ANALYSIS OF THE MULTI-POINT RELAY SELECTION IN OLSR AND IMPLICATIONS

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Abstract OLSR is a promising routing protocol for multi-hop wireless networks, recently standardized by the IETF. It intensively uses the concept of MPR to minimize the routing messages and limit the harmful effects of the broadcasting in such networks. In this article, we are interested in the performances of the Multi-Point Relay selection. We analyze the mean number of selected MPR per node and their spatial distribution with a theoretical approach and simulations. Then, we discuss the implications of these results on the efficiency of a broadcasting and on the reliability of OLSR when links between nodes may fail.

keywords: ad hoc, OLSR, MPR, performances, Palm.

1. Introduction

With the emergence of wireless technologies such as 802.11 or bluetooth, new challenges arise such as connecting wireless nodes without any infrastructure. If nodes are not in each other's radio range, packets need to be relayed by intermediate nodes which thus require forwarding capabilities and a routing protocol to find the available path to any destination. Nodes are mobile and may vanish or appear due to the wireless nature of the physical layer. The topology is thus in constant evolution. However, routing advertisements are expensive in resources since a node spends energy while transmitting as well as receiving and each message sent by a node is systematically received by all node in its transmission range. Therefore, not only the number of broadcast advertisements must be limited, but also the number of nodes which propagate them through the network. One of the recent proactive standardized protocols is OLSR (Optimized Link State Routing Algorithm) [1, 2]. Proactive routing protocols deeply rely on network broadcasting features and aim to reduce the impact of message flooding and reach scalability. In OLSR, only a subset of preselected nodes called MPR (Multi-Point Relays) are used to perform topological advertisements and to broadcast control messages. Thus, the number of emitter nodes is reduced, overhead and useless receptions of messages on nodes are minimized and the well known storm problem [3] avoided.

In this article, we are interested in the performances of the MPR selection. We analyze the mean number of selected MPR by a single node and their spatial distribution, using a theoretical approach and simulations. We then show that the selecting algorithm is efficient for certain quantities (as *e.g.* the number of redundant packets received by a node) and that the different proposed variants always lead to very close performances (as at least 75% of the selected MPR are the same nodes whatever the selection algorithm). We also discuss the implication of the different analytical results on the reliability of the protocol.

The remaining of the paper is as follows. In Section 2, we briefly detail the OLSR protocol and the MPR selection algorithm. In Section 3, we give results about probabilities and mean quantities relative to the MPR selection algorithm. We then discuss about the implication of these results on the performances of OLSR in Section 5. Numerical results and simulations are presented in Section 4. We lastly conclude and discuss of future works in Section 6.

2. OLSR

OLSR is a proactive routing protocol for ad-hoc networks, *i.e.*, it permanently maintains a network topology view on each node in order to provide a route as soon as needed. It uses the concept of Multi-Point Relays (MPR) to minimize the control traffic and to provide shortest routes (in number of hops) for all destination in the network. Each node chooses a subset of nodes in its neighborhood as its MPR (A MPR set is thus relative to each node) and keeps the list of its neighbors which have selected itself as a MPR. The shortest path to all possible destination is then computed from these lists, a path between two nodes being a sequence of MPR. When receiving a broadcast message M from a node u, a node v forwards it iff it is the first time v receives M and if node v is MPR of node u. This allows to reduce the number of transmitter nodes. The algorithm which allows a node u to select its MPR within its neighborhood consists in choosing nodes in such a way that the whole 2-neighborhood of u is covered by its MPR. In this way, MPR are selected in order to reach the 2-neighborhood of u in two hops from u, the k-neighborhood of u being reached within k hops. Paths are thus the shortest expected ones.

MPR selection: As the optimal MPR selection is NP-complet [7], we give here the one currently used: the Simple Greedy MPR Heuristic.

For a node u, let $N(u)$ be the neighborhood of u *e.g* the set of nodes in u's range and which share a bidirectional link with u: $v \in N(u) \Leftrightarrow u \in N(v)$. $N_2(u)$ is the 2-neighborhood of u, *e.g*, the set of nodes which are neighbors of at least one node of $N(u)$ but which do not belong to $N(u)$: $N_2(u) = \{v \text{ s.t. } \exists\, w \in N(u) \,|\, v \in N(w) \setminus \{u\} \cup N(u)\}$. A message sent by node u and relayed by a node $v \in N(u)$ reaches a node $w \in N_2(u) \cap N(v)$ in 2 hops.

For a node $v \in N(u)$, let $d_u^+(v)$ be the number of nodes of $N_2(u)$ which are in $N(v)$: $d_u^+(v) = |N_2(u) \cap N(v)|$. This quantity is the number of nodes of $N_2(u)$ that node u can reach in 2 hops via node v. For a node $v \in N_2(u)$, let $d_u^-(v)$ be the number of nodes of $N(u)$ which are in $N(v)$: $d_u^-(v) = |N(u) \cap N(v)|$. This quantity is the number of nodes in $N(u)$ which allow to connect nodes u and v in 2 hops. If $d_u^-(v) = 1$, there is only one node w in $N(u) \cap N(v)$ which allows to connect v and u in 2 hops. We say that v is an *isolated node* of node u. Note that "isolated nodes" are also relative to a node.

This algorithm is run at every node and selects the MPR in two steps. A node u selects in $N(u)$, a set of nodes which integrally covers $N_2(u)$. We define as $MPR(u)$ this set of MPR selected by u. $MPR(u)$ is such that: $u \cup N_2(u) \subset \bigcup_{v \in MPR(u)} N(v)$. We call $MPR_1(u) \subset MPR(u)$ the nodes that u elects at the first step. u selects as $MPR_1(u)$ the nodes which cover its isolated nodes. $MPR_1(u)$ are thus the only way to reach isolated nodes of u in 2 hops from u. Thus the first step is mandatory to totally cover $N_2(u)$ with MPR(u). At the second step, u considers the nodes in $N_2(u)$ not already covered by the $MPR_1(u)$. It chooses as MPR the node of $N(u)$ allowing to cover the maximal number of uncovered nodes of $N_2(u)$, and so on till getting $N_2(u)$ all covered. To better understand this algorithm, let's run it on the green node u on Figure 1. The isolated points of node u appear in red and $MPR_1(u)$ in blue. Node t is an isolated node as only node h allows to connect t and u in 2 hops. Node h is thus elected at the first step: $h \in MPR_1(u)$, as well as all red hatched nodes. Nodes $k, j, t, s, r, q, o, m, l$ in $N_2(u)$ are covered by them. Then, node u goes to step 2. It considers nodes of $N_2(u)$ not already covered (nodes p and n) and nodes in N_1 not selected as MPR_1 (nodes b, f, e and d). It thus only keeps the view of the topology illustrated by Figure 1(b). It first selects the node of $N(u)$ which has the highest degree on Graph 1(b): node e (e covers 2 nodes, n and p, f and d only cover one node, resp. p and n). From here, all nodes of $N_2(u)$ are covered by the selected MPR, the algorithm stops. We have: $MPR(u) = \{c, e, i, h, g\}$. Then, it is easy to see that nodes of $N(u)$ which cover "isolated nodes" must be included into the set of MPR if we want to integrally cover the $N_2(u)$, whatever the selection process. Thus, we can not skip or "compress" the first step of the algorithm in the MPR selection. Moreover, this step must be run first in order to minimize the number of MPR. Therefore, only the second step of the algorithm can be improved in order to find the minimum number of MPR.

Related works: Most of the literature about the performances of OLSR deals with the efficiency of the OLSR routing protocol itself or the different techniques using MPR ([4–7]). The goal is to minimize the number of transmitters and thus the number of selected MPR per node. Therefore, alternative algorithms to the classical MPR selection algorithm as [11, 10] aim to optimize the overlap between MPR or the global bandwidth. But, all results for the proposed algorithms are quite similar, particularly for the mean number of MPR per node. Therefore, in order to understand this phenomenon, we wished to analyze this selection more in details as only few papers have studied the different algorithm performances of the MPR selection. Only [11] gives an analysis of the MPR selection on the line. Other analytical results in different graphs are also given in [5]. Other interesting results are presented in [10].

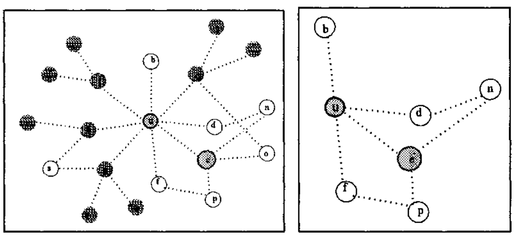
3. Analysis

We are interested in the properties of the MPR of a typical node. Therefore, we do not consider the whole network but only a "typical point" located at the origin of the plane and its 1 and 2-neighborhood. Our model is similar to the classical unit random graph used to model ad-hoc networks. This is a general model as we do not make any assumption about the wireless technology used.

Let $B(x, R)$ denote a ball of radius R centered in x. Let be a Poisson point process on $B(0, 2R)$ of intensity $\lambda > 0$. The intensity λ of such a process represents the mean number of points of the process by surface unit. We add a point 0 at the origin for which we study the MPR selection algorithm (Palm distribution). We assume that there is a bidirectional link between two nodes iff $d(u, v) \leq R$ where $d(u, v)$ is the Euclidean distance between u and v and $R \in I\!R^{+*}$ a constant. The neighborhood of 0 is thus constituted of the points of the Poisson process which are in $B(0, R)$. We still use N (resp. N_2) to design the 1-neighborhood (resp. the 2-neighborhood) of the point 0.

General results: Let $A(r)$ be the area of the intersection of two balls of radius R where the distance between the centers of the balls is r:
$A(r) = 2R^2 \arccos\left(\frac{r}{2R}\right) - r\sqrt{R^2 - \frac{r^2}{4}}$ and $A_1(u, r, R)$ the area of the union of 2 discs of radius R and u where the centers of the 2 balls are distant from r:
$A_1(u, r, R) = rR\sqrt{1 - \left(\frac{R^2 - u^2 + r^2}{2Rr}\right)^2} - R^2 \arccos\frac{u^2 - R^2 - r^2}{2Rr} - u^2 \arccos\frac{R^2 - u^2 - r^2}{2ur}$

The next proposition gives several general results as the mean value of the quantities d_0^+ and d_0^- as well as the mean size of the 1 and 2-neighborhood of a node when considering a Poisson point process distribution.



(a) Real topology - Isolated points of u appear in horizontal red, $MPR_1(u)$ in vertical blue. (b) Topology considered by node u at the second step

Figure 1. Illustration of the MPR selection algorithm.

Proposition 1 *Let u be a point uniformly distributed in $B(0,R)$. u is thus such that $u \in N$.*
The mean number of node u's neighbors lying in $B(0,2R)/B(0,R)$ is given by: $\mathbb{E}\left[d_0^+(u)\right] = \frac{\lambda}{\pi R^2}\int_0^{2\pi}\int_0^R(\pi R^2 - A(r))rdrd\theta = \lambda R^2\frac{3\sqrt{3}}{4}$.
The idea is to count the number of the process points lying in the intersection of $B(u,R)$ and $B(0,2R)/B(0,R)$.

Let v be a point uniformly distributed in $B(0,2R)\backslash B(0,R)$. The mean number of node v's neighbors lying in $B(0,R)$ is given by:
$\mathbb{E}\left[d_0^-(v)\right] = \lambda\frac{2}{3R^2}\int_R^{2R} A(r)rdr = \lambda R^2\frac{\sqrt{3}}{4}$.
The idea here is to count the number of process points in the intersection of $B(v,R)$ and $B(0,R)$. Node v may lie in $B(0,2R)\backslash B(0,R)$ without belonging to N_2 if $N(v)\cap N = \emptyset$. So, to obtain the quantity above for nodes in N_2 we have to condition it by the probability that $v \in N_2$.
We obtain: $\mathbb{E}\left[d_0^-(v)|v\in N_2\right] = \frac{\mathbb{E}\left[d_0^-(v)\right]}{\mathbb{P}(d_0^-(v)>0)}$,
with $\mathbb{P}\left(d_0^-(v)>0\right) = 1 - \frac{2}{3R^2}\int_R^{2R} exp\{-\lambda A(r)\}rdr$.
This last equation gives the probability that a node in $B(0,2R)/B(0,R)$ has at least one neighbor in $B(0,R)$ which makes it a 2-neighbor of node 0.

The mean number of nodes in N is given by: $\mathbb{E}\left[|N|\right] = \lambda\pi R^2$.
The mean number of nodes in N_2 is given by:
$\mathbb{E}\left[|N_2|\right] = 3\lambda\pi R^2\mathbb{P}\left(d_0^-(v)>0\right) = 3\lambda\pi R^2\left(1 - \frac{2}{3R^2}\int_R^{2R} exp\{-\lambda A(r)\}rdr\right)$.

All these quantities can be computed in the same way. We use the following properties of a Poisson point process: conditioned by the number of points in $B(0,R)$ (resp. in $B(0,2R)\backslash B(0,R)$), the points are independently and uniformly distributed in $B(0,R)$ (resp. in $B(0,2R)\backslash B(0,R)$) and are independent of the points of $B(0,2R)\backslash B(0,R)$ (resp. $B(0,R)$).

Analysis of the first step of the MPR selection: In this section, we compute several quantities relative to the first step of the algorithm. In the next proposition, we give the mean number of points $v \in N_2$ such that $d_0^-(v) = 1$. These points are the isolated points of 0. The points of N, neighbors of these isolated points, necessarily belong to MPR_1 as they are the only way to reach them from node 0 in 2 hops. However, this quantity does not give the size of MPR_1, since several isolated points can be reached by the same MPR_1 point. For instance, on Figure 1(a), we have four MPR_1 nodes but seven "isolated points". MPR_1 i covers two isolated points: j and k.

Proposition 2 *Let v be uniformly distributed in $B(0,2R)\backslash B(0,R)$ and D the set of points v such that $d_0^-(v) = 1$:*
$\mathbb{P}\left(d_0^-(v) = 1\right) = \frac{2}{3R^2}\int_R^{2R}\lambda A(r)exp\{-\lambda A(r)\}rdr$

As in Proposition 1, we only consider nodes v such that $v \in N_2$:
$\mathbb{P}\left(d_0^-(v) = 1 | v \in N_2\right) = \frac{\mathbb{P}\left(d_0^-(v)=1\right)}{\mathbb{P}\left(d_0^-(v)>0\right)}$.
The mean number of "isolated points" is then deduced and given by:
$\mathbb{E}\left[|D|\right] = 2\pi\lambda^2 \int_R^{2R} A(r) exp\{-\lambda A(r)\} r dr$.

Proposition 3 gives lower and upper bounds on the number of MPR_1.

Proposition 3 *Let u be a point uniformly distributed in $B(0,R)$:*

$$\mathbb{P}\left(u \in MPR_1\right) \geq \frac{2}{R^2}\mathbb{P}\left(d_0^+(u) > 0\right) \times \int_0^R \int_R^{R+r} f(x,r,R) \exp\left\{-\lambda\left(2\pi R^2 - A_1(R,x,R)\right)\right\} r dx dr$$

with $f(x,r,R)$ being the probabilistic distribution function:

$$f(x,r,R) = -\frac{\lambda\left[\frac{\partial}{\partial x}A_1(x,r,R) - 2\pi x\right]}{1 - \exp\left\{-\lambda(A_1(R,r,R) - \pi R^2)\right\}} \exp\left\{-\lambda\left(A_1(x,r,R) - \pi x^2\right)\right\}$$

The next formula gives the mean number of MPR_1. It is the direct consequence of the formula above:

$$\mathbb{E}\left[|MPR_1|\right] \geq 2\lambda\pi\mathbb{P}\left(d_0^+(u) > 0\right) \times \int_0^R \int_R^{R+r} f(x,r,R) \exp\left\{-\lambda\left(2\pi R^2 - A_1(R,x,R)\right)\right\} r dx dr$$

Moreover, since there is at least one isolated point by point of MPR_1, the mean number of isolated points offers an upper bound: $\mathbb{E}\left[|MPR_1|\right] \leq \mathbb{E}\left[|D|\right]$.

Proof 1 *To obtain a bound on the probability that a point in N belongs to MPR_1, we use a sufficient condition. Because of page restriction, we do not give here the proof but it can be found in [9].*

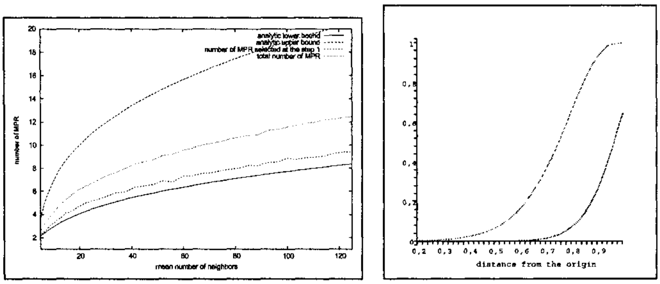
We are now interested in the spatial distribution of the MPR_1 points. For a node u such that $d(0,u) = r$, $r \leq R$, Proposition 4 gives lower and upper bounds on the probability that u belongs to MPR_1.

Proposition 4 *Let u be a point at distance r ($r \leq R$) from the origin. We fix the two points 0 and u and we distribute the Poisson point process in $B(0,2R)$ independently of these two points.*

$$\mathbb{P}\left(u \in MPR_1\right) \geq \left(1 - \exp\left\{-\lambda(\pi R^2 - A(r))\right\}\right) \times \int_R^{R+r} f(v,r,R) \exp\left\{-\lambda(2\pi R^2 - A_1(R,v,R))\right\} dv$$

$$\mathbb{P}\left(u \in MPR_1\right) \leq 1 - \left(1 - \exp\left\{-\lambda\frac{A(R+r)}{2}\right\}\right)^2$$

Proof 2 *The lower bound is obtained in the same way as the bound in Proposition 3 but given $d(0,u), u \in N$. Because of page restriction, we do not give detail the proof here but it can be found in [9].*



(a) Mean number of MPR and MPR_1 obtained by simulation when $\lambda\pi$ varies and comparison with analytical bounds. (b) Lower and upper bounds on the probability of belonging to MPR_1 *w.r.t.* the distance from the origin.

Figure 2. Simulation results.

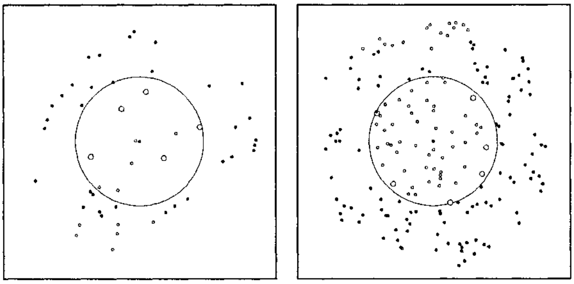
4. Numerical results and simulations

The nodes are deployed using a Poisson process in $B(0,2)$ for $R = 1$ and $\lambda > 0$. We add a point at 0 and study the number of MPR it selects at each step of the MPR selection. Figure 2(a) shows the mean number of MPR and MPR_1 obtained by simulation. We observe that approximately 75% of the MPR actually are MPR_1, which confirms that the MPR_1 almost cover the whole 2-neighborood. Figure 2(a) also show the analytic bounds. As explained before, the lower bound is very close to the mean size of the set MPR_1.

Figure 3 plots samples for different values of $\lambda\pi$ ($\lambda\pi$ being the number of a node's neighbors). The point 0 for which we compute the MPR is the black point in the middle. Points in the central circle are the points of N, the larger ones being the MPR_1. Points outside the circle are the points of N_2, the blue ones being the points of N_2 covered by the MPR_1. We note that in all cases, almost all nodes of N_2 are is covered by the MPR_1. Only one more MPR might suffice to cover the rest of N_2. We have shown in the previous section that there is an appreciable number of isolated points giving rise to a certain number of MPR_1. These MPR_1 seem to be distributed very close to the boundary of $B(0,R)$ and regularly scattered on it (which confirms the results of the Proposition 4). Therefore, they cover a very large part of N_2. The lower and upper bounds given in Proposition 4 allow us to show that the MPR_1 are very close to the boundary. Figure 2(b) show these bounds when the distance between 0 and its neighbors varies from 0.2 to 0.999 and with $\lambda = 15$. These curves incontestably show that MPR_1 points are distributed closely to the boundary of $B(0,1)$. We point out that these results depend on λ: as λ increases, the distance between MPR_1 points and 0 increases too.

5. Consequences

About the MPR distribution: When a message is sent by node u, only $MPR(u)$ forward the message. Neighbors commun to u and $MPR(u)$ thus receive several copies of the same message and spend energy uselessly. Yet, as shown in Section 4, most of $MPR_1(u)$ (and thus most of $MPR(u)$) are distributed very closely to the boundaries of the radio range of u. That means

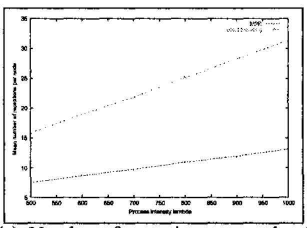


(a) $\lambda\pi = 15$ (b) $\lambda\pi = 45$

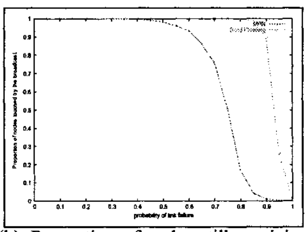
Figure 3. MPR selection with $\lambda\pi = 15$ and $\lambda\pi = 45$.

that the intersection between u and its of each MPR radio areas is minimized and so the number of common neighbors and so the energy uselessly spent.

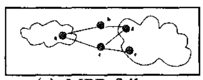
The easiest way to broadcast a message over a network is the blind flooding, where each node re-emits the message upon first reception of it. To illustrate the number of receptions saved by the MPR, we computed by simulation the number of receptions per node of a broadcast message. The nodes are randomly deployed using a Poisson process in a 1×1 square with various levels of intensity λ (and thus various numbers of nodes) for $R = 0.1$. x and y are connected if and only if $d(x, y) \leq R$. Figure 4(a) compares the results obtained by both metrics.For the blind flooding, the number of receptions per node corresponds to the mean number of neighbors (as every node forwards the message once). With OLSR, approximately 40% of the nodes participate to the diffusion. It is drastically less than the blind flooding and it is a priori sufficiently high to be robust.



(a) Number of receptions per node of a broadcast message initiated at a random source.



(b) Proportion of nodes still receiving a broadcast message when applying a failure probability on links.



(c) MPR failure.

Figure 4. Some consequences with $\lambda = 1000$.

About the MPR_1: The number of MPR elected per node aims to be as low as possible. The Greedy heuristic of MPR selection presented here is the original one. As we mentioned in Section 1, some works have been lead in order to enhance this algorithm and elect less MPR per node. But, only the second step of the Greedy algorithm may be improved as the first one is mandatory to cover the whole 2-neighborhood of a node and can not be reduced. And, as the first step leads to the election of more than 75% of the MPR, the improvements can only concern less than 25% of the MPR and thus can not be significant, which explains that all works lead to similar results and minor improvements. Unfortunately, this feature also underlines a robustness problem. Indeed, if 75% of node u's MPR cover at least one isolated, if some $MPR(u)$ fail, there is a great probability that at least one node v in $N_2(u)$ does not receive messages from u. Of course, v may receive it from another path but, this path would not be optimal anymore. Because of it, parts of the network can be isolted during the broadcasting task as illustrated by Figure 4(c). Clouds represent parts of the network. As node e is an isolated point for node a, a has to elect node c as one of its MPR but does not elect node b as node d is already covered by c. Let's suppose that the link between a and c fails and a diffusion is performed before a re-computes its MPR. The network is still connected, nevertheless, as node b is not a MPR of node a, it does not forward the message. A whole part of the network is isolated. In order to measure this robustness problem, we simulate a broadcasting task, applying a failure probability over links. We measure the proportion of nodes still receiving the broadcast message. Figure 4(b) shows the results. As in the blind flooding, every node retransmits the message, if some nodes do not receive it, that means that the network is disconnected. We can see that this happens when 85% or more of links are down. However, every node does not receive the message with the MPR heuristic when only 45% of links are down whereas the network is still connected. This failure model may seem not very realist as links can fail because of congestion and, as the blind flooding induces more messages than the MPR protocol, more links fail. Nevertheless, we use the results of the blind flooding in this situation to give an information on the network connectivity. However, failures of a MPR may also be due to the node mobility. Indeed, if a MPR moves, it may leave the radio scope of the node for which it is a MPR or does not cover the same set of nodes in the 2-neighborhood anymore.

6. Conclusion

In this article, we have computed several quantities relative to the MPR selection algorithm in OLSR. We have shown that approximately 75% of the MPR are chosen during the first step of the algorithm. Since this step always is necessary for the MPR set to cover the whole 2-neighborhood, variants of the algorithm used in OLSR, trying to minimize the number of selected MPR, lead to similar performances. We have also highlighted the fact that these MPR are distributed close to the radio range boundaries, limiting the overlap between MPR. This feature also underlines a robustness problem. This robustness problem is intented to be analyzed with other robustness models. A deeper study about the influences of isolated points on the reliability of OLSR will be lead in future works. These results have been presented for a particular model using Poisson point process. Other models, more realistic, which take into account the properties of the radio layer could be considered in future works. Results obtained here could be compared to simulations considering CDMA network or 802.11 network.

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