MPR-based broadcasting in ad hoc and wireless sensor networks with a realistic environment

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Summary
Most existing broadcasting protocols for ad hoc and wireless sensor networks use the standard Unit Disk Model (UDM) to represent the physical layer. Whenever this model does not take into account the fluctuations of radio signal, these protocols must be modified to adapt to transmissions in a real environment. In this paper, we apply the Log-Normal Shadowing Model (LNSM) to represent a realistic simulation environment and focus our study particularly on the performance of broadcasting Multipoint Relay Protocol (MPR). Thus, using LNSM we conduct extensive simulations to illustrate the effects of radio signal fluctuations on protocol performance. Unfortunately, our findings show that fluctuation presence has a significant impact on protocol performance. Hence to improve these performances, within this framework we propose two schemes: the first one optimizes the probability of successful reception by the selected neighborhood as relay nodes, and the second uses one probability threshold to select the relay nodes and another to maximize the probability of correct reception by two-hop neighbors of the source node. Finally, simulation results are presented, showing that our schemes provide a better performance over the ideal model.

Key words:
Ad hoc Networks, Multipoint Relays, Log-Normal Shadowing Model, Unit Disk Model, Wireless Sensor Networks.

1. Introduction

Broadcast process is a fundamental operation in ad hoc and wireless sensor networks. It consists in transmitting a message, since a node called source forwards all the network nodes. This process can be used in these networks; however as communication ranges are limited; many nodes must retransmit the message to obtain a total coverage of the network. It is used to support various important functions such as route discovery procedure, diffusion of a request or disseminating information among a set of receivers.

The earliest broadcast mechanism proposed in the literature was blend flooding [5], wherein every node in the network retransmits a message to its neighborhood after receiving it. Although this scheme is extremely simple and easy to implement, it was shown in [11,12] that flooding can be very inefficient and can lead to serious redundancy, causing contention, packet collisions and ultimately wasting precious limited bandwidth. Since then, a lot of research [1,7,10,13] has been directed towards reducing broadcast protocols which reduce redundancy by decreasing the number of retransmissions. But most existing solutions rely on a physical layer based on an ideal model which is represented by the unit disk model. We believe that the inclusion of radio signal fluctuations will lead to interesting and important findings in order to study the effect of these fluctuations on the behavior of broadcasting protocols for ad hoc and wireless sensor networks. Among all these solutions, we have chosen to focus on the multipoint relay protocol (MPR) described in [7] for several reasons: it provides good results using an ideal physical layer and it is used in the famous routing protocol OLSR [3]. In this scheme, the sending node selects neighboring nodes that must relay the message to complete the broadcast.

In this paper, we use the Log-Normal Shadowing model for a realistic simulation environment and analyze the performance of the multipoint relay protocol with this model. The considered model takes into account radio signal fluctuations, and could therefore be more realistic than the commonly used static unit disk model. Moreover, it computes the probability of successful reception between nodes in wireless networks according to the distance separating them. Then we accordingly propose two improved versions of this protocol to adapt it to a real environment. In our contribution, we assume that if the probability of reception without error is lower than a certain threshold, the message will be corrupted.

The remainder of this article is organized as follows. Section 2 provides some preliminaries necessary for describing our heuristics and the model used for the realistic physical layer. In section 3, we review related work. Section 4 covers the performance of the original MPR heuristics with the LNSM model. In Section 5, we detail our contribution and present simulations results. Finally, Section 6 concludes the paper with a summary and future work related to this topic.

2. Preliminaries

Before proceeding with the main ideas of our paper, we will give some definitions and notations that will be used in our presentation later.

2.1 Notations and assumptions

Ad hoc and wireless sensor networks are abstracted as a graph $G=(E,V)$, called a connectivity graph, where V represents the set of nodes and $E \subseteq V^2$ is the set of edges that gives the available communications: an edge $e=(u,v)$ belongs to E if and only if the node u is physically able to transmit messages to v and vice versa. Each node $u \in V$ is assigned a unique value to be used as an identifier (id), so that the identifier of u is denoted by $id(u)$ and all links in the graph are bidirectional. The set of neighbors of a node u is represented by $N_1(u)$ where $N_1(u)=\{v \in V \mid v \neq u \wedge (u,v) \in E\}$. The size of this set is known as the degree of u, denoted by $\delta(u)$ and the density of the graph is the average degree for each node. The set of two-hop nodes of node u i.e. the nodes which are the neighbors of node u's neighbors except for the nodes that are the neighbors of node u, is represented by $N_2(u)$ as follows : $N_2(u)$ $=\{w \in V \mid (v,w) \in E \text{ where } w \neq u \wedge w \in N_1(u) \wedge (u,v) \in E\}$
The combined set of one-hop and two-hop neighbors of u is denoted as $N_{12}(u)$ wherein $N_{12}(u)=N_1(u) \cup N_2(u)$. We measure the distance between two nodes u and v in terms of number of hops, which is simply the minimum number of edges that a message has to cross from u to v.

We consider the following assumptions on a wireless network model: Each node has an omni-directional antenna. This is attractive because a single transmission of a node can be received by all nodes within its vicinity. We also assume that the nodes are almost static in a reasonable period of time and a node is considered the neighbor of another node if the probability of receiving Hello messages from each other is greater than a certain threshold p_0. Indeed, we assume that a packet can be received without any error, if the distance separating the transmitter and the receiver is less or equal to R wherein the probability of successful reception at this distance is equal to p_0.

2.2 Radio model

In this subsection, we primarily present the unit disk model. Let us assume a graph $G=(E,V)$, where all nodes have the maximum range of communication denoted by R_c, is the same for all vertices. The unit disk model defines the set E of the edges as follows:
$E=\{(u,v) \in V^2 \mid u \neq v \wedge dist(u,v) \leq R_c\}$ where $dist(u,v)$ is the Euclidean distance between u and v. This model although commonly used cannot be considered as a realistic model since it assumes that the messages are always received without any error, as long as the distance separating the transmitter and the receiver is less or equal to transmission radius R_c of the radio signal. This assumption does not take into account the random fluctuations of the radio signal, which can have a significant impact on the transmissions because of the errors that these fluctuations generate in the messages exchanged between nodes.

In this paper, we focus our work on determining the probability of successful reception between nodes in order to know if the message is received or it is corrupted. Since the computation of this probability is influenced by several factors such as signal power, the distance separating the transmitter from the receiver, and the presence of obstacles, it may be difficult to obtain a precise evaluation for all these factors which are themselves prone to errors. For this reason, we assume that transmitted signal are received correctly when the received signal power is more than a minimum required threshold value p_0 and steadily decreases with distance. Therefore, the probability of reception without any error can be calculated according to the distance separating two nodes. Thus, we propose using LNSM model described in [8] to evaluate this probability between nodes. This model enables to generate a weighted graph where the weight of each edge $(u,v) \in E$ is equal to the probability $p(u,v)$ of reception without any error between nodes u and v. So, to evaluate this probability, we chose to use an approximated function $P(x)$, described in [4] as follows:

$$P(x)=\begin{cases} 1-\dfrac{\left(\dfrac{x}{R_c}\right)^{2\alpha}}{2} & \text{if } 0 < x \leq R_c \\ \dfrac{\left(\dfrac{2R_c - x}{R_c}\right)^{2\alpha}}{2} & \text{if } R_c < x \leq 2R_c \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

In this function, α represents the power attenuation factor which depends on the environment and x is the considered distance separating the transmitter from the receiver. This function assumes that the probability of reception without any error with R_c range is equal to $P(R_c)=0.5$. Fig.1 illustrates this function for $R_c=1$ and $\alpha=2$.

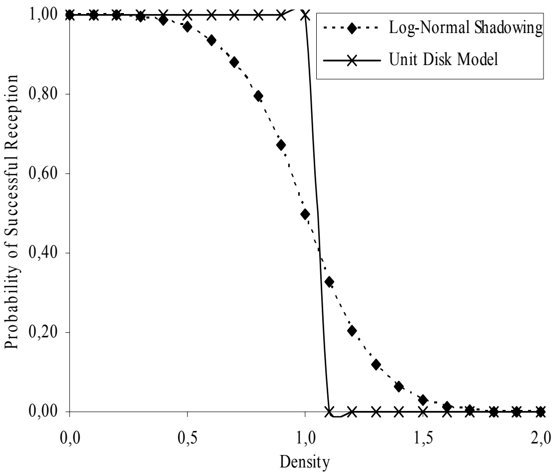

Fig. 1 Probability of successful reception with UDM and LNSM models with $R_c = 1$ and $\alpha = 2$.

3. Related work

Broadcast in ad hoc and wireless sensor networks has previously been studied in various papers [6,9,14,13]. However, these studies were conducted with an ideal simulation environment.

As mentioned earlier, in this paper we have proposed using the LNSM model to study broadcasting of MPR protocol in a realistic scenario. The considered model allows for the dynamics of radio signal power variations which are unavoidably caused by obstructions and irregularities in the surroundings of the transmitting and receiving antennas. Therefore, this model is more realistic than the unit disk model.

In this section, we review some related works which have been carried out to alleviate broadcast in wireless networks with a realistic scenario. To the best of our knowledge, [2] is the only existing paper which considers broadcasting with a realistic simulation environment. In this paper, the authors proposed three heuristics based on broadcasting by MPR protocol in wireless networks. Unfortunately, these solutions require some improvements. Firstly, they did not give enough importance to the problem of finding a maximum probability of successful reception between a node and its one-hop neighbors which forward the broadcast. Secondly, it is more difficult to guarantee the coverage of all the two-hop neighbors. Thus, a threshold must be used to compute an optimal selection of the sending node's direct neighbors to act as relays, in order to reach as many of its two-hop neighbors as possible. Moreover, it is necessary to specify a percentage of coverage for the stop criterion of the proposed algorithms.

4. Proposed schemes

Before presenting our contribution, it is necessary to discuss the original greedy heuristics proposed by Qayyum and al. in [7] and evaluate it with the LNSM model in order to illustrate its limitations.

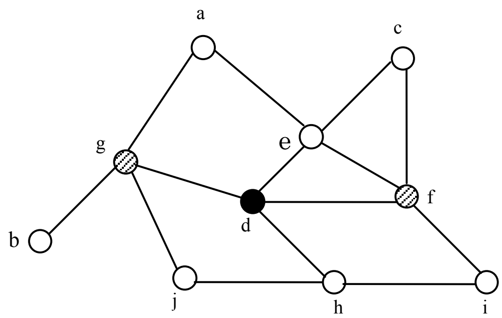

Fig. 2 Applying MPR at node d : $MPR(d)=\{f,g\}$

4.1 Analysis of the original heuristics with the LNSM model

As mentioned above, in this paper we consider the broadcast flooding rely on MPR protocol with a realistic model represented by the LNSM model. Thus, we study the performance of the original greedy heuristics with the considered model to point out its weaknesses. In this way, we create a simulation environment that incorporates the LNSM model, and we provide experimental results comparing the performance of MPR protocol in terms of reachability and the percentage of nodes which rebroadcast the message in the network.

In these heuristics, each node u is aware of its two-hop neighborhood and from it, selects a set of nodes among its one-hop neighbors which become node u's $MPR(u)$. $MPR(u)$ are chosen in such a way that, if u emits and only its $MPR(u)$ forward the message, every node $w \in N_2(u)$ receives the message. Yet, a node v forwards a message received from node u if and only if v belongs to $MPR(u)$. This gives an efficient broadcast ensuring that every node in the network receives the packet at least once when the network is connected and in an optimal number of hops if we assume an ideal physical layer. The computation of the smallest multipoint relay set is a NP-complete problem, as proven in [7]. Assume that $MPR_1(u)$ represents u's uncovered two-hop neighbors and $MPR(u)$ the set of selected nodes that relays the message. An applied example of these heuristics is provided by Fig.2. We summarize the pseudo-code of the original greedy heuristics as follows:

Pseudo-code of the $MPR(u)$ algorithm

1: Initially, $MPR(u) = \varnothing$, $MPR_1(u) = N_2(u)$

2: { Find in $MPR_1(u)$ the nodes which have a single parent in the 1-neighbors set $N_1(u)$, add their parents to $MPR(u)$, and remove all the neighbors of their parents from $MPR_1(u)$ }

while $\exists w : w \in MPR_1(u) \wedge \exists! v \in N_1(u) : w \in N_1(v)$ **do**

$MPR(u) = MPR(u) \cup \{v\}$

$MPR_1(u) = MPR_1(u) / \{w\}$

end while

3: { Choose the 1-neighbor $v \in N_1(u)$ not present in $MPR(u)$ that cover the greatest number of nodes in $MPR_1(u)$. In case of a tie, choose the node with the highest degree, add it to $MPR(u)$ and remove its neighbors from $MPR_1(u)$ }

Choose $v \in N_1(u)$:

$|N_1(v) \cap MPR_1(u)| = Max(|N_1(v) \cap MPR_1(u)| : v_i \in N_1(u))$

$MPR(u) = MPR(u) \cup \{v\}$

$MPR_1(u) = MPR_1(u) / \{w\}$

4: Repeat the various steps until $MPR_1(u)$ becomes empty.

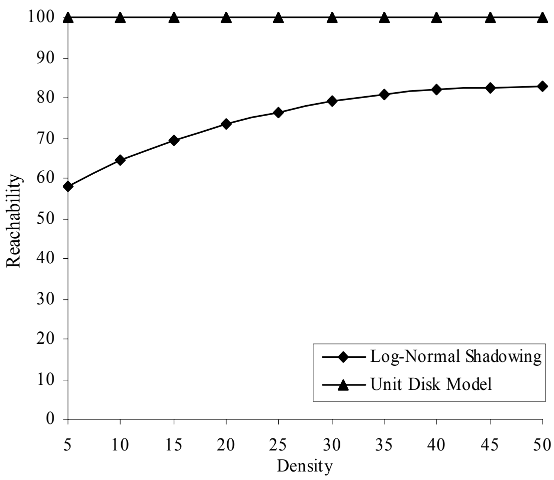

Fig. 3 Reachability with UDM and LNSM models

The primary goal of a broadcast protocol is to disseminate a message to a large fraction of nodes in the network. Thus among the effectiveness criteria of broadcasting protocol is the reachability which is denoted RE and defined as the average fraction of nodes in the network that receive a typical message. If the network consists of n nodes and the value $E[N_r]$ denotes the average number of nodes receiving the message, then the reachability is $RE = E[N_r]/n$. Furthermore, a broadcast protocol is valid if and only if its reachability (RE) exceeds 90% i.e. if it ensures at least 90% coverage of the network.

Our findings observed in Fig.3 provide a comparison of reachability in both LNSM and UDM models and illustrates the significant impact of radio signal fluctuations on MPR performance with the LNSM model. We notice that in the original greedy heuristics, the coverage ratio is always 100% for deployed nodes with an ideal environment i.e. all the nodes are reachable if the network is connected. On the other hand, in the LNSM model, this percentage decreases to 58% with low density (density=5) and to 83% with high density (density=50) indicated in Fig.3. This is due on the one hand to the presence of unreliable communication links and on the other hand to the fact that there is no guarantee that every node successfully receives the message.

4.2 Our contribution

The above analysis shows that it is necessary to improve the performance of MPR protocol, so that it adapts to a realistic environment. Indeed, we have proposed two broadcast schemes relying on this protocol with the LNSM model, in order to overcome these limitations: for example, when nodes cannot communicate correctly causing an increase in the number of corrupted packets. We have attempted to improve the ratio of reachability.

Our designed techniques take into account the presence of unreliable communication links. Thus, they assume that a node is considered the neighbor of another node if the probability of receiving Hello messages from each other is greater than a certain threshold p_0, and each node is able to evaluate the distance separating it from its neighbors, which in turn, enables it to compute the probability of reception without error. Consequently, in order to avoid the selection of malicious nodes which can jam the broadcasting process, a sending node must select relays in its neighborhood from among those nodes which have a high probability of successful reception with it. Therefore, to favour this selection, we propose squaring this probability between the source node and its one-hop neighbors.

In the proposed heuristics, the sending node selects neighboring nodes that must relay the message to complete the broadcast as follows. In the first step of both proposed schemes, we remove only the isolated nodes from set $MPR_1(u)$ instead of removing all neighbors of the selected node v as being a relay node. In the second step, we favour the selection of the one-hop neighbors which can receive the message correctly from source node u as relay nodes. Moreover, to guarantee the successful reception of the message by u's two-hop neighbors, we suggest in the second scheme selecting among the u's one-hop neighbors, those which are successfully transmit the message to its two-hop neighbors.

The connection of the network is not guaranteed since we have assumed that there are unreliable communication links. Therefore, it is necessary to modify the stop criterion of broadcasting algorithm. Thus, instead of using broadcasting the message throughout the network as a stop criterion, we propose using the coverage of all network nodes and,, when necessary, using reachability which exceeds 90% of the network.

Scheme 1: Basic Scheme

The aim of this scheme is to select u's best neighboring nodes as relay for forwarding broadcast. Thus, firstly sending node checks: if the probability of correct reception with its one-hop neighbors is higher than a certain threshold p_0, u will compute the weight of each neighboring node denoted $W_u(v)$ as follows:

$$W_u(v) = p(u,v)^2 \times \sum_{i=1}^{|MPR_1(u) \cap N_1(v)|} p(v, w_i) \quad (2)$$

Finally, u selects as a relay node, the neighbor who has the greatest value $W_u(v)$. We summarize the algorithm of this scheme as follows:

Pseudo-code of the $MPR(u)$ algorithm

1: Initially, $MPR(u) = \varnothing$, $MPR_1(u) = N_2(u)$

2: { Find in $MPR_1(u)$ the nodes which have a single parent in the 1-neighbors set $N_1(u)$, add their parents to $MPR(u)$, and remove them from $MPR_1(u)$ }

while $\exists w : w \in MPR_1(u) \wedge \exists! v \in N_1(u) : w \in N_1(v)$ **do**

$MPR(u) = MPR(u) \cup \{v\}$

$MPR_1(u) = MPR_1(u) / \{w\}$

end while

3: **while** $MPR_1(u) \neq \varnothing$ **do**

$MPR_2(u) = MPR_1(u)$

{ Compute the weight of node v if the probability of successful reception between u and v is higher than p_0 }

for each node $v \in N_1(u)$ **do**

if $p(u,v) > p_0$ **then** Calculate $W_u(v)$

4: { Choose the node which has the greatest weight among u's neighbors }

Choose $v \in N_1(u) : W_u(v) = Max(W_u(v_i) : v_i \in N_1(u))$

$MPR(u) = MPR(u) \cup \{v\}$

$MPR_1(u) = MPR_1(u) / (N_1(v) \cap MPR_1(u))$

5: { Check that it is possible to cover other nodes. Either check that the reachability exceeds 90% or decrease the threshold of a certain value ξ }

if $MPR_2(u) = MPR_1(u)$ **then**

$RE = E[N_r]/N$

if $(RE < 0.9)$ and $(p_0 = p_{00})$ then $p_0 = p_0 - \xi$

else break;

end if

end while

Table I below illustrates an example of weighted graph $G = (V, E)$ wherein we attribute an edge weight which represents the probability of correct reception between two nodes. Applying our approach with $p_0 = 0.5$, we obtain $MPR(d) = \{e, g, h\}$ as relay nodes for node *d*.

Table 1: Edge weights for the weighted graph

Edge	(a,e)	(a,g)	(b,g)	(c,e)	(c,f)	(d,e)	(d,f)
Weight	0.5	0.6	0.5	0.8	0.5	0.6	0.5
Edge	(d,g)	(d,h)	(e,f)	(f,i)	(g,i)	(h,i)	(h,j)
Weight	0.5	0.7	0.5	0.5	0.6	0.6	0.5

Scheme 2: Robustness Scheme

This scheme ensures a certain robustness for the broadcast process. Thus instead of using only one threshold for selecting the best neighbors as relay nodes, we propose using another threshold p_1 to guarantee that these selected neighbors can relay the message to the 2-neighborhood of the sending node with a high probability of no error. Indeed, the considered node also evaluates the weight of connectivity $WW_u(v)$ between its neighboring nodes and its 2-neighborhood as follows:

$$WW_u(v) = 1 - |MPR_1(u) \cap N_1(v)| \times \prod_{i=1}^{|MPR_1(u) \cap N_1(v)|} (1 - p(v, w_i)) \quad (3)$$

After that, it checks if the computed value $WW_u(v)$ is greater than threshold p_1, and if so, that it will compute weight $W_u(v)$ of its neighbors v, and finally select among its neighbors those who have the highest value $W_u(v)$. In case of a tie, it chooses the node with the greatest probability of correct reception between the sending node and its neighboring nodes. We summarize the algorithm of this scheme as follows:

Pseudo-code of the $MPR(u)$ algorithm

1: Initially, $MPR(u) = \varnothing$, $MPR_1(u) = N_2(u)$

2: { Find in $MPR_I(u)$ the nodes which have a single parent in the 1-neighbors set $N_I(u)$, add their parents to $MPR(u)$, and remove them from $MPR_I(u)$ }

While $\exists w : w \in MPR_I(u) \wedge \exists! v \in N_I(u) : w \in N_I(v)$ **do**

$MPR(u) = MPR(u) \cup \{v\}$

$MPR_I(u) = MPR_I(u) / \{w\}$

end while

3: { Compute the weight of node v if the probability of successful reception between u and v is higher than p_0. }

for each node $v \in N_I(u)$ **do**

if $p(u,v) > p_0$ **then** Calculate $(WW_u(v))$

if $WW_u(v) \geq p_1$ **then** $W_u(v) = p(u,v)^2 \times WW_u(v)$

end if

4: { Choose the node which has the greatest weight $W_u(v)$ among u's neighbors }

Choose $v \in N_I(u) : W_u(v) = Max(W_u(v_i) : v_i \in N_I(u))$

$MPR(u) = MPR(u) \cup \{v\}$

$MPR_I(u) = MPR_I(u) / (N_I(v) \cap MPR_I(u))$

5: { Check that it is possible to cover other nodes. Either check that reachability exceeds 90%, or decrease threshold p_I of a certain value ξ }

if $MPR_2(u) = MPR_I(u)$ **then**

$RE = E[N_r]/N$

if $(RE < 0.9)$ and $(p_I = p_{II})$ then $p_I = p_I - \xi$

else break;

end if

end while

5. Performance Evaluation

In our experiments, we conducted extensive simulations with the LNSM model in order to evaluate the performance of the proposed schemes. Thus, we considered a network topology where nodes are randomly distributed between $(x = 0, y = 0)$ and $(x = 500, y = 500)$. We also carried out simulations using two distinct value thresholds $p_0 = 0.5$ and $p_0 = 0.6$ for probability of reception without error in the first scheme and thresholds $p_0 = 0.5$ and $p_I = 0.5$ to ensure respectively better connectivity between the node source and its relay nodes and connectivity between the relay nodes and its neighborhood in the second scheme. Parameter ξ is used to converge our algorithm towards a reasonable reachability. Thus, in the first scheme, if this reachability is not attained we decrease p_0 of a value ξ until either one obtains a reasonable reachability or p_0 is equal to a limited value p_{00}. Similarly, for the second scheme, as long as we do not obtain an exceeding reachability above 90% and threshold p_I is always higher than value p_{II}, we decrease threshold p_I of value ξ.

To integrate the LNSM model using NS_2, it is enough to evaluate the distance between the nodes and to introduce the found value as a parameter in the approximated function described above in order to compute the probability of reception without error. Here, we consider only the nodes with that probability as neighborhood.

The metrics to be observed in this studies concern the reachability (RE) and the percentage of re-transmitting nodes. Thus, we primarily evaluate the reachability which means computing ratio $E[N_r]/N$ where $E[N_r]$ is the average number of nodes receiving the broadcast packet and N is the total number of nodes that are reachable, directly or indirectly, from the source node. After that, we measure the percentage of retransmitting nodes. To do this, the number of nodes that rebroadcasts the message is counted and compared to the total number of nodes. In our simulations, some assumptions are made as follows:

- each link between a pair of nodes is a perfect bi-directional link;
- the only traffic carried within the network is that of the broadcast flooding packet;
- the probability of correct reception depends on the distance separating the transmitter from the receiver;
- mobility is not considered.

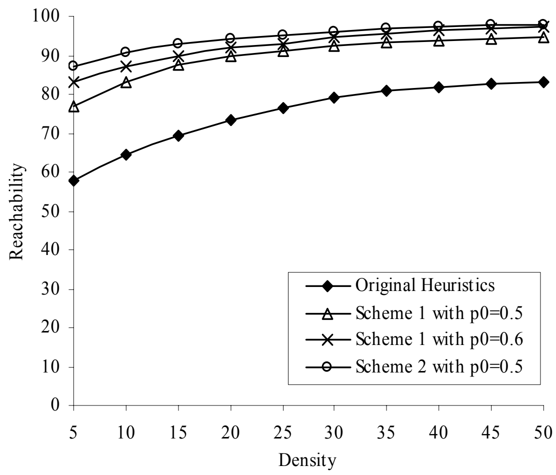

Fig. 4 Comparing reachability

Fig.4 compares the observed reachability when applying the two schemes and the original heuristics. In this figure, we see that reachability increases when density increases. In cases where density is greater than 20, the proposed schemes provide good results particularly the second scheme. This is due to the robustness of the latter which selects the best neighborhood as relay nodes thus avoiding unreliable communication links.

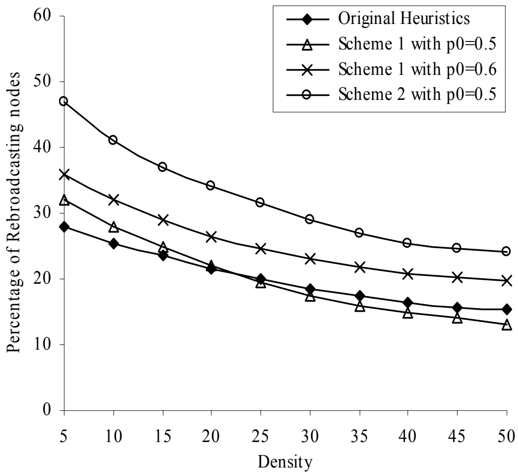

Fig.5 Comparing percentages of rebroadcasting nodes

Moreover, Fig.5 illustrates the percentages of retransmitting nodes. We observe that these percentages are conversely proportional to density i.e. because when density increases, the percentage of rebroadcasting nodes diminishes. As mentioned in [7], the computing the smallest multipoint relay set is a NP-complete problem. Indeed, the various obtained results confirm this design. In addition, we notice in particular that the second scheme provides quite a high percentage relative to the first scheme and the original heuristics because the size of the set of selected relay nodes is a little larger than that of the first scheme and the original heuristics.

6. Conclusion

In this paper we have proposed using the LNSM model to evaluate the performance of MPR protocol. This model takes into account the fluctuations of radio signals, and could therefore be more realistic than the commonly used static UDM model. Our findings demonstrate weaknesses of MPR protocol performance in a realistic simulation environment such as the LNSM model. With this model, we have proposed two schemes to improve the protocol's performance: simulation results show that our proposed schemes compared with the original greedy heuristics and the previous heuristics presented in [2] provide much better performance.

In summary, our experiments have demonstrated, through simulations, the efficiency of these improvements with a significant increase in reachability. Furthermore, with high density the proposed schemes provide good results, but broadcast is not significant with low density.

Since most existing solutions rely on a physical layer based on the UDM model, evaluating this protocol in a realistic layer could be interesting. Our further work includes analysing other protocols in a realistic environment.

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