DIFFUSION MECHANISMS FOR MULTIMEDIA BROADCASTING IN MOBILE AD HOC NETWORKS

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ABSTRACT
Scarce bandwidth and interferences in mobile ad-hoc networks yield the need for more efficient diffusion techniques than these employed on usual wired networks, especially in dense environments. In this paper, we compare some optimized flooding mechanisms that were proposed in view to gain enough performance and allow applications such as multimedia diffusion in an ad hoc environment. We namely present multi-point relay (MPR) flooding and gateway flooding. We investigate the matter theoretically via mathematical modelling, as well as practically via simulations. It is shown how well each of these techniques improve the diffusion performances: when the network is dense, 2/3 of the gateway nodes participate in the retransmissions, while the density of multi-point relay retransmitters is $1/\nu$, where ν is the node density.

KEY WORDS
flooding, diffusion, optimization, ad hoc, network, wireless

1 Introduction

Mobile ad hoc networking is the emergent concept in view to interconnect wireless devices from computers to mobile phones, and from sensors to vehicles. Since higher radio link capacity implies shorter radio ranges in ground communications, the routing protocol used between mobile nodes is the key network feature. Still, radio bandwidth is limited compared to that of wired networks and therefore the reduction of any overhead is an essential issue.

Flooding (*i.e.* diffusing some data to each and every node in the network) is on one hand a big part of the routing overhead and on the other hand, a mechanism used by various higher level applications (such as, for example, multimedia broadcasting). The technique used at the routing level in wired networks is rather brutal: basically, from the source, each node redistributes the information to all its neighbours and so on until the entire network is inundated. This is namely the case with classic protocols like OSPF or IS-IS (see [5] [6]).

When the network is dense, this approach leads to too much overhead: not only are most retransmissions actually unnecessary, but even a single broadcast could break the network down in an ad-hoc environment, where the scarce bandwidth and the radio interferences between users will jam the traffic. This leaves room for optimization, which is absolutely needed in view to develop efficient ad-hoc networking (see [3]), and which might also be of some use on usual wired networks.

There are many proposals as far as ad-hoc routing protocols are concerned, many of them in the IETF framework within the MANET Working Group [2]. Most of these protocols depend on a flooding mechanism at some point in their algorithm. In the present paper we focus on the broadcast performances of two techniques: multi-point relays (MPR) and gateway nodes. These are extracted from two different routing protocols that were proposed: OLSR (Optimized Link State Routing [1]) and DDR (Distributed Dynamic Routing [4]).

The paper is organized as follows : we will first describe simply each of the two flooding mechanisms in Section 2 and 3, before comparing their abilities via mathematical modelling in Section 4. Section 5 will present the results we obtained via simulation before we conclude on the matter.

2 The Gateway Mechanism

Gateway node flooding is a broadcast technique which is extracted from the ad-hoc routing protocol DDR [4]. The protocol uses a forest of logical trees interconnected between them via a set of gateway nodes as foundation for its broadcast mechanism.

More precisely, the protocol initially forms trees in the following way: each node selects as parent its preferred neighbour, *i.e.* the neighbour which has itself the maximum number of neighbours, in other words, the maximum degree. A node which is a local maximum degree-wise (all its neighbours have lower degree) is then the root of its tree. Inside a tree a node is either a leaf or an internal node. A leaf is a node which is parent of none of its neighbours. On the other hand, an internal node is a node which is parent of at least one of its neighbours.

Under such considerations, the network can be viewed as a so-called forest, *i.e.* a collection of disconnected logical trees, each of them being identified by a random identifier which is flooded from root to leaves via the logical links. In order to interconnect those trees, one considers the gateway nodes between them, a gateway node being a node which has neighbours in its range that are in a different tree than its own.

Therefore, the broadcast mechanism can be summed up as follows:

> *A node retransmits a broadcast packet if it is either a gateway node or an internal node in the tree it belongs to.*

3 The MPR Technique

Multipoint relay (MPR) flooding is a broadcast mechanism which is extracted from the ad-hoc routing protocol OLSR [1]. We will describe it now: the principle is that each node features a multipoint relay set (*i.e.* a subset of its neighbours), and only these selected neighbours, the so-called multipoint relays of the node, will retransmit a packet broadcasted by the node. Obviously, the smallest this set is, the more efficient the optimization will be.

More precisely, this is done in a distributed fashion as follows. Let A be a given node in the graph. Let the neighbourhood of A be the set of nodes which have an adjacent link to A. And let the two-hop neighbourhood of A be the set of nodes which don't have a valid link to A but that have a valid link to the neighbourhood of A. Note that the information about the two-hop neighbourhood and the two-hop links can be made available simply via hello packets, like in OLSR for instance, with every neighbour of A periodically broadcasts information about their adjacent links in order to continuously cross-check them as valid or invalid, as well as discover new ones.

The multipoint relay set of A, $\mathrm{MPR}(A)$, is then a subset of the neighbourhood of A which satisfies the following condition: every node in the two-hop neighbourhood of A must have a valid link toward $\mathrm{MPR}(A)$. As we already stated, the smaller the multipoint relay set (*i.e.* MPR set), the more the broadcast mechanism is optimized.

In a nutshell, the MPR flooding mechanism works as follows, in a distributed fashion, on each node:

> *A node retransmits a broadcast packet only if it receives its first copy from a neighbour that has chosen the node as multipoint relay.*

4 Performance Evaluation via Mathematical Modelling

The comparison parameter we consider is the number of retransmissions of a single packet via each broadcast technique. The model under which we investigate the performance of these flooding mechanisms is the unit disk model, *i.e.* nodes are randomly dispatched uniformly on a map and the network graph is then the network obtained by connecting nodes which are at a distance smaller than or equal to the unit. The density of nodes is ν, which is the average number of nodes contained in an unit disk. In other words, ν is the average number of neighbours of a random node. This model is a classic in the field of performance analysis of wireless networks, although not fully realistic since it omits interferences with obstacles and between simultaneous transmitters. Notice that the number of nodes that is contained in an region of size a is a Poisson distribution of mean $a\nu$. We investigate dense networks, *i.e.* mathematically when $\nu \to \infty$.

In the present analysis we will restrict our mathematical model to the linear map, *i.e.* the model addresses networks with geographic locations that mainly stretch on a single geometric dimension, *e.g.* a road. Note that the simulation results presented in Section 5 show figures for both the linear map and the planar map, where the network can stretch in two dimensions, therefore extrapolating to most of the real cases.

4.1 Gateway Flooding

Our aim is to find the probability for a random node to be a gateway node. Gateway flooding introduces the so-called preferred neighbour of a given node, which is its neighbour with largest degree, *i.e.* the neighbour that has itself the largest number of neighbours. When several neighbours attain this maximum, the node selects the one with largest ID. The selection criterion is thus said to be (degree, ID). A node selecting itself as its preferred neighbour corresponds to it being a local maximum with respect to the selection criterion. Such a local maximum is therefore the root of its region tree.

In the following subsections we gather some mathematical results about the density of trees and the proportion of gateway nodes via the analysis of local maxima distribution with various selection criteria (degree and ID).

4.1.1 Density of Trees

In this section we evaluate the tree density, which corresponds to the distribution of local maxima for the selection criterion. As mentioned earlier, there are two distinct criteria: ID and degree. Note that the local maxima distributions vary depending on the criterion.

Theorem 1 *The probability that a node is a local maximum for the ID selection criterion is $\frac{1}{\nu} + O(e^{-\nu})$ in the case of the unit disk graph model in dimension 1.*

Proof - Without loss of generality we can assume that IDs are uniformly distributed in the interval $(0, 1)$. The probability that a node with ID equal to x is a local maximum is $\exp(-(1 - x)\nu)$. Therefore the unconditional probability that a node is local maximum is $\int_0^1 \exp(-(1 - x)\nu)dx = \frac{1-e^{-\nu}}{\nu}$. This is exponentially close to $1/\nu$. From this result we can say that the density of trees is in this case close to 1 per neighbourhood area, in other words the average interval covered by a tree is 1.

Theorem 2 *The probability that a node is a local maximum for the degree selection criterion is equivalent to $\frac{2}{\pi\nu}$ when ν increases.*

A corollary of the previous theorem is that the average density trees in this case is close to $\frac{2}{\pi}$ per neighbourhood area, which is less than with the ID criterion.

Lemma 1 *Right maxima and left maxima are independent events.*

Proof - Let $N(x)$ be the number of neighbours of a node at location x on the segment map. Let $I([a, b])$ be the number of nodes contained by interval $[a, b]$. Therefore $N(x) = I([x - 1, x + 1])$. Let $\delta(x) = N(x) - N(0)$. If $x \in [0, 1]$, then we have $\Delta(x) = I([-1, -1 + x]) - I([1, 1 + x])$. If $x \in [-1, 0]$ then $\Delta(x) = I([-1 + x, -1]) - I([1 + x, 1])$. Since the intervals don't overlap then $\Delta(x)$ and $\Delta(y)$ are independent when x and y have different signs.

Theorem 3 *The probability that a node is a right maxima is equivalent to $\sqrt{\frac{2}{\pi\nu}}$ when ν increases.*

Lemma 2 *Let $P(\nu)$ be the probability that a node is a right maxima, we have*

$$\int_0^\infty P(\nu)e^{-\omega\nu}d\nu = \frac{\sqrt{(1 + \omega)^2 - 1}}{\omega} - 2. \qquad (1)$$

Proof - Having $\Delta(x) \geq 0$ for all $x \in [0, 1]$ is equivalent to an M/M/1 system with service rate and arrival rate equal to 1, starting with one customer, and that does not empty its queue during a time interval of $\nu/2$. Let $f(\omega)$ be the Laplace transform of the distribution of the time T needed to empty the queue $f(\omega) = E[e^{-\omega T}]$. Let θ be the time needed for the exit of the first customer, we have from classic queuing theory:

$$T = \theta + N_\theta \times T \qquad (2)$$

where N_θ is a Poisson random variable of mean θ and $N \times T$ means the addition of N independent copies of T (N i.i.d. variables distributed as T). Therefore:

$$\begin{aligned} f(\omega) &= \int_0^\infty P(\theta = x)e^{-x\omega}e^{xf(\omega)-x}dx \qquad (3) \\ &= \frac{1}{2 + \omega - f(\omega)}. \qquad (4) \end{aligned}$$

Lemma 3 *Quantity $P(\nu) \sim \sqrt{\frac{2}{\pi\nu}}$.*

Proof - We have:

$$P(\nu) = \frac{1}{2i\pi}\int_{-i\infty}^{+i\infty} \frac{(1 - f(\omega))}{\omega}e^{\omega\nu/2}d\omega. \qquad (5)$$

Using the fact that $f(\omega) \sim \sqrt{\omega} + O(\omega)$ when $\omega \to 0$ we have from Flajolet and Odlyzko [7]:

$$\frac{1}{2i\pi}\int_{-i\infty}^{+i\infty} \frac{(1 - f(\omega))}{\omega}e^{\omega y}d\omega \sim \frac{\Gamma(1/2)}{\pi}y^{-1/2}. \qquad (6)$$

4.1.2 Density of Gateway Nodes

In this section we evaluate the density of gateway nodes in a forest of trees formed with the ID selection criterion. As seen in the previous section, this criterion yields more trees and likely, more gateways nodes than the (degree, ID) selection criteria used in gateway flooding. However, we believe that this gives a good idea of what kind of density we can expect, and we confirm this with the simulations in section 5.

Once again, without loss of generality we will assume that the identifiers of the nodes are randomly uniformly distributed between 0 and 1.

Theorem 4 *When the preferred neighbour is the one with highest ID, the probability that a randomly picked node is a gateway node is larger than $\frac{2}{3} + O(\frac{1}{\nu})$, when the network follows the unit disk model in dimension 1.*

Proof - If a node is not root for its tree, then its preferred node is either in the left part of its neighbourhood or in the right part. Let us call a node with preferred neighbour on its left, a leftist node. Conversely, we will call a node with preferred neighbour on its right, a rightist node. A centrist node, which is a node that is both leftist and rightist, is then root for its tree. Note that when a node is leftist, then the root of its tree is in the left part of the network, but not necessarily in its neighbourhood.

A sufficient condition for a leftist node to be a gateway node is to have a rightist node in the right part of its neighbourhood. Indeed, if all the right neighbours belonged to the same tree, then they would all be leftist.

Let us consider a random node A at a position y on the network map. We split the interval $[y - 1, y + 1]$ into four parts of equal size: $I_1 = [y-1, y-\frac{1}{2}]$, $I_2 = [y-\frac{1}{2}, y]$, $I_3 = [y, y + \frac{1}{2}]$, $I_4 = [y + \frac{1}{2}, y + 1]$. Let x_k be the greatest identifier in the interval I_k.

Neglecting the cases when these numbers are not all different (with probability $O(\frac{1}{\nu})$) we consider the order of the sequence (x_1, x_2, x_3, x_4). If $x_2 > x_3$ then the node A is leftist. If $x_3 < x_4$ then the rightmost node which has a position smallest to $y + \frac{1}{2}$ is rightist, excepted if it is not neighbour of the node that has identifier x_4, which occurs with probability $O(\frac{1}{\nu})$. Therefore all orders such that either $x_2 > x_3 < x_4$ (right case) or $x_1 > x_2 < x_3$ (left case) imply with probability $1 - O(\frac{1}{\nu})$ that the node A is a gateway node.

Let s_k be the order of x_k in sequence (x_1, x_2, x_3, x_4). If x_k is the largest number then $s_k = 1$, if it is the second largest number then $s_k = 2$, etc. We call T the order tuple (s_1, s_2, s_3, s_4). If $x_1 > x_2 > x_3 > x_4$ then $T = (1, 2, 3, 4)$. The tuples that correspond to the right case are:

(1,2,4,3), (1,3,4,2)
(2,1,4,3), (2,3,4,1)
(3,1,4,2), (3,2,4,1)
(4,1,3,2), (4,2,3,1)

The left case is symmetric, therefore there are 16 order tuples that lead node A to be a gateway node with probability $1 - O(\frac{1}{\nu})$. Given that there are $4! = 24$ order tuples and that they are all equiprobable, the node A is a gateway node with probability greater than $\frac{2}{3} + O(\frac{1}{\nu})$.

4.2 MPR Flooding

Conversely, our goal is now to find the probability for a random node to be used as a multi-point relay during a flooding.

Theorem 5 *The probability for a random node to retransmit during an MPR flooding is* $\frac{1}{\nu} + O(\frac{1}{\nu^2})$*, when the network follows the unit disk model in dimension 1.*

In the linear map case, the number of MPR per any given node is exactly 2: one at each end of its neighbourhood segment, right and left. When a flooding occurs, a packet is retransmitted via MPR on the right side and on the left side of the segment: retransmissions jump from one MPR to another MPR, with hops of length equal to the radio range. Therefore, the number of retransmitters that participate in an MPR flooding sums up to exactly 2 nodes per neighbour segment length (*i.e.* radio range).

5 Performance Evaluation via Simulation

In parallel with the theoretical modelling, we have also carried out simulations to evaluate the density of broadcast retransmitters in the case of MPR flooding on the one hand and gateway flooding on the other hand. The simulations were carried out in C++ and did not take into account the actual exchange of protocol messages between nodes, but rather, were simply based on the unit disk model as the analysis in Section 4. However, we have simulated both the road map case (nodes randomly spread on one dimension) and the planar map case (nodes randomly spread on two dimensions), in view to validate our theoretical results for the road map, as well as further, to extrapolate to the two-dimensional case. The figures we obtained come from averages over several hundred random distributions of the nodes.

5.1 Gateway Simulations

The simulations for the road map confirm the predictions of the mathematical models of section 4.1. Roughly, when the density is such that on average, a given node has more than a dozen neighbours, approximately half of the nodes are retransmitting broadcasts in the end, *i.e.* counting retransmissions inside the trees (the internal nodes) and retransmissions *between* trees (the gateway nodes). This is shown in Figure 1, where the total percentage of retransmitters as well as the percentage of gateway nodes alone (dashed) are plotted.

Though we didn't prove anything mathematically in the two dimensions, we can anticipate intuitively that it will turn out to be worse than with one dimension, in terms of number of retransmissions. The simulations for the planar map are consistent with this intuition as they show that when the density is such that on average, a given node has a dozen neighbours, approximately 2/3 of the nodes participate in the broadcast retransmissions. When the density is higher, up to 3/4 of the nodes turn out to be retransmitters. Once again, as with only one dimension, the vast majority of these are gateway nodes as shown in Figure 2, where the total percentage of retransmitters as well as the percentage of gateway nodes alone are plotted.

It is obvious that retransmissions within a tree are pretty much optimized, as the protocol specifically designed it to be. The simulations confirm this point, with very reasonable numbers for internal retransmitters. On the other hand, as we have already stated, the number of gateway retransmitters between trees is very substantial and this because not at all optimized in the gateway flooding mechanism specifications. There is indeed a vacuum here, and the protocol would very much benefit from further specifications on this point, if possible.

5.2 MPR Simulations

The simulations for the road map confirm the mathematical model of section 4.2. The percentage of retransmitters decreases when the density increases in a way that is roughly proportional to $1/\nu$. This is shown in Figure 3.

Once again, we didn't prove anything mathematically for the planar map, but we anticipate that the behaviour will roughly hold. Indeed, the simulations for the planar map show that the highest percentage of retransmitters is about 45%, which coincides with a density of a dozen

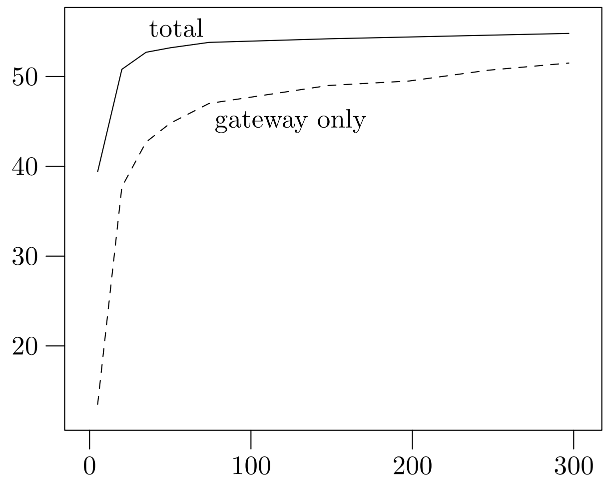

Figure 1. Percentage of gateway retransmitters in the one-dimension case

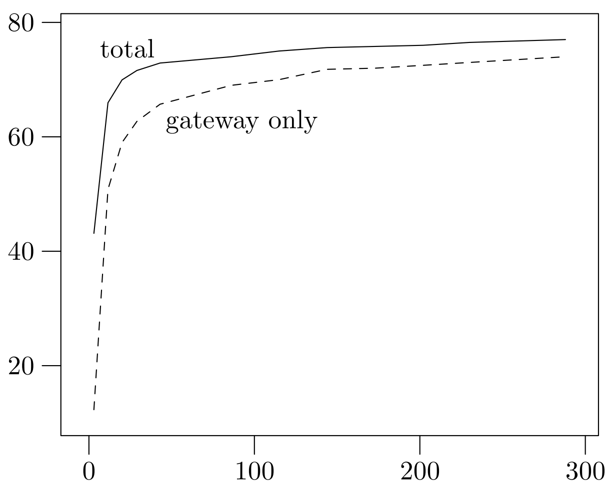

Figure 2. Percentage of gateway retransmitters in the two-dimensional case

neighbours. On the other hand, for higher densities, the model seems to be confirmed with once again a percentage of retransmitters that drastically decreases when the density increases, and such in a hyperbolic fashion. This is shown in Figure 4.

It is to note that the good simulation results obtained here with MPR diffusion conform with the actual live testing of multimedia broadcasting over OLSR that we have carried out.

6 Conclusions

In this paper we have analysed and compared two recently proposed flooding algorithms (*i.e.* MPR flooding and gateway flooding), in view to improve the usual broadcast tech-

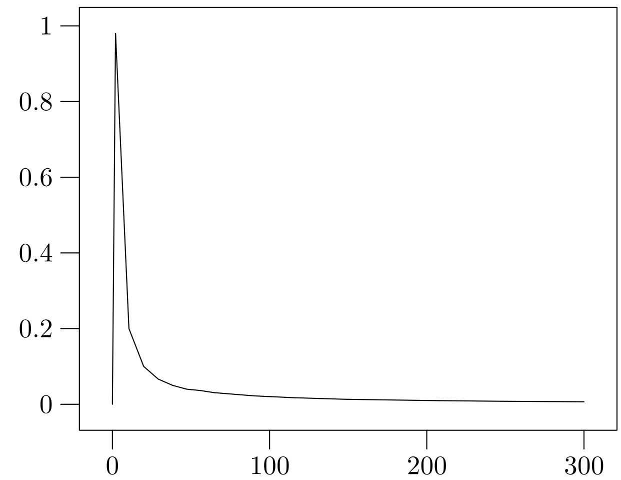

Figure 3. Percentage of MPR retransmitters in the one-dimension case

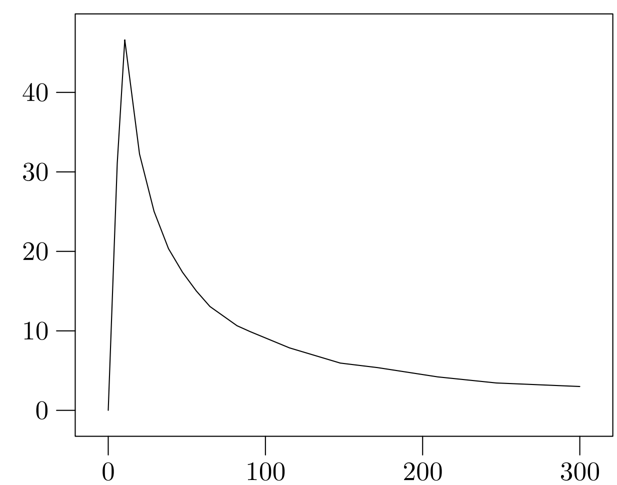

Figure 4. Percentage of MPR retransmitters in the two-dimensional case

nique - like OSPF's - that has been in use for years on wired networks. The flooding algorithm is an essential part of most routing protocols and is also used by various higher level applications, such as multimedia diffusion. However, the usual mechanism is too brutal to work efficiently in an ad-hoc environment, where the bandwidth is limited and interference between users is a big issue when a lot of retransmissions occur. We have shown via mathematical analysis and simulations how well these techniques improve flooding performances. Our results namely show that MPR flooding presents a much better optimization than gateway nodes flooding, and we have also pointed out why the latter is not as fully optimized as it may be.

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