Carleton University, Systems and Computer Engineering, Technical Report SCE-06-01, January 2006

EXTENDING NETWORK KNOWLEDGE: MAKING OLSR A QUALITY OF SERVICE CONDUCIVE PROTOCOL

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January, 2006

This report examines mechanisms to gradually and dynamically increase the partial view of the network topology that is advertised by the ad hoc routing protocol Optimized Link State Routing (OLSR) in order to find more robust and reliable paths oriented to support Quality of Service (QoS). Such mechanisms maintain the optimal OLSR flooding mechanism.

TABLE OF CONTENTS

LIST OF FIGURES

Figure **Page**

LIST OF TABLES

Table **Page**

LIST OF GRAPHS

Graph **Page**

Graph **Page**

ABSTRACT

Finding paths between nodes that want to communicate in wireless ad hoc networks is not trivial due to network mobility, environmental conditions and constantly changing multi-hop paths (constructed by several nodes). Even more, once that the paths have been found, they have to be also maintained. Therefore, robust and efficient ad hoc routing algorithms are required. OLSR is a routing algorithm for ad hoc wireless networks that makes use of an optimized broadcasting mechanism, based on Multipoint Relay nodes (MPRs), to reduce the network load when broadcasting control messages and to support path computation. OLSR proactively provides paths to every feasible destination making use of Minimum Hop Count (MHC) as the metric to find routing paths. However, it is not very efficient due to its lack of knowledge, such as full topology, node and link status (e.g. buffer, battery, link quality, etc.) and network load when finding routing paths. Actually, MHC paths are usually constructed by longer links (between nodes located at farther distances), which tend to provide lower throughput and frequent breakage. The aim of this research is to extend the amount of network information that is available for OLSR in order to find more robust and reliable paths. In this research, such network information to be extended is the network topology knowledge. We examine different strategies to gradually and dynamically increase the partial view of the topology. Different TC_Redundancy strategies are combined with the MPR_Coverage feature of OLSR in order to provide extended topology knowledge while maintaining the optimal OLSR flooding mechanism. Experimental results show that extended topology knowledge would make OLSR a supportive routing protocol for Quality of Service (QoS). A possible NS-2 *bug* is also discussed. Statistical analysis is applied to eliminate any effect that this *bug* may have had.

1. INTRODUCTION

Mobile ad hoc networks (MANETs) are infrastructure-less networks where mobile nodes communicate with each other by means of the wireless media. The absence of infrastructure allows free node mobility, which translates into a constantly changing network topology. MANETs are also considered as best alternative to provide networking connectivity on rough scenarios (e.g. disaster relief areas, battle fields) where environmental conditions are another factor that changes the network topology. The network topology is described by the location of nodes and by the availability of direct communication between each pair of nodes, meaning network links. However, pure knowledge about link existence is insufficient because the traffic load that each link can carry completely depends on its quality, which also depends on the distance between the nodes at both ends of the link and, on the surrounding environment. It means that two different links in the network may provide completely different delivery rates, even without considering the fact that delivery rates of symmetric links are usually different for the uplink and the downlink [1]. Also, if we consider mobile nodes we have to think on nodes running on batteries, batteries that will not last forever, and given the fact that the more information is transmitted the more battery is spent, then if extending network life is an issue, load balancing must be a concern.

The aforementioned exemplifies the importance of accurate knowledge about nodes, links and network status in general. Basically, the more accurate knowledge is available the better decisions can be taken. When data traffic has to be sent from one node in the network to another and both nodes are not in direct communication range of each other, then the first step is to find a path from the source to the destination node. The task of finding paths in the network is the job of routing protocols. Routing protocols may behave in a *proactive mode* [4, 10], by finding paths to every other node in the network before the paths are actually required, or in a *reactive mode* [11] (on demand), by finding paths at the time that they are actually required. Because reactive protocols only look for routing paths at the time that they are requested, this type of protocols do not load the network with high volumes of communication overhead, however, the delay that may be experienced by nodes wishing to establish communication with any other node in the network may be too long. Such a long delays may not be affordable for critical systems requiring high levels of Quality of Servive (QoS), then, proactive protocols that maintain *ready to use paths* become a more feasible alternative.

OLSR (Optimized Link State Routing) protocol is a well known proactive routing protocol for MANETs, which has been broadly tested and implemented [2, 3]. As a link state protocol, OLSR keeps track of the existing links in the network, which are periodically advertised by means of broadcast control messages known as Topology Control messages (TC messages). However, in order to decrease the network load imposed to the network when advertising link information, TC messages only advertise a partial set of the network links and they are only forwarded by a subset of the nodes called Multipoint Relay Nodes (MPRs). MPRs optimize broadcasting and are also used as the core of all routing paths. To construct optimal paths to each destination OLSR makes use of Minimum Hop Count (MHC) as its metric, however, MHC only cares about the existence of links but not about their quality (link throughput strongly depends on link quality), therefore, two links with completely different qualities (high and poor quality) may be evenly chosen by MHC; or even worst, a one-hop path built by one poor quality link may be chosen over a two-hops path built by two high quality links. Also, OLSR does not consider any other information about nodes or network status. Then, the lack of broader knowledge constrains OLSR to choose paths solely based on its knowledge about links existence, however, this knowledge is also partial because nodes are only aware of a subset of the network topology.

The aim of this research is to extend the amount of network information available for OLSR in order to find more robust and more reliable paths. We focus on extending the network topology knowledge by looking at different strategies that gradually and dynamically increase it. Three TC_Redundancy strategies described on the OLSR RFC [4], plus two more proposed strategies, are combined with the MPR_Coverage feature of OLSR in order to achieve our objective, while maintaining the optimal broadcasting mechanism supported by the MPR nodes. Experimental results show the different trade-offs that can be achieved in terms of additional topology knowledge and communication overhead along with the feasibility to convert OLSR into a supportive routing protocol for Quality of Service (QoS). Finally, a possible *bug* in NS-2 was detected and explained. Statistical analysis was applied to overcome the inaccurate results that were generated due to this *bug*.

The rest of the report is organized as follows. Section 2 discusses the Related Work. Section 3 describes the OLSR routing protocol. Section 4 describes the proposed method to extend the topology knowledge. Section 5 details the research methodology and Section 6 presents the experimental results. Finally, Section 7 presents the conclusions.

2. RELATED WORK

OLSR is a well-known routing protocol for ad hoc networks. It has been broadly examined [2, 7], implemented and deployed [3, 6]. Reference [7] provides performance measurements over a real test-bed and concludes that even when the protocol seems to be well adapted to military mobile ad hoc networks it suffers from high variability of performance depending on the hop number, and from unfairness depending on the topology and on traffic nature. Therefore, QoS features could perfectly complement OLSR. Reference [8] proposes a new MPR selection mechanism based on link bandwidth, and a new route calculation algorithm to find maximum bandwidth paths in order to provide QoS with OLSR. Finally [2] investigates the impact of the partial topology information available for OLSR when increasing MPR Coverage and redundant topology information. They show higher delivery rates under moderate mobility when increasing redundant topology information; however, such benefits were not found in our research, even when our scenarios used the same simulation parameters (except for the protocol implementation for NS-2) described in [2]. This research expands the work done in [2] and entirely focuses on understanding the trade-offs of increasing accurate topology knowledge. It also analyses additional aspects of the OLSR performance such as percentage of MPRs and availability of routing paths besides a rigorous analysis of Per Packet Delay that discovered a possible *bug* in NS-2. In addition, the support of OLSR to Quality of Service is discussed.

3. SUPPORTIVE ROUTING PROTOCOL

To achieve desired topology knowledge, a supportive mechanism that advertises such information is required. The main objective of a communication network is the exchange of data between nodes; therefore, routing protocols to construct paths between nodes are also required. In this paper, OLSR is proposed as the routing protocol to construct routing paths because it allows the manipulation of the amount of topology knowledge that is advertised into the network. Extended topology knowledge allows the construction of more robust routing paths and even multiple paths to the same destinations in order to provide QoS. A brief description of OLSR is given next.

3.1 OLSR Protocol

OLSR (Optimized Link State Routing) protocol is a proactive table driven routing protocol for mobile ad hoc networks and is fully described on RFC 3626 [4]. As a link state routing protocol, OLSR periodically advertises the links building the network, however, OLSR optimizes the topology information flooding mechanism, by reducing the amount of links that are advertised and by restraining the number of nodes forwarding each topology message to the MPR set only. Each message advertising topology information is called Topology Control (TC) message and it is broadcasted into the network. TC messages are only originated at the nodes that have been selected as Multipoint Relays (MPRs) by some other node in the network. MPRs are selected in such a way that a minimum amount of MPRs, located one-hop away from the node doing the selection (called MPR Selector), are enough to reach every single neighbour located two-hops away from the MPR selector. By applying this selection mechanism only a reduced amount of nodes (depending on the network topology) will be selected as MPRs. Every node in the network is aware of its one-hop and two-hop neighbours by periodically exchanging HELLO messages containing the list of its one-hop neighbours. On the other hand, TC messages will only advertise the links between the MPRs and their selectors, then, only a partial amount of the network links (the topology) will be advertised, also MPRs are the only nodes allowed to forward TC messages and only if the messages come from a MPR Selector node. These forwarding constrains considerable decrease the amount of flooding retransmissions. *Figure 1* shows an example of a message transmitted by the source node *S* which is only retransmitted by the nodes *M* that *S* selected as its MPRs. This example shows the efficiency of the MPR mechanism because only five transmissions are required to reach all the 15 nodes building the network, which is a significant saving when compared to traditional flooding mechanism where every node is asked to retransmit once.

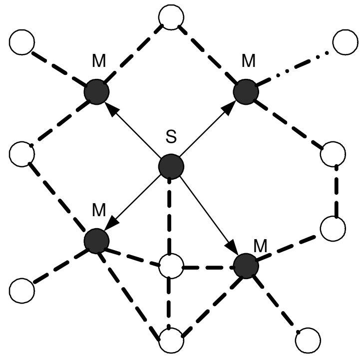


Figure 1. Flooding with MPR mechanism

4. EXTENDING TOPOLOGY KNOWLEGDE

OLSR is a proactive routing protocol that periodically broadcasts the links in the network. As an optimization over some other link state routing protocols, that advertise the entire set of links in the network, OLSR only advertises a subset of them, providing a partial view of the network topology. The MPR flooding mechanism along with the reduction on the amount of advertised links considerably decrease the communication overhead. Therefore, in terms of overhead reduction, OLSR provides a very attractive alternative; however, the partial topology knowledge may represent a severe shortcoming when constructing routing paths. As not all the links in the network are advertised, partial topology knowledge causes some of the nodes to be reachable only through one path even when there may well exist several. The lack of topology information and of any other information about link and node status acts against desired robustness and reliability features of routing protocols especially if QoS wants to be supported. Also, the mechanism to select the links to be advertised, does not consider any link attribute (e.g. link quality, signal strength) rather than its existence, neither any node attribute (e.g. battery left), such information could be useful when constructing paths, because more knowledge usually allows taking better decisions. OLSR makes use of Minimum Hop Count (MHC) as the metric to select the paths in the network, however, if more network topology information is available additional metrics rather than pure MHC could be applied. The additional metrics could consider one or more features at a time such as network information (e.g. network load), node status and link status. Therefore, to take better routing decisions, this research proposes to extend the topology knowledge. Obviously, a full link-state routing protocol such as OSPF [12] would provide a complete view of the topology. We are, however, interested in mechanisms to gradually increase topology knowledge and to explore the resulting increase in control message overhead. Understanding this trade-off will allow a network operator to set the protocol parameters based on their primary goals (reducing control message overhead vs. increased routing choices). The examined mechanisms are described next.

4.1 Redundant Topology Information

In OLSR, the network topology is broadcasted into the network by means of TC messages. TC messages advertise the links between every MPR node and its MPR Selectors. This is the minimal set of links that any node must advertise in its TC messages in order to support path computation [4]. However, additional links to neighbour nodes that are not MPR Selectors may also be advertised in order to extend the network topology knowledge. The RFC of OLSR [4] describes a parameter called *TC_REDUNDANCY* as part of the OLSR protocol which defines the links to be advertised on each TC message. The RFC describes three different values, 0, 1, 2 for this parameter; the meaning according to the RFC is as follows:

- If TC_Redundancy = 0 then the advertised link set of the node is limited to the links with its MPR Selectors.
- If TC_Redundancy = 1 then the advertised link set of the node is the union of the

links with its MPR Selectors and the links with its MPRs.

- If TC_Redundancy = 2 then the advertised link set of the node is its full set of links with all of its neighbours.

From the previous descriptions it is worth pointing out an unclear description given in [4]: for TC_Redundancy values equal to 1 and 2, the nodes generating TC messages are not constrained to MPRs, actually for these two values every single node in the network will be generating TC messages. And, for every case, only MPRs will be forwarding the TC messages.

4.1.1 Additional Redundant Topology Information Strategies

In the previous section the three redundant topology information strategies that are part of the OLSR RFC [4] are described. In this section, two more strategies identified with the TC_Redundancy parameter values 3 and 4 are proposed as part of the mechanisms to be examined. The description of the additional strategies is as follows:

- If TC_Redundancy = 3 then only nodes selected as MPRs will generate TC messages and, the advertised link set of the MPR node is the union of the links with its MPR Selectors and the links with its own MPRs.
- If TC_Redundancy = 4 then only nodes selected as MPRs will generate TC messages and, the advertised link set of the MPR node is its full set of links with all of its neighbours (this strategy is called *MPR full link-state* in [2]).

Therefore the performance of the five strategies mentioned above will be evaluated when combined will the MPR_Coverage feature of OLSR which is described next.

4.2 MPR Redundancy

As previously mentioned, each node in the network has to select a set of one-hop neighbours called MPR set, which is constructed by the smallest number of nodes that allow the MPR Selector node to reach every two-hop neighbour trough, at least, one of its MPRs. The OLSR RFC [4] describes the parameter MPR_COVERAGE which allows increasing the number of nodes through which, the MPR Selector can reach every two-hops neighbour. For example, if MPR_COVERAGE=m it means that, if possible, every two-hop neighbour can be reached through at least m nodes. Thus, MPR_COVERAGE parameter must be greater than zero.

Additional MPR redundancy impacts the overhead by increasing the number of nodes advertising links, the amount of links being advertised and the number of nodes forwarding broadcast messages. However, the additional overhead may be traded-off for other benefits such as network maps of higher accuracy and multiple paths for every destination, both of them supported by extended topology knowledge. Different values for the MPR_COVERAGE parameter are combined along with the previously described Redundant Topology Information Strategies in order to extend the topology knowledge.

5. METHODOLGY

With the aim of evaluating the cost-benefit of extending the topology knowledge, simulation work was done using the NS-2 network simulator along with the OLSR implementation provided by the Hipercom project, which is called OOLSR [6]. The only modifications made to the all-in-one (NS-2 ver. 2.27 plus OOLSR ver. 0.99.15) source code available for download were: adding packet delay measurement at the Loss Monitor Agent and, a few data outputs to generate the required data files for analysis, therefore, experimentation can be easily repeated. The simulation work was performed following the next steps. First, all the Redundant Topology Information Strategies were combined along with a few values of MPR Redundancy over static scenarios without data traffic. Once these initial scenarios were analyzed, data traffic was added to the static networks. Finally, mobile scenarios with data traffic were analyzed and a rigorous analysis of Per Packet Delay was performed. The discovery of a possible *bug* in NS-2 required the use of statistical analysis to eliminate any effect that this *bug* may have had.

Every scenario, static and mobile, was generated using the node-movement generator *setdest,* provided with NS-2, and making sure that no Unreachable Destinations existed. In order to make fair performance comparisons, exactly the same scenarios for same mobility speeds were always utilized when evaluating each strategy. Each experimental stage is described in the following sections.

5.1 Static Scenarios

As a first stage, simulation was performed over static networks without sending data traffic between nodes. The objective of this stage was to achieve basic understanding on the impact of the proposed strategies. Graphical and numerical analysis was performed. The simulation parameters are listed in Table 1.

Simulation Parameters	
Simulator	NS-2
Propagation Model	TwoRayGround
Network Type	802.11
Transmission range	250m
Field Size	1500 x 300
Number of nodes	50
Node Type	Static
Simulation time	50 seconds
Number of scenarios	30
TC Redundancy	0, 1, 2, 3, 4
MPR Coverage	1, 2, 3
TC message rate	Every 5 seconds

Table 1. Simulation Parameters for Static Scenarios.

The metrics that were utilized to measure the performance of the protocol are as follow:

1. **TC messages.** This metric counts the number of generated TC messages only, it does not count the retransmissions.
2. **TC messages overhead**. This metric counts the total amount of bytes composing all the generated TC messages.
3. **Percentage of known links**. This metric counts the percentage of known links by each node, over the total amount of existing links. It is averaged over all the nodes in the network.
4. **Percentage of MPRs**. This metric counts the number of nodes in the network that have been selected, by any other node, as an MPR.

5.2 Static Scenarios with Data Traffic

In a second stage, data traffic was added to the static scenarios. The objectives this time were to measure the data delivery rate and the impact of the data traffic over the achieved network topology knowledge. The simulation parameters are listed in Table 2.

Simulation Parameters	
Simulator	NS-2
Propagation Model	TwoRayGround
Network Type	802.11
Transmission range	250m
Field Size	1500 x 300
Number of nodes	50
Node Type	Static
Simulation time	50 seconds
Number of scenarios	30
TC Redundancy	0, 1, 2, 3, 4
MPR Coverage	1, 2, 3
TC message rate	Every 5 seconds
Topology Knowledge	
Snapshot frequency	Every 20 seconds
First Snapshot	Simulation time 10
Data Traffic	
Data streams	20
Stream duration	20 seconds
Stream start	Random between simulation time 20 and 29
Traffic Rates	640, 3200, 6400 Bytes/s

Table 2. Simulation Parameters for Static Scenarios with Data Traffic

The same metrics than the ones for Static scenarios were used plus the data delivery rate, which measures the rate of data packets that are properly received at the destination node.

5.3 Mobile Scenarios with Data Traffic

Once that the protocol performance over static networks with data traffic was analyzed, the next step is moving towards mobile scenarios with data traffic. This time the objective is to measure the impact of mobility over the protocol performance. The previous simulation scenarios were always static, which means that the topology and the routing paths did not change. However, when node mobility is allowed, network topology and routing paths change constantly, therefore, topology knowledge accuracy has to be also measured. The corresponding simulation parameters are listed in Table 3.

Simulation Parameters	
Simulator	NS-2
Propagation Model	TwoRayGround
Network Type	802.11
Transmission range	250m
Field Size	1500 x 300
Number of nodes	50
Node Type	Mobile
Simulation time	300 seconds
Number of scenarios	10
TC Redundancy	0, 2, 4
MPR Coverage	1, 2
Topology Knowledge	
Snapshot frequency	Every 20 seconds (15 total)
First Sample	Simulation time 50
TC message rate	Every 5 seconds
Data Traffic	
Data streams	20
Stream duration	30 seconds
Start of first stream	Simulation time 50
Stream start frequency	One every 10 seconds
Traffic rates	640, 3200, 6400 Bytes/s

Table 3. Simulation Parameters for Mobile Scenarios with Data Traffic

For the mobile simulation work all the metrics described in the previous sections were used along with a few more, which are listed next. Also the definition of the *Generated TC messages* metric changed to include retransmissions.

1. **TC messages.** Counts the number of TC messages transmitted including retransmissions.
2. **Accuracy of Topology Information**. This metrics show the percentage of the topology knowledge is accurate and does not correspond to stale links.

3. **Per Packet Delay**. This metric counts the accumulated delay that is experienced by each packet when travelling from source to destination. The measured values are averaged over all the packets that were properly delivered for each data stream.
4. **Accuracy of Topology Information**. Measures the percentage of topology knowledge that is accurate and does not correspond to stale links.
5. **Per Packet Delay (PPD).** Measures the transmission delay experienced by each data packet. It is averaged over all the packets properly delivered for each data stream.
6. **Percentage of Reachable Destinations.** Counts the number of nodes for which a routing path exists. It is averaged over all the nodes in the network.
7. **Path Length.** Counts the average path length between every source-destination pair.

5.4 Statistical Analysis

Several metrics were applied in order to evaluate the performance of the protocol. Most of these metrics are averaged values over a set of simulation scenarios. The PPD metric is a metric that is averaged over all the packets properly delivered for each of the data streams and for all the mobile scenarios. Therefore, there is an averaged value for each combination of: 1) Data traffic rate, 2) Mobility speed, 3) MPR Coverage parameter and, 4) TC Redundancy parameter. From simulation results it was observed that data outliers could exist for the PPD metric. Outliers are observations that lie at an abnormal distance from other values in a random sample from a population. Therefore, data examination to identify outliers and remove them, if they existed, was required. A detailed analysis of the simulation results showed a likely bug in NS=2 that generated the PPD outliers. A problematic scenario which was found in the simulation results is explained next.

5.4.1 Bug in NS-2

Fig. 2 illustrates the scenario that generates the PPD outliers. Fig. 2a shows a set of four nodes where node S is sending data to node D, using node A as a forwarding node. However, node A is moving southwest and, at some point in time, its movement causes the breakage of the link A-D. After detecting the link breakage node S changes the routing path to node D by using node B as a forwarder instead (see fig. 2b); however, there was one packet sent by A to D before the detection of the link breakage. This packet should had been considered as lost; however, the packet still existed in the simulation, and when the link A-D was re-established, more than 150 seconds later, the packet was delivered from node A to node D accumulating a huge PPD. The average PPD of this specific example, found in the simulation results, increased from 0.00671 seconds to 1.04435 seconds due to a single packet that was sent by node S at time 50 and received by node D at time 204.60907 accumulating a PPD of 154.60907 seconds. Therefore, to eliminate the effect of this bug which only affects the PPD metric, a statistical method to identify and remove outliers was required. The Box Plot technique [5], described in the following section, was chosen to identify the PPD outliers

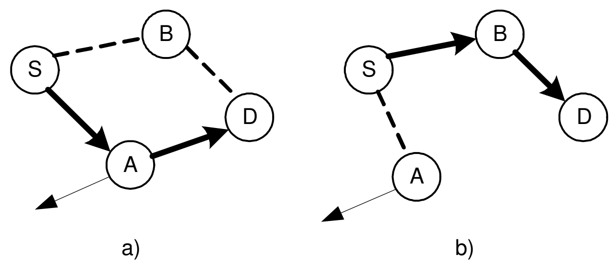


Fig. 2. Problematic Scenario in NS-2

5.4.2 Box-and-Whisker Plot

The box-and-whisker plot [5] (sometimes simply called box plot) is a graphical display method for describing data behaviour in the middle and at the end of the distributions. It makes use of the median, the lower quartile (25th percentile) Q1, the upper quartile (75th percentile) Q3 and the inter-quartile range IQ, which is the difference (Q3-Q1). The box plot is a box that contains all the values located between Q1 and Q3. To identify outliers in the tails of the distribution, the following quantities, called fences, are needed.

- Lower inner fence: Q1 – 1.5*IQ
- Upper inner fence: Q3 + 1.5*IQ
- Lower outer fence: Q1 – 3*IQ.
- Upper outer fence: Q3 + 3*IQ

Points located beyond inner fences are considered mild outliers. Points located beyond outer fences are considered extreme outliers. For the purpose of this research, PPD mild outliers and PPD extreme outliers were considered abnormal observations and both of them were singled out before computing averaged values for PPD. As a result, 10.1% of the PPD results were singled out.

6. EXPERIMENTAL RESULTS

Simulation work was performed as described in the previous sections. In this section the corresponding results are shown and commented. For practical reasons, from now on, graphs and tables of results will make reference to TC_Redundancy parameter as TC and to MPR_Coverage parameter as MPR.

6.1 Static Scenarios

The initial simulation work which was performed over static scenarios wanted to achieve some basic understanding about protocol's performance and to get some insights on the effects of each proposed strategy to increase the topology knowledge. Numerical results are usually the most common alternative to analyze the behaviour of protocols; however, to get quicker insights and to prove the necessity for extending the topology knowledge, the aid of visual tools was required. Therefore, using the java programming language, a software tool was developed in order to load the output files from NS-2 and to plot the partial network topology view perceived by the nodes in the network. Figures 3 to 7 show the topology knowledge rise that is achieved when applying some of the proposed strategies over the same scenario. The knowledge shown in each graph is the one that is available at a certain node in the network. In this case the chosen node was one of the central nodes connecting left and right network areas. Because topology knowledge is learnt throughout TC messages, which are broadcasted into the network, every node is expected to have similar amount of topology knowledge. In figures 3 to 7 the links shown are the ones that the node does know about. The total number of links in the network is 303. The achieved topology knowledge *TK* ranges from 27% (81/303) for MPR=1 and TC=0, to 100% (303/303) for MPR=1 and TC=2. MPR=1 and TC=4 provide a significant rise achieving 79% of topology knowledge. Complementary graphs for some other combinations of TC and MPR parameters are shown in Appendix A.

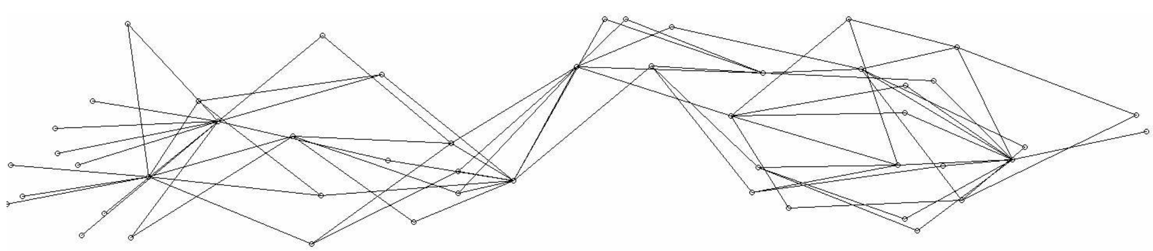


Figure 3. Topology Knowledge for MPR=1, TC=0 TK=82/303

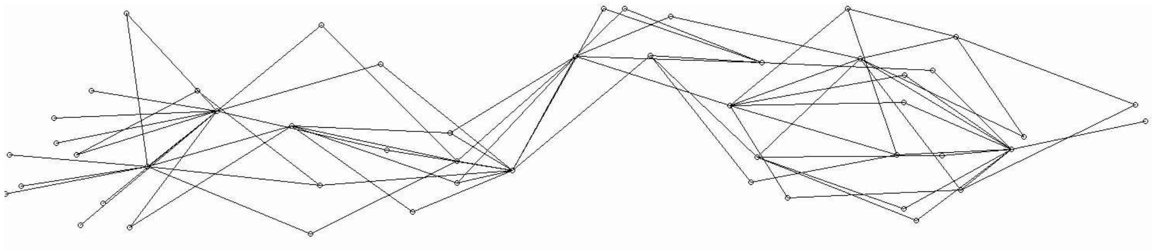


Figure 4. Topology Knowledge for MPR=1, TC=3 TK=82/303

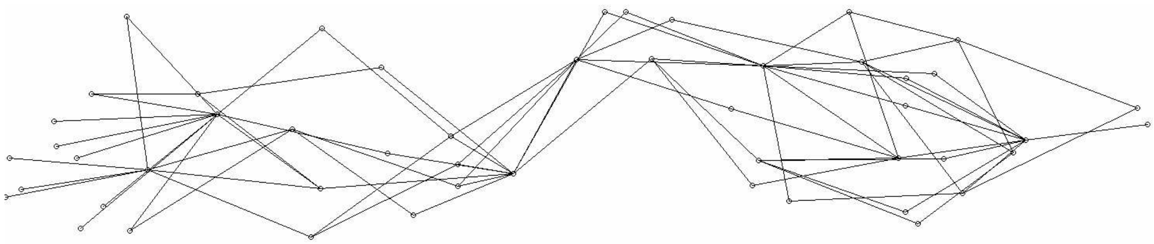


Figure 5. Topology Knowledge for MPR=1, TC=1 TK=82/303

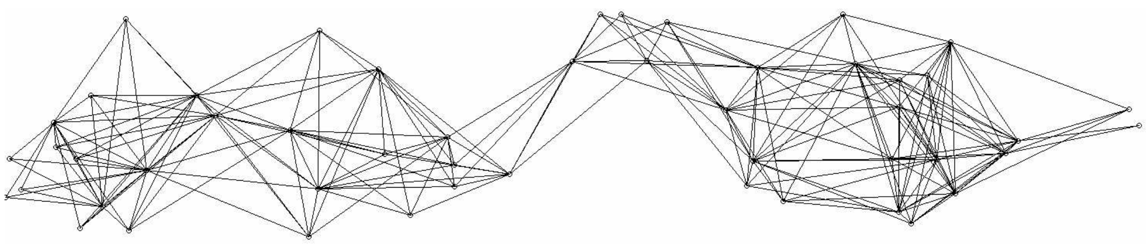


Figure 6. Topology Knowledge for MPR=1, TC=4 TK=228/303

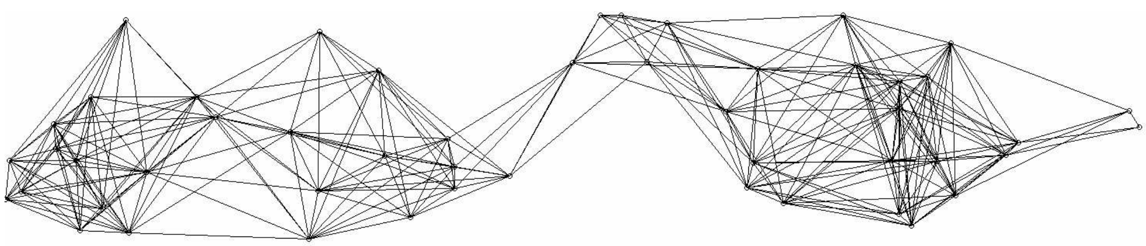
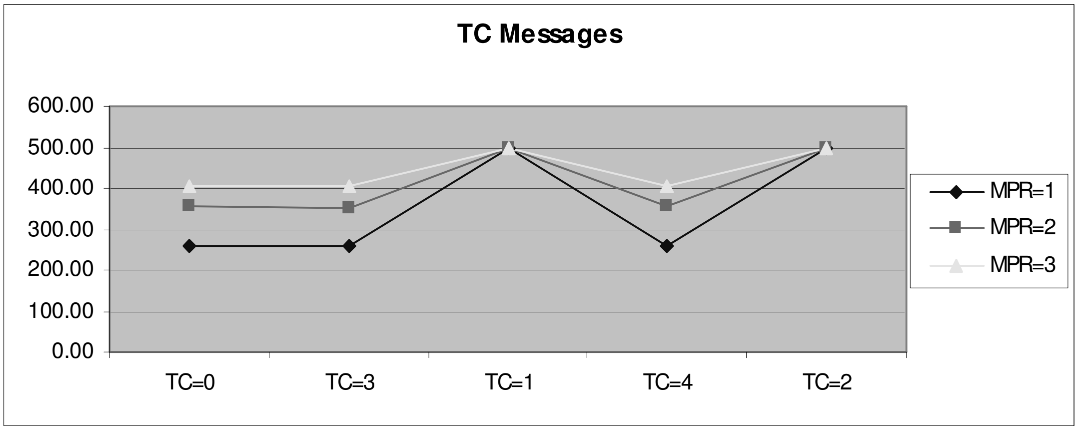


Figure 7. Topology Knowledge for MPR=1, TC=2 TK=303/303

The previous topology graphs show that extending topology knowledge is possible by applying the proposed strategies. Tables 4 to 8 along with Graphs 1 to 4 show the measured values obtained for each metric.

	TC Messages				
	TC=0	TC=3	TC=1	TC=4	TC=2
MPR=1	257.27	256.37	500.00	259.43	500.00
MPR=2	355.90	351.33	500.00	358.23	500.00
MPR=3	406.67	406.70	500.00	405.60	500.00

Table 4. TC Messages for Different Values of MPR and TC

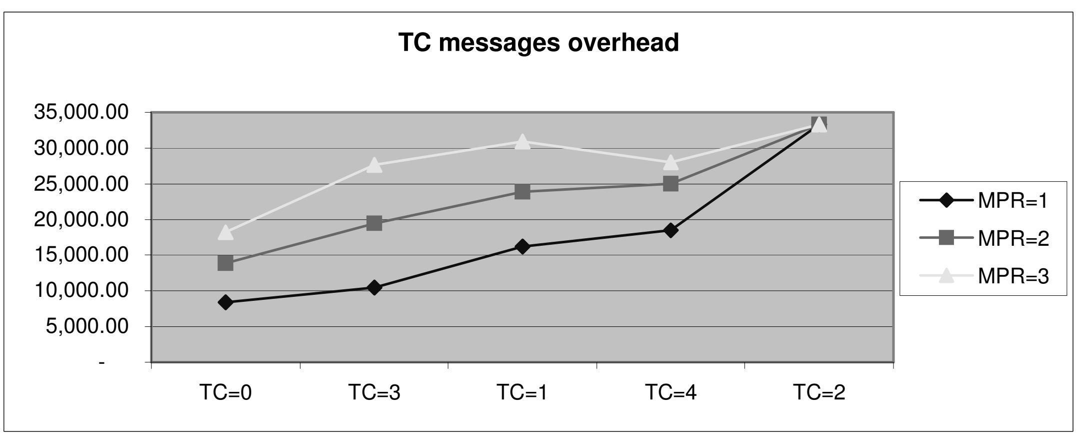


Graph 1. TC Messages for Different Values of MPR and TC

Graph 1 corresponds to the values shown in Table 4 for the number of TC messages generated for different values of MPR and TC. It is clear that the amount of TC messages increases when increasing the MPR parameter except for TC=1 and TC=2 because for those two strategies every single node in the network generates TC messages regardless of the value for MPR. On the other hand, the strategies TC=0, TC=3 and TC=4, which are affected by the MPR parameter, generate similar amount of messages. This result was expected because TC message generation is constrained to MPRs only; however, the size on bytes of the TC messages might not be the same.

	TC messages overhead				
	TC=0	TC=3	TC=1	TC=4	TC=2
MPR=1	8,390.53	10,465.07	16,171.87	18,459.47	33,320.00
MPR=2	13,864.93	19,456.13	23,893.20	25,021.47	33,320.00
MPR=3	18,183.87	27,659.87	30,924.40	28,044.40	33,320.00

Table 5. TC Messages Overhead for Different Values of MPR and TC.

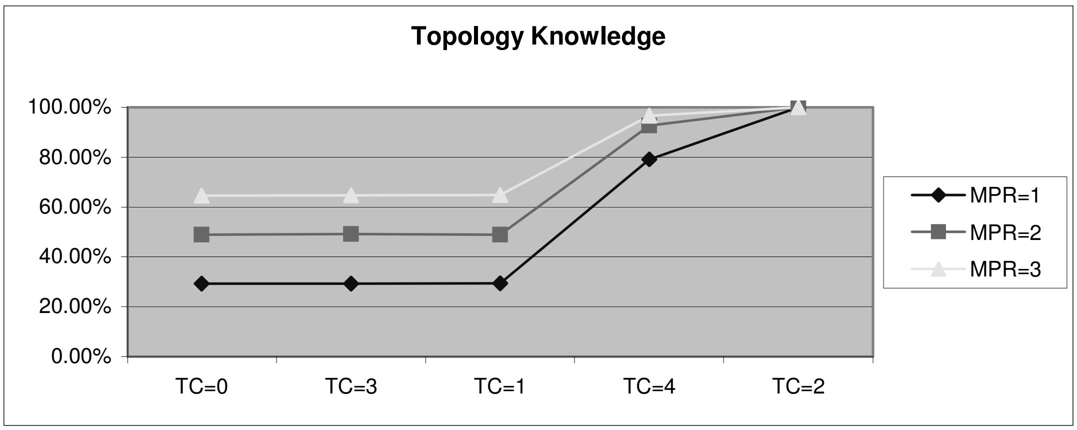


Graph 2. TC Messages Overhead for Different Values of MPR and TC

Table 5 and its corresponding graph, Graph 2, show that even when some TC strategies may generate the same amount of TC messages, the size of them is not the same. The generated TC messages overhead, in Bytes, directly corresponds to the number of links being advertised. Larger MPR parameters increase the overhead for every strategy except for TC=2 because all the nodes advertise all of their links every time. TC=0 generates the less overhead.

	Topology Knowledge				
	TC=0	TC=3	TC=1	TC=4	TC=2
MPR=1	29.15%	29.13%	29.24%	79.10%	99.98%
MPR=2	48.86%	49.08%	48.88%	92.71%	100.00%
MPR=3	64.58%	64.75%	64.89%	96.62%	99.99%

Table 6. Percentage of Topology Knowledge for Different Values of MPR and TC.



Graph 3. Percentage of Topology Knowledge for Different Values of MPR and TC

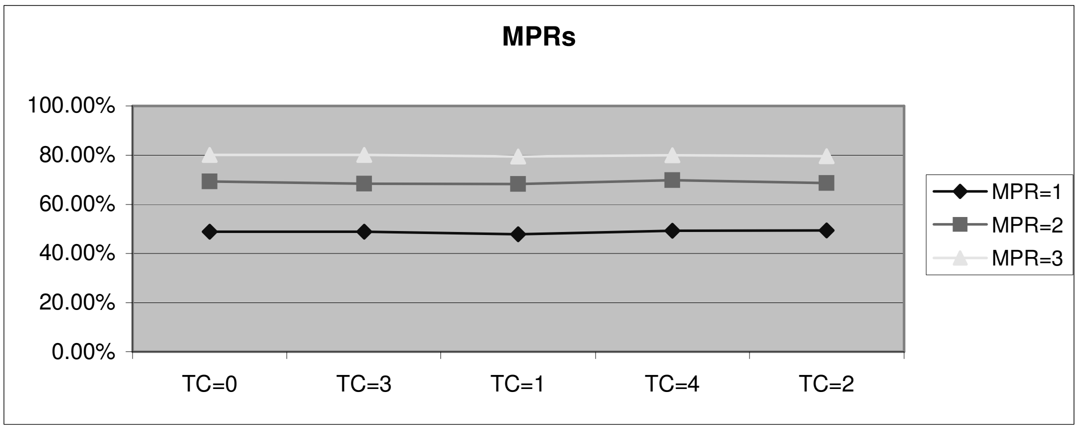
Table 6 and its corresponding graph, Graph 3, show the percentage of topology knowledge achieved by each strategy. It is clear that topology knowledge increases with the MPR parameter and that TC=2 is the only strategy able to reach 100% knowledge. TC=0, TC=3 and TC=1 achieve same knowledge and TC=4 achieves 79% of knowledge for MPR=1 and over 92% knowledge for MPR>1.

	MPRs				
	TC=0	TC=3	TC=1	TC=4	TC=2
MPR=1	48.73%	48.73%	47.73%	49.20%	49.33%
MPR=2	69.40%	68.47%	68.40%	69.93%	68.73%
MPR=3	80.13%	80.20%	79.53%	80.00%	79.60%

Table 7. Percentage of Nodes Selected as MPRs for Different Values of MPR and TC.

Table 7 and its corresponding graph, Graph 4, show how the amount of nodes selected as MPRs increase with the MPR parameter. Also, it is possible to notice that the amount of chosen MPRs is not affected by the TC strategy.

Considering that the objective of this research was to evaluate the cost-benefit in terms of the additional topology knowledge achieved by applying each of the proposed strategies, at the cost of increasing the communication overhead, from previous results we can argue that strategies TC=1 and TC=3 increase the communication overhead when compared to TC=0, for all values of MPR, but without providing any additional topology knowledge with respect to TC=0, therefore no benefit is gained but additional cost in terms of communication overhead is paid. On the other hand TC=2 achieves 100% of topology knowledge at the most expensive overhead cost. Finally TC=4 provides a trade off between topology knowledge rise (>79%) and communication overhead cost.

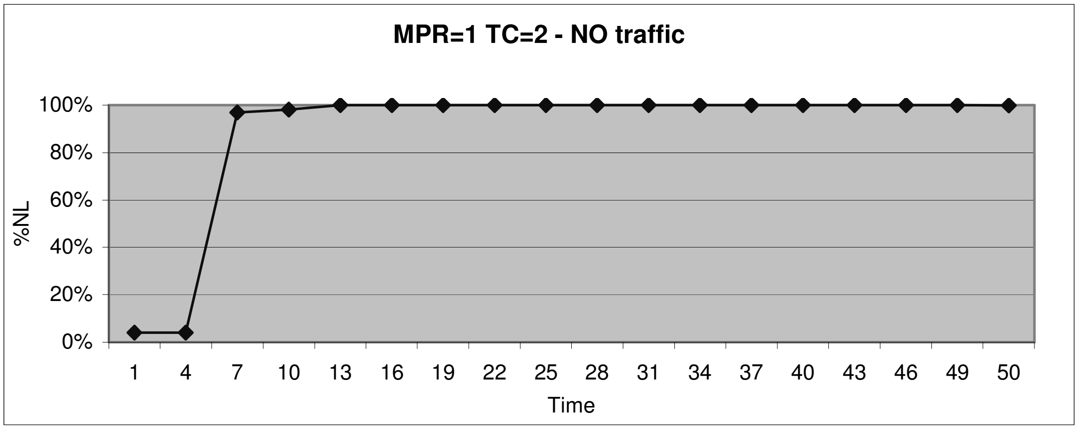


Graph 4. Percentage of Nodes Selected as MPRs for Different Values of MPR and TC

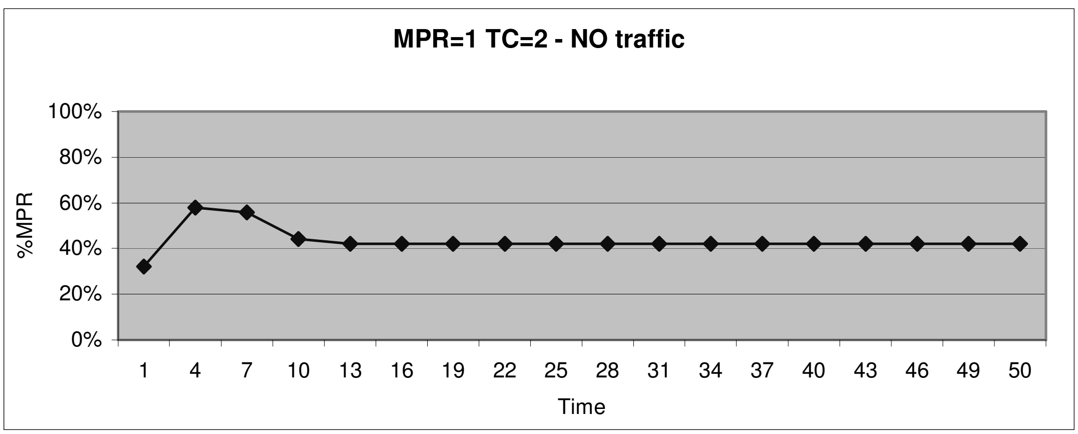
6.2 Static Scenarios with Data Traffic

In the previous simulation, no data traffic was sent and all the scenarios were static, therefore, it is possible to assume that at some point in time the network reaches an stability state where the topology does not change, the nodes that were chosen as MPRs do not change their status and, for the same reason, the topology knowledge does not change either. Therefore, if that is true, what has to be examined is, at which point in time the network stabilizes and, what is the impact of data traffic over the stability state. With that aim one single scenario was chosen and all the different strategies and traffic rates were applied to it while keeping track second by second of the Topology Knowledge and the percentage of nodes chosen as MPRs. Graphs 5 to 8 show the simulation results for the strategy MPR=1, TC=2 when no traffic is applied and when high traffic is applied. This MPR-TC strategy was chosen because the impact on it is the clearest. However, similar impacts are reflected for the rest of the MPR-TC strategies and traffic rates.

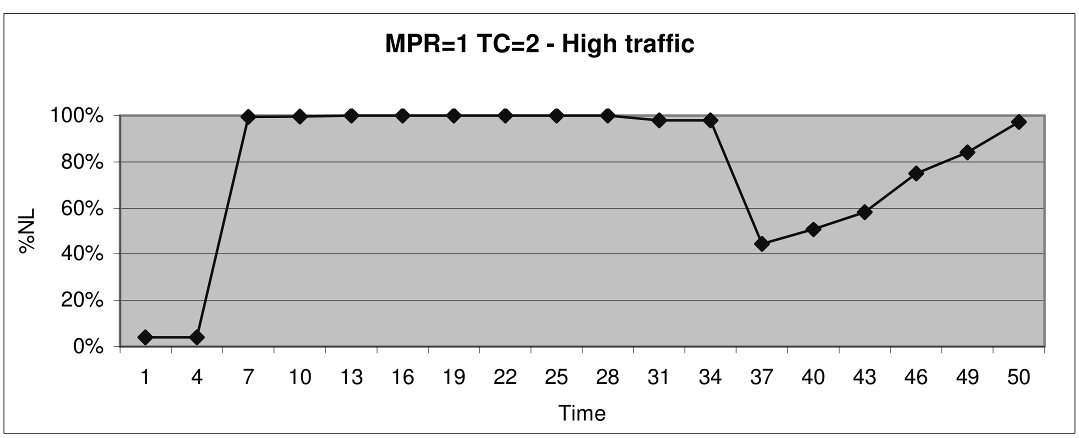
Graphs 5 shows how much time it takes for MPR=1 TC=2 to achieve its highest topology knowledge level which is 100%. It takes about 11 seconds to reach its highest point and then it remains stable. On the other hand, graph 6 shows the amount of nodes that are chosen as MPRs along the 50 seconds of simulation time. It also takes about 11 seconds to reach a stability level of about 42%. Because no data traffic is injected into the network and the nodes remain static, the network keeps this steady state. However, when data traffic is injected the results change. Graphs 7 and 8 show same metrics over the same scenario than graphs 5 and 6 do but, with 20 data streams sending 6400Bps for 20 seconds, and starting at random between seconds 20 and 50.



Graph 5. Topology Knowledge for MPR=1 TC=2 with No Traffic

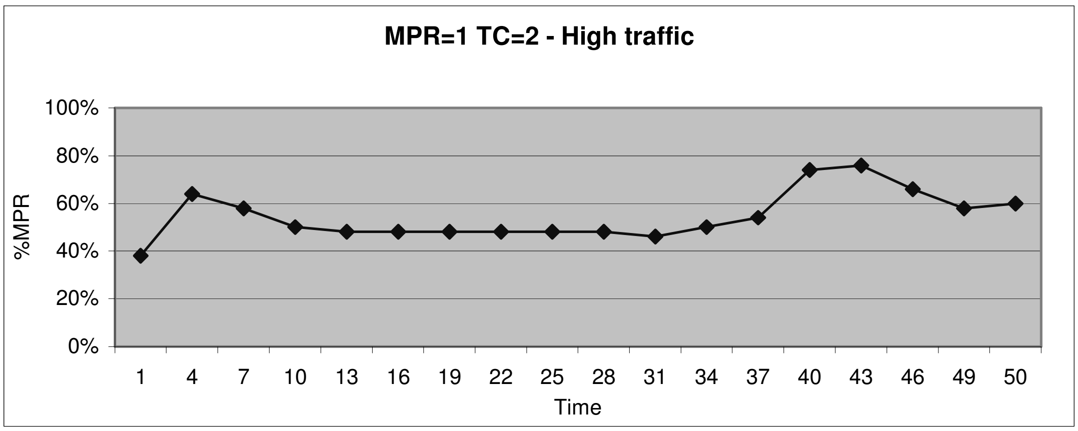


Graph 6. Percentage of MPRs for MPR=1 TC=2 with No Traffic



Graph 7. Topology Knowledge for MPR=1 TC=2 under High Traffic

Graph 7 shows how the topology knowledge dramatically decreases when data traffic is injected. The topology knowledge drop is at second 35 which means that the last set of broadcasted TC messages properly received was at second number 20, right before the data sources started sending traffic. The last because the protocol configuration says that TC message information has to be kept as valid for up to TOP_HOLD_TIME=15 seconds if no more information is received. Therefore, the lost of TC messages due to high traffic load is reflected with some delay as a decrease on the topology knowledge. Once that the traffic load decreases the topology knowledge increases again. On the other hand, the traffic load also originates loses in terms of Hello messages, these loses are reflected as an increase on the number of MPRs (Graph 8).



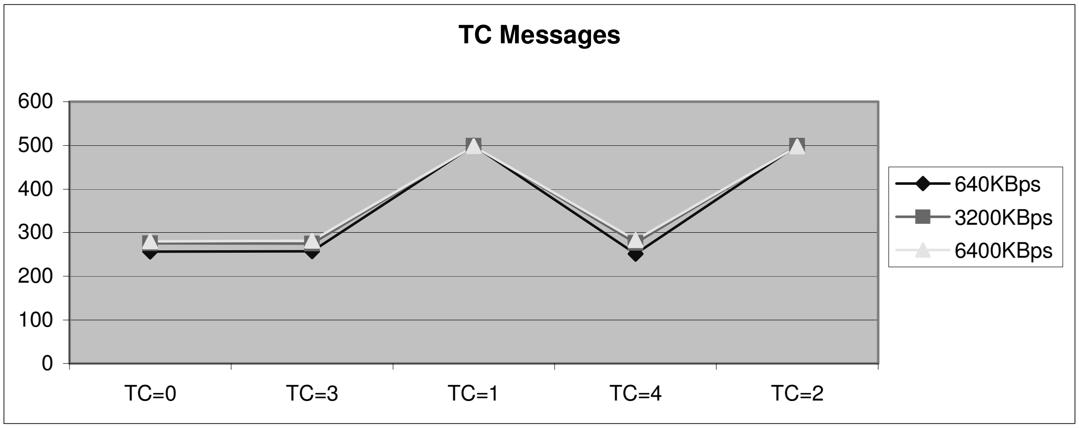
Graph 8. Percentage of MPRs for MPR=1 TC=2 under High Traffic

The previous graphs show that traffic load has a clear impact by decreasing topology knowledge and by increasing the number of MPRs. Actually even the strategy TC=2 that provides the highest topology knowledge on static networks is not able to maintain it under high traffic load, even when this knowledge decrease occurs for just a few seconds.

Tables 8 and 9 along with their respective graphs 9 and 10, show the impact of traffic load. They show that when traffic load increases, the amount of generated TC messages for TC=0, TC=3 and TC=4 increases a little bit due to the increase on the amount of MPRs (as explained above). Also, the increase on the amount of generated TC messages has the effect of increasing the Topology Knowledge for all the TC strategies but TC=2.

	TC Messages				
MPR=1	**TC=0**	**TC=3**	**TC=1**	**TC=4**	**TC=2**
640Bps	256.03	256.60	500.00	251.43	500.00
3200Bps	275.03	274.73	499.50	275.77	499.10
6400Bps	279.83	280.77	498.20	282.70	497.83

Table 8. TC Messages under Different Traffic Rates for MPR=1.

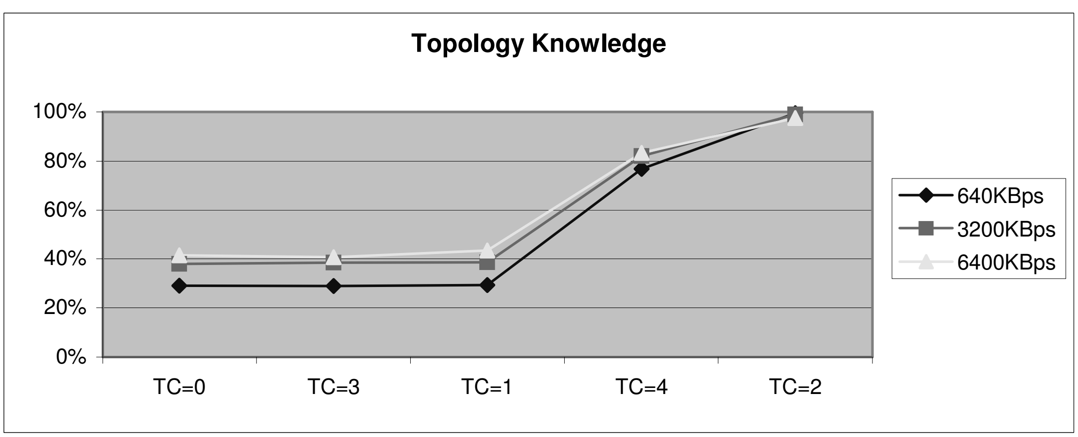


Graph 9. TC Messages under Different Traffic Rates for MPR=1

	Topology Knowledge				
MPR=1	**TC=0**	**TC=3**	**TC=1**	**TC=4**	**TC=2**
640Bps	29.05%	28.96%	29.32%	76.89%	99.53%
3200Bps	37.83%	38.37%	38.59%	82.01%	98.99%
6400Bps	41.45%	40.61%	43.36%	83.29%	97.53%

Table 9. Topology Knowledge under different traffic rates for MPR=1.

Finally, the last metric that tells about protocol performance is the data delivery rate and it is shown in Table 10. In this table we can clearly observe that the data delivery rate decreases with the traffic load going from 98% to 25% approx. Also the largest difference between every strategy combination, under the same traffic load, is not larger than 4%, which means that the MPR-TC strategies do not have a strong impact on data delivery rates. However, we can observe that by increasing the MPR parameter from MPR=1 to MPR=3, the data delivery rate tends to decrease, this may be due to the increased communication overhead produced by the increased number of nodes chosen as MPRs, which advertise topology information.



Graph 10. Topology Knowledge under Different Traffic Rates for MPR=1.

		Traffic Rates		
MPR	**TC**	**640Bps**	**3200Bps**	**6400Bps**
1	0	96.17%	42.28%	27.41%
1	1	96.62%	42.30%	26.49%
1	2	98.26%	41.12%	26.34%
1	3	95.57%	41.78%	26.67%
1	4	97.73%	40.90%	26.97%
2	0	98.33%	39.50%	25.80%
2	1	97.85%	38.62%	25.30%
2	2	97.51%	39.42%	25.59%
2	3	98.06%	39.69%	25.58%
2	4	98.40%	40.61%	25.54%
3	0	97.67%	39.41%	24.88%
3	1	98.13%	38.74%	25.28%
3	2	97.77%	38.93%	25.24%
3	3	97.75%	38.66%	25.59%
3	4	98.03%	38.79%	25.01%

Table 10. Data Delivery Rates for Different Parameters MPR and TC.

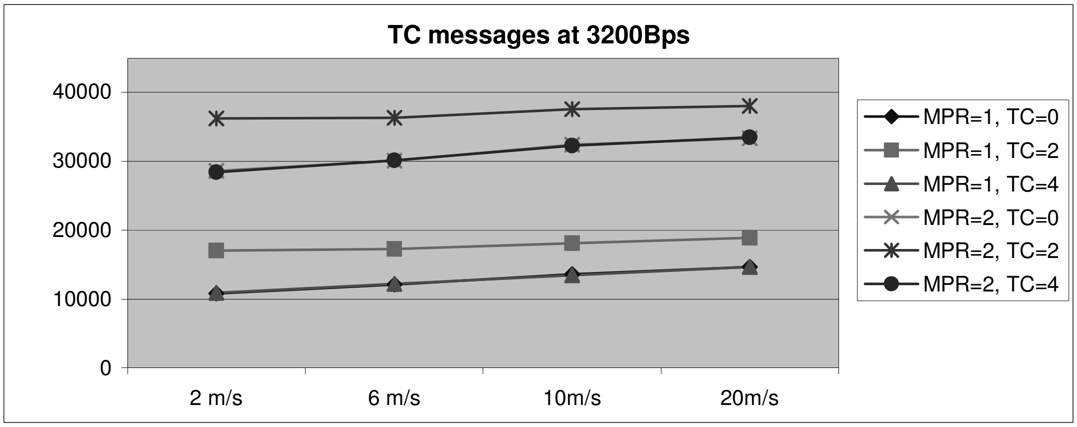
6.3 Mobile Scenarios with Data Traffic

The experimental results show that TC=1 and TC=3 performed the same as TC=0, over static networks, but at an additional overhead cost, additionally, these two strategies provide much more less topology knowledge than their corresponding similars TC=2 and TC=4. For this reason, they were dropped and not tested under mobile scenarios.

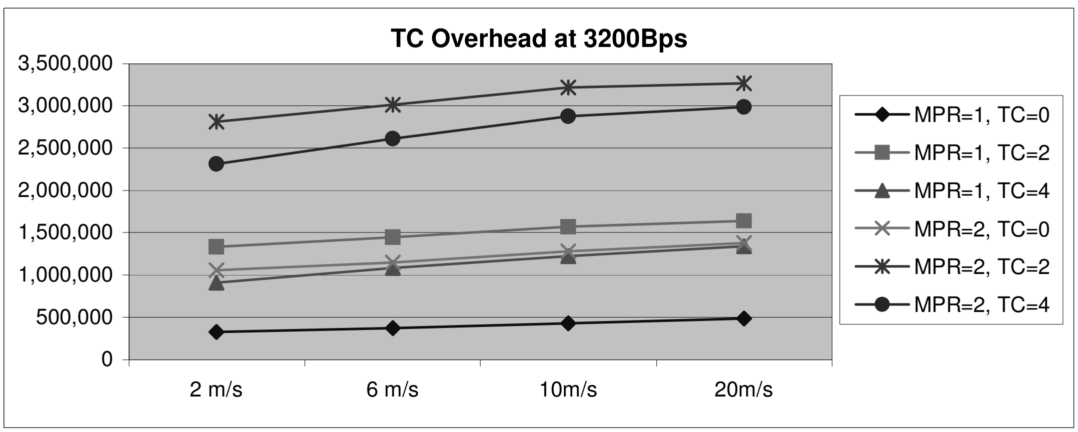
Simulation results, under mobility, for TC messages, TC messages overhead, Percentage of MPRs, Topology knowledge and Accuracy of Topology Information produce similar results regardless of the traffic rate. Therefore, only results under a traffic rate of 3200Bps are shown. Graph 11 shows the number of TC messages generated for different values of MPR and TC at a traffic rate of 3200Bps and at different mobility speeds. It is clear that the number of transmitted TC messages increases with mobility and with the MPR parameter. TC=0 and TC=4 both constrain the TC message generation to MPRs only; therefore, both of them always generate the same amount of messages. In the case of TC=2, every node in the network generates TC messages; therefore, TC=2 generates the largest amount of TC messages. The additional amount of generated messages for TC=2, with respect to the other two strategies, decreases with mobility, from 56% when mobility speed is 2m/s, to 28% when mobility is 20m/s for MPR=1. For MPR=2 it decreases from 26% to 13%. Increasing the value of MPR from MPR=1 to MPR=2 may generate up to 163% more messages for TC=0 and TC=4, and up to 113% more for TC=2. Additional rises of about 5% occur when traffic rate is increased from 640Bps to 6400Bps. Therefore, TC messages increase with mobility, traffic rate, MPR parameter and TC=2.

On the other hand, even when the amount of generated TC messages may be the same, for the case of TC=0 and TC=4, the produced overhead may be completely different. Graph 12 shows the produced communication overhead when traffic rate is

3200Bps. It shows that TC=0 produces the lowest communication overhead; in fact, the communication overhead for TC=0 when MPR=2 is smaller than the one for TC=2 when MPR=1. Mobility, traffic rate, MPR parameter and TC=2 are the factors increasing the communication overhead.

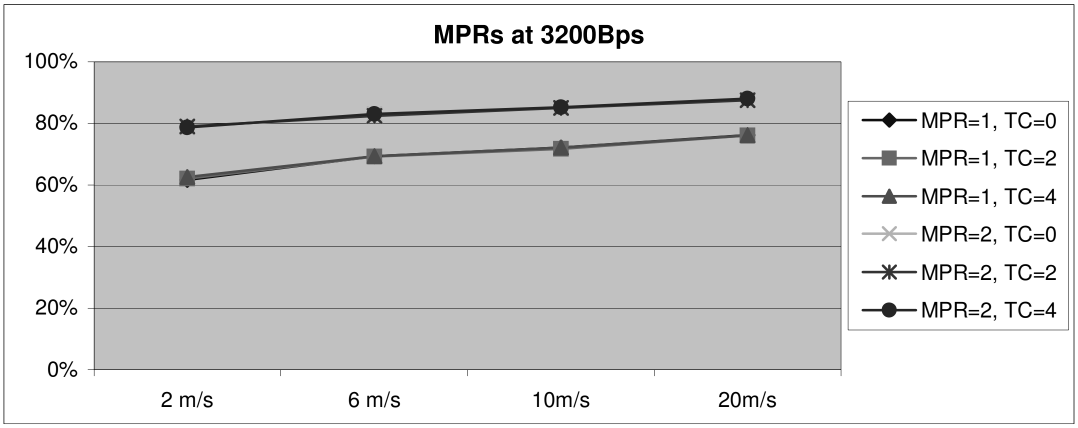


Graph 11. TC Messages under Traffic Rate of 3200Bps



Graph 12. Communication Overhead under traffic rate of 3200Bps

Graph 13 shows the amount of nodes that were selected as MPRs. It is clear that the results are organized in two disjoint sets depending on the MPR parameter. This means that the amount of nodes that are selected as MPRs, does not depend on the selected TC strategy, but rather depends on the MPR parameter. However, this metric is also impacted by mobility, increasing from 62% to 76% for MPR=1, and from 78% to 89% for MPR=2. The increase on the amount of MPRs explains the increase in communication overhead shown in Graph 12 because there are more nodes generating TC messages for TC=0 and TC=4. Also, there are more nodes forwarding TC messages, a fact that impacts the overhead for every strategy regardless of the chosen TC strategy. The number of selected MPRs is not impacted by traffic rate; the same results are obtained for 640Bps, 3200Bps and 6400Bps.

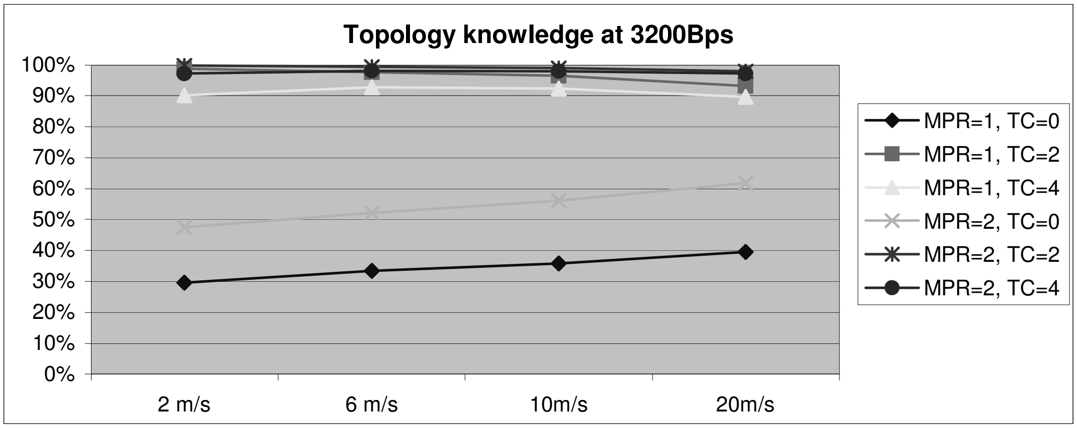


Graph 13. Nodes Selected as MPRs under Traffic Rate of 3200Bps.

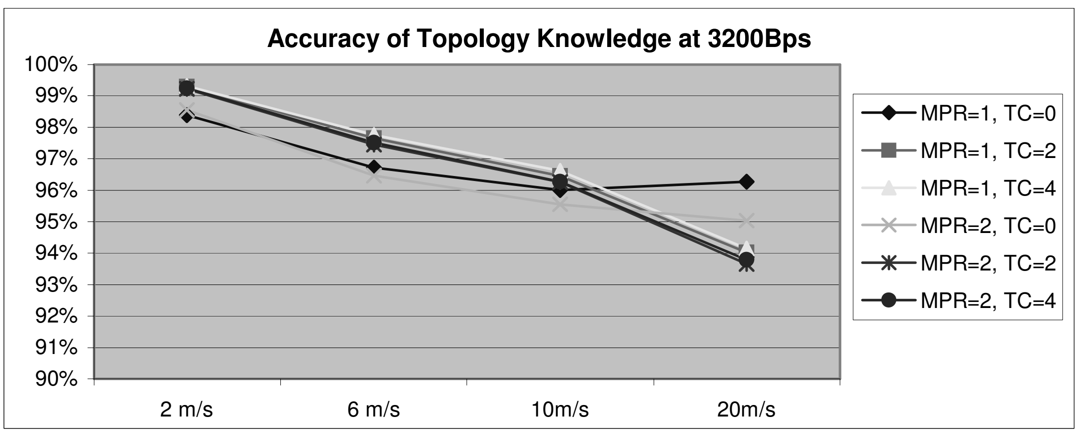
Graph 14 shows the benefit obtained in return for the cost paid in terms of communication overhead when applying each of the different MPR-TC strategies under 3200Bps of data traffic. It is the accurate topology knowledge that is achieved. The increase that may be reached for TC=2 and TC=4 regardless of the MPR parameter when compared to a maximum topology knowledge of 39.5% for standard OLSR (MPR=1 TC=0) is obvious. TC=4 reaches a topology knowledge between 89% and 92% for MPR=1 and between 97% and 98% for MPR=2 which represents a benefit of about 150%. On the other hand, TC=2 achieves a higher topology knowledge between 93% and 99% for MPR=1, and between 98% and almost 100% for MPR=2. Graph 14 shows accurate topology knowledge only, stale links are neglected. The validity of topology knowledge expires sooner with mobility, increasing the amount of stale links. This fact is illustrated in Graph 14 with the reduction experienced by TC=2 and TC=4 under mobility speeds of 10m/s and 20m/s. TC=0 seems not to be affected by mobility; however, its highest topology knowledge achieved is only 62%, for MPR=2 under mobility speed of 20m/s. The increase in topology knowledge experienced by TC=0 is explained by the increase in transmitted TC messages at higher mobility speeds.

The accuracy of the topology knowledge is shown in Graph 15. In this graph, we notice that as soon as mobility is introduced, even at low speeds, the accuracy of topology knowledge decreases to about 99% for all strategies. For mobility speeds of up to 10m/s the accuracy is always higher for TC=2 and TC=4 than for TC=0; however this difference decreases with mobility and reverts for higher mobility speeds of 20m/s. TC=0 may achieve up to 3% higher accuracy than the other two TC strategies. The accuracy drop for TC=2 and TC=4 is more significant because they provide much higher topology knowledge.

Graph 16 shows the impact on delivery rate. All the strategies experience very similar delivery rates, therefore for simplicity we only show the results for MPR=1 and TC=0. It is clear that mobility speed and traffic rates impact delivery rate. Delivery rate drops from 90% to 60% at a traffic rate of 640Bps and from 75% to 55% at a traffic rate of 6400Bps. The fact that all the strategies achieve the same delivery rate is very encouraging because it means that the additional communication overhead that is produced for some strategies, in order to achieve higher topology knowledge, does not impact the main functionality of the network which is data delivery.



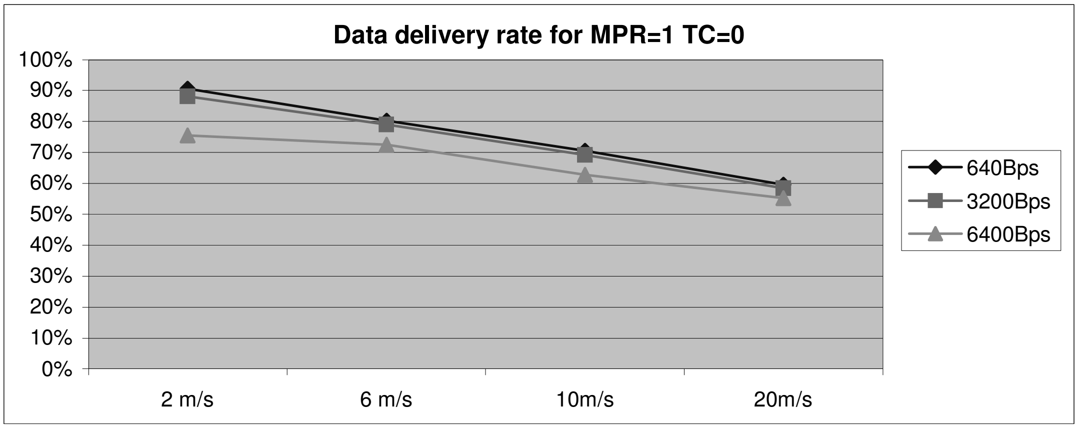
Graph 14. Accurate Topology Knowledge under Traffic Rate of 3200Bps



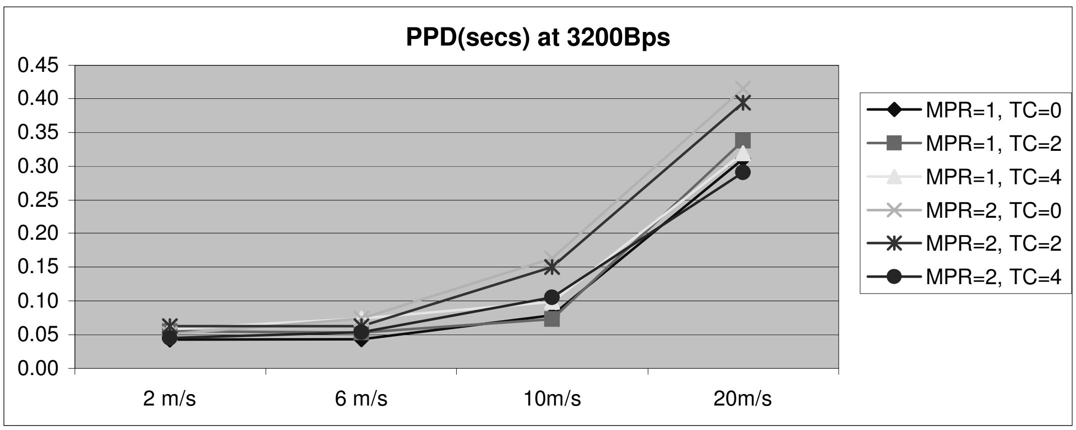
Graph 15. Accuracy of Topology Knowledge under Traffic Rate of 3200Bps

Graphs 17 to 21 show the PPD results. Graph 17 shows the PPD before removing the outliers and Graph 18 shows the PPD after removing the outliers. Both graphs show that the PPD increases with mobility; however, the results in Graph 17 are in the range of 0-0.45 seconds while the results in Graph 18 are in the range of 0-0.10 seconds. In Graph 18, we can observe that for MPR=1, the strategy TC=0 experiences the smallest PPD and TC=4 experiences the largest PPD with TC=2 in between both; however, for MPR=2, the strategy TC=4 experiences the lowest PPD for mobility speeds of up to 10m/s, meanwhile TC=0 still experiencing the smallest PPD under high mobility.

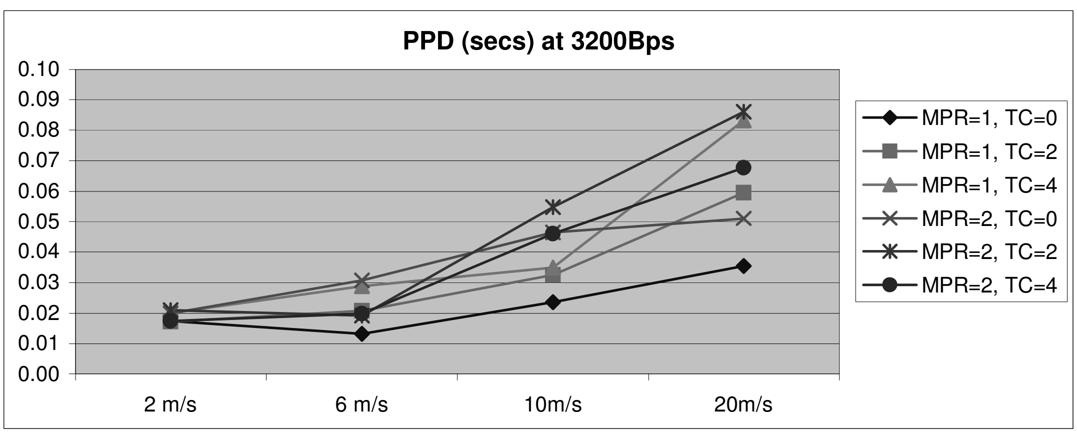
Graphs 19 to 21 show the effect of traffic rate on PPD. Comparing Graph 19 and Graph 20, we can again observe the effect of mobility which increases the PPD. Looking individually at both graphs we can observe that the PPD increases with the traffic rate as well. The differences in PPD experienced at each traffic rate are more significant under high mobility. On the other hand, the impact of each MPR-TC strategy does not seem to exist under low mobility; however, at a high mobility speed of 20m/s and at a traffic rate of 6400Bps, the PPD increases when MPR increases from MPR=1 to MPR=2.



Graph 16. Data Delivery Rate for MPR=1 TC=0

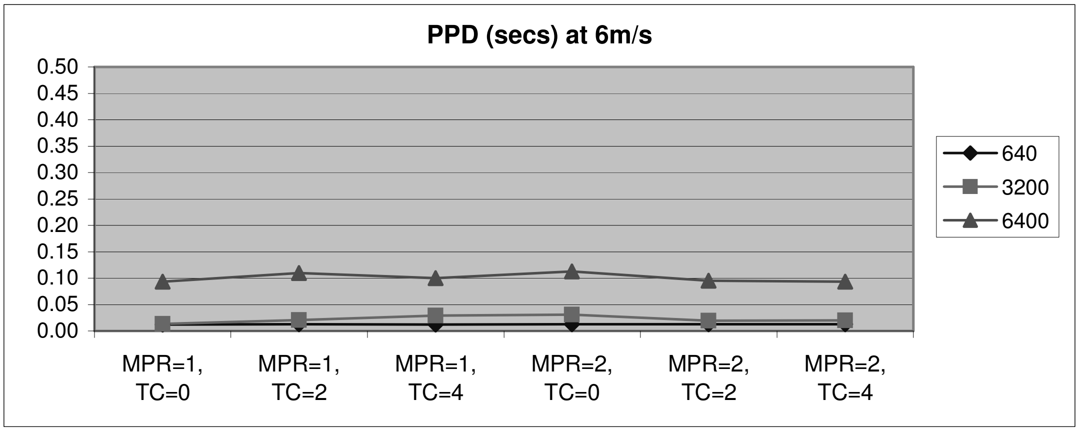


Graph 17. Per Packet Delay under Traffic Rate of 3200Bps with Outliers

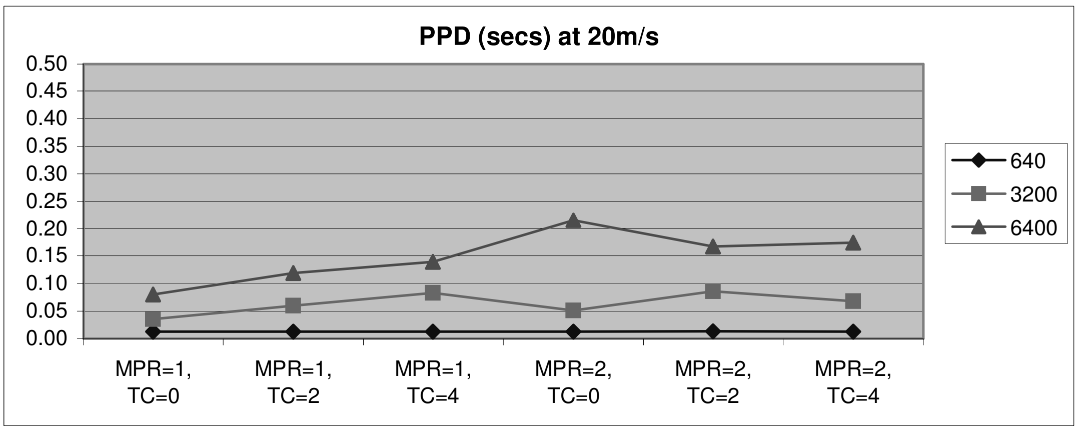


Graph 18. Per Packet Delay under traffic rate of 3200Bps

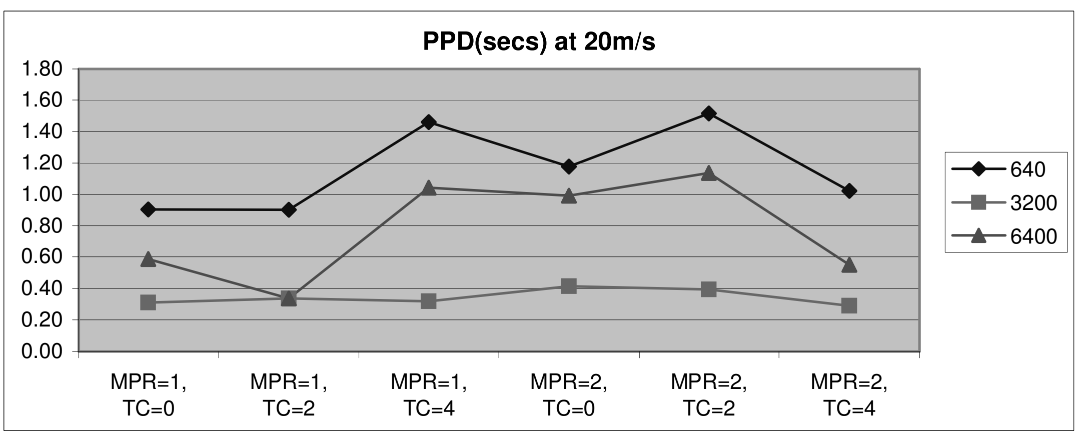
Graph 21 shows the unexpected results obtained in terms of PPD at a high mobility speed of 20m/s which encouraged performing a more profound data analysis and the removal of the PPD outliers. This graph shows that the PPD experienced by a traffic rate of 6400Bps is higher than the PPD experienced by a traffic rate of 3200Bps, as expected; however the highest PPD is experienced by the lowest traffic rate of 640Bps.



Graph 19. Per Packet Delay when Mobility is 6m/s

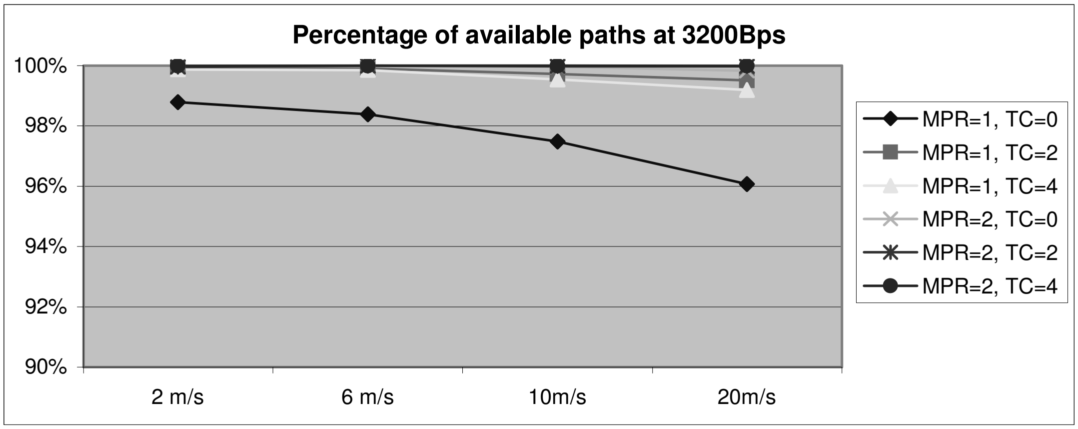


Graph 20. Per Packet Delay when Mobility is 20m/s



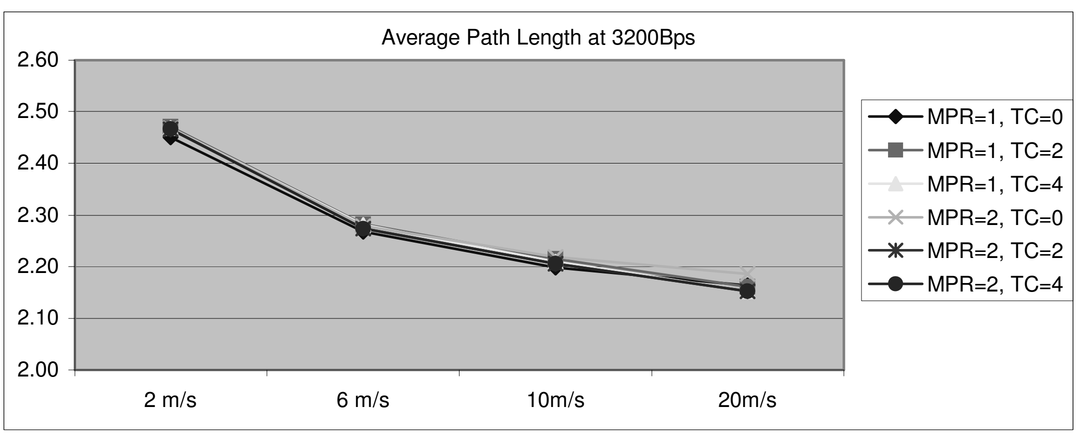
Graph 21. Per Packet Delay with Outliers when Mobility is 20m/s

Another very important factor to be analyzed is the availability of routing paths. OLSR as a proactive routing algorithm computes and maintains routing paths to every possible destination before they are actually needed; therefore, it is expected that at any given time a path for every destination exists. However, simulation results show that this is not always the case. Graph 22 shows that the percentage of available routing paths decreases with mobility and especially for standard OLSR (MPR=1-TC=0). With a traffic rate of 3200Bps and a mobility speed of 20m/s, the percentage of available paths for a standard OLSR decreases to 96%. On the other hand, the percentage of available paths for all the other strategies also decreases with mobility but always remains over 99%.



Graph 22. Percentage of available paths at 3200Bps

Finally, Graph 23 shows the impact of mobility over the average path length, in hops, at a traffic rate of 3200Bps. First, we can observe that the average path length always remains between 2 and 2.5 hops. Second, the average path length is the same regardless of the MPR-TC strategy. And third, the path length decreases with mobility. This reduction must be due to the nature of the random waypoint mobility model which tends to move the nodes to the center of the simulation area reducing distances between them (an effect which is more significant at a higher mobility).



Graph 23. Average path length (hops) at 3200Bps

7. CONCLUSIONS

The objective of this research was to extend the network knowledge, in the form of topology knowledge, in order to make OLSR a supportive routing protocol for QoS. OLSR is a routing protocol that allows the manipulation of the amount of topology information that is advertised into the network at a consequent cost in terms of communication overhead. Several Redundant Topology Information strategies were evaluated in combination with the MPR Redundancy feature of OLSR. Simulation work in NS-2 was done at different node mobility speeds and under different traffic rates. Obtained results provide a clear understanding of the topology knowledge can be achieved, at different overhead costs, by different strategies, without impacting the data delivery rate. Therefore, the criterions that should be used to decide which strategy to use are: 1) the allowed communication overhead and, 2) the desired level of topology knowledge. If the topology knowledge has to be maximized, TC=2 is the best option. If the communication overhead has to be minimized, then TC=0 might be the best option. On the other hand, TC=4 offers a fair trade-off between topology knowledge and communication overhead. However, when high traffic load is present, no strategy is able to keep 100% topology knowledge. Also, the data delivery rates decrease when either data traffic or mobility increases.

The selection of a topology control strategy that increases the topology knowledge might provide significant benefits for communication protocols. This additional knowledge may support the construction of more robust routing paths, or even multi-paths, in order to provide Quality of Service support. Therefore, the amount of topology knowledge that wants to be achieved and its corresponding communication overhead cost entirely depend on the network administrator and the network applications that want to be supported. Then, the results in this research should be used as a guideline for tuning the configuration of the OLSR protocol.

Appendix A
Topology Knowledge Achieved by Several Strategies

This appendix shows additional network topology graphs as the ones shown in Section 6.1.

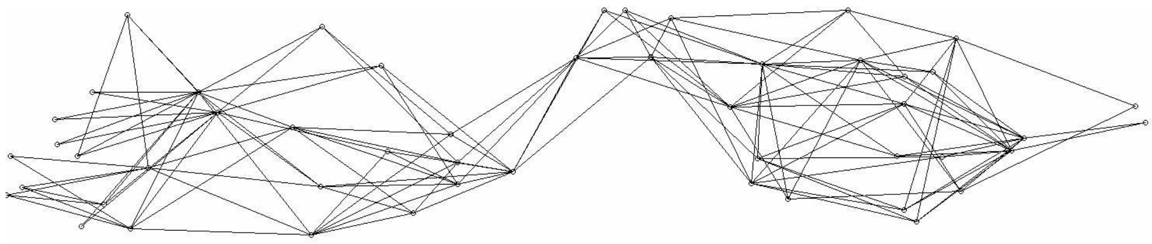


Figure A.1. Topology knowledge for MPR=2, TC=0 TK=145/303

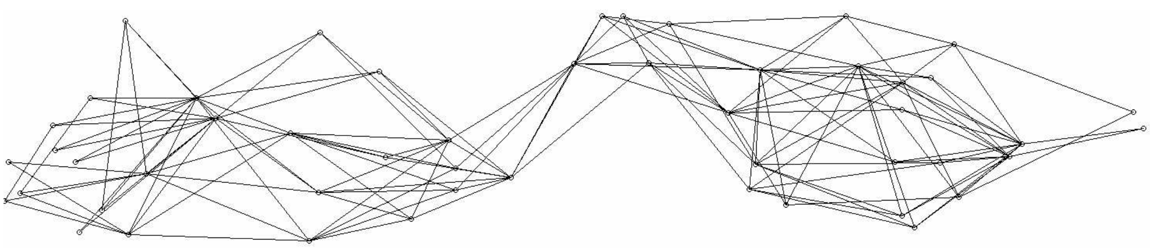


Figure A.2. Topology knowledge for MPR=2, TC=3 TK=147/303

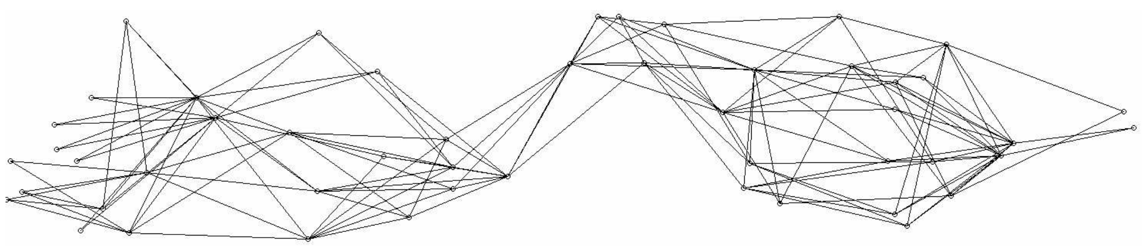


Figure A.3. Topology knowledge for MPR=2, TC=1 TK=145/303

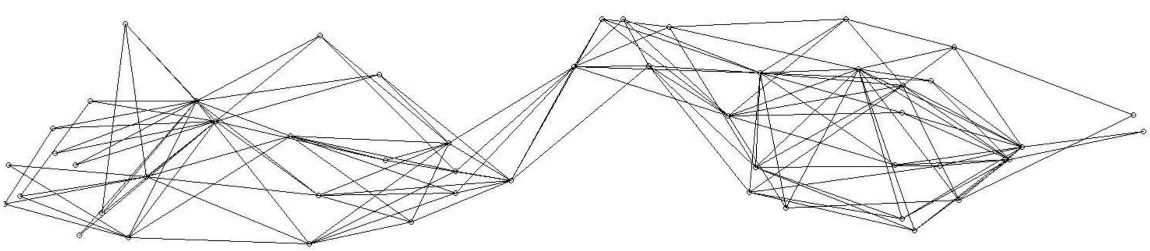


Figure A.4. Topology knowledge for MPR=2, TC=4 TK=273/303

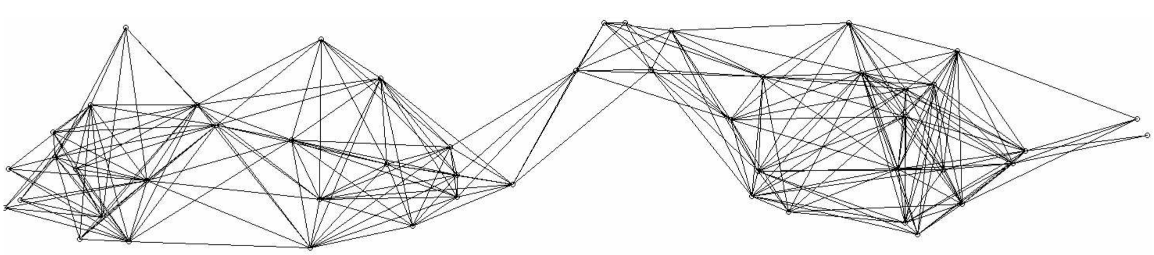


Figure A.5. Topology knowledge for MPR=2, TC=2 TK=303/303

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