. Simulation based experiments are performed in order to quantify the impact of several factors on the performance. The results of our analysis reveal that, in low-density networks, topology redundancy improves the routing throughput, at the cost of increased control overhead. In high-density networks, topology redundancy leads to performance degradation.**

I. INTRODUCTION

Routing in Mobile Ad hoc Networks (MANETs) is challenging because mobility causes frequent topology changes and resilient and robust mechanisms are thus required to discover and maintain real-time route state information. When the nodes move, the established routes may get broken, and the routing protocols must respond quickly to such failure and find an alternative loop-free route. Besides the topology dynamics, the routing protocols in MANETs have to deal with resource constraints, such as bandwidth and energy consumption, inherent in wireless environments.

Proactive routing protocols for MANETs are table-driven, by which means the nodes maintain routes to all destinations. In the presence of the frequent topology changes, the nodes broadcast periodic Topology Control (TC) messages in the network to enable other nodes to maintain correct routing information. Due to the limitations on bandwidth and energy, the dissemination of topology advertisements needs to be optimized in order to reduce the resource consumption.

For example, Optimized Link State Routing (OLSR)[1] uses a Multi-point Relay (MPR)[2] mechanism to reduce the amount of state information in each TC message[1], the number of TC messages generated and the number of TC message retransmissions. Existing studies of the performance of the MPR mechanism prove its validity in delivering the messages to each node[3], and its efficiency[2][4]. However, it is not clear how the optimized topology advertisement method and routing changes (in the control plane) may impact data transfer performance metrics (in the user plane) like end-to-end throughput. More generally, it is necessary to clarify how *state redundancy* (i.e. extra link state information in each TC message) affects the routing and data transfer performance. Although it is known that spatial redundancy in state advertisements introduces extra control overhead, the possible improvements on routing performance and data transfer performance are not well studied.

Clausen *et al* [5] investigated two topology advertisement options, namely (1) MPR full link-state option (i.e. only MPR nodes advertise links to all their neighboring nodes) and (2) full link-state option (i.e. all nodes advertise the links to all their neighboring nodes). They conclude that the additional link state information provides better robustness against moderate node mobility.

In this study, we present an in-depth analysis of the impact of spatial topology redundancy on OLSR routing performance under various factors, including node velocity, node density and refresh intervals. Three types of topology information are considered: (1) partial topology based on a directed MPR subgraph, (2) partial topology based on an undirected MPR subgraph and (3) full topology consisting of all symmetric links in the network.

The rest of the paper is organized as follows. Section 2 gives background information on the topology diffusion mechanisms in original OLSR routing protocol. Section 3 presents the proposed topology advertisement options. Section 4 describes the NS2 simulations used in this study. Section 5 shows our observations based on the simulations. Conclusions and future work are summarized in section 6.

II. THE OPTIMIZED LINK STATE ROUTING PROTOCOL

In the following paragraphs, we introduce briefly the topology diffusion mechanisms in OLSR routing protocol.

OLSR inherits the concept of the link state (LS) routing but with flooding optimizations. In traditional LS-based routing protocols, each node floods its local link-state information to other nodes in the network once it detects the link changes between itself and its neighbors. Unlike the traditional LS method, OLSR uses MPRs [2][3] [4] to optimize the message flooding.

Each node selects a set of its neighbor nodes as MPRs. A node, which has selected its neighbor A as its MPR, is called the *MPR Selector*[1] of node A.

The selective flooding based on MPR is *efficient* in terms of control message delivery. In [3] it is shown that, such flooding eventually reaches all the nodes in the graph. Also, for each node pair in the network, the subgraph consisting of the unidirectional MPR links in the network and all adjacent links (of the node pair) contains a *shortest* path with respect to the *original* graph.

In particular, the MPR optimization includes the following three aspects.

First, in OLSR, only the MPR nodes are responsible for forwarding control traffic. This significantly reduces the number of retransmissions required to flood a message to all nodes in the network.

Second, the partial link state is advertised in order to provide shortest path routes. In OLSR, only the states from the *MPR selector set* is advertised in the topology control messages. Although bi-directional, only the *unidirectional* link states (i.e. the link status from the MPR nodes towards their corresponding MPR selectors) are advertised, from which the nodes eventually obtain a *directed* MPR subgraph of the whole network topology. The motivation for such partial state advertisement is to reduce the size of the topology control messages.

Third, only MPR nodes generate the topology control messages (TC), since the MPR selector set in non-MPR nodes is *NULL*. This reduces the number of the topology messages generated in the network.

With all the optimizations above, the MPR mechanism provides an efficient method for flooding control traffic by reducing the number of transmissions required and the amount of control traffic flooded. Further details of OLSR and MPR can be found in [1][2][3] [4].

III. PROPOSED TOPOLOGY ADVERTISING STRATEGIES

In this section, we list the three topology advertisement options investigated. These options determine the level of each node's knowledge of network topology and impact the routing performance.

A. Options for Topology Advertisements

First, we introduce some commonly used symbols in this section.

In the graph $G=(V,E)$, let $M \subseteq V$ be the MPR set of G, i.e. a set of nodes that are selected as MPR by at least one node in the network.

For each node $u \in V$, let

1) $N(u) \subset V$ be the neighbor set of node u.
2) $MPR(u) \subset N(u)$ be the MPR set of u, i.e. a set of neighboring nodes that u selects as MPRs.
3) $MPRSEL(u) \subset N(u)$ be the MPR selector set of u, i.e. a set of neighboring nodes that select u as MPR.

The topology advertisement options are listed as follows.

- **Partial Topology Advertisement** option of **Directed** MPR subgraphs (*pta_d*) is the default strategy used in the standard OLSR protocol.
  In this option, only the nodes selected as MPRs generate the TC messages with the state information of the MPR-selector neighbors. That is, for each node $u \in M$, the TC messages contain the state information of the directed link (u,v) for each $v \in MPRSEL(u)$. Therefore, the unidirectional links from the MPR nodes towards the MPR selectors are advertised in each TC message. Each node holds a directed subgraph of the network topology that consists of these unidirectional links.
- **Partial Topology Advertisement** option of **Undirected** MPR subgraphs (*pta_u*) advertises both *the MPR selector set* and *the MPR set*.
  In this option, the nodes selected as MPRs generate the TC messages with the state information of the MPR neighbors and the MPR-selector neighbors. Non-MPR nodes generate the TC messages with their MPR state information only. That is, for each node $u \in M$, the TC messages contain the state information of the directed link (u,v) for each $v \in MPRSEL(u)$ and the state information of the directed link (u,v') for each $v' \in MPR(u)$. For each node $u' \in V - M$, the TC messages contain the state information of the directed link (u',v') for each $v' \in MPR(u)$. Therefore, the bi-directional links between the MPR nodes and their MPR selectors are advertised. Each node obtains an undirected subgraph of the network topology which consists of these links.
- **Full Topology** option (*ft_s*) advertises all *symmetric* links in the network. In this option, each node advertises all the symmetric links to its neighbors. That is, for each node $u \in V$, the TC messages contain the state information of the directed link (u,v) for each $v \in N(u)$ if (u,v) is symmetric. Therefore, each node obtains a full undirected graph of the network topology.

B. The Impacts of Topology Redundancy on MANET Routing

By introducing topology redundancy, there are two potential changes to OLSR's routing processes.

Firstly, it is known that applying topology redundancy introduces extra control message overhead. In terms of the options listed above, the size of control messages of option *pta_u* and *ft_s* is likely to result in a larger overhead than that in option *pta_d*. Moreover, more control messages are generated in option *pta_u* and *ft_s*. The increased control traffic leads to an increase in buffer occupancy and network channel contention, which may cause an increase in packet collisions in the wireless medium. In addition, the increased packet size may cause an increase of packet error rate (PER) for a given bit-error rate (BER).

Since we do not change the MPR-based flooding mechanism, the control messages are still re-transmitted by the MPR nodes only. Therefore, for each control message, the number of the re-transmissions is not changed.

Secondly, with topology redundancy, the nodes have more choices in route selection, which improves the route availability. In the presence of route breakage, the nodes can re-establish a new route quickly and thus the packet drops caused by route unavailability can be reduced. The route length (number of router hops) between any two nodes is the same under the different topology options[3] because the nodes always select the shortest paths as the routes.

Other network characteristics, such as link duration and link change rates, are unchanged, since the node distribution and mobility is unaffected by (or dependent upon) the topology advertisements.

IV. PERFORMANCE EVALUATION

A. *Simulation Configuration*

The simulation study was conducted with the OLSR implementation from [6] which is implemented under version 2.9 of NS2 [7] and uses the ad-hoc networking extensions provided by CMU [8], with a radio range (r) of 250m radius and the use of MAC/802_11 as the media access control. By default, each wireless node has 50 packet buffer spaces and its raw radio link capacity is 2M bps.

We use a network consisting of n nodes: $n = 20$ to simulate a low-density network, $n = 50$ to simulate a high-density network. The nodes are randomly placed in an area of 1000m by 1000m. All simulations run for 100s.

We use the Random Trip Mobility Model, ”... a generic mobility model that generalizes random waypoint and random walk to realistic scenarios ...” [9] and performs ”perfect” initialization. Unlike other random mobility models, Random Trip reaches a steady-state distribution without a long transient phase and there is no need to discard initial sets of observations.

The mean node speed, v, ranges between 1m/s to 30m/s. For example, when the mean node speed is 20m/s the individual node speeds are uniformly distributed between 0m/s and 40m/s. The average node pause time is set to 5s.

The traffic model consists of randomly distributed CBR flows, which allows every node in the network to be a potential traffic source and destination. The CBR packet size is fixed at 512 bytes. There are at least $n/2$ data flows that cover almost every node.

B. *Metrics*

In each simulation, we measure the throughput of each CBR flow and control traffic overhead and then calculate the mean performance of each metric as the result of the simulation.

Throughput is computed as the amount of data transferred (in bytes) divided by the simulated data transfer time (the time interval from sending the first CBR packet to receiving the last CBR packet).

In order to gauge the routing protocol overhead, we measure both the number of routing messages, including HELLO messages and TC messages, and the number of bytes in the routing packets transmitted. Considering the broadcasting nature of the control message delivery, the packets are counted by summing up the size of all the control packets *received* by each node during the whole simulation period.

In order to gain good confidence in the measurement results, we run the simulations 100 times for each data point, with different mobility pattern files, i.e. different starting states for the node positions.

V. OBSERVATIONS

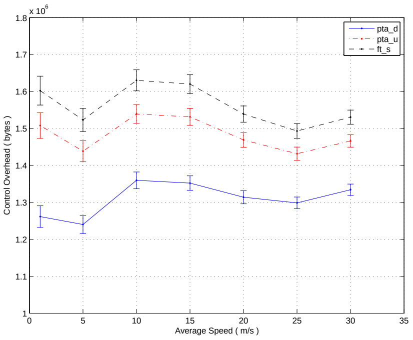
In this section, we present the observations from the simulations on the performance under various values of the parameters such as node density and node velocity, and consider the impact of cross-layer support.

A. *Control Overhead*

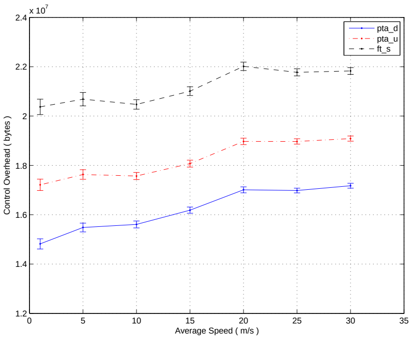
The amount of control overhead is determined by (1) the topology redundancy options (*pta_d*, *pta_u* or *ft_s*), (2) the value of the control message *refresh intervals* (e.g. HELLO intervals h and TC intervals t) and (3) the node density.

For Fig 1, 2 and 3, we hold h, t and *radio range* (r) constant, and all figures are obtained with cross layer support.

From Fig 1 we can see that, the topology redundancy options introduce extra control traffic overhead. As expected, full-topology advertisement generates more overhead than partial-topology advertisement. For example, option *pta_u* leads to 10% -20% increase of bandwidth consumption, while option *ft_s* leads to up to 35% increase.



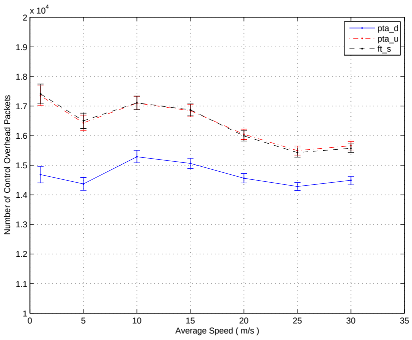
(a) Low Density (n=20)



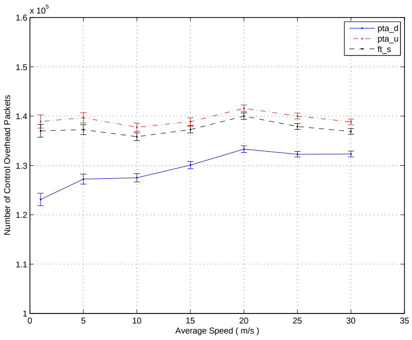
(b) High Density (n=50)

Fig. 1. The Amount of Control Overhead under Option *pta_d pta_u* and *ft_s* (h=1, t=5, r=250)

Fig 2 and 3 give a further look into the overhead increase from the aspects of packet number and packet size.

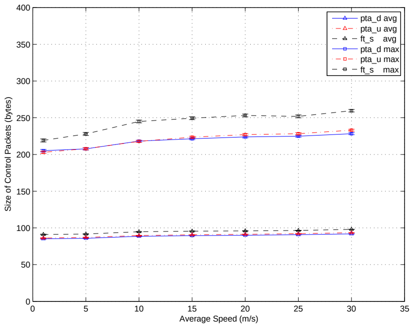


(a) Low Density (n=20)

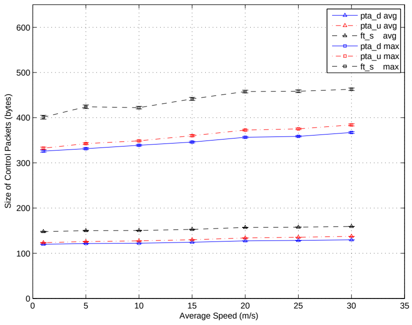


(b) High Density (n=50)

Fig. 2. The Number of Control Packets under Option *pta_d*, *pta_u* and *ft_s* (*h*=1, *t*=5, *r*=250)



(a) Low Density (n=20)



(b) High Density (n=50)

Fig. 3. The Size of Control Packets under Option *pta_u* and *ft_s* (*h*=1, *t*=5, *r*=250)

From Fig 2 we can see that, state redundancy options *pta_u* and *ft_s* generate 14%-17% more control packets in low-density networks, while 3%-13% in high-density networks.

From Fig 3 we can see that, the control packet size under option *pta_u* is almost the same as that under the standard MPR option. In low density networks the average packet size under option *ft_s* is just slightly larger than that under the other two options, while the maximum packet size is increased up to 15%. In high-density networks, the packet size under option *ft_s* is increased up to 1/3.

Based on these observations we find that, compared to option *pta_d*, the extra overhead of option *pta_u* is mainly due to the increase in the number of control packets, since the size of the packets is almost unchanged. On the other hand, the overhead increase of option *ft_s* is from both sources.

In addition, compared with option *pta_u*, the extra overhead of option *ft_s* is mainly from the increase in control packet size, since option *pta_u* propagates almost the same number of control packets as option *ft_s*.

Furthermore, by comparing Fig 1(a)2(a) 3(a) with Fig 1(b)2(b) 3(b) we find that, option *ft_s* is more sensitive to network size than option *pta_u*.

Note that, in IEEE 802.11 wireless networks, the bit error rate (BER) can be quite low. For example, a bit error rate of better than 10e-5 is considered acceptable in wireless LAN applications. Therefore, with the above increase of packet size, the packet error rate would not increase significantly.

So, in this study, the overhead introduced by *pta_u* and *ft_s* will not lower the performance of the data packet delivery.

B. *Throughput*

Below, we describe the observations of throughputs under different conditions. In particular, we use MAC layer notification to facilitate link failure detection[10]. Figs 4 and 5 are with MAC layer support, while Figs 6 and 7 are not.

For all the figures in this section, we hold *h*, *t* and *r* constant.

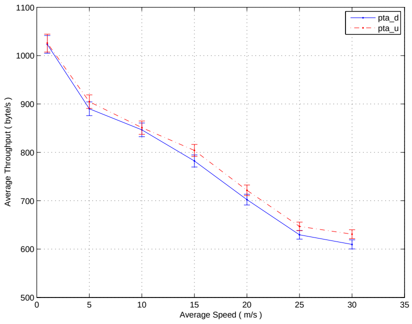
The observations under MAC layer support are as follows.

From Fig 4(a) and 5(a), we can see that, in low-density networks, introducing state redundancy improves the throughput. As expected, option *ft_s* leads to better performance than option *pta_u*. The improvements are significant when the node velocity is relatively high (i.e. *v* greater than approximately 12m/s).

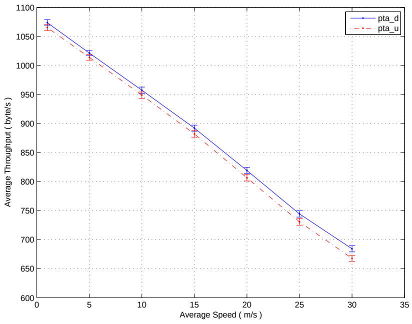
Surprisingly, from Fig 4(b) and 5(b), it follows that in high-density networks, the throughput with topology redundancy is lower than that with partial topology information. In addition, option *ft_s* leads to more degradation than option *pta_u*. Specifically, the performance degradation starts when the node velocity is relatively low (i.e. *v* greater than approximately 2m/s) and then gets more significant with the increase of node velocity.

After removing the MAC layer support from OLSR, the observations are as follows.

From Fig 6 and 7, we can see that in networks without the cross-layer optimization, the impact of state redundancy is less

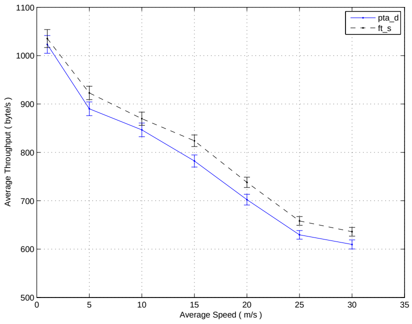


(a) Low Density (n=20)

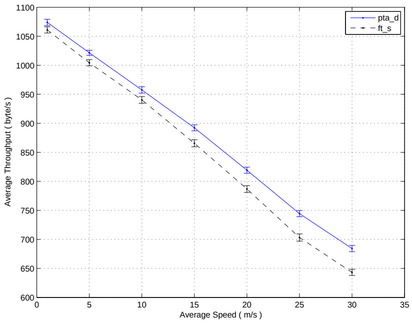


(b) High Density (n=50)

Fig. 4. Throughput under Option *pta_d* and *pta_u* with Cross Layer Support (*h*=1, *t*=5, *r*=250)

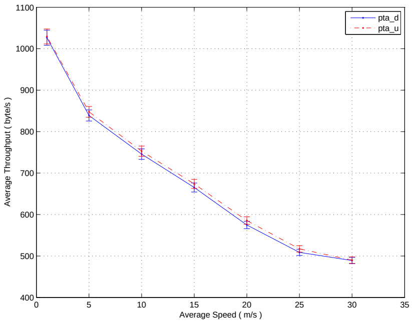


(a) Low Density (n=20)

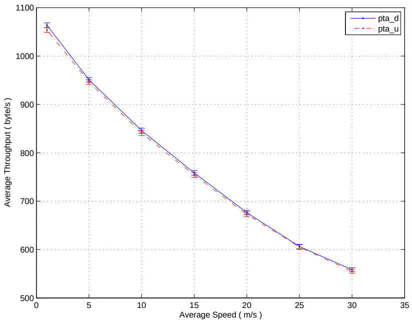


(b) High Density (n=50)

Fig. 5. Throughput under Option *pta_d* and *ft_s* with Cross Layer Support (*h*=1, *t*=5, *r*=250)

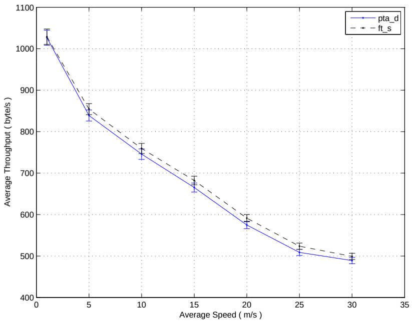


(a) Low Density (n=20)

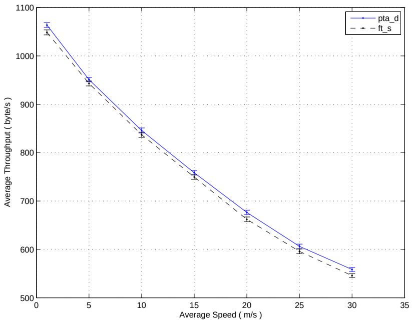


(b) High Density (n=50)

Fig. 6. Throughput under Option *pta_d* and *pta_u* without Cross Layer Support (*h*=1, *t*=5, *r*=250)



(a) Low Density (n=20)



(b) High Density (n=50)

Fig. 7. Throughput under Option *pta_d* and *ft_s* without Cross Layer Support (*h*=1, *t*=5, *r*=250)

significant. In particular, less improvement is observed in low-density networks, while insignificant performance degradation is observed in high-density networks.

Introducing state redundancy in low-density networks can therefore lead to performance improvements due to increased route availability. In high-density networks, however, the inverse phenomenon is observed. State redundancy lowers the performance. In addition, through comparing the performance with and without MAC support, we find that the MAC layer notification mechanism is one of the key factors that contribute to the impact of state redundancy on routing performance, especially for the performance degradation in high-density networks.

VI. CONCLUSIONS AND FUTURE WORK

In this study, we present a quantitative study of the impact of spatial topology redundancy on the performance of proactive MANET routing protocols. Our simulation results show that the impact depends on a range of factors, including node velocity, node density and cross-layer optimization.

We find that, the impact of spatial redundancy is more significant in moderate or high mobility networks. In particular, in low-density networks with moderate or high mobility, the redundancy of topology information improves the performance. In relatively stable networks, there is no obvious improvement observed.

Moreover, performance degradation is observed when spatial topology redundancy is applied into high-density networks. Especially, the degradation is significant when full topology information is advertised in high-density networks with cross-layer optimization.

A theoretical model based on graph theory has been developed to explain the phenomena observed. Due to limited space, the model is not described in this work.

The impact of control overhead on throughput is not covered in this study. Further discussion on this issue will appear in our on-going work.

In addition to the factors studied in this paper, other factors, such as radio range and refresh intervals, also affect the impact of state redundancy. The analysis on this will appear in our future work.

The original data, the source code and the scripts used in this study are all available from the authors' websites (http://www.cs.ucl.ac.uk/staff/y.huang/topo_ad.tar.bz2).

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