Maximizing the Probability of Delivery of Multipoint Relay Broadcast Protocol in Wireless Ad Hoc Networks with a Realistic Physical Layer

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Abstract: It has been recently highlighted that the standard unit disc graph (UDG) used to model the physical layer in ad hoc networks does not reflect real radio transmissions, and that the log-normal shadowing (LNS) model better suits to experimental simulations. Therefore, many existing communication protocols must be adapted in order to still be efficient using the LNS model. In this paper, we consider broadcasting using this model and especially focus on the Multipoint Relay protocol (MPR). In the latter, each node has to choose a set of neighbors to act as relays in order to cover the whole 2-hop neighborhood. We give experimental results which show that the original heuristics provided to select the set of relays does not give good results with the LNS model. We also provide three new heuristics in replacement and their performances which demonstrate that they better suit to the LNS model. The first one maximizes the probability of correct reception between the node and the considered relays multiplied by their coverage in the 2-hop neighborhood. The second one replaces the coverage by the average of the probabilities of correct reception between the considered neighbor and the 2-hop neighbors it covers. Finally, the third heuristics keeps the same concept as the second one, but tries to maximize the coverage level of the 2-hop neighborhood: 2-hop neighbors are still being considered as uncovered while their coverage level is not higher than a given coverage threshold, many neighbors can thus be selected to cover the same 2-hop neighbors.

Key-words: Ad Hoc Networks, Broadcast Protocols, Multipoint Relay Protocol, Realistic Physical Layer, Log-Normal Shadowing, Unit Disc Graph

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Maximisation du taux de transmission du protocole de diffusion par relais multipoints dans les réseaux ad hoc avec une couche physique réaliste

Résumé : Il a récemment été avancé que le modèle du disque unitaire (UDG) utilisé pour modéliser la couche physique dans les réseaux ad hoc ne reflète pas la réalité des transmissions radio, et que le modèle du masquage log-normal (LNS) est bien plus adapté aux simulations expérimentales. Ainsi, beaucoup de protocoles de communication existants doivent être modifiés afin de garder leur afficacité avec le modèle LNS. Dans cet article, nous considérons la diffusion d'informations avec ce modèle et nous nous concentrons plus particulièrement sur le protocole de diffusion par relais multipoints (MPR). Dans ce dernier, chaque nœud doit choisir un sous-ensemble de ses voisins à 1 saut afin de servir de relais pour atteindre le voisinage à 2 sauts. Nous fournissons des résultats expérimentaux montrant que l'heuristique originale pour sélectionner l'ensemble des relais ne donne pas de bons résultats avec le modèle LNS. Nous donnons également trois nouvelles heuristiques ainsi que leurs performances, démontrant qu'elles sont bien plus adaptées au modèle LNS. La première maximise la probabilité de réception sans erreur des relais choisis multipliée par la couverture fournie par ces relais dans le voisinage à 2 sauts. La deuxième remplace cette couverture par la moyenne des probabilités de réception sans erreur par les voisins à 2 sauts. Enfin, la dernière heuristique garde le même calcul de 'score' que la deuxième, mais essaie de maximiser le niveau de couverture des voisins à 2 sauts: ces derniers sont toujours considérés comme non couverts tant que leur couverture ne dépasse pas un seuil fixé par avance. De cette manière, plusieurs voisins peuvent être choisis comme relais pour couvrir les mêmes voisins à 2 sauts.

Mots-clés : Réseaux ad hoc, Protocoles de diffusion, Protocole de diffusion par relais multipoints, Couche physique réaliste, Masquage log-normal, Graphe du disque unitaire

1 Introduction

Nowadays, wireless networking has become an indispensable technology for many business men, who travel a lot and still want to keep in touch with their family of their office. However, the most deployed technology, known as WiFi, is too restrictive, as users must stay near to the needed infrastructure, composed by fixed access points. This causes many problems, because the latter must be sufficiently deployed and correctly configured to offer a good quality of service. Moreover, there exists some more unusual situations where an infrastructure may be completely unavailable (battlefields, rescue area...). The future of this technology most probably lies in wireless ad hoc networks, which are designed to be functional even without any available infrastructure. They are usually defined to be composed by a set of mobile or static hosts operating in a self-organized and decentralized manner, which communicate together thanks to radio interfaces. The main difference with the currently deployed technology lies in the fact that hosts can be either terminals or routers, depending on the needs of the system, leading to a cooperative multi-hop routing.

Broadcasting is one of the most important communication task in those networks, as it is used for many purposes such as route discovery (DSR [1], OLSR [2]...), publication of services or even alarming. In a straightforward solution to broadcasting, hosts only need to blindly relay packets at least once to their neighborhood in order to fully cover the network. However, due to known physical phenomena, this leads to the broadcast storm problem [3]. Moreover, this is a totally inefficient algorithm, because a great part of the retransmissions are not needed to ensure the global delivery of the broadcasted packet, and a huge amount of energy is thus unnecessarily wasted, while it is a resource of prime importance. Many other algorithms have been proposed in replacement. Some of them are centralized (a global knowledge of the network topology is needed to apply them), while the others are localized (hosts only need to know their local neighborhood to take decisions). Clearly, localized algorithms better fit to ad hoc networks and their decentralized architecture.

However, all the proposed broadcasting protocols have always been studied under ideal scenario, where the unit disc graph is used to model communications between hosts. In this model, two hosts can communicate together if the distance between them is no more than a given communication radius, and packets are always received without any error. Recently, this model has been criticized as it does not correctly reflect the behavior of transmissions in a real environment [4]. Indeed, it has been demonstrated that signal strength fluctuations have a significant impact on performances, and thus cannot be ignored when designing communication protocols for ad hoc networks. Unfortunately, this has been the case until now.

In this paper, we consider the well-known Multipoint Relay Protocol (MPR) [5], used for broadcasting in ad hoc networks, under a more realistic scenario where the probability of correct reception of a packet depends on the distance between the emitter and the receiver(s). We thus replace the unit disc graph model by the log-normal shadowing model [6] to represent a realistic physical layer, and analyse the experimental results obtained after this change. As they demonstrate the need for a more suitable algorithm, we also propose several modifications to MPR in order to maximize the delivery ratio of the broadcasted packet, while trying to minimize the number of needed retransmissions. By experimentations, we show that these new versions are much more efficient than the original one under the considered realistic scenario.

The remainder of this paper is organized as follows: in the next section, we provide the definitions needed by our models, while in Sec. 3 a review of the existing works is proposed. In Sec. 4, we provide an analysis of the behavior of the original algorithm used in MPR with the realistic physical layer. We then describe in Sec. 5 new algorithms that better fit the latter. We finally conclude in Sec. 6 and give some directions for future work.

2 Preliminaries

The common representation of a wireless network is a graph $G = (V,E)$, where V is the set of vertices (the hosts, or nodes) and $E \subseteq V^2$ the set of edges which represents the available communications: there exists a pair $(u,v) \in V$ if the nodes u and v are able to directly communicate together. The neighborhood $N(u)$ of the node u is defined as $\{v : (u,v) \in V\}$. This function is naturally extended to sets of nodes: for a given subset $V' \subset V$, $N(V') = \bigcup_{u \in V'} N(u)$. The degree of a node u is simply equal to $|N(u)|$. The density of the network is equal to the average degree of nodes. Each node u is assigned a unique identifier $\mathrm{id}(u)$ (this can be, for instance, IP or MAC address). Finally, we measure the distance between two nodes u and v in terms of number of hops, which is simply the minimum number of edges a message has to cross from u to v.

The existence of a pair $(u,v) \in V$ is determined by the considered physical layer and depends on several conditions, the most obvious one being the distance between u and v. In the most commonly used model, known as the unit disc graph (UDG) model, a bidirectional edge exists between two nodes if the distance between them is no more than a given

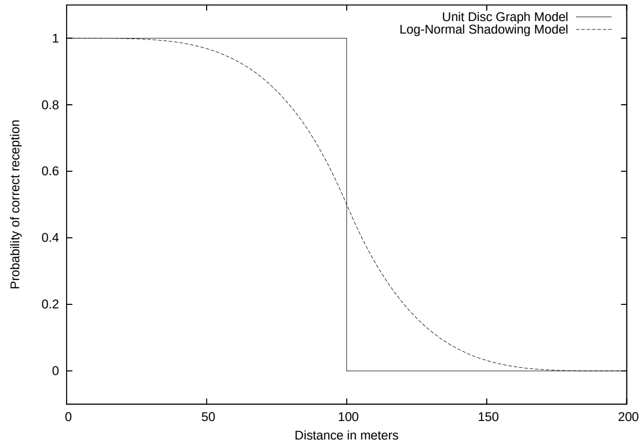


Figure 1: UDG and LNS models, for $R = 100$.

communication radius R (it is assumed that all nodes have the same communication radius). In this model, the set E is then simply defined by:

$$E = \{(u,v) \in V^2 \mid u \neq v \wedge d(u,v) \leq R\},$$

$d(u,v)$ being the Euclidean distance between nodes u and v. This model, while being well spread in papers about ad hoc networks, cannot be considered as realistic. Indeed, it is assumed that packets are always received without any error, as long as the distance between the emitter and the receiver is smaller than the communication radius. This totally ignores random variations in the received signal strength, while it was demonstrated that these fluctuations have a significant impact on performances, sometimes "outperforming" the impact of mobility. In [4], authors propose to use a model named log-normal shadowing (LNS) as a realistic physical layer, where the fluctuations of signal are taken into account: packets have now a probability to be received without error that smoothly decreases with the distance. This model is illustrated in Fig. 1, where the probabilities for LNS are given by the approximated function $P(x)$, described in [7], which is equal to:

$$P(u) = \begin{cases} 1 - \frac{(\frac{x}{R})^{2\beta}}{2} & \text{if } x < R, \\ \frac{(\frac{2R-x}{R})^{2\beta}}{2} & \text{otherwise,} \end{cases}$$

β being the power attenuation factor. We used $\beta = 2$ in Fig. 1. We can clearly notice that the UDG model inaccurately depends on a unique threshold. In the LNS model, we have assumed that the communication radius R is equal to the distance such that $p(R) = 0.5$, which is 100 in this example. Throughout this paper, we use the simplified notation $p(u,v)$ instead of $p(d(u,v))$.

In this paper, we assume that each node is aware of its 2-hop neighbors, which can be achieved, for example, by at least two rounds of beacon (HELLO) messages: nodes can indeed insert the identifiers of their neighbors in their own beacon messages. The question of correctly gathering neighborhood information considering the LNS model is a whole problem, because HELLO messages are themselves subject to the probability of correct reception. This problem is not in the scope of this paper, but we nevertheless give in Sec. 4 indications of how it can be considered when generating graphs for simulations, and what decisions we took in the implementation of our simulator.

We also assume that nodes are able to determine the probability of correct reception of a packet that would be sent to a neighbor. This can be simply achieved by using the approximated function illustrated in Fig. 1: the 'real' probability depends on the size of the packet, but using an approximation gives sufficiently correct results. The distances between neighbors must also be known: they can be computed using the positions of the nodes. The latter can be acquired thanks to a location system like the GPS (Global Positioning System), or any other existing system.

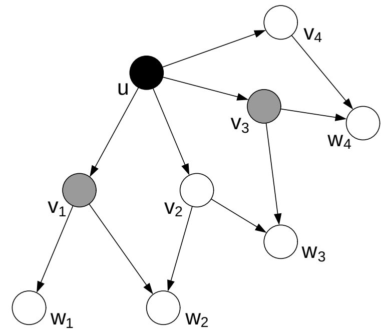


Figure 2: Applying MPR at node u: $S(u) = \{v_1, v_3\}$.

3 Related Work

To the best of our knowledge, this paper is the first one to consider broadcasting over a realistic physical layer, as previous works in this area mainly focused on routing. The foundations of this paper are based on [4] where authors clearly demonstrate the need to stop considering the unit disc graph model to analyze communication protocols by simulations. They proposed to replace this model by the log-normal shadowing model in which the probability $p(x)$ of correct reception of a packet depends on the distance x between the emitter and the receiver. They earlier proposed in [7] a reasonably accurate approximation for $p(x)$ and assumed that the transmission radius R is determined by $p(R) = 0.5$. We use the proposed approximation throughout this paper.

As stated in Sec. 1, the easiest method for broadcasting a packet is to have all nodes act as routers and relay it at least once to their neighborhood: this method is known as *blind flooding*. However, such a simple behavior has huge drawbacks: too many packets are lost due to collisions between neighboring nodes (this can lead to only a partial coverage of the network) and far too much energy is consumed. Many other solutions have been proposed to replace it, and an extensive review of them can be found in [8].

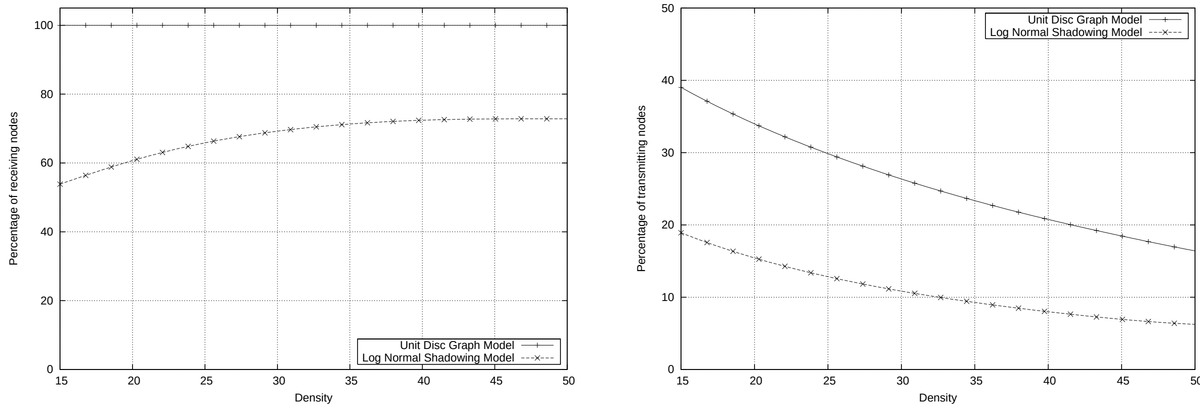
Among all these solutions, we have chosen to focus on the multipoint relay protocol (MPR) described in [5] for several reasons:

- It is efficient using the unit disc graph model,
- It is used in the well-known routing protocol OLSR [2],
- It can also be used for other purposes, like computing a connected dominating set [9].

In this algorithm, it is assumed that nodes have a 2-hop knowledge: they are aware of their neighbors (1-hop distance), and the neighbors of these neighbors (2-hop distance). Its principle is as follows. Each node u that has to relay the message must first elect some of its 1-hop neighbors to act themselves as relays in order to reach the 2-hop neighbors of u. The selection is then forwarded within the packet and receivers can thus determine if they have been selected or not: each node that receives the message for the first time checks if it is designated as a relay node by the sender, and if it is the case, the message is forwarded after the selection of a new relaying set of neighbors. A variant exists where nodes select their relays before having to broadcast a packet, and selection is sent within HELLO messages.

Obviously, the tricky part of this protocol lies in the selection of the set of relays $S(u)$ within the 1-hop neighbors of a node u: the smaller this set is, the smaller the number of retransmissions is and the more efficient the broadcasting is. Unfortunately, finding such a set so that it is the smallest possible one is a NP-complete problem, so a greedy heuristics is proposed in [5]. Considering a node u, it can be described as follows:

1. Place all 2-hop neighbors (considering only outgoing links) in a set $S'(u)$ of uncovered 2-hop neighbors.
2. While there exists a 1-hop neighbor v which is the only common neighbor of u and some nodes in $S'(u)$, add v to $S(u)$, and remove all its neighbors from $S'(u)$.
3. While the set $S'(u)$ is not empty, repeatedly choose the 1-hop neighbor v not present in $S(u)$ that cover the greatest number of nodes in $S'(u)$. Each time a new node is added to $S(u)$, remove its neighbors from $S'(u)$. In case of tie, choose the node with the highest degree.



(a) Receiving nodes (b) Transmitting nodes

Figure 3: Performances of MPR with the two considered physical models.

There exists a variant with a fourth step, where a few 'useless' relays can be removed: these are the nodes which cover the same set of 2-hop neighbors as a set of other relays. This step increases the complexity of computation, and does not bring a really noticeable improvement. Moreover, the removal of redundant relays greatly decreases the probability of delivery using the LNS model, this is why we chose to not consider this extra step in this paper.

An example of this heuristics is given in Fig. 2, starting with $S(u) = \emptyset$. The node v_1 is the only one able to reach w_1, so it is added to $S(u)$ and nodes w_1 and w_2 are removed from $S'(u)$. No other 'essential' 1-hop neighbor of u exists, so other relays are selected according to the number of nodes in $S'(u)$ they cover. Nodes v_2 and v_4 cover only one node in $S'(u)$, while node v_3 covers at the same time w_3 and w_4, so v_3 is chosen and added to $S(u)$. The set $S'(u)$ being empty, no other nodes are selected. We finally have $S(u) = \{v_1, v_3\}$.

Being the flooding protocol used in OLSR, MPR has been the subject of many studies since its publication. For example in [10], authors analyse how relays are selected and conclude that almost 75% of them are selected in the first step of the greedy heuristics, so that improving the second step is not really useful. This conclusion seems correct, as long as the unit disc graph model is used.

4 Original Greedy Heuristics

In this section, we provide results about the performances of MPR over our considered realistic physical layer, the log-normal shadowing model (LNS). We chose not to use a general purpose simulator in order to isolate the good parameters: we thus implemented algorithms and models in our own simulator, so that we had to decide how to generate 'realistic' graphs considering the LNS model. We chose to consider probabilitic graphs: a bidirectional edge exists between two nodes if the probability of correct reception between these two nodes is different from 0, and edges are weighted by this probability. The resulting graph is thus asymmetrical from the point of view of nodes, because messages are not always correctly received. This method does not imply any underlying neighborhood discovery method, as stated in Sec. 2.

All the results were obtained with the following parameters. The network is static and always composed of 500 nodes randomly distributed in a uniform manner over a square area whose size is computed in order to obtain a given average degree. Edges are created using the method described in the previous paragraph, and for each measure, we took the average value obtained after 500 iterations. We fixed the communication radius to be equal to 75 meters in both physical models. An ideal MAC layer is considered to isolate the intrinsic properties of the selected relays: collisions of packets could skew both results and analyses.

We give in Fig. 3 the performances of the original version of MPR over the two considered physical layers. In 3(a) is given the percentage of nodes which received the broadcasted message. Using the UDG model, the diffusion is complete because MPR is a deterministic algorithm. However, this is not the case with the LNS model due to the errors of transmission: the percentage of diffusion is under 70% for all degrees, and is as low as 55% for a 'standard' value such as 15. These poor performances can be explained by the fact that, as highlighted in [10], the chosen relays are located at the limit of the communication range, where the probability of correct reception is low. This is confirmed by our experiments,

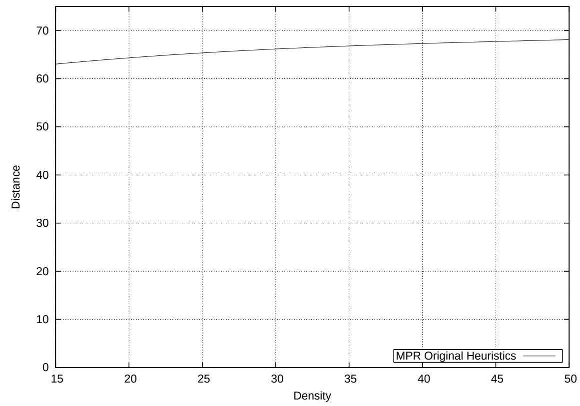


Figure 4: Average distance between a node and its relays.

as illustrated by Fig. 4: the average distance between a node and its relays is almost equal to 68 meters, while the maximal communication range is 75 meters. Moreover, [10] also states that 75% of the relays are chosen during the first step: this means that, when a relay does not correctly receive the message, there is a risk of 75% that this relay was the only one able to reach an isolated node, which will thus not receive the message, potentially leading to a partition of the network.

In 3(b) is given the percentage of nodes which received and relayed the message. It is interesting to note that this percentage is different with the two models. Indeed, as only nodes which received the message are taken into account, one would have expected to observe the same values in both cases. This means that the needed number of relaying nodes does not linearly vary with the number of covered nodes: obviously, only a few relays are needed to cover a high number of different nodes, but a larger number is needed to cover the last few remaining ones.

5 New Heuristics for MPR

As illustrated in the previous section, the original greedy heuristics provided in [5] is not suitable to obtain a correct diffusion of the broadcasted message under a realistic physical layer. We thus provide in this section new heuristics, in order to maximize the delivery ratio while trying to minimize the percentage of retransmissions. In all these new heuristics, the first step of the original algorithm is always kept as it is mandatory, only the second one is modified.

5.1 Heuristics 1: Straightforward Approach

The low delivery ratio of MPR is caused by relays which are too far from the node, and are highly likely to not receive the message. The idea here is to straightforwardly take into account the probability of correct reception when choosing the relays, the goal being to balance the number of covered 2-hop neighbors and the probability of correct reception by the relays. At each iteration, a 'coverage value' is thus computed for each 1-hop neighbor: the one with the highest value is then chosen as a relay. As in the original heuristics, this value for a given 1-hop neighbor v is based on the number of uncovered 2-hop neighbors it covers, but we now multiply it by the probability of correct reception by the node v. In Fig. 5, the coverage value of node v_1 is equal to $p(u,v_1) \times 3$ (considering that nodes w_1, w_2 and w_3 are not yet covered).

5.2 Heuristics 2: Clever Approach

The previous heuristics still has obvious flaws: as the number of uncovered 2-hop nodes is still considered, one can imagine a situation where a very distant neighbor would cover a high number of other nodes. This neighbor would still be selected, even with its very low probability of correct reception. It is also possible that the distance between this relay and its covered nodes is very high, so that its retransmission would have great risks to not reach them, which is not a good thing to maximize the delivery. We thus expand the concept of using the probabilities when computing the coverage value by using the probabilities between the considered 1-hop neighbor and the 2-hop neighbors it covers. This time, we compute the average coverage probability of the 1-hop neighbor instead of using its degree. Thus, still considering Fig. 5, the coverage value of node v_1 is now equal to $p(u,v1) \times ((p(v_1,w_1) + p(v_1,w_2) + p(v_1,w_3))/3)$ (still considering that nodes w_1, w_2 and w_3 are not yet covered by other relays).

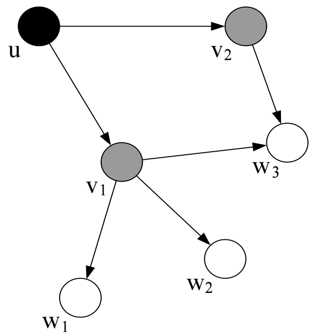


Figure 5: How relays are selected in our new heuristics.

5.3 Heuristics 3: Robustness Approach

In this heuristics, we keep the same coverage value as in the previous one, but to increase the probability of a total diffusion in the network, we change the way nodes are removed from the uncovered 2-hop neighbors list. In all the previous heuristics, as soon as a 1-hop neighbor is chosen as a relay, all its neighbors are removed from the list, even if the probability of correct reception is very low. We now remove a node from the list only if its 'coverage level' is higher than a given constant threshold. This level is simply equal to the probability for the considered node to correctly receive the message. In Fig. 5, if nodes v_1 and v_2 are relays, the probability of the node w_3 to receive the message is equal to $1-(\overline{p(v_1,w_3)} \times \overline{p(v_2,w_3)})$: the probability that 'at least one of them reach w_3' is the inverse of 'none of them reach w_3'. Many relays can thus now be selected to cover the same set of nodes, thus increasing the probability of reception by these nodes.

One can notice that in these three new heuristics, if all probabilities are equal to 1 (UDG model), then we always obtain the same results as with the original heuristics.

5.4 Performances

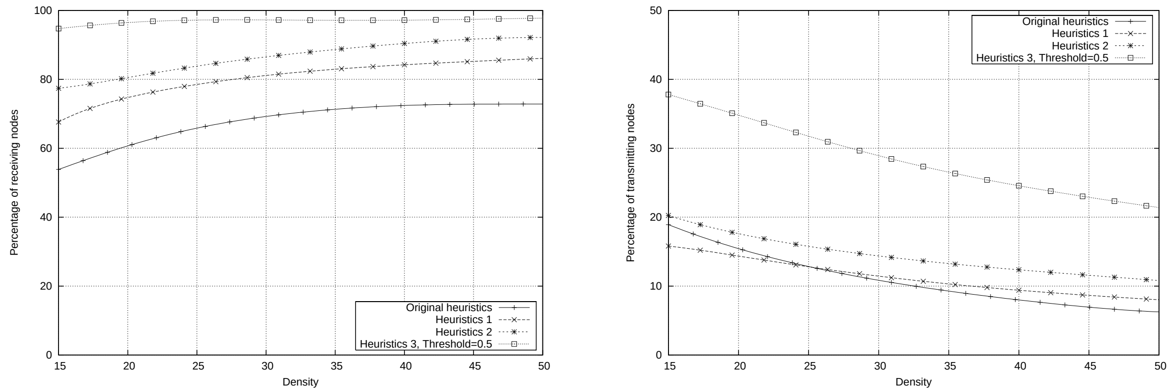
We used the same parameters as in Sec. 4.

In Fig. 6 are given the performances of the proposed heuristics, including the original one when considering the LNS model. Not surprisingly, the three new heuristics obtain better performances by taking into account the probabilities given by the physical layer. The second one gives a higher percentage of diffusion than the first one, simply because it considers probabilities between 1-hop and 2-hop neighbors and thus a 1-hop neighbor with a high degree is no more chosen when it is too far from the 2-hop neighbors it covers. Considering the degree 30, the original heuristics covers only 67% of nodes using 11% of them as relays, while the second heuristics covers 85% of nodes using 15% of them as relays. The coverage is thus greatly increased, while still minimizing the percentage of needed relays. The third heuristics has been considered with a threshold equal to 0.5: the coverage is almost total with 96% of covered nodes, but the percentage of relaying nodes is higher with a value of 28%. This seems a high value compared to other curves, but considering the results given in Fig. 3 with the UDG model, values are almost the same for the original heuristics. This means that the number of chosen relays is almost the same, but their choice is of better quality considering the probabilities.

We also give in Fig. 7 the performances of the third heuristics for different values of the threshold parameter. As expected, the coverage is proportional to the value of this parameter while the number of relays is inversely proportional to it. Choosing a threshold equal to 1 is almost useless as a total coverage can nearly be achieved with a value between 0.4 and 0.5 with far less relaying nodes. Using a threshold of 0 does not lead to an empty diffusion, because the first step is still applied to cover isolated nodes.

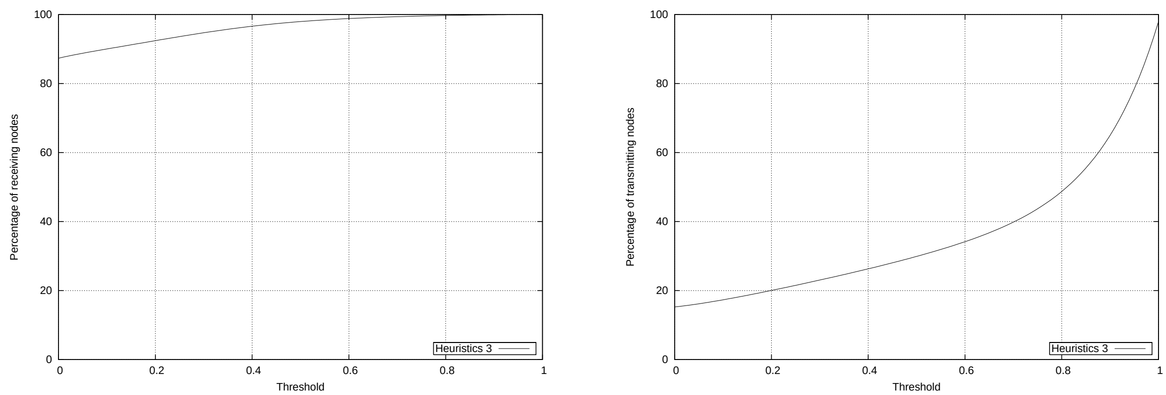
6 Conclusion

In this paper, we considered and analysed the Multipoint Relay protocol using a realistic physical layer, where the unit disc graph model has been replaced by the log-normal shadowing model. Our analysis showed that the original heuristics proposed by the authors of MPR is not suitable for the considered model, because the delivery ratio is too low for a broadcasting protocol. We thus proposed new heuristics which take into account the probabilities of correct reception



(a) Receiving nodes (b) Transmitting nodes

Figure 6: Performances of the different heuristics using the LNS model.



(a) Receiving nodes (b) Transmitting nodes

Figure 7: Performances of the third heuristics for varying thresholds and a density equal to 30.

induced by the physical layer, and gave experimental results. The latter showed that our new heuristics better fit to the realistic model and give very good performances regarding both the delivery ratio and the percentage of relaying nodes.

Nevertheless, there is a huge amount of work left to be done about broadcasting with a realistic physical layer. Indeed, as with MPR, many known protocols will not correctly work with this model and will have to be adapted. Amongst them, we can cite the case of connected dominating sets, which are used a lot in sensor networks. Algorithms used for their computation does not take into account probabilities of correct reception, and we can thus expect bad performances because of partitioned network. Neighborhood discovery protocols must also be studied, as almost all broadcasting algorithms assume a correct knowledge of the neighborhood, and current discovery protocols may not work as expected.

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