Optimizing Route Discovery in Reactive Protocols for Ad Hoc Networks

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Thème 1 — Réseaux et systèmes
Projet Hipercom

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Abstract:
Many protocols for Mobile Ad-hoc Networks such as AODV propose construction routes reactively using flooding. The advantage hereof is, that no prior assumptions of the network topology are required in order to provide routing between any pair of nodes in the network. In mobile networks, where the topology is subject to frequent changes, this is a particularly attractive property. In this paper, we investigate the effect of using flooding for acquiring routes. We show, that flooding may lead to non-optimal routes in terms of number of hops. This implies that more retransmissions are needed to send a packet along a route. We proceed by providing a qualitative analysis of the route lengths. Finally, we propose and evaluate through simulations, alternative flooding schemes such as MPR flooding and Suoerflooding. MPR flooding considerably reduces the flooding overhead and provides shorter routes very close to optimal. Superflooding provides optimal routes but to the cost of an significant but anyhow reasonable increase of flooding overhead.

Key-words: Internet, Mobile ad hoc networks, routing, flooding

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Optimisation des constructions de routes dans les protocoles de routage réactifs pour les réseaux ad hoc

Résumé : De nombreux protocoles pour les réseaux *ad hoc* mobiles proposent la construction des routes par inondation à la demande. L'avantage de cette stratégie est qu'aucune hypothèse n'a besoin d'être faite *a priori* sur la topologie du réseau pour établir un routage entre deux nœuds distants. Pour des réseaux mobiles où la topologie est susceptible de changer fréquemment c'est propriété très intéressante. Dans ce rapport nous étudions l'effet de l'inondation dans l'acquisition des routes. Nous montrons que l'innondation peut construire des routes clairement sous-optimales en termes de nombre de sauts. Ceci implique que les paquets subissent plus de retransmissions que nécessaires quand ils empruntent ces routes. Nous présentons des analyses quantitatives de la longueur des routes et de l'encombrement des innondations. Nous proposons et évaluons au travers de simulations deux algorithmes alternatifs pour l'innondation: l'innondation par les MPR et la super-innondation. Le premiers réduit très sensiblement l'encombrement des innondations tout en réduisant la longueur des routes. Le second permet d'atteindre des routes de longueurs optimales mais en augmentant le coût de l'innondation de manière sensible mais raisonnable.

Mots-clés : Internet, réseaux mobiles ad hoc, routage, innondation

1 Introduction

Growing interest has been given to the area of Mobile ad-hoc networking since the the apparition of powerful radio devices allowing to connect mobile nodes. A key-point in connecting a group of mobile nodes is the design of a routing protocol that allows distant nodes to communicate through relaying of their traffic by intermediate nodes. Development and standardization is the subject of the IETF working group MANet [3], [6], in which several protocols have been proposed. A subset of those protocols are those constructing routes from a source node to a destination on demand, i.e. when the source node has data traffic to transmit to the destination node. These are usually identified as reactive protocols [12], [10], [5], [9], [1].
These protocols basically construct routes using the following mechanism:

1. The source node emits a request packet, which is retransmitted once by all nodes which receives it, incrementing the packet hop counter;

2. The destination acknowledges the request packets by sending back reply packets via the reverse path to the source node;

3. Among the paths acknowledged by the destination, the shortest one is used for the data.

The protocols differ about how to store the path followed by the request (stored in the intermediate nodes in AODV, in the packet, in DSR) without altering the route discovery principle. There are also other techniques in order to reduce the flooding cost. For example many protocols attempt to reduce the cost of flooding by allowing intermediate nodes to omit request retransmission if they already know a route to the destination. However, when a destination is requested for the first time, full flooding is still required.

The work presented in this paper is focused on in-depth analysis of two problems related to route discovery, namely:

1. Flooding generates a large amount of control traffic and thus introduce a large overhead;

2. Routes, discovered through flooding. may be suboptimal.

A good part of the literature about manet routing protocols has been devoted to the analysis of their control overhead (*i.e.* overhead due to control traffic), while little has been devoted to the overhead due to route length sub-optimality. Indeed, route length sub-optimality may also add a non negligible source of protocol overhead since it is proportional to the actual traffic. However, in situations where the network is close to overloaded, route sub-optimality may be the main source of overhead and network limitation.

The first result in this paper concerns the analysis of route length as obtained by flooding. Simulations and analytical means are employed to show that routes created by flooding are often suboptimal. This result corresponds with the result presented in [2], however we present a more qualitative insight on how much and when sub-optimality is observed.

The second result in this paper concerns two, complementary, solutions, proposed as ways of obtaining shorter routes through flooding. The first solution, called "MPR flooding", relies on the usage of multipoint relays [4] to both reduce the length of the obtained routes as well as the number of emissions required to complete the flooding. The second solution, called "Super flooding" is an expansion of full flooding scheme. The purpose is to get optimal routes at the expanse of more emissions. Combining this two solutions may be a promising way for optimizing route length in reactive protocols.

Section 2 first presents the proposed modifications of flooding rules which potentially yield better performance with regard to route length. These modifications can easily be adapted to be employed in most reactive protocols. Then, in section 3, we provide an explanation of why and under which conditions suboptimal routes are obtained by flooding. We utilize an "ideal physical layer" and present both analytical results and simulations. Finally, in section 5, we then validate these results under more realistic settings using the network simulator ns2 [13].

2 New schemes for optimizing route length discovered by flooding

In this section, we propose two modified schemes for flooding. Both schemes rely on modifying the rules a node obeys when deciding if a given, flooded, packet is to be retransmitted or not. Reactive protocols use sequence numbers to prevent a node from relaying a flooded message more than once. I.e. a node obeys, by default, the following rule:

- a message is forwarded if it is the first time it is encountered by that node.

The two schemes we propose are complementary in the sense that the first scheme makes this rule "looser" while the second scheme makes it "stricter". Both schemes can easily be combined.

Before describing the schemes in detail, it is important to notice that reactive protocols often employ more complex mechanisms than simple flooding, in order to save control traffic. For example, utilizing expanding ring flooding will prevent distant nodes from retransmitting a flooded message through utilizing a TTL, associated with the flooded message. Also, an intermediate node may omit a retransmission if it is able to provide a valid a route to the required destination (e.g. from a local cache). This are classical restrictive retransmission rules (used in AODV and DSR for example). It is important to notice, that our schemes are compatible with such additional rules.

2.1 Super Flooding scheme

Our first flooding scheme is called *super flooding*. We loosen the retransmission rule by allowing a node to forward a flooded control message more than once. Specifically, when a node receives a flooded control message, it obeys the following rule:

- a message is retransmitted if:
  - the message has not been recieved by the node before, or
  - the hop-count of the message is smaller than the hop-count of the previously retransmitted instance of the message.

Notice that this require that a node is able to get the hop count for a received message. In the case of AODV and DSR, for instance, this information is already available.

This scheme has the advantage of providing optimal routes when no collisions occur at the cost of more control traffic.

2.2 MPR flooding

Our second flooding scheme is called *multipoint-relay flooding* or *MPR flooding* for short. It is inspired by the broadcasting scheme of the pro-active protocol OLSR [7]. This scheme requires a neighbor discovery mechanism which allows a node to acquire information about the nodes in its neighborhood as well as the neighborhood of these neighbor-nodes (i.e. a nodes 2-hop neighborhood).

The multipoint-relay principle is the following: a node selects, among its neighbors, a set of nodes, called "*multipoint-relays*", such that any node in the 2-hop neighborhood is reachable through at least one multipoint-relay. A node should try to get the smallest number of multipoint-relays as possible.

The rule for retransmission of a flooded control message is thus restricted as follows:

- a message is retransmitted if:
  - the message has not been recieved by the node before, AND
  - the node is selected as multipoint relay by the node from which it recieved the message (the "previous hop" of the message).

Notice that if a node has recieved a message once (from any neighbor), it will not retransmit any other instances of the message, regardless if the first instance was retransmitted or not and regardless any following instances arrive from nodes which have selected it as multipoint relay.

Also notice that the definition of multipoint-relay insures that the packet is propagated to the entire network (if no other restrictive rule prevents from that). A large amount of control traffic can be saved with scheme especially in dense networks (see [7], [8] for more details and for a heuristic for computing multipoint-relays).

This scheme implies some additional control traffic in form of a neighbor discovery mechanism. The benefit of this scheme is, then, that it allows a reduction of the overhead from flooding control messages.

Intuitively, using this scheme may yield shorter routes:the minimization of the number of multipoint-relays encourages that a node select neighbors that cover a large fraction of the 2-hop neighborhood. This increases the probability of using long range links.

3 Ideal physical layer analysis

In this section, we will explore the details of flooding with the purpose of discovering how suboptimal routes may occur. We will do so in the context of an "ideal physical layer".

Thus, we will continue by defining the model for this "ideal physical layer", followed by an analysis and simulations conducted in accordance with this model.

3.1 Model

We assume a network of nodes, connected through wireless links, the radio interfaces (transmitters and antennas) being identical for all nodes in the network. We assume that the radio interfaces have a fixed range, and that a collision avoidance scheme is employed. In this section, we further suppose that no collisions occur and that access to the radio media is fair (i.e. among the nodes competing for the right to transmit in a region, all nodes have the same probability of succeeding). Notice, that "real" link layers such as IEEE 802.11 usually strive to reach these goals of collision avoidance and fairness which we assume.

We call *covering area* of a node the disk of radius its range centered at the node. A node can communicate directly to any node in its covering area. The nodes in our network are randomly placed in a rectangular field. Finally, the analysis in this section assume that no mobility is present (i.e. nodes do not move).

This radio model does not take shadowing effects into account While this "free space rectangular field" model is highly improveable, it provides an approximation to the "real world" in which it is possible to conduct an analysis. In section 5, we provide simulations using a more comprehensive model of the network (and indeed the physical layer), intended to validate the results of the analysis in this approximated model.

This model is related to the unit graph model [4] where nodes are distributed in a square and a valid link exist between any pair of nodes as long the distance between the nodes is shorter than the unit (the radio range).

3.2 Unidimensional analysis

In this section, we analyze the length of routes as constructed by flooding in a unidimensional (1D) network. This model can be seen as a dense strip (*i.e.* high density and very narrow field). A practical example of an one dimensional network, consider cars (equipped with radio communication units) on a highway.

We are going to show that the ratio route length over optimal distance asymptotically tends to 4/3. This basically means that the "farther away" a node is, the less optimal will the route to that node be.

Obviously, the path a message will take when being flooded in an 1D network will describe a straight line. In a 2D-network, intuitively, the a flooded packet has the possibility to follow any curved path available. Thus, it can be assumed that, though this analysis concerns only an 1D network, the average flooding distance in a 2D network will be greater than that of the 1D network.

We will now go on to present a formal proof of the above assertion.

To simplify the analysis, we restrict the definition of flooding distance by the length of the **first** path reaching the destination and not the **shortest** path reaching the destination. However, since the shortest path always comes from a neighbor node for which it was a first path, the length of the shortest path will at least be the estimated length minus one. Thus, our asymptotic estimations are thus valid for the flooding scheme, described in section 2.

In principle, a single flooding creates a route from the source of the flooding to any node receiving the flooding packet. We call *flooding distance* of a node the length of the route obtained for that node.

Suppose that the nodes are densely placed on a line (an 1D network), as illustrated in figure 1. We now consider propagation of one flooded message.

In figure 1, we consider the propagation of the flooding as a message, originated in the left-hand side of the network, propagating to the right. The unit indicated is the covering area of a node (an emission at position x covers $[x-1, x+1]$).

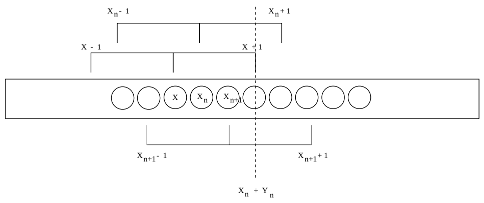

Figure 1: A sample 1D network. A message emitted (originated or forwarded) by x is heard by nodes in the interval $[x-1, x+1]$. The first node to forward the message in the interval $]x, x+1]$ is x_n. $x_n + y_n$ denotes the limit between the nodes which have recieved the message with the same flooding distance as x_n and those, which receive it with a larger flooding distance.

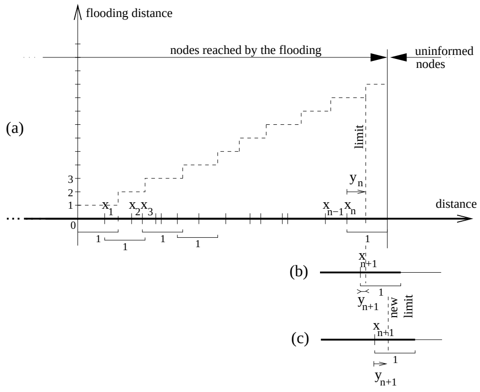

Figure 2: (a) Flooding distance versus distance after the emission of x_n. Discontinuities in this function are called limits. A limit is always at position $x_i + 1$ for some x_i. (b) Case where the next emission on the right of x_n is on the left of the limit $x_n + y_n$. (c) Case where the next emission on the right of x_n is on the right of the limit $x_n + y_n$.

Nodes in the interval $[x-1, x]$ will already have recieved the flooded message, and will hence not consider the message again, according to the forwarding rule described in section 2. Nodes in the interval $]x, x+1]$ will receive this message for the first time and will hence attempt to re-emit the message.

At a given time, the nodes, willing to re-emit the message, form a dense set in the interval $]x, x+1]$. Any node in that set may succeed in emitting (due to randomization in the channel access protocol).

Let $x_0 = 0$, x_1 be the position of the first (re)emission of the flooded message in the interval $]0, 1]$,..., and for $n \geq 1$ let x_{n+1} be the position of the first reemission in $]x_n, x_n + 1]$.

In $]x_n, x_n + 1]$ (the interval of nodes, which are reached by the retransmission from x_n), let $x_n + y_n$ be the limit between the nodes that have same flooding distance as x_n and those having flooding distance one more than x_n. (The flooding distance is clearly an increasing function, and as the nodes in $]x_n, x_n + 1]$ have received the emission of x_n, their flooding distance is not greater than the flooding distance of x_n plus one.). This is illustrated in figure 1 and in figure 2.

We can compute the probability distribution of y_n. Let $f_n(y)\mathrm{d}y$ be the probability that $y_n = y$. Notice that y_{n+1} depends only on y_n. As illustrated by Figure 2, there are mainly two cases, depending on the position of x_{n+1} with regard to the limit $x_n + y_n$. If it is on the left, one gets $x_{n+1} + y_{n+1} = x_n + y_n$, the limit for $]x_{n+1}, x_{n+1} + 1]$ is the same as for $]x_n, x_n + 1]$. If it is on the right, one gets $x_{n+1} + y_{n+1} = x_n + 1$, the limit for $]x_{n+1}, x_{n+1} + 1]$ is the right bound of $]x_n, x_n + 1]$. We immediately deduce the following recurrence (remember that x_{n+1} is uniform in $]x_n, x_n + 1])$:

$$f_{n+1}(y) = \int_y^1 f_n(z) \times \mathrm{d}z \ + \ \int_0^{1-y} f_n(z) \times \mathrm{d}z$$

Clearly $f_1(y) = 1$. We thus deduce $f_2(y) = 1 - y \ + \ 1 - y = 2(1 - y)$. We then compute $f_3(y) = 2 - 2y - 1 + y^2 \ + \ 2(1-y) - (1-y)^2 = 2(1-y)$. f_n is thus stationary for $n \geq 2$ with $f_n(y) = 2(1 - y)$.

The mean value of y_n is thus $\int_0^1 2(1 - y)y\mathrm{d}y = 1 - 2/3 = 1/3$. The probability that a new flooding distance limit is created is thus $2/3$. The average distance of x_n is clearly $n/2$. Its flooding distance is the number of distinct flooding limits in $[0, x_n]$, *i.e.* $2/3 \times n$. The ratio flooding distance over distance in this model is thus asymptotically $4/3$ when n increases.

3.3 Simulation of various flooding schemes

We conduct a number of simulations, using the ideal physical layer. The purpose of these simulations is to expose the problem of flooding distance using basic flooding, as well as to investigate the impact on the flooding length of using super-flooding and MPR-flooding.

We conduct simulations, using two basic scenarios:

strip
A field-size of $1500\text{x}300m^2$. Varying node density (50 nodes, 111 nodes and 222 nodes)

square
A field-size of $1000\text{x}1000m^2$. Varying node density (111 nodes and 222 nodes)

The nodes are randomly distributed throughout the field. The covering area of each node is 250m. Nodes are fixed (i.e. no mobility) and placed randomly in the field.

In the following subsections, we present our simulation results, comparing the various flooding schemes.

*** From here on, and until the ns2-section, I (Thomas) has changed absolutely nothing ***

3.4 Distribution of flooding distances

We simulate the distribution of flooding distance.

Figure 3 shows the distribution of flooding distances of nodes in a strip network 1500x300 with a total of 111 nodes. Figure 4 shows the distributions of flooding distance with 111 nodes but in a square network 1000x1000. There are several plots corresponding to basic flooding, MPR flooding and super flooding. Notice that MPR and Super Flooding provides sharper distribution, denoting a shorter flooding distance. MPR flooding distance and Super Flooding distances are very close, prooving that MPR flooding distances are close to optimal distance which, by definition, is given by Super Flooding.

One should not confuse the distance obtained via MPR flooding and the distance obtained by the computation of routes via MPR as provided in OLSR[7], [8]. The latter routes are optimal but needs the proactive advertizement of MPR links throughout the network via Topology Control (TC) messages.

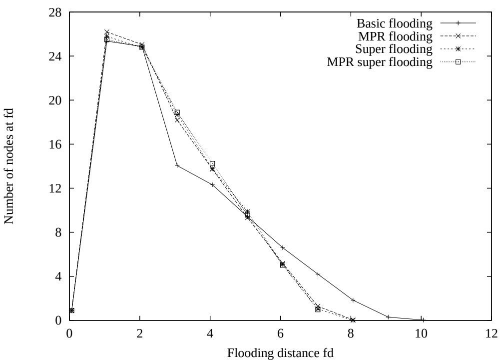

Figure 3: Histogram of number of nodes observed at a certain flooding distance for various schemes in the 1500x300 strip with 111 nodes.

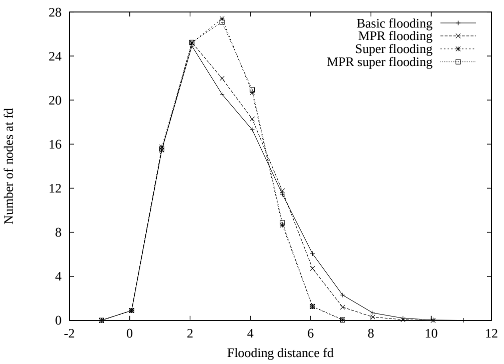

Figure 4: Histogram of number of nodes observed at a certain flooding distance for various schemes in the 1000x1000 square with 111 nodes.

3.5 Comparaison flooding versus MPR flooding

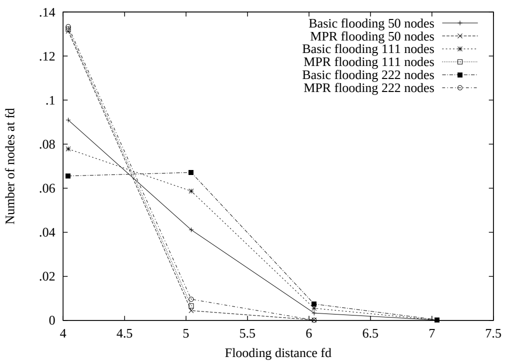

Figure 5: Histograms of the fraction of nodes observed at a certain flooding distances in the 1500x300 strip. Only nodes at optimal distance 4 where considered.

In figure 5 we display the flooding distance distribution when the optimal distance is fixed (for instance an optimal distance of 4 hops). As expected the MPR flooding distances are shorter and have less variations.

In figure 6 we display the flooding distance distribution in a square network for nodes at optimal distance 4. The difference with MPR flooding is not so important as in the strip network.

3.6 Ratio flooding distances with optimal distance

Figure 7 displays the average ratio between flooding distance and optimal distance versus respectively obtained obtained with 50, 111, 222 and 300 nodes. The simulation is done in a 1500x300 strip which corresponds more or less to the 1D model.

Figure 8 displays the same quantity but with MPR floodings.

Figure 9 show the same quantities as the two previous figures but in a 1000x1000 square network.

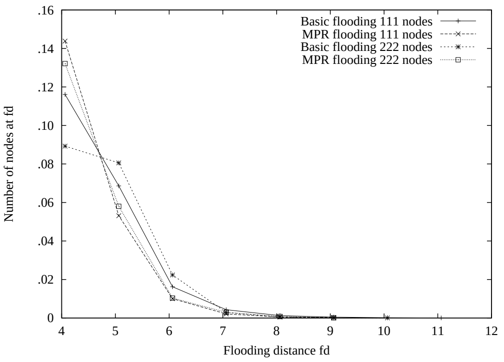

Figure 6: Histograms of the fraction of nodes observed at a certain flooding distances in the 1000x1000 square. Only nodes at optimal distance 4 where considered.

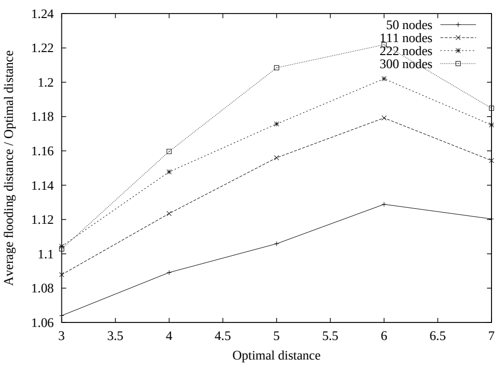

Figure 7: Ratio flooding distance over optimal distance in the 1500x300 strip with basic flooding.

3.7 Average path length

Figure 10 displays the average path length for the strip network.

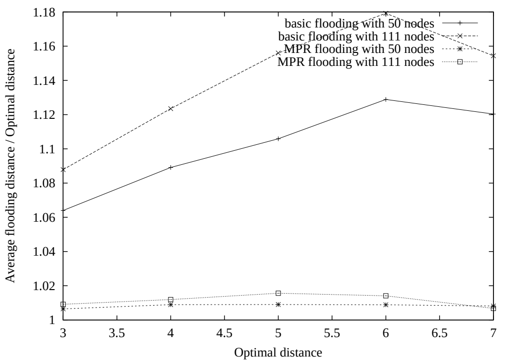

Figure 8: Ratio flooding distance over optimal distance in the 1500x300 strip with basic flooding and multipoint-relay flooding.

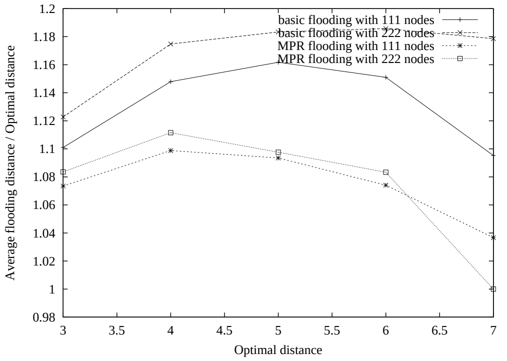

Figure 9: Ratio flooding distance over optimal distance in the 1000x1000 square with basic flooding and multipoint-relay flooding.

4 Control traffic overhead

Figures 11displays the number of request packet retransmission in the different flooding, for the strip network. It comes out that MPR flooding cause a tremendous gain in packet retransmission and that super flood-

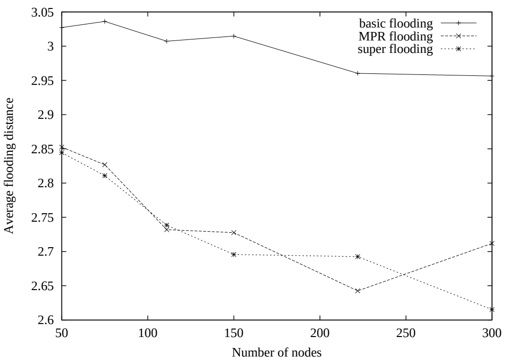

Figure 10: Average path length in the 1500x300 strip for various number of nodes.

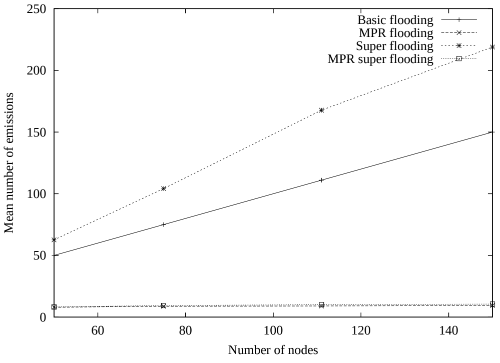

Figure 11: Average number of emissions in the 1500x300 strip for various number of nodes.

ing does not amplify too much basic flooding overhead.

5 Approximated real-world simulations

We conduct simulations using the network simulator ns2[13] with the purpose of validating that our results using the ideal physical layer and the free space rectangular field are indicative for real-world networks.

As a real-world network, we pick a MANET, running the reactive routing protocol AODV [11]. The scenario we use are the same as those used in section 3.3, except that we introduce a number of (low-intensity) CBR data traffic. We do this since AODV is a reactive routing protocol, and hence doesn't attempt at setting up routes before traffic is needed. We conduct simulations using basic flooding as well super-flooding, and measure the average route length, taken by the data traffic.

The data traffic pattern we employ have the following characteristic: 50 concurrent streams (source,destination pairs), each stream with a duration of 10 seconds (after which the sources and destinations change), each stream carries 64bytes/s.

Furthermore, we conduct our simulations both with and without node mobility. With node mobility, the nodes move at an individually randomly chosen speed between $1\frac{m}{s}$ and $8\frac{m}{s}$.

For each of the described scenarios, we randomly generate 10 different scenario files for ns2. Thus, with traffic streams of 10 seconds, we get, for each scenario, 2500 samples of the route length, provided. We use the exactly same scenario files for the simulations of AODV as well as AODV + super-flooding. We compute and compare the average route lengths and the control traffic overhead of the two approaches in the different scenarios.

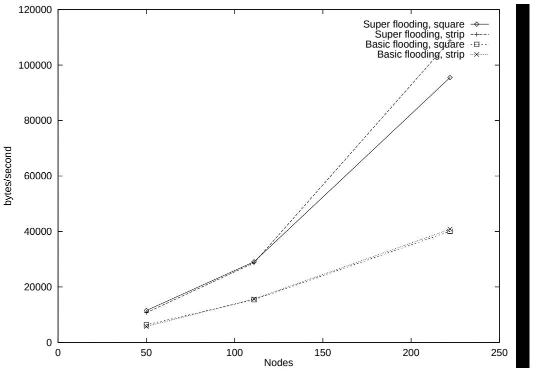

Figure 12: Control traffic overhead.

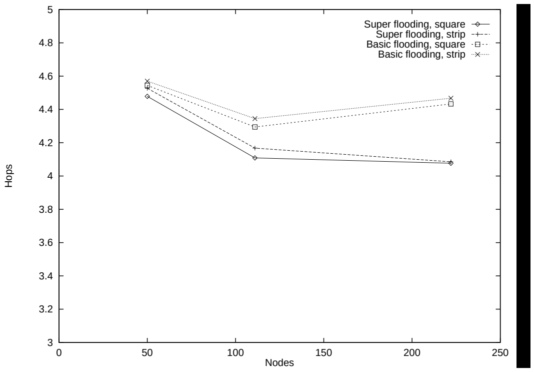

Figure 13: Path length.

5.1 Control traffic overhead

Our first observation concerns the amount of control traffic generated by the two flooding schemes. We recall that, from the definition of the flooding schemes in section 2, a node may potentially forward the same message when recieved multiple times, depending on the TTL of the message. We notice, that assuming the first message, recieved by the node, has traveled the shortest possible path, the exact same amount of control traffic overhead should occur with both basic flooding and super flooding.

Our simulation results, describing the control traffic overhead, are included in figure 12. We observe that the amount of control traffic generated through using super flooding is orders of magnitude larger than that of using basic flooding. Given that we used exactly identical simulation scenarios and traffic patterns, this leads to the conclusion that basic flooding does, indeed, not provide optimal routes.

The observed path lengths are included in figure 13. We observe that, consistently, the path length as obtained by super flooding is shorter than that of basic flooding. Relating the path length obtained by basic flooding to the path length obtained by super flooding (i.e. “optimal” paths), we further observe that the path lengths provided by basic flooding consistently are 5-10% longer.

6 Conclusion and further works

The total overhead, incurred by a routing protocol, consists of two elements: overhead in form of control traffic generated by the protocol, as well as overhead from data traffic, forwarded through routes of non-optimal length. Such non-optimal routes brings an a non negligible overhead that is proportional to the data load of the network.

We have shown through a simple analysis that basic flooding does, indeed, yield non-optimal routes. We have then proposed two simple, complimentary, flooding schemes, which aim at reducing route length overhead: MPR flooding and super-flooding. MPR flooding reduces both the route discovery flooding overhead as well as provides shorter routes. The drawback is the requirement of a neighbor sensing mechanism. Super-flooding, likewise, provides shorter path - however at the cost of an increased route discovery overhead. We have presented simulations, substantiating our analytical results.

Since the MPR flooding scheme and the super-flooding scheme are complimentary, we anticipate that combining the two could yield substantial benefits. Investigating this hypothesis will constitute parts of our future efforts.

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