Broadcast analysis in Multi-hop Wireless Networks

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***Abstract*— Multi-hop wireless networks consist of sets of mobile wireless nodes without the support of a pre-existing fixed infrastructure. Each host/node acts as a router and may arbitrary appear or vanish. This feature makes protocol designs adapt to frequent changes of network topologies. When dealing with sensor networks, the scalability becomes also a crucial aspect. In such large networks, we need not only to be able to route messages from any node to any other node but also to spread some information over the whole network. Till nowadays, it seems that these two properties have only been studied separately. In this paper, we propose to use our existing clusterization algorithm to perform in the same time an efficient and robust broadcast over it. We show that our broadcast technique gives good results in term of performances compared to existing broadcast methods.**

I. INTRODUCTION

Multi-hop wireless networks (MWN) are mobile networks without any infrastructure, which allows them to be fastly implanted. Each node acts as a router and may arbitrary appear or vanish. So, protocols must adapt to frequent changes of network topologies. Nowadays, with networks evolutions and the development of sensors networks, searchers try to find solutions for using them over large scale without generating too many traffic neither too many information to store. We still need not only to be able to route messages from any node to any other node but also to spread some information over the whole network. Nevertheless, it seems that these two functionalities (routing and broadcast) have only been studied separately. A solution to provide routing schemes over large scale networks is to introduce a hierarchical routing by grouping nodes into clusters and then applying different routing schemes in an between clusters. Solutions proposed to optimize broadcast lie on selecting a subset of nodes which are the only ones to forward. In this paper, we propose to use our clustering algorithm introduced in [5] to perform a broadcast over it. We made theoretical analysis and simulations in order to compare our scheme to other broadcast techniques. We compare different performance metrics as the mean number of receptions per node or the latency. We use a Poisson point process to simulate the location of nodes in space from which we deduce the network topology. The remainder of this paper is organized as follows. Section II defines the system model and introduces some notations. Section III presents a fast overview of broadcast in a multi-hop wireless network and explains our goals. Section IV briefly presents the architecture we use for the broadcast. The broadcast algorithm is thus evaluated via theoretical analysis and simulation experiments in Section V. Finally, we conclude in Section VI.

II. SYSTEM MODEL

In a MWN, all nodes are mobile and have to collectively make decisions. All communications are performed over wireless links. We classically model a MWN by a graph $G = (V, E)$ where V is the set of mobile nodes ($|V| = n$) and $e = (u, v) \in E$ represents a wireless link between a pair of nodes u and v if and only if they are within communication range of each other.

Let's introduce some notations. We note $\Gamma_1(u)$ the 1-neighborhood of a node u, *i.e.* $v \in \Gamma_1(u)$ iff $\exists\ e = (u, v) \in E$. We have $|\Gamma_1(u)| = \delta(u)$ being the degree of node u. Note that node u does not belong to $\Gamma_1(u)$.

In all our propositions and simulations, we assume an ideal MAC layer and that the algorithm is performed during a time while which the network is static.

III. RELATED WORK AND MAIN GOALS

Two ways have to be explored. On one hand, we have solutions proposed for broadcast, but, as far as we know, they are all performed without any hierarchy. On the other hand, we have solutions to organize a MWN into a hierarchy for routing but none seems to have been studied for broadcast.

Broadcast without hierarchy. The easiest way to broadcast a message over a network is the blind flooding, *i.e.*, each node re-emits the message upon first reception of it. Obviously, this causes a great bandwidth occupation, many collisions and each node wastes its energy for receiving several copies of a single message. Therefore, this broadcast technique can not be envisaged over large scale or very dense networks.

The common goal of actual broadcast protocols consist of selecting a subset of nodes which transmit the message. As a node spends energy while transmitting as well as receiving a packet, the main challenge is to minimize the number of these transmitters as well as the number of copies of a same message received by a node, keeping the property that every node in the network receives the packet at least once, when the network is connected.

In [8], Qayyum et al. introduce the use of multi-point relay nodes (MPR). Each node u is aware of its 2-neighborhood and from it, selects a set of nodes among its 1-neighbors which become node u's MPR. MPR are chosen in such a way that, if u emits and only its MPR forward, all node u's 2-neighbors receive the message. Yet, when a broadcast is performed, a node v forwards a message received from node u if and only if v is a MPR of node u. This gives an efficient broadcast ensuring that every node in the network receives the packet at least once when the network is connected.

Other schemes have been proposed for selecting subsets of nodes for forwarding broadcasted messages: the clusters-based algorithms and some approaches based on dominating sets. In cluster-based schemes, the idea is to create groups of nodes (or *clusters*) by locally electing some cluster-heads using criterion as the nodes' ID [2] or degree [3]. Every node is either a cluster-head, either directly linked to a cluster-head which it joins. A cluster is then composed of a cluster-head and of every node which had joined it. Nodes which belong to several clusters are called *gateways*. When a packet is broadcasted, only cluster-heads and gateways forward.

In [9] and [11], a simple algorithm, the NEB (*Neighbors Elimination-Based*) introduces the notion of *intermediate* nodes. Node A is *intermediate* if there exist nodes B and C in $\Gamma_1(A)$ which are not direct neighbors. Two selection rules are then introduced to reduce the number of transmitter nodes.

Thus, many works have been lead in order to optimize broadcast in MWN, but, as far as we know, none has tried to use structures already built over such networks.

Hierarchical organization. Some studies have proposed to organize networks into clusters to introduce a hierarchical routing, in order to allow scalability in MWN. Indeed, over large scale, flat routing protocols (reactive or proactive) become ineffective because of bandwidth (flooding of control messages) and processing overhead (routing table computation). Introducing a hierarchical routing by grouping geographically close nodes into clusters and by using an "hybrid" routing scheme: classically proactive approach inside each cluster and reactive approach between clusters ([4]), can solve this scalability problem. Such an organization also presents numerous advantages as to synchronize stations in a group or to attribute new service zones more easily. As far as we know, none of these structures have been studied for other purposes. All these clustering algorithms aim to identify subsets of nodes within the network and most of them bind each subset to an unique leader to identify the clusters. All nodes having the same leader belong to the same cluster. Generally, nodes locally elect their cluster-head in a distributed way by using a metric as an identity criteria (*e.g.* the lowest identity [2]) or a connectivity criteria (as maximum degree [7] or density [5]) or a connectivity and identity criteria ([1]). When each node has to elect its parent among the nodes in its 1-neighborhood, the clusters construction leads in the same time to the formation of trees, where the roots are the cluster-heads. Then, each node joins its parent in the tree. Nodes which have been elected by no other one become the leaves of trees. This is the case in our heuristic [5].

To sum up, current efficient solutions for broadcast in MWN are the ones based on MPR, clusters or dominating sets. Our main goal is to propose a reliable approach based on a clusters structure originally built to perform routing and monitoring in large scale networks. Using it also for broadcast will not be more costly. Indeed, while building clusters, a spanning forest is constructed. This process makes a selection between nodes labeling them as roots, leaves or regular nodes over the network and in this way creates subsets of nodes. We wish to use the clustering algorithm as transmitters/dominating sets selection: only nodes which are non-leaves re-transmit a broadcast packet. We can then perform two kinds of broadcast: a broadcast within a cluster where the cluster-head needs to spread information over its own cluster only, and general broadcast where a single node spreads information over the whole network. In this second case, gateways between trees are thus needed to connect the trees and relay packets between clusters. In this paper, we deal only with the broadcast within a whole network.

IV. THE CLUSTERS AND TREES FORMATION

A. The metric

This algorithm is introduced in [5]. It needs a metric we call *density* (also noted $\rho(u)$). The notion of density characterizes the "relative" importance of a node in the

MWN and within its neighborhood. The underlying idea is that if some nodes move in $\Gamma_1(u)$ (*i.e.*, a small evolution in the topology), changes affect the microscopic view of node u (its degree $\delta(u)$ may change) but its macroscopic view in fact does not evolve a lot since globally the network does not drastically change and its $\Gamma_1(u)$ globally remains the same. Thus, the density wants to smooth local changes down in $\Gamma_1(u)$ to avoid to trigger clusters reconstruction for a small modification of the topology.

***Definition** 1:* The density of a node $u \in V$ is

$$\rho(u) = \frac{|\{(v,w) \in E \,|\, w \in \{u\} \cup \Gamma_1(u) \; and \; v \in \Gamma_1(u)\}|}{\delta(u)}$$

B. Clustering tree construction

The basic idea of this heuristic is the following. Each node locally computes its density value and regularly broadcasts it to all its 1-neighbors (*e.g.*, using `Hello` packets). Each node is thus able to compare its density value to its 1-neighbors' one and decide by itself whether it joins one of them (the one with the highest density value) or it wins and elects itself as cluster-head. If there are some joint winners, the smallest Id decide between them. This way, two neighbors can not be both cluster-heads. If node u has joined node w, we say that w is node u's parent in the clustering tree and that node u is node w's child. A node's parent can also have joined another node and so on. The cluster-head is the node which has elected itself. If none of nodes has joined node u, node u becomes a leaf and do not belong to the dominating set. Note that a cluster can then extend itself until it reaches another cluster frontier. Thus, this way, as every node chooses its parent among its 1-neighbors, a cluster is an oriented tree which root is the cluster-head. We thus build a spanning forest composed of as many trees as clusters. Clusters and trees construction is more detailed in [6].

V. BROADCAST OVER A NETWORK

As mentioned in Section III, we wish to use the density-based algorithm (see Section IV) as a dominating set selection. In this section, we briefly describe our broadcast heuristic (Section V-A). Theoretical and simulation-based analysis are then done to compare this transmitters selection to other techniques (see Sections V-C and V-D).

A. Broadcast algorithm

The broadcast process is quite simple. We have a spanning forest composed of several disjoint trees. Previously, we need to connect these trees. For it, some nodes within the radio range of different trees are selected. These nodes are called *gateways*. We also introduce the notion of *mirror-gateway node*. If u is a gateway node, its mirror-gateway v is such that v does not belong to the same cluster as u and $v \in \Gamma_1(u)$. More details about the gateways and mirror-gateways selection may be found in [6].

Once our trees are connected, when a broadcast over the whole network is performed, node u forwards a packet received from node v if

(i) it is the first time it receives it AND it is not a leaf.

(ii) it is the first time it receives it AND u and v in the same cluster AND u is a gateway.

(iii) it is the first time it receives it AND u and v not in the same cluster AND u is a mirror-gateway.

As, by construction, every single node is connected to a non-leaf node and that the set of trees consists of a spanning forest of the network, every node should receive the packet when the network is connected.

B. Simulation model

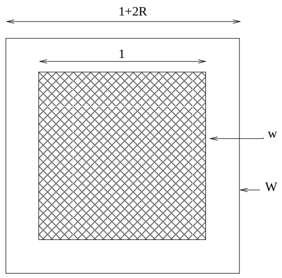


Fig. 1. Only points in w are considered to estimate the different quantities, but the point process is generated in W in order to avoid edge effects.

All simulations we performed and which are evoked in the following sections, follow the same model. We use a simulator we developed. The geometric approach used in the analysis allows to model the spatial organization of networks. The nodes are randomly deployed using a Poisson process in a $(1+2R) \times (1+2R)$ square with various levels of intensity λ (and thus various numbers of nodes). The communication range R is set to 0.1 in all tests. Two nodes (x, y) are connected if and only if $d(x, y) \leq R$ where d is the Euclidean distance. We then obtain, a graph describing the network connectivity as explained in Section II.

In each case, each statistic is the average over 1000 simulations and we fix a minimum radius and/or number of nodes such that the network is connected. When several algorithms are compared, they are compared for each iteration over the same nodes distribution. Only the points within the square w of size 1×1 are taken into account to estimate the different quantities (mean degree, mean density, etc.). But in order to avoid edge effects, the samples of the point process are generated in a larger window W. Both windows are shown in Figure 1. This technique is called ”minus-sampling”. A more detailed description can be found in [10].

C. Analysis

In this section, we analyze the number of messages received by a typical node for a given broadcast. The results presented here do not depend on the relays selection algorithm. We give two formulae of the mean number of receptions. We use Palm calculus to derive the mean number of receptions perceived by a typical node. More details about Palm-Calculus can be found in [10].

Poisson Point Process. Let Φ be a homogeneous Poisson Point Process of intensity λ ($\lambda > 0$) distributed in the plane. Let Φ_{Relay} be a thinning of Φ. The points of Φ_{Relay} represent the relays. We note that Φ_{Relay} is not a priori an independent thinning of Φ and thus, is not a priori a Poisson point process. However, we assume that Φ_{Relay} is still a stationary point process of intensity λ_{Relay}. We assume that two points (x, y) of Φ are connected if and only if the Euclidean distance between x and y is lower than R ($d(x, y) \leq R$). We consider the only nodes/points within an observation window W, which is a square of size $L \times L$ with $L \in \mathbb{R}^+$. Since the Poisson point process is distributed in $\mathbb{R}^2$, nodes of W may receive the broadcast from nodes outside W. For a typical point, *i.e.* the point in 0 under Palm probabilities, the mean number of receptions corresponds to the mean number of points of Φ_{Relay} at distance lower than R. If $\overline{r}$ is the mean number of receptions per node,

$$\overline{r} = \mathbb{E}^o_\Phi \left[\Phi_{Relay}(B'_0)\right]$$

where $\mathbb{E}^o_\Phi$ is the expectation under palm probabilities *w.r.t.* the process Φ and $B'_x = B(x, R)\backslash\{x\}$. According to the Mecke Formula (see [10]), the total number of receptions Z received by the nodes standing in W is

$$\mathbb{E}\left[\int_W \Phi_{Relay}(B'_x)\Phi(dx)\right] = \lambda\mathbb{E}^o_\Phi \left[\Phi_{Relay}(B'_0)\right]$$

By stationarity of the two point processes Φ and Φ_{Relay}, we have,

$$\mathbb{E}\left[\int_W \Phi_{Relay}(B'_x)\Phi(dx)\right] = \mathbb{E}\left[\int_W \Phi(B'_x)\Phi_{Relay}(dx)\right]$$

The left hand side of the equality is the total number of receptions perceived by nodes in W (relays can be outside) and the right hand side is the total number of receptions perceived by every point of Φ but generated by the relays in W only. Applying the Mecke formula to both sides of the equality,

$$\lambda\mathbb{E}^o_\Phi \left[\Phi_{Relay}(B'_0)\right] = \lambda_R \mathbb{E}^o_{\Phi_{Relay}} \left[\Phi(B'_0)\right]$$

and,

$$\begin{aligned}
\overline{r} &= \mathbb{E}^o_\Phi \left[\Phi_{Relay}(B'_0)\right] \\
&= \mathbb{E}^o_{\Phi_{Relay}} \left[\Phi(B'_0)\right] \mathbb{P}^o_\Phi \left(0 \in \Phi_{Relay}\right) \\
&= \frac{\lambda_{Relay}}{\lambda} \mathbb{E}^o_{\Phi_{Relay}} \left[\Phi(B'_0)\right]
\end{aligned}$$

This last formula may be interpreted as follows: the mean number of receptions per node is the product of the degree of a relay and the probability for a node to be a relay (or equivalently the mean ratio of relays/nodes). An efficient relays selection must choose relays in a way to minimize this product. In the next sections, we shall use this result to compare different relays selection algorithms and their impact on the mean number of receptions. We shall observe the degree of the relays and the number of relays for different relays selection algorithms. We shall show that they minimize either the degree of the relays (for instance for the MPR) either the number of relays used (for instance with our clustering algorithm).

Remark *1:* If we just consider points of W as relays and receivers, the total number of receptions becomes:

$$\begin{aligned}
&\mathbb{E}\left[\int_W \Phi_{Relay}(B'_x \cap W)\Phi(dx)\right] \\
&= \mathbb{E}\left[\int_W \Phi(B'_x \cap W)\Phi_{Relay}(dx)\right] \\
&= \lambda_{Relay} \int_W \mathbb{E}^o_{\Phi_{Relay}} \left[\Phi(B'_0 \cap (W - x))\right] dx \\
&= \lambda \int_W \mathbb{E}^o_\Phi \left[\Phi_{Relay}(B'_0 \cap (W - x))\right] dx
\end{aligned}$$

Unfortunately, neither the degree of relays nor the proportion of relays can be found for the considered algorithms but the blind flooding for which the results are trivial. However, these quantities can be evaluated by simulations. It is the goal of the next sections.

D. Broadcast evaluation

In order to evaluate our algorithm, we compare it to other broadcast techniques as blind flooding, Multi-Point Relay [8] and Neighbors Elimination Scheme [9].

The broadcast is initiated by a randomly-chosen source over the whole network. Significant characteristics we note are the mean number of copies of the broadcasted message that a node receives and the broadcast latency (number of hops required to reach all nodes). The number of receptions is one of the most important features as our goal is to limit energy spending and bandwidth occupation in order to maximize the network lifetime. These values have to be as low as possible, keeping the property that every node receives the packet at least once when the network is connected. As shown in Section V-C, this quantity depends on the relays degree and the proportion of transmitters. These two quantities are also used to compare the different kinds of relays selection.

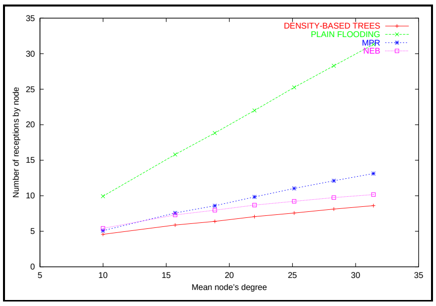


Fig. 2. Number of receptions by node in fct of the nodes degree.

As Figure 2 plots, when a broadcast is initiated in the network by a random node, our algorithm induces less re-transmissions and less receptions than other metrics. Thus, it spends less energy and resources.

In Figure 3(a), we draw the mean degree of the relays when the different broadcast techniques are used. We observe that the density-based relays selection maximizes the mean degree of the relays unlike the NEB technique for which the mean degree of transmitters is smaller than the mean degree of nodes expressed by the blind flooding. Since the mean node density value is almost proportional to the mean node degree (see [6]), density-based selection elects nodes with a high degree. We also note that MPR selection elects transmitters without favoring nodes with small or high degree.

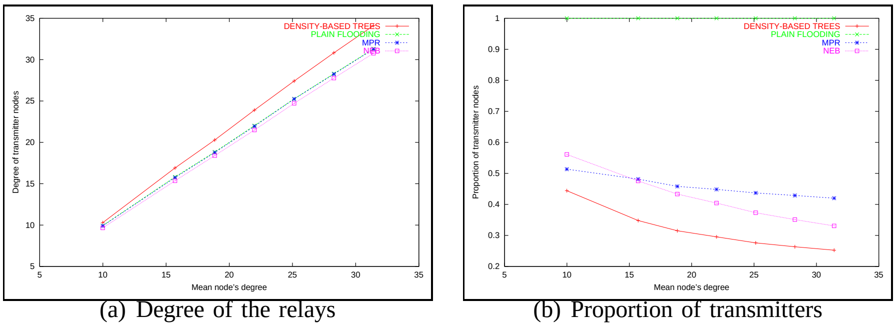
In Figure 3(b), we show the proportion of transmitters used in a broadcast. For a node, this ratio corresponds to the probability to be a relay. All algorithms used notably less relays than flooding and this proportion decreases with the mean degree of nodes (intensity of the process). There is a economy of scale when the process intensity increases: when new points appear, there is no need of new transmitters since the square is already covered by transmitters. If we compare the proportion of relays for the different metrics, it appears that it is the density metric which notably minimizes the number of relays. With this metric, we then have a small number of transmitters with high degree. But, Figure 2 shows that it is this algorithm which offers the best performance with regard to the mean number of receptions per node. It would be interesting to compare these results with optimal selections of relays found in a centralized way. That could allow us to confirm that algorithms selecting a small number of transmitters with high degree give best results in terms of performance. We reserve this task for future works.

Thus, we showed that the density-based relays selection minimizes the mean number of receptions. However, other performance metrics may be taken into account. For instance, we wondered about the induced latency, *i.e.* how much time we need to insure that every node has received the packet. Since in the MPR selection, relays are selected in order to reach the 2-neighborhood after two hops, the k-neighborhood of the node beginning the broadcast is reached within k hops. As we consider an ideal MAC layer, MPR gives the optimal results. We thus compare our heuristic to the MPR one to measure how far we are from the optimal solution. We consider a time unit as a transmission step (*i.e.* 1 hop). Table I presents results. ”MAX” values represent the time needed for every node to receive the packet at least once. ”MEAN” values represent the mean time a node has to wait till the first reception of the packet.

Yet, we can note that, even if our algorithm is not optimal, results are not so far. Figure 4 represents, for both algorithms, the propagation in time for a broadcast initiated by a centered source at time 0. Cluster-heads appear in blue and source in green. The color of other nodes depends on the time they receive the broadcast. The darker the color is, the shorter the time is. In Figure 4(a), we can observe with concentric circles that MPR effectively performs a broadcast within an optimal time.

VI. CONCLUSION

We have proposed a new scheme for selecting transmitter nodes to reduce the cost of broadcasts in multi-hop wireless networks. The proposed approach has the main advantage to use an existing architecture. This architecture is initially used to perform hierarchical routing and thus does not add extra protocol overhead. The proposed selection algorithms is then analyzed and compared to existing techniques. Surprisingly, the proposed relays selection shows good performances in terms of mean



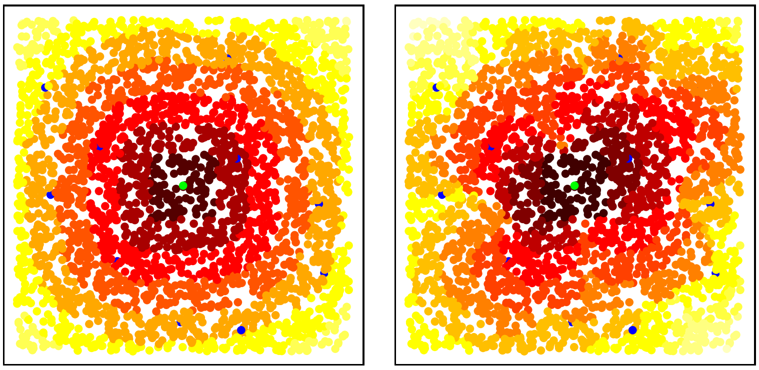
(a) Degree of the relays (b) Proportion of transmitters

Fig. 3. Mean degree of relays and Proportion of transmitters in function of the mean nodes degree $(\lambda\pi R^2 - 1)$ *w.r.t.* the different metrics.

	500 nodes		700 nodes		800 nodes		900 nodes		1000 nodes	
	MEAN	MAX	MEAN	MAX	MEAN	MAX	MEAN	MAX	MEAN	MAX
MPR	5.13	8.97	4.88	8.40	4.88	8.40	4.81	8.23	4.78	8.07
Density	6.31	11.05	6.22	10.78	6.24	10.95	6.15	10.66	6.19	10.74

TABLE I

MEAN AND MAX TIME FOR RECEIVING THE MESSAGE.



(a) Propagation with the MPR (b) Propagation with the density metric

Fig. 4. Propagation time of a packet broadcasted by a centered source using MPR *(a)* or density-based trees *(b)*.

number of receptions by node and latency as it turns out to give better results than other broadcast methods.

In future, we intend to analyze deeper this algorithm regarding stability and robustness over nodes mobility.

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