Optimizing Route Length in Reactive Protocols for Ad Hoc Networks

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Abstract— **Many protocols for Mobile Ad-hoc Networks propose construction of routes reactively using flooding. The advantage hereof is that no prior assumption of the network topology is required in order to provide routing between any pair of nodes in the network. In mobile networks, where the topology may be 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 alternative flooding schemes and evaluate these schemes through simulations. We find that using these schemes, it is indeed possible to provide shorter routes.**

I. Introduction

Growing interest has been given to the area of Mobile ad-hoc networking since the apparition of powerful radio devices allowing connection of mobile nodes. A keypoint 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], [7], in which several protocols have been proposed. A subset of those protocols are those constructing routes from a source node to a destination node on demand, i.e. when the source node has data traffic to transmit to the destination node. These are usually identified as reactive protocols [14], [11], [6], [10], [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 receive it, incrementing a hop counter in the packet;
2) The destination node 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 transmission.

The protocols differ in how they store the path followed by the request (e.g. the path is stored in the intermediate nodes in AODV, and in the packet in DSR), however without altering the basic 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 introduces 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. However, route length sub-optimality may also be a non-negligible source of protocol overhead since it is proportional to the actual data traffic. Indeed, in situations where the network is close to overloaded, route sub-optimality may be the main source of overhead and thus of 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 results presented in [2], however we present a more qualitative insight on how much and when

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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 "Super Flooding" is an expansion of a full flooding scheme. The purpose is to get optimal routes at the expense of more emissions. The second solution, called "MPR flooding", relies on the usage of multipoint relays [5] to both reduce the length of the obtained routes as well as the number of emissions required to complete the flooding. Combining this two solutions may be a promising way for optimizing route length in reactive protocols.

A. Paper Outline

The remainder of this paper will be organized as follows: section II 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 III, 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 (in section III) and simulations (in section IV). Finally, in section V, we then validate these results under more realistic settings using the network simulator ns2 [15].

II. 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. by default a node obeys the following rule, in the following denoted *basic flooding*:

- 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 time-to-live (TTL), which is associated with the flooded message. Also, an intermediate node may omit a retransmission if it is able to provide a valid route to the required destination (e.g. from a local cache). These are classical restrictive retransmission rules (used e.g. in AODV and DSR). It is important to notice that our schemes are compatible with such additional rules.

A. 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 received 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 requires that a node is able to get the hop-count for a received message. In the case of e.g. AODV and DSR this information is already available.

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

B. 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 proactive protocol OLSR [8]. 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 node's 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 possible.

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

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

Notice that if a node has received a message once (from any neighbor), it will not retransmit any other instances of the message, regardless of whether the first instance was retransmitted or not and regardless of any following instances arriving 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 applies which prevents that). A large amount of control traffic can be saved with this scheme, especially in dense networks (see [8], [9] 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 MPRs that each cover a large fraction of the 2-hop neighborhood. This increases the probability of using long range links.

III. 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 of the optimality of routes obtained through basic flooding. This ideal physical layer will also be used for the simulations described in section IV.

A. 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.

The *covering area* of a node is a circular disk, 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 assumes 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 V, we provide simulations using a more comprehensive model of the network (and, indeed, the physical layer), intended to validate the results from the analysis in this approximated model.

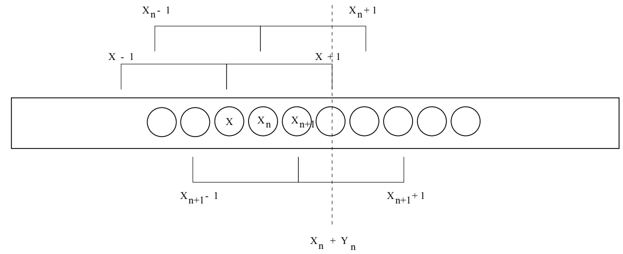

Fig. 1. Propagation of a flooding message in 1D network.

This model is related to the unit graph model [5] where nodes are distributed in a square and a valid link exists between any pair of nodes as long the distance between the nodes is shorter than the unit (the radio range).

B. 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). As a practical example of an one dimensional network, consider a highway with cars, equipped with radio communication units.

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

Obviously, the path which a message will take when being flooded in an 1D network will describe a straight line. In a 2D-network, intuitively, 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 may be greater than that of the 1D network.

We will now 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 valid for the flooding scheme, described in section II.

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

We consider the propagation of the flooding as a message, originated in the left-hand side of the network, prop-

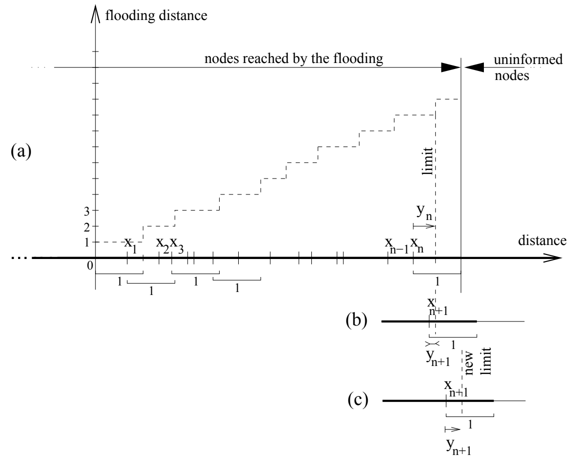

Fig. 2. Flooding distance versus cartesian distance in 1D network.

agating to the right. The unit indicated is the covering area of a node (an emission at position x covers $[x-1, x+1]$).

Nodes in the interval $[x-1, x]$ will already have received the flooded message, and will hence not consider the message again, according to the forwarding rule described in section II. 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 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 and which have not received the transmission before), 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.

In the figure 2 the flooding distance, since integer, have discontinuities which corresponds to the limits above described. (a) presents the limits before x_n including the current limit at x_n+y_n. (b) corresponds to the case where the next emission on the right of x_n is on the left of the limit $x_n + y_n$. (c) corresponds to the case where the next emission on the right of x_n is on the right of the limit $x_n + y_n$.

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.

IV. Ideal Physical Layer Simulations

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 network
: A field-size of 1500x300m^2. Varying node density (50 nodes, 111 nodes and 222 nodes)

square network
: A field-size of 1000x1000m^2. Varying node density (111 nodes and 222 nodes)

The nodes are randomly distributed throughout the field. The covering area of each node is a disk with radius 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.

A. Distribution of Flooding Distances

Figure 3 shows the distribution of flooding distances of nodes in the strip network with a total of 111 nodes. Figure 4 shows the distributions of flooding distance with 111 nodes but in the square network. We present results

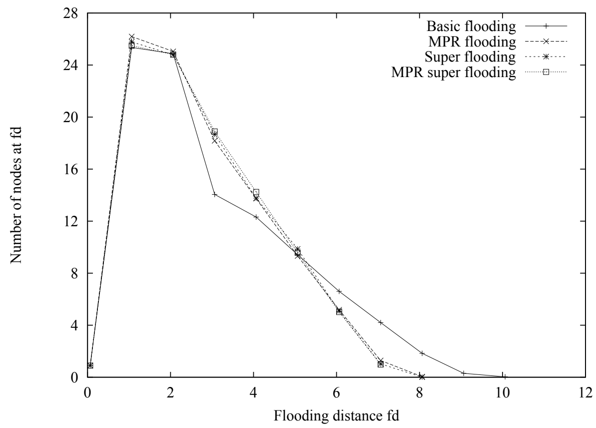

Fig. 3. Number of nodes observed at a certain flooding distance for various schemes in the strip network with 111 nodes.

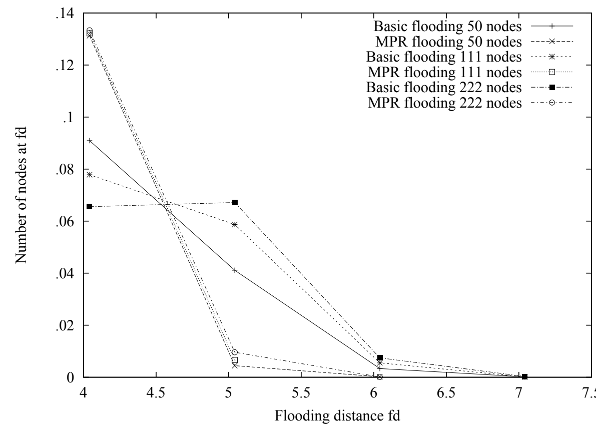

Fig. 5. Fraction of nodes observed at a certain flooding distances in the strip network. Only nodes at optimal distance 4 where considered.

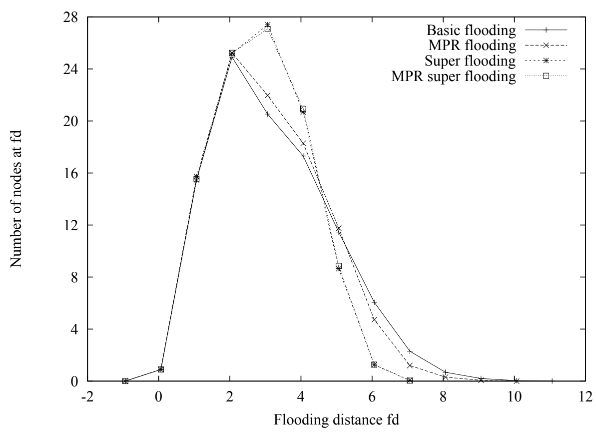

Fig. 4. Numberumber of nodes observed at a certain flooding distance for various schemes in the square network with 111 nodes.

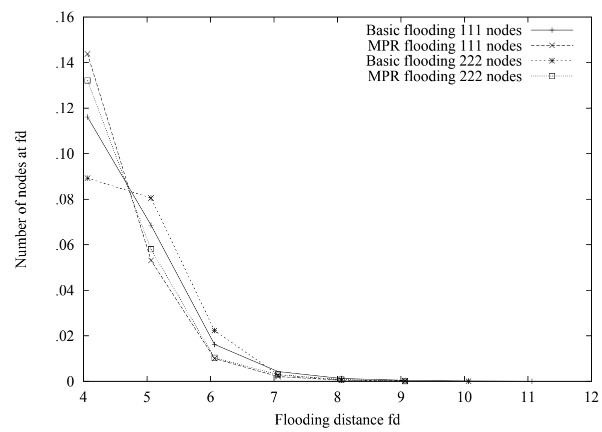

Fig. 6. Fraction of nodes observed at a certain flooding distances in the square square. Only nodes at optimal distance 4 where considered.

corresponding to basic flooding, MPR flooding and Super Flooding. Notice that MPR and Super Flooding provides sharper distribution, denoting a shorter flooding distance than basic flooding. MPR flooding distance and Super Flooding distances are very close, proving 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 [8], [9]. The latter routes are optimal but needs the proactive advertisement of MPR links throughout the network via Topology Control (TC) messages.

B. *Comparison Flooding versus MPR Flooding*

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 as significant as in the strip network.

C. *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 the square network.

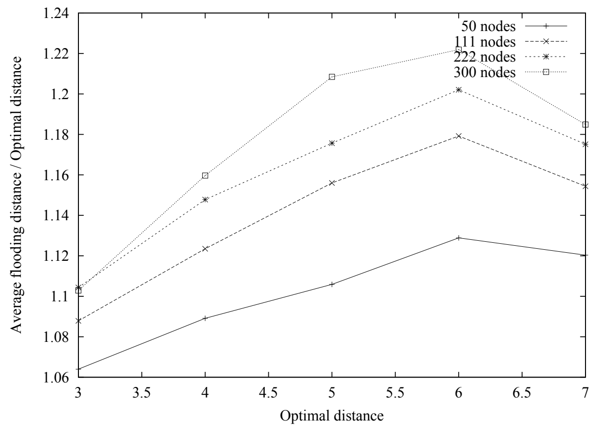

Fig. 7. Ratio flooding distance over optimal distance in the strip network with basic flooding.

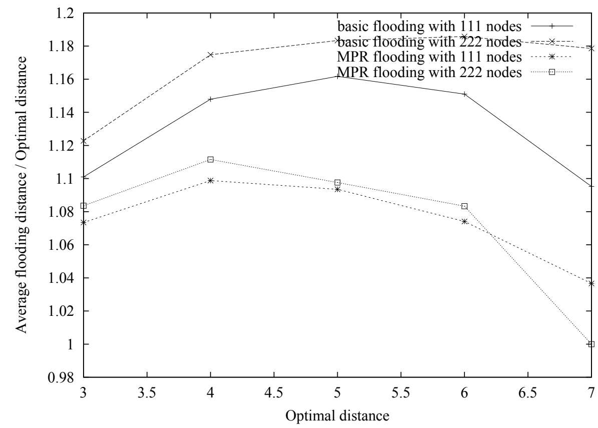

Fig. 9. Ratio flooding distance over optimal distance in the square network with basic flooding and multipoint-relay flooding.

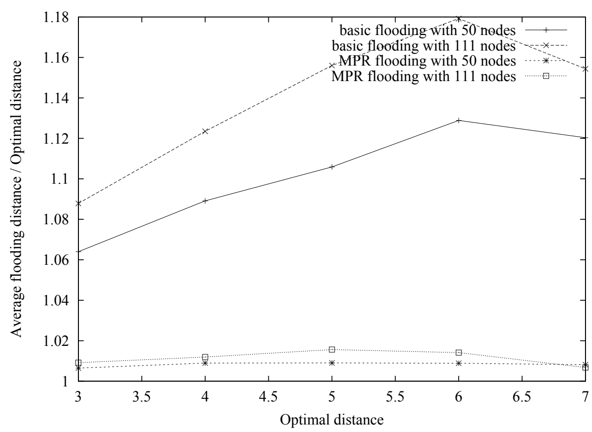

Fig. 8. Ratio flooding distance over optimal distance in the strip network with basic flooding and multipoint-relay flooding.

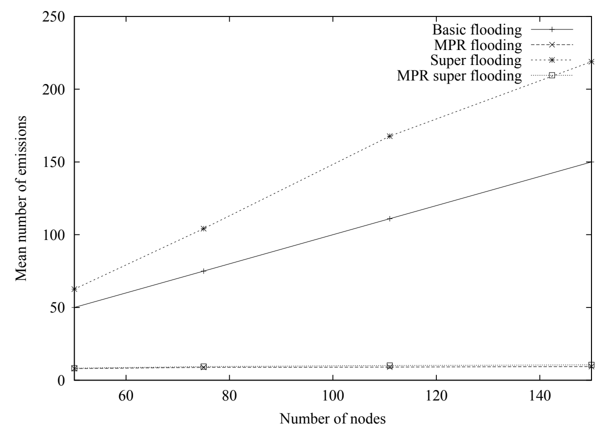

Fig. 10. Average number of emissions in the strip network for various number of nodes.

D. Control Traffic Overhead

Figure 10 displays the number of request packet retransmission using the different flooding mechanisms in the strip network. It is noticed that MPR flooding causes a tremendous reduction in packet retransmission and that the extra transmissions caused by Super Flooding, as compared to basic flooding, is still reasonable.

V. NS-2 Simulations

We conduct simulations using the network simulator ns2 [15] with the purpose of validating that our results from 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 [13]. The scenario we use are the same as those used in section IV, except that we introduce a number of (low-intensity) CBR data traffic streams. We do this since AODV is a reactive routing protocol, and hence doesn't attempt to set up routes before data transmission 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), and 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, for each scenario we get 2500

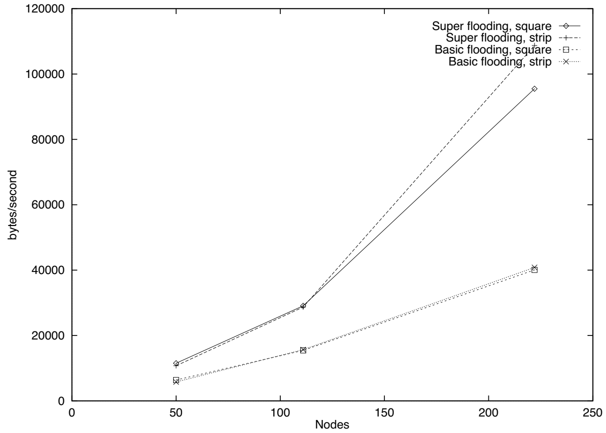

Fig. 11. Control traffic overhead in a static network.

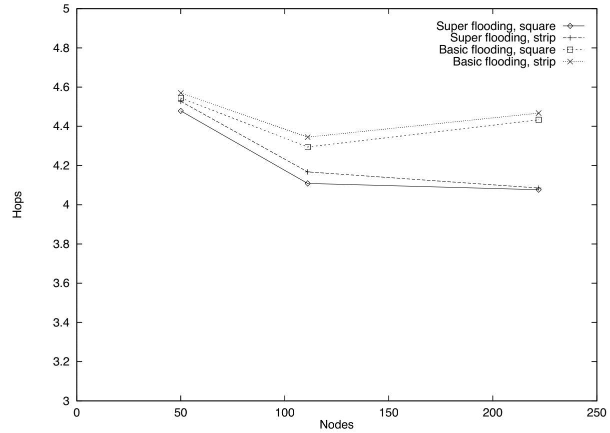

Fig. 12. Path length in a static network.

samples of the route length, provided. We use the exact 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.

A. 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 II, a node may potentially forward the same message when receiving it multiple times, depending on the TTL of the message. We notice, that assuming the first message received 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 11. 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 have used 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 12. 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. This makes Super Flooding attractive as soon the traffic payload exceeds ten times the flooding route request overhead.

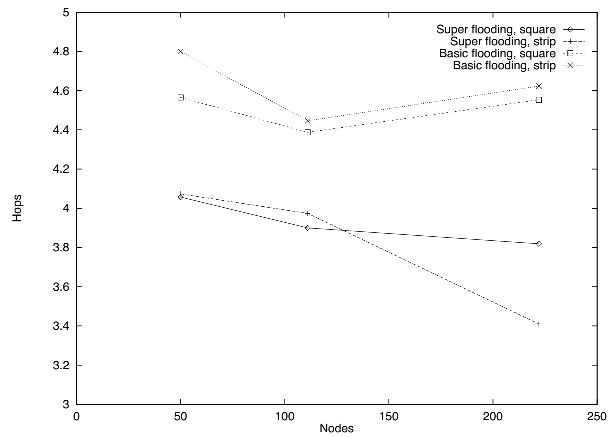

Fig. 13. Path length in a network with mobility.

Figure 13 shows the path lengths in a network with mobile nodes. We observe, that the difference between the path lengths, obtained through Fuper Flooding and through basic flooding are substantial - and in favor of Super Flooding. We notice that the paths are significantly longer than the paths obtained by the simulations on the ideal physical layer. This is caused by two reasons: (i) the simulated physical layer on ns2 is not "ideal" and hence, since it is more realistic, collisions occur that may kill propagation on more optimal path, (ii) special AODV feature such as local route repair, one-hop route request, or expanding ring search, are likely to increase the path length, with or without Super Flooding.

Figure 14 shows the amount of control traffic, generated by the routing protocols. It is evident that, as in figure 11 the cost of using Super Flooding to obtain optimal routes is a substantial increase in control traffic. Anyhow, this cost is likely to be absorbed by the spare in packet retransmissions due to reduced path length.

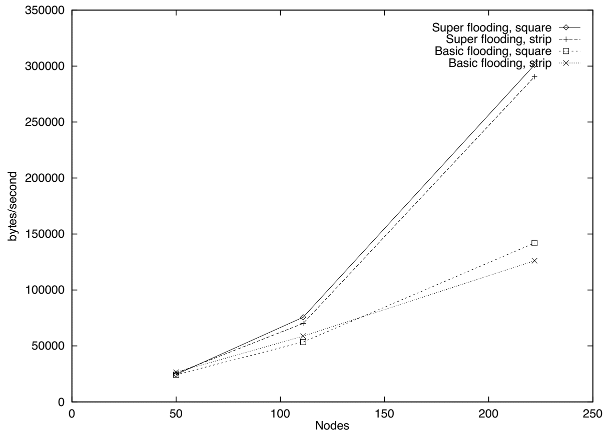

Fig. 14. Control traffic overhead in a network with mobility.

VI. 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 bring 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 some benefits. Investigating this hypothesis will constitute parts of our future efforts.

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