Optimal Path Selection in a Link State QoS Routing Protocol

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Abstract: A link state routing approach makes available detailed information about the connectivity and the topology found in the network. The OLSR protocol is an optimization of the classical link state algorithm tailored to the requirements of a mobile wireless LAN. OLSR introduces an interesting concept, the multipoint relays (MPRs), to mitigate the message overhead during the flooding process. The heuristic for MPRs selection limits its number in the network, ensures that the overhead is as low as possible. However, there is no guarantee that OLSR finds the optimal path in terms of QoS requirements. Moreover, in QoS routing, if the same heuristic used in the standard OLSR protocol for MPR selection is applied, the good quality links may be hidden to other nodes in the network. In this paper, we introduce two algorithms for MPRs selection based on QoS measurements. Analysis ,numerical evaluation and simulations are presented. We show that the proposed algorithms QOLSR_MPR2 finds optimal widest paths on the known partial network topology and presents the best performance.

I. INTRODUCTION

A link state routing approach makes available detailed information about the connectivity and the topology found in the network. Moreover, it increases the chances that a node will be able to generate a route that meets a specified set of requirements constraints. OLSR protocol [1], [2] is an optimization over the classical link state protocol for the mobile ad hoc networks. It performs hop-by-hop routing, i.e. each node uses its most recent information to route a packet. Therefore, each node selects a set of its neighbor nodes as *multipoint relays* (MPRs) [3]. In OLSR, only nodes, selected as such MPRs, are responsible for forwarding control traffic, intended for diffusion into the entire network. MPRs provide an efficient mechanism for flooding control traffic by reducing the number of transmissions required. Nodes, selected as MPRs, also have a special responsibility when declaring link state information in the network.

We have proposed the QOLSR protocol in [4], which is an enhancement of the OLSR routing protocol to support multiple-metric routing criteria [5]. We include quality information in TC messages about each link, between a node and its MPR selectors. MPRs aim at mitigating the message overhead during the flooding process. The heuristic for MPRs selection limits its number in the network, ensures that the overhead is as low as possible. However, there is no guarantee that OLSR finds the optimal path in terms of QoS requirements. Moreover, in QoS routing, if the same heuristic used in the standard OLSR protocol for MPR selection is applied, the good quality links may be hidden to other nodes in the network. In this paper, we introduce two algorithms for MPRs selection based on QoS measurements.

II. HEURISTICS FOR THE SELECTION OF MULTIPOINT RELAYS

Finding a MPR set with minimal size falls in the category of dominating set problem, which is known to be *NP-complete* [6]. The information needed to calculate the MPRs is the set of one-hop neighbors and two-hop neighbors. To select the MPRs for the node x, the following terminology is used in describing the heuristics:

- $\mathrm{MPR}(x)$: the multipoint relay set of node x which is running this algorithm;
- $\mathrm{N}(x)$: the one hop neighbor set of node x containing only symmetric neighbors;
- $\mathrm{N2}(x)$: the two hop neighbor set of node x containing only symmetric neighbors in $\mathrm{N}(x)$. The two hop neighbor set $\mathrm{N2}(x)$ of node x does not contain any one hop neighbor of node x;
- $\mathrm{D}(x, y)$: degree of one hop neighbor node y (where y is a member of $\mathrm{N}(x)$), is defined as the number of symmetric one hop neighbors of node y excluding the node x and all the symmetric one hop neighbors of node x, i.e., $\mathrm{D}(x, y)$ = number of elements of $\mathrm{N}(y) - x - \mathrm{N}(x)$;
- Widest path: is a path with maximum bandwidth, calculated by the source node with its known partial network topology. In the widest path, any intermediate node is MPR of its previous node;
- Shortest-widest path: is the widest path, and with shortest delay when there is more than one widest path;
- Optimal widest path: is the widest path between two nodes in the whole network topology. Any node in the network can be selected as an intermediate node in the optimal widest path;
- Optimal shortest-widest path: is the shortest-widest path between two nodes in the whole network topology. Any optimal shortest-widest path is an optimal widest path.

The heuristic used in the standard OLSR protocol computes a MPR set of cardinality at most $\log n$ times the optimal multipoint relay number, where n is the number of nodes in the network. The approximation factor of the upper bound can be given by $\log\Delta$ where Δ is the maximum number of two-hop nodes a one-hop node may cover.

The standard OLSR heuristic limits the number of MPRs in the network, ensures that the overhead is as low as possible. However, in QoS routing, by such a MPR selection mechanism, the good quality links may be hidden to other nodes in the network.

Theorem 1: *There is no guarantee that OLSR finds the optimal shortest-widest or optimal widest path.*

Proof: 1) By construction. The heuristic for the selection of multipoint relays in the standard OLSR does not take into account the bandwidth and delay information. It computes a multipoint relay set of minimal cardinality. So, the links with high bandwidth and low delay can be omitted. After, the path calculated between two nodes using the shortest-widest path algorithm has no guarantee that is the optimal widest path or shortest-widest path in the whole network. 2) By example. From Figure 1 and Table I:

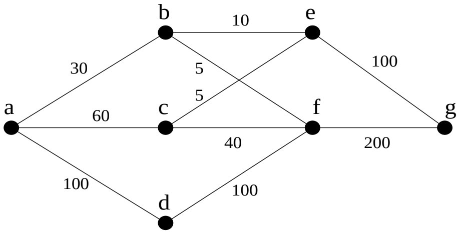

Fig. 1. Network example for MPR selection

Node	1-hop neighbors	2-hop neighbors	MPRs
a	b, c, d	e, f	b
b	a, e, f	c, d, g	f
c	a, e, f	b, d, g	f
d	a, f	b, c, g	f
e	b, c, g	a, f	b
f	b, c, d, g	a, e	c
g	e, f	b, c, d	f

TABLE I

MPR SELECTED IN THE STANDARD OLSR

When g is building its routing table, for destination a, it will select the route (g, f, b, a) whose bandwidth is 5. The optimal widest path between g and a is (g, f, d, a). It has 100 as bandwidth. This completes the proof.

The decision of how each node selects its MPRs is essential to determinate the optimal bandwidth and delay route in the network. In the MPR selection, the links with high bandwidth and low delay should not be omitted.

A. QOLSR_MPR1

In this protocol, MPR selection is almost the same as that of the standard OLSR. However, when there is more than 1-hop neighbor covering the same number of uncovered 2-hop neighbors, the one with maximum bandwidth link (a widest link) to the current node is selected as MPR. If there is more than one widest link, we choose the one with the shortest delay. The heuristic used in QOLSR_MPR1 protocol is as follows:

Step 1: Start with an empty multipoint relay set $\mathrm{MPR}(x)$;

Step 2: Calculate $\mathrm{D}(x, y)$, ∀ nodes $y \in \mathrm{N}(x)$;

Step 3: First, select those one-hop neighbor nodes in $\mathrm{N}(x)$ as the multipoint relays which provide the only path to reach some nodes in $\mathrm{N2}(x)$, and add these one-hop neighbor nodes to the multipoint relay set $\mathrm{MPR}(x)$;

Step 4: While there still exist some nodes in $\mathrm{N2}(x)$ that are not covered by the multipoint relay set $\mathrm{MPR}(x)$:

Step 4.a: For each node in $\mathrm{N}(x)$ which is not in $\mathrm{MPR}(x)$, calculate the number of nodes that are reachable through it among the nodes in $\mathrm{N2}(x)$ and which are not yet covered by $\mathrm{MPR}(x)$;

Step 4.b: Select that node of $\mathrm{N}(x)$ as a MPR which reaches the maximum number of uncovered nodes in $\mathrm{N2}(x)$;

Step 4.c: In case of a tie in the above step, select that node with higher bandwidth as MPR.

Step 4.d: In case of a tie in the above step, select that node with minimum delay as MPR.

Step 5: To optimize, remove each node in $\mathrm{MPR}(x)$, one at a time, and check if $\mathrm{MPR}(x)$ still covers all nodes in $\mathrm{N2}(x)$.

The third step permits to select some one-hop neighbor nodes as MPRs which must be in the $\mathrm{MPR}(x)$ set, otherwise the $\mathrm{MPR}(x)$ will not cover all the two-hop neighbors. So these nodes will be selected as MPRs in the process, sooner or later. In step 5, an optimization is performed by reducing the number of MPRs, if possible.

This heuristic has the same time complexity of the standard OLSR heuristic. It computes a MPR set of cardinality at most log$n$ times the optimal multipoint relay number where n is the number of nodes in the network.

Theorem 2: *There is no guarantee that QOLSR_MPR1 finds the optimal shortest-widest or optimal widest path.*

Proof: 1) By construction. The heuristic for the selection of multipoint relays in the QOLSR_MPR1 is almost the same as that of the standard OLSR. We use the bandwidth and delay information when there is more than one one-hop neighbor covering the same number of uncovered two-hop neighbors. So, the links with high bandwidth and low delay can be omitted. 2) By example. From Figure 1 and Table II, we have: Between b and c, c is selected as a's MPR because it has the larger bandwidth. When g is building its routing table, for destination a, it will select the route (g, f, c, a) whose bandwidth is 40. The optimal widest path between g and a is (g, f, d, a). It has 100 as bandwidth. This completes the proof.

Node	1-hop neighbors m	2-hop neighbors	MPRs
a	b, c, d	e, f	c

TABLE II

MPR SELECTED IN THE OLSR_MPR1

B. QOLSR_MPR2

In this protocol, neighbors that guarantee maximum bandwidth and minimum delay among two-hop neighbors are selected as MPRs. The heuristic used in QOLSR_MPR2 protocol is as follows:

Step 1: Start with an empty multipoint relay set $\mathrm{MPR}(x)$;

Step 2: Calculate $\mathrm{D}(x, y)$, ∀ nodes $y \in \mathrm{N}(x)$;

Step 3: First, select those one-hop neighbor nodes in $\mathrm{N}(x)$ as the multipoint relays which provide the only path to reach some nodes in $\mathrm{N2}(x)$, and add these one-hop neighbor nodes to the multipoint relay set $\mathrm{MPR}(x)$;

Step 4: While there still exist some nodes in $\mathrm{N2}(x)$ that are not covered by the multipoint relay set $\mathrm{MPR}(x)$:

Step 4.a: For each node in $\mathrm{N}(x)$ which is not in $\mathrm{MPR}(x)$, calculate the number of nodes that are reachable through it among the nodes in $\mathrm{N2}(x)$ and which are not yet covered by $\mathrm{MPR}(x)$:

Step 4.b: Select that node of $\mathrm{N}(x)$ with the maximum bandwidth and minimum delay as a MPR;

Step 4.c: In case of a tie in the above step, select that node which reaches the maximum number of uncovered nodes in $\mathrm{N2}(x)$;

Claim 1: Let p =(a_1,...,a_{i-1}, a_i, a_{i+1},...,a_k) an optimal widest path, $k \geq 3$. For any intermediate node a_i ($i \neq 1$) in p that is not selected as MPR by its previous node a_{i-1}, we can find a node b_i selected as MPR by a_{i-1} such as the path (a_1,...,a_{i-1},b_i,a_{i+1}, ...,a_k) has the same bandwidth performance.

Proof: Let p =(a_1,...,a_{i-1}, a_i, a_{i+1},...,a_k), $k \geq 3$ an optimal widest path from a_i to a_k (Figure 2).

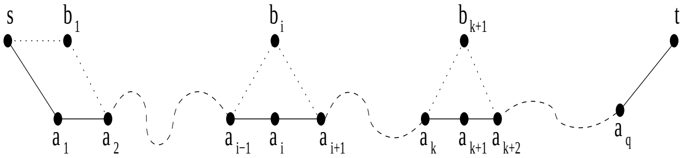

Fig. 2. Optimal widest path from s to t

Suppose that on the optimal widest path, the node a_i is not selected as MPR by its previous node a_{i-1}. We can assume that for each node on the path, its next node in the path is its 1-hop neighbor, and the node two hops away from it is its 2-hop neighbor. For example, a_i is a_{i-1}'s 1-hop neighbor, a_{i+1} is a_{i-1}'s 2-hop neighbor. Based on the basic idea of the MPR selection that all the 2-hop neighbors of a node should be covered by this node's MPR set. So, a_{i-1} must have another neighbor b_i, which is selected as its MPR, and is connected to a_{i+1}. Let p' =(a_1,...,a_{i-1}, b_i, a_{i+1},...,a_k), $k \geq 3$. According to the criteria of MPR selection specified on QOLSR_MPR2, a_{i-1} selects b_i instead of a_i as its MPR because:

$$\mathrm{Bw}_{a_{i-1}b_ia_{i+1}} > \mathrm{Bw}_{a_{i-1}a_ia_{i+1}} \tag{1}$$

Or

$$\begin{cases}\mathrm{Bw}_{a_{i-1}b_ia_{i+1}} = \mathrm{Bw}_{a_{i-1}a_ia_{i+1}} \\ \mathrm{del}_{a_{i-1}b_ia_{i+1}} < \mathrm{del}_{a_{i-1}a_ia_{i+1}}\end{cases} \tag{2}$$

From (1) we have $\mathrm{Bw}(p') \geq \mathrm{Bw}(p)$ and there is no guarantee about $\mathrm{del}(p') \geq \mathrm{del}(p)$.
From (2) we have

$$\begin{cases}\mathrm{Bw}(p') = \mathrm{Bw}(p) \\ \mathrm{del}(p') < \mathrm{del}(p)\end{cases} \tag{3}$$

In both cases, $\mathrm{Bw}(p') \geq \mathrm{Bw}(p)$. Based on our assumption, path p is an optimal widest path. So, path p' is also optimal widest. This completes the proof.

Claim 2: There is an optimal widest path in the whole network such that all the intermediate nodes are selected as MPR by their previous nodes.

Proof: By a recurrence. Let p =(s,a_1,...,a_{i-1}, a_i, a_{i+1},...,a_k,...,a_q, t), $k < q$ an optimal widest path (Figure 2).

a) We demonstrate that the first intermediate node a_1 is selected as MPR by source s. By using the claim 1, we can find a node b_1 selected as MPR by s such as the path p' =(s,b_1,...,a_{i-1}, a_i, a_{i+1},...,a_k,...,a_q, t) has the same bandwidth performance of the optimal path (p' is also an optimal widest path). So, source's MPR are on the optimal widest path.

b) We assume that all the nodes $\{a_1$,...,a_{i-1}, a_i, a_{i+1},...,$a_k\}$ are selected as MPR by their previous node in the path p. We prove that the next hop node of a_k on p is a_k's MPR. Suppose that a_{k+1} is not an MPR of a_k. Same as above, by using the claim 1, we can find a node b_{k+1} selected as MPR by a_k such as the path p' =(s,a_1,...,a_{i-1}, a_i, a_{i+1},...,a_k,b_{k+1},...,a_q, t) has the same bandwidth performance of the optimal widest path (p' is also an optimal widest path). So, in an optimal widest route, the (k+1)th intermediate node is the MPR of the (k)th intermediate node.

Based on (a) and (b), all the intermediate nodes of an optimal widest path are the MPRs of the previous nodes.

By the claim 2, there is an optimal widest path such that all the intermediate nodes are the MPR of the previous nodes on the same path. So the optimal widest path for the whole network topology is included in the partial topology the node knows. And by using the shortest-widest path algorithm, we can compute the optimal widest path in the partial network topology. We can conclude that the QOLSR_MPR2 finds the optimal widest path.

Theorem 3: *QOLSR_MPR2 finds optimal widest paths using only the known partial network topology.*

The heuristic used in the QOLSR_MPR2 finds exactly the optimal MPRs that guarantee maximum bandwidth and minimum delay. So, this heuristic is an algorithm. The upper bound of the time complexity of This algorithm is O(α) where α is the maximum number of two-hop nodes.

III. PERFORMANCE EVALUATION

A. Heuristic evaluation in static networks

In this section, we simulate our MPR selection algorithms and compare the results in satatic networks.

1) MPR selection Simulation Model and results: We assume that the ad hoc network topology is stable (a wireless network consisting of desktops, laptops and printers for home business may keep its original topology for a long time until someone moves one of the laptops to another room). We generate 100 random networks of 100 nodes. Each node is placed in an area of $1000m \times 1000m$ randomly selecting its x and y co-ordinates. Each node is randomly assigned an idle_time ranging from 0 to 1. Each link has the same bandwidth, 2Mb/s. The available link bandwidth between two nodes is equal to the minimum of their idle_time × $\mathrm{max\_bandwidth}$.

In our simulated scenarios, we collect results over three values of range transmission (100 meters, 200 meters, 300 meters). Table III shows the average number of 1-hop neighbors and 2-hop neighbors. We can see that when the range transmission decreases, the number of (1, 2)-hop neighbors decreases. These values affect the MPR number in the network. By assuming high connectivity of the network: (1) the more 1-hop neighbors a node has, the less MPRs it may select, because with a high probability a small subset of its 1-hop neighbor can reach a high number of the 2-hop neighbors, (2) the more 2-hop neighbors a node has, the more MPRs may be needed to cover them all.

Transmission range	300 m	200 m	100 m
1-hop neighbors	21	10	2
2-hop neighbors	33	15	4

TABLE III

AVERAGE NUMBER OF (1,2)-HOP NEIGBORS

The next results show the performances of the routes found by the implemented algorithms (Standard OLSR, QOLSR_MPR1, QOLSR_MPR2, Pure link state algorithm: each node floods its link state information into the entire network). The results are given in two categories: performance and cost. Performance is characterized by: (a) Error rate: the percentage of the bad routes (bandwidth not optimal), (b) Average difference: the average of the difference between the optimal bandwidth and current bandwidth found in routing algorithms in percentage. The larger the value is, the worse the result. Cost is measured by: (a) Overhead: average number of the TC messages are transmitted in the network, (b) MPR number: average number of the MPRs in the network.

Algorithm	Transmission Range	Performance		Cost	
		Error rate	Average Difference	Overhead	Nb MPR
Standard OLSR	300m	28%	46%	12	65
	200m	41%	51%	24	68
	100m	12%	45%	5	42
QOLSR_MPR1	300m	14%	22%	12	65
	200m	21%	26%	24	68
	100m	8%	44%	5	42
QOLSR_MPR2	300m	0%	0%	26	71
	200m	0%	0%	38	73
	100m	0%	0%	5.7	44
Pure link state	300m	0%	0%	1245	100
	200m	0%	0%	979	100
	100m	0%	0%	28	100

TABLE IV

PERFORMANCE AND COST

Table IV shows that for each transmission range the standard OLSR has the worst performance (it has the highest Error Rate and Average Difference). The bandwidth difference between the paths found by the standard OLSR and the optimal paths is large. QOLSR_MPR1 achieves a large improvement in performance than the standard OLSR. The explanation is that the shortest-widest path algorithm enhances the bandwidth of the found paths. However, QOLSR_MPR1 does not always find an optimal path, as its MPR selection heuristic may omit the optimal bandwidth link from the partial network topology the node learned. QOLSR_MPR2 achieves the best performance at each time (it finds the optimal bandwidth route).

The cost is directly related to the number of the re-transmitting nodes. If the number of the re-transmitting nodes increases, the cost increases. Pure Link State algorithm has the highest overhead, because each node re-transmits the messages it receives. As the MPR selection heuristic in the standard OLSR and QOLSR_MPR1 emphasizes on reducing the number of MPRs in the network, the standard OLSR and QOLSR_MPR1 have the same and the lowest MPR number, and so the lowest overhead compared with QOLSR_MPR2 and Pure Link sate algorithm. QOLSR_MPR2 selects more MPRs, so more overhead than the standard OLSR and QOLSR_MPR1.

We can see that the standard OLSR and QOLSR_MPR1 and QOLSR_MPR2 have more MPRs and so more overhead with transmission range of $200m$. In a higher density network (such as for a node transmission range of $300m$), node connectivity is also high (see Table III), so a node may need fewer MPRs to cover its 2-hop neighbors. In lower density network (such as for a node transmission range of $100m$), because the lower connectivity, a node may have fewer 2-hop neighbors; therefore, it also needs fewer MPRs. However, the transmission range of $200m$ falls within these two extremes, so it may well result in the largest number of MPRs to produce the highest overhead. This situation is not found in the pure link state algorithm, where a node's entire neighbor set is its MPR set.

2) Performances in varying load conditions: in this simulation, we study the behavior if QOLSR, QOLSR_MPR1 and QOLSR_MPR2 protocols and the maximum utilization of the bandwidth by varying the load in the network. we have taken a static network composed of 50 nodes without uni-directional links. This network operates in a stable state when each node has complete and correct information about the network. all nodes are packet generating source. we have taken the mean packet size as 1K bytes, 200 packet for each transmit buffer and the same size as receive buffer. We increase the data packet arrival rate from 100 packets per second (which represents approximately 100 k bytes per second) up to 1400 per second. With the arrival rate equal to 100 packets per second, each node generates 2 packets per second in the average.

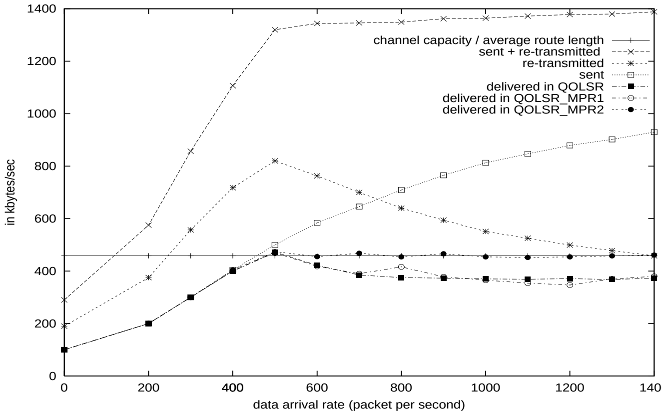

Fig. 3. Data load transmitted in varying load conditions

In Figure 3, the data load delivered to the destination is plotted. As average route length is 3 hops, therefore the maximum throughput of data that we can obtain is:

$$\begin{aligned}\text{max throughput} &= \frac{\text{channel capacity}}{\text{average route length}}\\ &= \frac{(11000kbps/8)}{3} = 458.3K\ bytes/sec\end{aligned}$$

We can see the network attains almost the maximum throughput before saturation for both protocols. The drop in throughput after the saturation point using QOLSR and QOLSR_MPR1 is due to the absence of any congestion control mechanism as each node continues to generate data packet at a high rate. However, the throughput after saturation using the QOLSR_MPR2 remains stable in the maximum utilization bandwidth because all the paths founded are optimal widest paths and are between nodes that have enough space in their buffers.

B. *Heuristic evaluation in mobile networks*

The simulation model introduced in [7] is very close to a real Ad-Hoc network operations. At each time, we can detect the position of mobiles by our mobility model. Each node is represented by a subqueue and placed in the region by randomly selecting its x and y co-ordinates. The number of nodes can reach 100000 nodes. With our method, the simulation model is very optimized that enables to reduce the CPU time and consequently to increase the time of simulation.

The random mobility model proposed is a continuous-time stochastic process. Each node's movement consists of a sequence of random length intervals, during which a node moves in a constant direction at a constant speed. A detailed description can be found in [7].

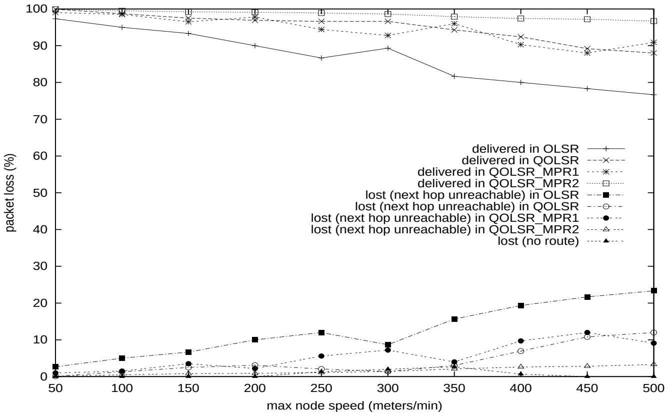

Fig. 4. Data load transmitted in varying load conditions

Figure 4 shows the results of our simulation in which the data packets sent and successfully delivered are plotted against the increasing speed. The speed is increased from $50 meters/minute$ $(3Km/hr)$ up to $500 meters/minute$ $(30Km/hr)$. In this simulation, 50 nodes constitute the network in a region of $1000^2 m^2$, and all the 50 nodes are packet-generating sources. We also keep the movement probability as 0.3, i.e., only 20% of nodes are mobile and the rest are stationary. Each mobile node selects its speed and direction which remains valid for next 60 seconds. We can see that when the mobility (or speed) increases, the number of packets delivered to the destinations decreases. This can be explained by the fact that when a node moves, it goes out of the neighborhood of a node which may be sending it the data packets. There are about 99.92% of packets delivered for QOLSR at a mobility of 2 meters/minute (99.01% for QOLSR_MPR1 and 99.99% for QOLSR_MPR2). At a mobility of 500 meters/minute, 88% of packets delivered for QOLSR (90.9 % for QOLSR_MPR1 and about 97% for OLSR_MPR2). QOLSR_MPR2 has the highest packets delivered because the routes are optimal and chosen with minimal interferences. The data packets are lost because the next-hop node is unreachable. QOLSR with the classic MPR selection algorithm and QOLSR_MPR1 have the same performances in term of lost packets. A node keeps an entry about its neighbor in its neighbor table for about 6 seconds. If a neighbor moves which is the next-hop node in a route, the node continues to forward it the data packets considering it as a neighbor. Also, the next-hop is unreachable if there are interferences. Few of packets are also lost because of unavailability of route and it is the same for OLSR with or without QoS. This happens when a node movement causes the node to be disconnected from the network temporarily, until it re-joins the network again.

IV. CONCLUSIONS

We have discussed the heuristics for the selection of multipoint relays. The heuristic used in the standard OLSR finds a MPR set with minimal size. There is no guarantee that OLSR finds the optimal widest path. We have proposed two heuristics that allow OLSR to find the maximum bandwidth path. In order to improve quality requirements in the MPRs selection and also in routing information, delay and bandwidth measurements are applied. Delay and bandwidth are calculated between each node and its neighbors having direct and symmetric link. We have demonstrated and also by simulations that QOLSR_MPR2 finds optimal widest paths using only the known partial network topology. From the analysis of the static and mobile networks simulation, QOLSR and QOLSR_MPR1 present the same performances.

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