Gossip-Based Ad Hoc Routing

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***Abstract*—Many ad hoc routing protocols are based on some variant of flooding. Despite various optimizations of flooding, many routing messages are propagated unnecessarily. We propose a gossiping-based approach, where each node forwards a message with some probability, to reduce the overhead of the routing protocols. Gossiping exhibits bimodal behavior in sufficiently large networks: in some executions, the gossip dies out quickly and hardly any node gets the message; in the remaining executions, a substantial fraction of the nodes gets the message. The fraction of executions in which most nodes get the message depends on the gossiping probability and the topology of the network. In the networks we have considered, using gossiping probability between 0.6 and 0.8 suffices to ensure that almost every node gets the message in almost every execution. For large networks, this simple gossiping protocol uses up to 35% fewer messages than flooding, with improved performance. Gossiping can also be combined with various optimizations of flooding to yield further benefits. Simulations show that adding gossiping to AODV results in significant performance improvement, even in networks as small as 150 nodes. Our results suggest that the improvement should be even more significant in larger networks.**

***Index Terms*—Ad hoc networks, gossiping, percolation theory, phase transition, routing.**

I. Introduction

An *ad hoc network* is a multi-hop wireless network with no fixed infrastructure. MIT *Rooftop* networks and sensor networks are two examples of networks that might be implemented using the ad hoc networking technology.

Ad hoc networks can be usefully deployed for communication in applications such as disaster relief, tetherless classrooms, and battlefield situations.

In ad hoc networks, the power supply of individual nodes is limited, wireless bandwidth is limited, and the channel condition can vary greatly. Moreover, since nodes can be mobile, routes may constantly change, requiring frequent route discovery among communicating parties. Thus, to enable efficient communication, robust routing protocols must be developed.

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Many ad hoc routing protocols have been proposed. Some, such as LAR [16], GPSR [15], and DREAM [1] assume that nodes are equipped with GPS hardware and thus know their locations; others, such as DSR [14], AODV [24], ZRP [12], and TORA [23], do not make this assumption. Essentially all protocols that do not use GPS (and some that do, such as LAR and DREAM) make use of flooding, usually with some optimizations.

Despite the optimizations, in routing protocols that use flooding, many routing messages are propagated unnecessarily. In this paper, we show that *gossiping*—essentially, tossing a coin to randomly decide whether or not to forward a message—can be used to significantly reduce the number of routing messages sent.

It follows from results in percolation theory [10], [20] that gossiping exhibits a certain type of bimodal behavior. Let the gossip probability be p. Let $\theta^S(p)$ be the fraction of executions where gossiping with probability p dies out, and let $\theta^R(p)$ be the fraction of nodes getting the message when gossiping does not die out. Then, in sufficiently large "nice" graphs (where "nice" graphs include regular graphs and random graphs) the gossip quickly dies out in $1-\theta^S(p)$ of the executions and, in almost all of the fraction $\theta^S(p)$ of the executions where the gossip does not die out, a fraction $\theta^R(p)$ of the nodes get the message. Moreover, in many cases of interest, $\theta^R(p)$ is close to 1. Thus, in almost all executions of the algorithm, either hardly any nodes receive the message, or most of them do. Ideally, we could make the fraction of executions where the gossip dies out relatively low while also keeping the gossip probability low, to reduce the message overhead. The goal of this paper is to investigate the extent to which this can be done. Our results show that, by using appropriate heuristics, we can save up to 35% message overhead compared to flooding. Furthermore, adding gossiping to a protocol such as AODV not only reduces the number of messages sent, but also results in improved network performance in terms of end-to-end latency and throughput. (For readers unfamiliar with AODV, a brief overview is given in Section VI-A.) We expect that the various optimizations applied to flooding by other protocols (for example, the cluster-based scheme of [22]) can also be usefully combined with gossiping to get further performance improvements.

We are certainly not the first to use gossiping in networking applications. For example, it has been applied in networked databases to spread updates among nodes [9] and to multicasting [3]. However, in almost all of the earlier work on gossiping, it is assumed that any node in the network can send a message to any other node, either because there is a direct link to that node or because a route to that node is known. Gossiping proceeds by choosing some set of nodes at random to which to gossip. We do not have the luxury of being able to make such an assumption

in the context of ad hoc networks. Our problem is to *find routes* to different nodes.

In an ad hoc network, if a message is transmitted by a node, it is in fact usually sent as a broadcast rather than a point-to-point communication, and thus is received by all the nodes one hop away from the sender. Because of the fact that wireless resources are expensive, it makes sense to take advantage of this physical-layer broadcasting feature of the radio transmission. In our gossiping protocol, we control the probability with which this physical-layer broadcast is sent.

The rest of this paper is organized as follows. Section III discusses the basic bimodal behavior of gossiping in more detail. Section IV provides experimental evidence of the bimodal effect in networks of reasonable size, and also gives a sense of how the probability varies with the average degree of the network and the initial conditions. Section V presents a number of heuristics that could improve the performance of gossiping in networks of interests, and investigates the extent to which they do so experimentally. Section VI shows that gossiping can help in practical settings by considering the effect of adding gossiping to AODV. We show by simulation that even in networks with 150 nodes only, adding gossiping to AODV can result in significant performance improvements on all standard metrics. We expect that this improvement will be even more significant in larger networks. Section VII concludes our paper.

II. Related Work

Gossiping, as we are viewing it, is an instance of *percolation*. There is a great deal of work on percolation in the mathematics community, but, to the best of our knowledge, it has not been applied before to routing in ad hoc networks. The monographs of Grimmett [10] and Meester and Roy [20] give the results of most relevance to our work.

There has been some recent work on applying random routing in ad hoc networks, but the focus, and thus the techniques used, have been quite different from our work. We briefly discuss the related work here, and point out the differences from our approach.

- Vahdat and Becker [29] apply gossiping to ad hoc unicast routing. However, their usage of gossiping is very different from ours. In their work, they try to ensure that messages are eventually delivered, even if there is no connected path between the source and the destination at any given point in time. As long as there exists a path using communication links at some point in time, messages can be delivered through a random pair-wise exchanges among mobile hosts. Their techniques are not intended for and would not perform well in our setting, where we are trying to find routes that we assume exist, because we assume that network partition is a rare event.
- Chandra *et al.* [6] and Luo *et al.* [19] use a gossiping mechanism to improve multicast reliability in ad hoc networks; they do not use gossiping to reduce the number of messages sent. Indeed, they start with an arbitrary, possibly unreliable, multicast protocol to multicast a message. They then use gossiping (under the assumption that routes are known) to randomly exchange messages between nodes in order to recover lost messages.
- Heinzelman *et al.* [13] have applied gossiping in data dissemination in wireless sensor networks, using techniques similar in spirit to those of [29]. As discussed above, the focus on unicast makes their results quite different from ours.
- Chlebus *et al.* [7] use the term "gossiping" to refer to a somewhat different problem from the one we consider here. They assume that each node has its own distinct message, which has to be distributed to all other nodes. The channel access model they use is time-slotted. Due to the overhead and difficulty of clock synchronization, our paper, as most papers in the ad hoc network literature do, assumes a random access model.
- Ni *et al.* [22] propose five different approaches to reduce broadcast redundancy. One of them (briefly mentioned in a few sentences) is gossiping. However, they do not study the properties of gossiping, nor do they consider heuristics for dealing with problems introduced by gossiping in realistic ad hoc network topologies. Their experiments do show, however, that, in a 100-node network, using gossiping can save messages.
- Braginsky and Estrin [4] propose *rumor routing* for routing queries to events in sensor networks. The idea is to send a query on a random walk until it finds a node with a path to the event. Their approach can incur higher delay and potentially generate more messages than our approach. Thus, it is not appropriate in our setting, since high delay in route discovery can cause many packets to be dropped in the routing layer.
- Sasson *et al.* [27] study the phase-transition phenomenon in a small 802.11 ad hoc network setting. They claim that they do not observe the bimodal effect in their setting. However, their setting is quite different from ours. In their setting, a transmission can block many messages. For example, a transmission at the center of the network can cause more than 80% of the nodes not to receive a message. As a result, a larger probability of broadcasting can result in a smaller probability of propagating the messages in the network. Not surprisingly, the probability that leads to most nodes receiving the message is as low as 0.1. This observation emphasizes the fact that their result applies only to small networks. With a large network, a gossip probability of 0.1 is very likely to be below the phase-transition threshold, so would result in few nodes receiving the message in most executions.
- Li *et al.* [18] propose a gossip-based ad hoc routing protocol that works under the assumption that the destination and the source location can be discovered by means of a location service. This allows gossiping to be localized to nodes within the ellipse centered at the source and destination. Since we do not make this assumption, their protocol applies in more restricted settings than ours. We remark that, with location information, much more efficient routing protocols such as GPSR [15] exist.

III. The Bimodal Behavior of Gossiping

Since flooding is a basic element in many of the ad hoc routing protocols, as mentioned in Section I, we start by comparing gossiping to flooding.

Our basic gossiping protocol is simple. A source sends the route request with probability 1. When a node first receives a route request, with probability p it broadcasts the request to its neighbors and with probability $1-p$ it discards the request; if the node receives the same route request again, it is discarded. Thus, a node broadcasts a given route request at most once. This simple protocol is called GOSSIP1(p).

GOSSIP1 has a slight problem with initial conditions. If the source has relatively few neighbors, there is a fair chance that none of them will gossip and that the gossip will die. To make sure this does not happen, we gossip with probability 1 for the first k hops before continuing to gossip with probability p. We call this modified protocol GOSSIP1(p, k).[1]

The performance of GOSSIP1(p, k) clearly depends on the choice of p and k. Clearly, GOSSIP1(1,1) is equivalent to flooding. What happens in general? This depends in part on the topology of the network (particularly the average degree of the network nodes), the gossip probability p, and the initial conditions (as determined by k). If we think of gossiping as spreading a disease in an epidemic, this simply says that the likelihood of an epidemic spreading depends in part on how many people each person can infect (the degree), the likelihood of the infection spreading (the gossip probability), and how many people are initially infected.

As we said in the introduction, gossiping and, in particular, the performance of GOSSIP1($p, 0$) (that is, the scenario where even the source gossips with probability p) has been well studied in the work on percolation theory [10], [20]. Quite a few types of networks have been studied in the literature. In this section, we focus on two of them. We first study regular networks, since they allow us to easily analyze how GOSSIP1 behaves with respect to different parameters, such as the gossip probability, network size, and node degree, without other complicating factors. We then study random networks constructed as follows. Nodes are placed at random on a two-dimensional area; an edge is placed between any pair of nodes less than a fixed distance d apart. This type of random graph seems appropriate for modeling a number of applications involving ad hoc networks. Nodes have a limited amount of transmission power, and so can communicate only with other nodes that are reasonably close. The random placement can be viewed as modeling features such as the random mobility of nodes or the random placement of sensors in a large region.

The following theorem, whose proof can be found in [10] and [20], gives a sense of the type of results that have been proved.

Theorem III.1: For all $p \geq 0$, for all infinite regular graphs G, and for almost all (i.e., a measure 1 subset) of the infinite random graphs G constructed as above, if GOSSIP1($p, 0$) is used by every node to spread a message, then there is a well-defined probability $\theta_0^S(p) < 1$ that the message reaches infinitely many nodes. Moreover, in an execution where the message reaches infinitely many nodes, the probability $\theta_0^F(p)$ that a node receives the message and forwards it is equal to $\theta_0^S(p)$.[2]

Note that the probability of a message dying out (i.e., not spreading to infinitely many nodes) is averaged over the executions of the algorithm. That is, the theorem says that if we execute the algorithm repeatedly, the probability that a message does not die out in any given execution is $\theta_0^S(p)$. On the other hand, $\theta_0^F(p)$ talks about the probability that a node receives and forwards the message in a given execution of the algorithm. The intuition behind the equality of $\theta_0^S(p)$ and $\theta_0^F(p)$ is easy to explain. A gossip initiated by a source n_0 dies out if there is a set N of nodes that disconnects n_0 from the rest of the graph; that is, there is a set N of nodes such that, for infinitely many nodes n, every path from n_0 to n goes through a node in N. Thus, $\theta_0^S(p)$ is the probability that there is no disconnecting set N such that none of the nodes in N forwards the message. (Note that N could consist of the singleton node n_0 itself.) Similarly, the probability $\theta_0^F(p)$ that a random node n receives and forwards the message is precisely the probability that there is no set N' such that N' disconnects n from n_0 and none of the nodes in N' forwards the message. Therefore, $\theta_0^S(p) = \theta_0^F(p) \stackrel{\text{def}}{=} \theta_0(p)$.

It follows from these results that, in an execution where the message does not die out, the probability that a random node receives the message is $\theta_0(p)/p$, since receiving the message is independent of forwarding it. Thus, in terms of the notation used in the introduction, $\theta^S(p) = \theta_0(p)$ and $\theta^R(p) = \theta_0(p)/p$.

Let $\theta_k^S(p)$ be the probability that a message reaches infinitely many nodes if GOSSIP1(p, k) is used. It is easy to see that $\theta_1^S(p) = \theta_0(p)/p$, since the probability that the message reaches infinitely many nodes using GOSSIP1($p, 1$) is precisely the probability that a message reaches infinitely many nodes using GOSSIP1($p, 0$) given that the source actually gossips. However, note that the probability that a node receives and forwards a message if GOSSIP1(p, k) is used, given that the message does not die out, is still $\theta_0(p)$. That is, the probability that a node receives the message is independent of the choice of k. On the other hand, it is not hard to see that if each node learns the network topology in a zone of radius k (so that it can route a message directly to any node in its zone), then the probability that a node receives and forwards a message given that the message does not die out is $\theta_k(p)$.

Theorem III.1 applies to infinite graphs. It is not hard to show that essentially the same results hold for finite graphs, except possibly near the network boundary. In sufficiently large finite graphs, there will be two types of executions: those where hardly any node gets the message and those where the message makes it all the way to the boundary. Since the probability that a node receives the message in an execution where the gossip does not die is $\theta_0(p)/p$, the expected fraction of nodes that do not receive the message in an execution is $\theta_0(p)/p$. Moreover, it can be shown that the variance of this fraction is low. Thus, by the Central Limit Theorem, in sufficiently large graphs, in almost all executions where the gossip does not die out, a fraction close to $\theta_0(p)/p$ of nodes will get the message. That is, we expect

[1] Of course, the fact that gossiping has difficulties if a node has relatively few neighbors is true not just initially. We return to this point in the next section, when we discuss optimizations.

[2] Note that this bimodal effect is different from that discussed by Birman *et al.* [3]. They describe bimodal behavior where either all of the processes receive a multicast message or none do.

bimodal behavior: either hardly any nodes get the message or a fraction close to $\theta_0(p)/p$ receives the message. As we shall see, in cases of interest, $\theta_0(p)$ is quite close to p. Thus, in almost all executions of the algorithm in sufficiently large graphs, either hardly any nodes receive the message, or most do.

This leads to a number of obvious questions:

- How large is "sufficiently large"?
- What is the behavior of $\theta_k(p)$ for different graphs of interest?
- What can be done to improve the performance of gossiping in realistic settings, where the network graph may be neither regular nor random, and transmission is not reliable and is subject to congestion loss or loss due to the effect of MAC layer?

We investigate these questions in the next two sections.

Given our intended application of these results to mobile network, we close this section with some comments on mobility. Theorem III.1 presumes that nodes are stationary. Clearly, this is an inappropriate assumption in mobile networks. How node movement impacts Theorem III.1 depends on the mobility model. To get a sense of what is going on, suppose that we start with a (large) finite area where nodes are uniformly distributed and, for some fixed distance d, two nodes are joined by an edge if they are at most d apart. This gives a random graph (and, indeed, is how we construct the random graph in our simulations). There are two commonly used mobility models in the literature, the *random-direction* model and the *random-waypoint* model. In the random-direction model, a node chooses a direction to travel in, a speed at which to travel, and a time duration for this travel. If the node hits the boundary, then the node either wraps around or bounces back. Nain *et al.* [21] show that, in this model, the distribution of nodes continues to be uniform at all times. Therefore, for this mobility model, it seems that Theorem III.1 should hold with no change in proof (although we have not checked the details). In the random-waypoint model [30], a node chooses a point within the space with equal probability and a speed from some given distribution. Bettstetter *et al.* [2] show that, with this mobility model, the distribution of nodes does not remain uniform. After a while, the center of the region will have the highest density of nodes. Nevertheless, as we shall see in Section VI, by choosing the gossiping probability appropriately, we still obtain the bimodal behavior predicted by Theorem III.1. We discuss this further in Section VI.

IV. Gossiping in Finite Networks

We performed a large number of experiments to investigate the behavior of gossiping. We summarize some of the more interesting results here. We assumed an ideal MAC layer for these experiments because we wanted to decouple the effect of the MAC layer from the effect of gossiping; using IEEE 802.11 MAC leads to similar results. An ideal MAC layer is one that is not subject to packet loss. When we consider more realistic scenarios in Section VI, we use the IEEE 802.11 MAC layer. In this section, we focus on regular graphs and the random graphs discussed in the previous section. We focus here on phase-transition phenomena in "medium-sized" networks of roughly 1000 nodes and larger networks of 1 000 000 nodes. Of course, with larger networks, the phase-transition phenomena is even more marked. Although networks of more than 1000 nodes are not currently practical, given that hardware costs keep decreasing, we believe that they may well exist in the near future; for example, some researchers have envisioned large networks involving "smart dust."

Our first set of experiments involves medium-sized networks with 1000 nodes. We start by considering a 20-row by 50-column grid (i.e., a regular graph of degree 4). We focus on GOSSIP1$(p, 4)$, since taking $k = 4$ produces a reasonable tradeoff. (We report the effect of varying k towards the end of this section.) The results depend in part on where we place the route request source. As we would expect from the theoretical arguments, the location of the source node does not affect the fraction of nodes receiving the message. However, it does affect the number of executions in which the gossip dies out. The number of executions in which the gossip does not die out is higher for a more central node, and lower for a corner node. We report results here for the case where the route request source is at the left boundary of row 10. Our experiments show that, on average, the performance for other locations of the route request source is somewhat better than the results reported here. The results are illustrated in Fig. 1. Notice that GOSSIP1(0.72,4) on the grid ensures that almost all nodes get the message, except for a slight dropoff at distance greater than 50. This dropoff is a boundary effect, which we discuss in more detail below. Note that the graph in Fig. 1(a) represents an average of 120 executions of the protocol. With gossip probability 0.72 for this grid size, in almost all the executions of the algorithm, almost all nodes get the message.

The situation changes significantly if the gossip probability is even a little less than 0.7. For example, the average performance of GOSSIP1(0.65,4) is shown in Fig. 1(c). As the graph shows, at distance 40, on average 58% of the nodes got the message. However, in this case, the graph is somewhat misleading. The averaging is hiding the true behavior. As we would expect from Theorem III.1, there is bimodal behavior. This is illustrated in Fig. 1(d). If we consider nodes at distance 15–45 (so as to ignore initial effects and boundary effects), in 14% of the executions, fewer than 10% of the nodes get the message; in 19% of the executions, fewer than 20% of the nodes get the message; in 59% of the executions, more than 80% of the nodes get the message; and in 41% of the executions, more than 90% of the nodes get the message.

If we lower the gossip probability further, we get the same bimodal behavior; all that changes is the fraction of executions in which all nodes and no nodes get the message. The dropoff is fairly rapid. For example, Fig. 1(e) and (f) describe the situation for GOSSIP1(0.6,4). By the time we get to probability 0.6 on the grid, in only 4% of the executions of the algorithm do more than 90% of the nodes get the message; in only 11% of the executions do more than 80% of the nodes get the message; and in over 50% of the executions, fewer than 20% of the nodes get the messages.

We also investigated the effect of the degree of the network on gossiping. Not surprisingly, as the degree increases, gossiping becomes more effective. In a 20×50 regular network of degree 6, it suffices to gossip with probability 0.65 to ensure that almost all nodes get the message in almost all executions; with gossip

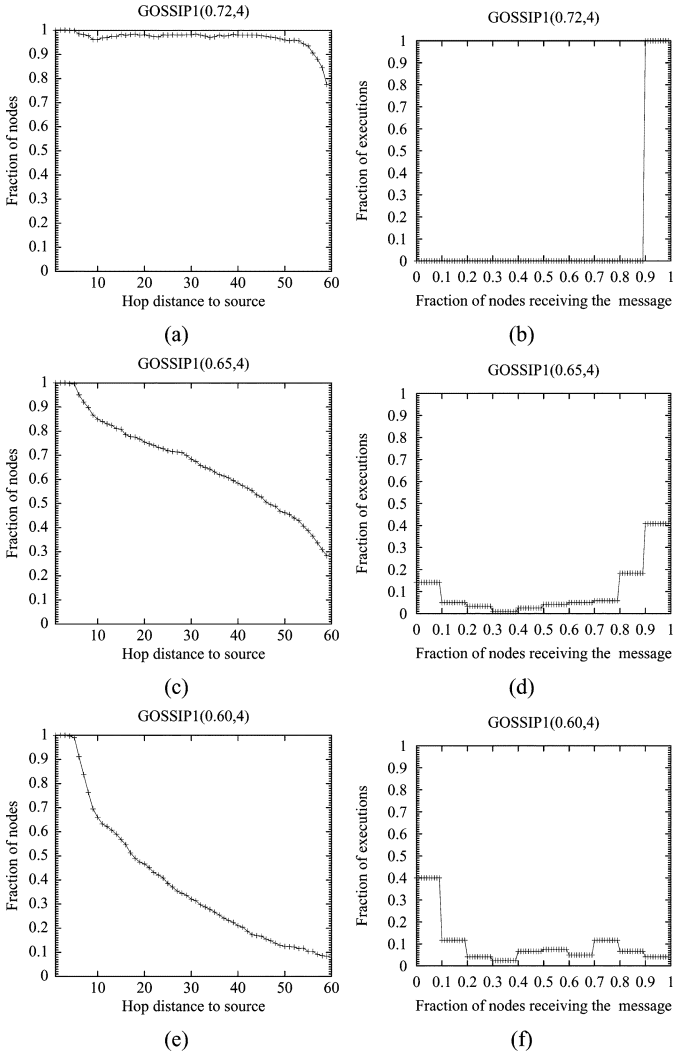

Fig. 1. The behavior of gossiping on a 20 × 50 grid.

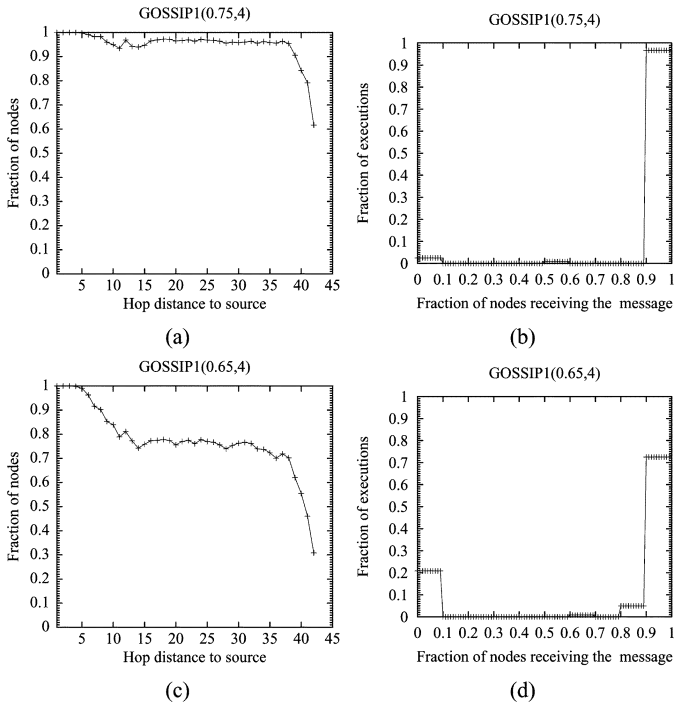

Fig. 2. Gossiping on a random network of the average degree 8.

probability 0.6, we start to see some dropoff. (Again, the numbers given in the graph are actually the result of averaging over a number of executions of the algorithm; this averaging masks the bimodal behavior observed in the executions.) On the other hand, for a 20 × 50 regular network of degree 3, we need to gossip with probability 0.86 to ensure that almost all nodes get the message in all executions.

While easy to study, regular graphs are not typical of the topology we expect in practical ad hoc networks. Random graphs are arguably somewhat closer to the topologies we expect to encounter. We considered two families of random graphs. In the first, we randomly placed 1000 nodes in a 7500 m × 3000 m rectangular region, where a node can communicate with another node if it is no more than 250 meters away. This results in a network with average degree 8. Since real networks have boundaries, we did not experiment on wrap-around meshes. As we shall see, dealing with nodes near the boundary raises some interesting issues. The results of our experiments, which are illustrated in Fig. 2, are qualitatively similar to those on the grid, as we would expect. Indeed, the bimodal effect is particularly pronounced with GOSSIP1(0.65,4), as shown in Fig. 2(d). If we consider nodes at distance 15–35, Fig. 2(d) shows, in 20% of the executions, fewer than 10% of the nodes get the message; in 70% of the executions, over 90% of the nodes get the message, and in 75% of the executions, over 80% of the nodes get the message.

To understand what happens in a higher-degree network, we placed 1200 nodes at random in the same rectangular region; this results in a network with average degree 10. In this network, it suffices to gossip with probability 0.65 to ensure that almost all nodes get the message in almost all executions.

All the graphs above show a marked dropoff in probability for nodes that are close to the boundary. This is not just an effect of averaging; this dropoff occurs in almost all executions of the algorithm. The dropoff is due to two related boundary effects:

1) Distant nodes have fewer neighbors, since they are close to the boundary.
2) Nodes at distance d from the source may well receive message due to "back-propagation" from nodes at distance $d' > d$ that get the message. Such back-propagation is not possible for boundary nodes.

We discuss some techniques to deal with this dropoff in Section V-D.

We did one last set of experiments to better evaluate $\theta_k(p)$. In these experiments, we used 1 000 000 nodes on a 1000 × 1000 grid and placed the source at the center of row 10. This is far enough away from the boundary to avoid significant boundary effects.[3] The results of using GOSSIP1(p, k) for particular values of p are illustrated in Fig. 3. As these results show, the bimodal effect is very marked by the time we get to such a large

[3]Experimental results show that there are nontrivial boundary effects for values of p very close to 0.59, no matter where we place the source. Intuitively, this is because for p very close to, but above 0.59, the probability of having a large set of nodes not receiving the message is nontrivial; nodes in the boundary are likely to be elements of such sets if the source is close to the boundary.

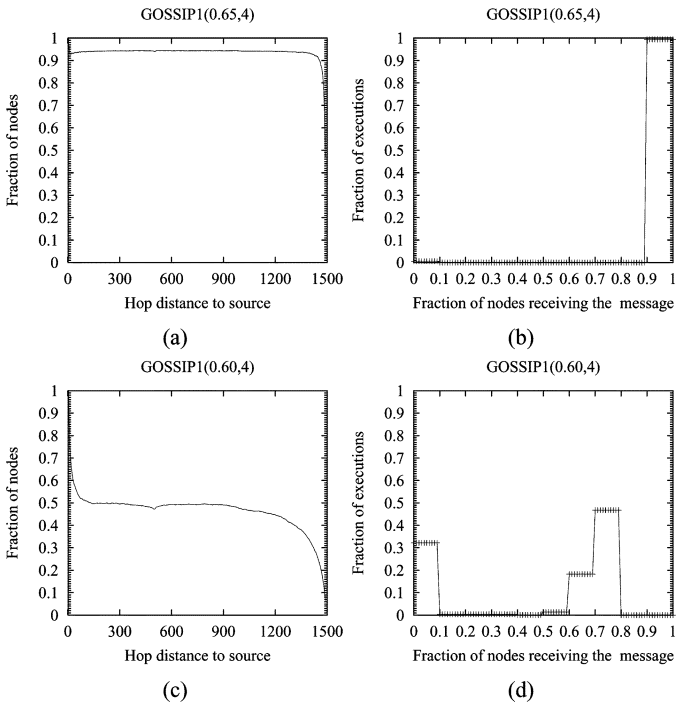

Fig. 3. The behavior of gossiping on a 1000 × 1000 grid.

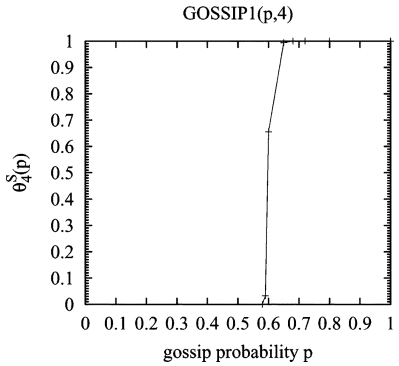

Fig. 4. $\theta_4^S(p)$ as a function of the gossip probability p on a 1000 × 1000 grid.

network, and begins to closely approximate the results expected from the theorem. Fig. 4 shows how $\theta_4^S(p)$ varies with p. As we can see, if p is below 0.59, then the gossip dies out in almost all executions. $\theta_4^S(p)$ then increases very rapidly, going from 0 at 0.59 to almost 1 at 0.65. (The rapid increase in the case of infinite graphs follows from a deeper mathematical analysis, and has been discussed in the percolation theory literature [10].) Note that we barely observe the phase-transition effect at probability 0.6 for the 20 × 50 grid. However, we clearly see the effect at probability 0.6 for the 1000 × 1000 grid. This shows that the phase-transition probability depends on the network size, although the main determinant is the average node degree.

Finally, we considered how $\theta_k^S(p)$ and $\theta_k^R(p)$ varied with k for a fixed value of p. As theory predicts, $\theta_k^R(p)$ does not change at all with p. There is some effect on $\theta_k^S(p)$. Of course, since $\theta_1^S(p) = \theta_0^S(p)/p$, there is a significant jump as k goes from 0 to 1. As k increases beyond 1, there is an increase in $\theta_k^S(p)$, but it is not so significant. For example, $\theta_1^S(0.65) = 0.95, \theta_2^S(0.65) = 0.98$, and $\theta_5^S(0.65) = 1$; similarly, $\theta_1^S(0.6) = 0.53$, $\theta_4^S(0.5) = 0.67$, and $\theta_{10}^S = 0.73$.

V. Heuristics to Improve the Performance of Gossiping

The results of the previous section suggest an obvious way that gossiping can be applied in ad hoc routing. Rather than flooding, we use GOSSIP1(p, k) with p sufficiently high to guarantee that almost all nodes will receive the message in almost all executions. We can practically guarantee that the destination node receives the message, while saving a fraction $1 - p$ of messages. In cases of interest, where the threshold probability is in the range 0.65–0.75, this means we can ensure that all nodes get the message using 25%–35% fewer messages than flooding. Notice that, if the network is congested and every node has a congestion dropping probability f, then to obtain the same results, the broadcast probability needs to be $\min(p/(1 - f), 1)$. If congestion is very localized, then we can simply use p because it is not likely to change the outcome of a given run of gossiping. However, the general interaction between gossiping and congestion is a topic that deserves further study.

The basic gossiping scheme can be optimized in a number of ways, using ideas that have been applied to flooding and ideas specific to gossiping. We discuss some optimizations in the remainder of this section. This section is intended as a proof of concept, showing that gossiping is a worthwhile approach to explore. We do not attempt to do an exhaustive analysis here to find the optimal parameters.

A. A Two-Threshold Scheme

In many cases of interest, a gossip protocol is run in conjunction with other protocols. If the other protocols maintain fairly accurate information regarding a node's neighbors, we can make use of this information to further improve the performance of GOSSIP1 by a simple optimization.

In a random network, unlike the grid, a node may have very few neighbors. In this case, the probability that none of the node's neighbors will propagate the gossip is high. In general, we may want the gossip probability at a node to be a function of its degree, where nodes with lower degree gossip with higher probability. To show the effect of this improvement, we consider a special case here: a protocol with four parameters, p_1, k, p_2, and n. As in GOSSIP1, p_1 is the typical gossip probability, but gossiping happens with probability 1 for the first k hops. The new features are p_2 and n; the idea is that the neighbors of a node with fewer than n neighbors gossip with probability $p_2 > p_1$. That is, if a node has fewer than n neighbors, it instructs its immediate neighbors to broadcast with probability p_2 rather than p_1. Call this modified protocol GOSSIP2(p_1, k, p_2, n). To understand why the *neighbors'* gossip probability is increased if there are few neighbors, consider the initiator of the gossip. Clearly, if none of its neighbors gossip, then the gossip will die. If the initiator has many neighbors, even if each gossips with relatively low probability, the probability that at least one of them will gossip is high. This is not the case if it has few neighbors.

GOSSIP2 is not of interest in regular networks. However, in random networks which typically have some sparse regions, it can have a significant impact. For example, for the

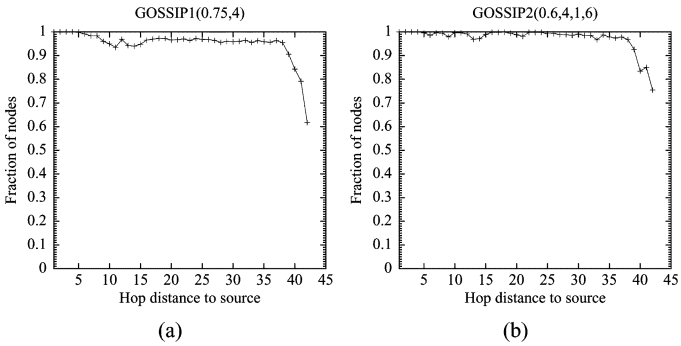

Fig. 5. Gossiping with two thresholds versus one on a random network of the average degree 8.

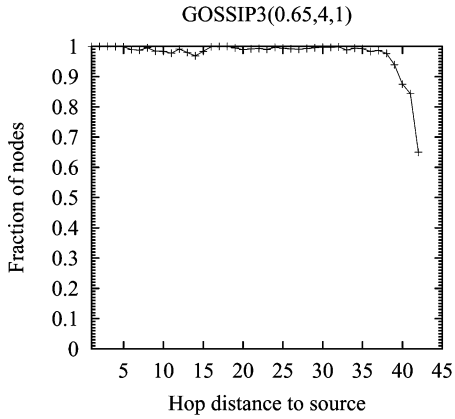

Fig. 6. GOSSIP3 on a random network of the degree 8.

1000-node random network with average degree 8, first considered in Fig. 2, GOSSIP2(0.6,4,1,6) has better performance than GOSSIP1(0.75,4), as shown in Fig. 5, while using 4% less messages than GOSSIP1(0.75,4). Only when $p \geq 0.8$ does GOSSIP1$(p, 4)$ begin to have the same performance as GOSSIP2(0.6,4,1,6); however, GOSSIP1(0.8,4) uses 13% more messages than GOSSIP2(0.6,4,1,6).

There may be other combinations of parameters for GOSSIP2 that give even better performance; we have not checked exhaustively. The key point is that using a higher threshold for successors of nodes with low degree seems to significantly improve performance.

B. Preventing Premature Gossip Death

As we have seen, the real problem with gossiping is that, if we gossip with too low a probability, the message may "die out" in a certain fraction of the executions. Measures can be taken to prevent this (for example, having successors of nodes with low degree gossip with a higher probability), but, unfortunately, there is no way for a node to know if a message is dying out. Nevertheless, a node may get some clues. One such clue is not getting too many copies of the message. Suppose that a node x got the message but does not broadcast it because its coin toss landed "tails." Further suppose that x has n neighbors. If the message does not die out, then it would expect that all of its neighbors would get the message as well, and thus, if the gossip probability is p, it expects to get pn messages from its neighbors. If it gets significantly fewer than pn messages within a reasonable time interval, then this is a clue that the gossip is dying out.

This suggests the following optimization of GOSSIP1 and GOSSIP2. If a node with n neighbors receives a message and does not broadcast it, but then does not receive the message from at least m neighbors within a reasonable timeout period, it broadcasts the message to all its neighbors. The obvious question here is what m should be. If m is chosen too large, then we may end up with too many messages. Our experiments show that we actually get the most significant performance improvement by taking $m = 1$. Let GOSSIP3(p, k, m) be just like GOSSIP1(p, k), except for the following modification. A node that originally did not broadcast a received message (because its coin landed tails), but then did not get the message from at least m other nodes within some timeout period, broadcasts the message immediately after the timeout period. (The choice of timeout period can be taken quite small. We discuss this issue in details in Section VI.) It may seem that such rebroadcasting can significantly effect the latency of the message. However, as the experiments discussed below show, if the parameters are chosen correctly, latency is not a problem at all.

As Fig. 6 shows, the performance of GOSSIP3(0.65,4,1) is even better than that of GOSSIP1(0.75,4). However, GOSSIP3(0.65,4,1) sends only 67% of the messages sent by flooding. By way of contrast, GOSSIP1(0.75,4) sends 75% of the messages sent by flooding. Thus, we get better performance using GOSSIP3 while sending 8% fewer messages.

To examine the effect of GOSSIP3 on latency, we recorded the number of timeout intervals a message experienced, using a variable L, which was augmented every time a message was forwarded after a timeout. Among all the messages sent by GOSSIP3(0.65,4,1), only 2% have $L \geq 1$. Among these messages with $L \geq 1$, 95% of them have $L \leq 2$. Thus, it seems that latency is not significantly affected by this modification.

C. Retries

The bimodal distribution observed in the use of gossiping can be viewed as a significant advantage. Once a route is found, acknowledgments are propagated back to the source along the route, so that the source can learn about the existence of the route. If a route is not found within a certain timeout period, there are two possibilities: either there is no route at all, or the protocol did not detect it. Our focus is on networks that are sufficiently well connected, in which typically a route exists. However, when using a gossiping protocol, there is always a possibility that a route will not be found even if it exists. Of course, there is a simple solution to this problem: simply retry the protocol. Thus, for example, the probability of finding a route within two attempts to a node at distance 25 using GOSSIP1(0.65,4) in the random network with average the outdegree 8 is 0.95: the probability of a node not receiving a message in any given execution of the protocol is 0.23, and executions are independent.

With retries, the bimodal message distribution works significantly to our advantage. As we observed, with GOSSIP1(0.65,4), in 72% of the executions, almost all nodes get the message. If we pick a destination at random, in

those executions where almost all nodes get the message, the destination is likely to get the message and a retry will not be necessary. On the other hand, in those executions where hardly any nodes got the message, a retry will probably be necessary. However, such failing gossip attempts do not involve too many transmissions, since most nodes do not get the message in the first place.

Of course, retries increase latency, even if they do not significantly increase the number of messages sent. This is especially true in large networks, where the timeout period will have to be large so as to allow the message to propagate throughout the network. However, even here, the bimodal distribution can be used to advantage to decrease the retry latency. Note that each message must keep track of the number of hops it has taken. We can modify the algorithm so as to require that any node that receives a message with, say, $h = 15$ hop counts forwards an acknowledgment to the sender along that route with some probability P_r. (The probability can be chosen so that the sender receives a mean number of, say, $c = 5$ acknowledgments if almost all nodes get the message.) Because of the bimodal distribution, if the sender receives several acknowledgments, then it can be fairly confident that the execution is one in which almost all nodes are getting the message. On the other hand, if it does not receive several acknowledgments, it is likely that the execution is one in which hardly any nodes get the message, and it should resend the message immediately. This shows that we can bound the latency of retry, independent of the network size.

Note that parameters h, c, and P_r can be set adaptively as follows so as to minimize the number of messages. Let N_s denote the mean number of acknowledgments received if a route reply is successfully received, and let N_f denote the average number of acknowledgments received if a route reply is not received.

- If both $N_f < c$ and $N_s < c$, this suggests that c is set too high, so we decrement c by 1.
- If both $N_f \geq c$ and $N_s \geq c$, this suggests that gossiping does not die out after h hops whether or not it is ultimately successful, so we increment h by 1.
- If $N_f < c$ and $N_s \geq c$, this suggests that c and h are set appropriately. We can try decrementing P_r slightly, say by 0.05, to see if we can still obtain this behavior while reducing the number of acknowledgments that need to be sent.

D. Zones

One of the best-known optimizations to flooding is the *zone routing protocol* (ZRP) [12]. In ZRP, each node u maintains a so-called *zone*, which consists of all the nodes that are at most ρ hops away from u, for some appropriately chosen *zone radius* ρ. A node that is exactly ρ hops away from u is called a *peripheral node* of u.

A node proactively tries to maintain complete routing tables for all nodes in its zone. Initially, a node discovers who its neighbors are and then broadcasts the identity of its neighbors to its zone (by using flooding up to hop count ρ). Then each time it discovers a change (i.e., that it has lost or gained a neighbor), it broadcasts an update. This procedure ensures that a node has an accurate picture of its zone.

If a source wants to send to a destination in its zone, it simply routes the message directly there, since it already knows the route. Otherwise, it sends a route request query to the peripheral nodes in its zone. If the destination is in a peripheral node's zone, the peripheral node replies with the route to the query originator. Otherwise, it forwards the query to its peripheral nodes, which in turn forward it to their peripheral nodes, and so on.

In the context of ZRP, there are two advantages of maintaining a zone. First, if a node is in the zone, flooding is unnecessary; a message can be sent directly to the intended recipient, saving much control traffic. This brings about a significant improvement in overall performance if a substantial fraction of nodes are in the zone (which is likely to be true in a small network, but far less likely in a large one). Second, if we want to send a message outside the zone, we can multicast to the boundary of the zone (or a subset of the nodes on the boundary), which can be a significant saving over flooding. However, there is a tradeoff in choosing the size of the zone: a larger zone benefits more from these two advantages, but also results in more overhead for proactive maintenance of the zones. In general, the optimal zone size will depend on factors like mobility and frequency of route requests.

The idea of zones can be used in gossiping as well. Here there is a third advantage: if a node in the zone receives a gossip message, then it can send it directly to any node in the zone. Thus, a zone serves as a "collector" of messages destined to nodes in the zone. This means that it would suffice for a gossiping protocol to get the message to a node in the intended recipient's zone. How much of an advantage is this? In large networks, the advantage is quite minimal. As we have observed, gossiping is essentially bimodal: for typical gossip probabilities, either hardly any nodes get the message or most of them do. Zones have a relatively small effect in either case. Thus, zones help only in the relatively few executions that exhibit "intermediate" behavior. Let GOSSIP4(p, k, k') be just like GOSSIP1(p, k), except that each node has a zone of radius k'. Comparing Fig. 7(b) to Fig. 7(a), we see that using a zone radius of 4 with gossiping probability 0.65 in the random network with the average degree 8 improves the performance by only a few percent over most of the distances. However, it does ameliorate the back-propagation effect. As shown in Fig. 7(c), increasing the zone radius to 8 does not significantly improve the limiting performance, but it has an even more beneficial effect on the back-propagation problem.

The situation is much different for smaller networks. Here zones can have a significant impact. For example, if we use gossip probability 0.65 in a random network with 100 nodes and average degree 13, the network is too small for the bimodal effect to show up. However, the back-propagation problem is significant. As Fig. 8 shows, for the small random network of 100 nodes, if we use GOSSIP1(0.65,1), then only 76% of nodes at distance 10 get the message. However, if we have a zone of radius 3 (GOSSIP4(0.65,1,3)), then 96% of nodes at distance 10 get the message.

VI. Incorporating Gossiping in AODV

How much does gossiping really help in practice? That depends, of course, on issues like the network topology, mobility, and how frequently messages are generated. We believe that

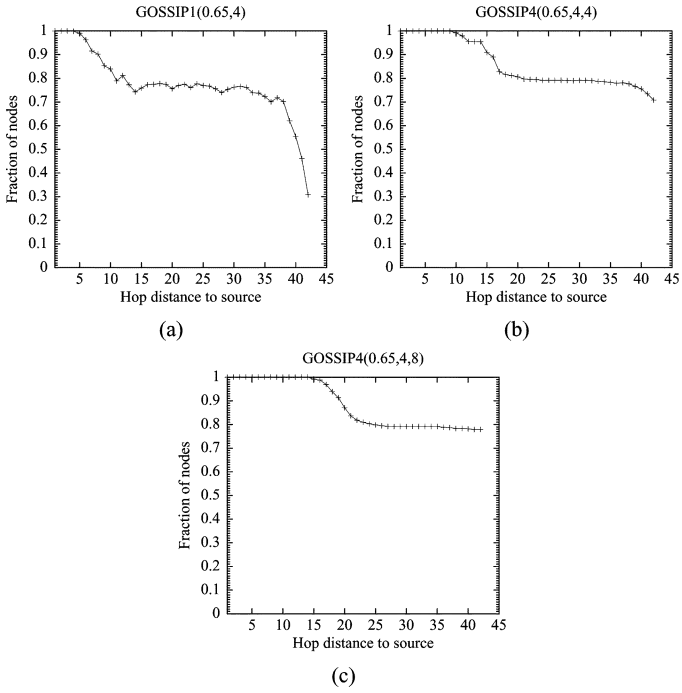

Fig. 7. Gossiping with zones on a random network of the average degree 8.

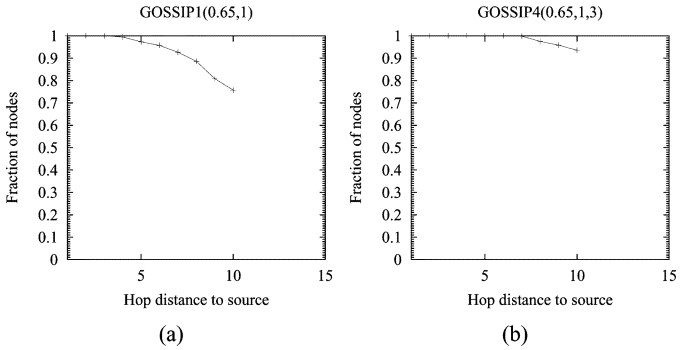

Fig. 8. Gossiping with zones on a 100-node random network.

in larger networks with high mobility many of the optimizations discussed in the literature will be much less effective. (We discuss this point in more detail below in the context of AODV.) In this case, flooding will occur more frequently, so gossiping will be particularly advantageous. However, as our results show, gossiping can provide significant advantages even in small networks.

To test the impact of gossiping, we considered AODV, one of the most-studied ad hoc routing protocols in the literature. We compared pure AODV to a variant of AODV that uses gossiping instead of flooding whenever AODV would use flooding. We do not have the resources to simulate the protocols in very large networks. However, our results do verify the intuition that, with high mobility (when flooding will be needed more often in pure AODV), gossiping can provide a significant advantage.

A. A Brief Overview of AODV

Using AODV, the first time a node u requests a route to node v, it uses an *expanding-ring search* to find the route. That is, it first tries to find the route in a neighborhood of small radius, by flooding. It then tries to progressively find the route in neighborhoods of larger and larger radius. If all these attempts fail, it resorts to flooding the message through the whole network. The exact choice of the neighborhood radii to try is a parameter of AODV. Typically, not too many radii are considered before resorting to flooding throughout the network.

AODV also maintains routing tables in the network nodes where it stores the routes after they have been found. If AODV running at node u gets any packet with source u and destination v, the route in the routing table will be tried first. If any node w on the route from u to v detects that the link to the next hop is down, then w generates a route error (RERR) message, which is propagated back to u. When u receives the RERR message, it deletes the route to v from its routing table.

B. GOSSIP3 in AODV

We added gossiping to AODV in a particularly simple way. If the expanding-ring search with a smaller radius fails, rather than flooding to the whole network, we use GOSSIP3(0.65,1,1). (We used these parameters since they gave good performance in the particular scenarios we considered.) The timeout period of GOSSIP3 should be large enough to allow neighboring nodes to gossip. The *NODE_TRAVERSAL_TIME* parameter of AODV is a conservative estimate of the average one hop traversal time for packets that includes queueing delays, interrupt processing times, and transfer times. In our experiments, we set the timeout interval to be $I \times$ *NODE_TRAVERSAL_TIME* where i is a small integer ($i = 5$ in our results reported here). Note that we do not use GOSSIP3 in the expanding-ring search with a smaller radius. Because of the back-propagation effects, flooding is actually more efficient than gossiping for a neighborhood with a small radius. We call the variant of AODV that uses GOSSIP3 AODV+G.

C. Simulation Model and Performance Results

Our simulation is done in the ns-2 [25] simulator. This is also the simulator most often used in the literature to evaluate AODV. We use the AODV implementation in ns-2 downloaded from the web site of one of its authors, using IEEE 802.11 as the MAC layer protocol. The radio model simulates Lucent's WaveLAN [28] with a nominal bit rate of 2 Mb/s and a nominal range of 250 meters. The radio propagation model is the two-ray ground model [26].

Our application traffic is CBR (constant bit rate). The source-destination pairs (connections) are chosen randomly. The application packets are all 512 bytes. We assumed a sending rate of 2 packets/s and 30 connections.

For mobility, we use the *random-waypoint* model [5] in a rectangular field, as modified by Yoon [30]; to prevent mobility from going asymptotically to zero, the minimal speed is set to 1. In the simulations, 150 nodes are randomly placed in a grid of 3300 m $\times$ 600 m; we chose this layout because in some sense it provides a worst-case estimate of the performance of gossiping. For this layout the gossip threshold is approximately 0.65. With other more "square" layouts, such as 1650 $\times$ 1200, it is possible to gossip with lower probability (closer to 0.5), so the saving due to gossiping will be even more significant. There are 30 connections, each generating 2 packets/s. The simulation time is

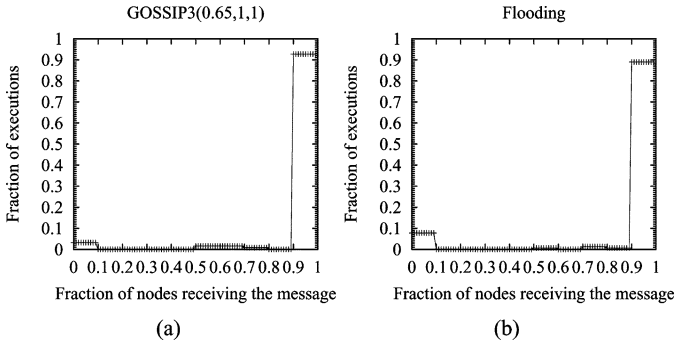

Fig. 9. The bimodal behavior of gossiping in the presence of mobility and congestion.

600 s; we start to inject traffic at time 300 when node mobility reaches stationarity. Each node moves with a randomly chosen speed (uniformly chosen from 1 to maxSpeed m/s). We set the pause time to zero. We vary maxSpeed to simulate different mobility scenarios. Each data point represents an average of five runs using the identical traffic model, but with different randomly generated mobility scenarios. To preserve fairness, identical mobility and traffic scenarios are used for both AODV and AODV+G.

We used the same configuration parameters for AODV as those used in [8]. Of particular interest to us are the expanding-ring search parameters. In the ns-2 implementation of AODV, first a neighborhood radius of 5 hops is tried; if no route is found, network-wide flooding is used.

We study the performance of the following four metrics, of which the first three were also studied in [8].

- The *packet delivery fraction* is the ratio of the number of data packets successfully delivered to the number of data packets generated by the CBR sources.
- The *average end-to-end delay* of data packets includes all possible delays caused by buffering during routing discovery, queueing at the interface queue, retransmission at the MAC layer, propagation, and transfer time.
- The *normalized routing load* represents the number of routing packets transmitted per data packet delivered at the destination. Each hop-wise packet transmission is counted as one transmission.
- The *route length ratio* compares the shortest route length found to the actual shortest route length.

First, we investigate the impact of mobility and network congestion on gossiping. Fig. 9 illustrates the fraction of nodes receiving the route request in various executions, using GOSSIP3(0.65,1,1) and flooding. We observe that, in more than 90% of the executions, more than 90% of the nodes receive the message. For most of the remaining executions, the gossip dies out quickly. Despite the fact that we are using the random-waypoint model of mobility, gossiping still has bimodal behavior. We believe that this is because, although the density of nodes in the center of the region increases over time using the random-waypoint model, our parameters ensure that there is still sufficient density at the boundaries to maintain enough connectivity for gossiping to work. We suspect that, if the graph were larger (but all other parameters remained the same), we would need to use a higher gossiping probability. Interestingly, there is bimodal behavior with flooding too; this is due to congestion. Because of congestion, there is a 10% chance of the gossip dying out (higher than with GOSSIP3(0.65,1,1)) and, even in executions where the gossip does not die out, fewer nodes receive the message than with GOSSIP3(0.65,1,1).

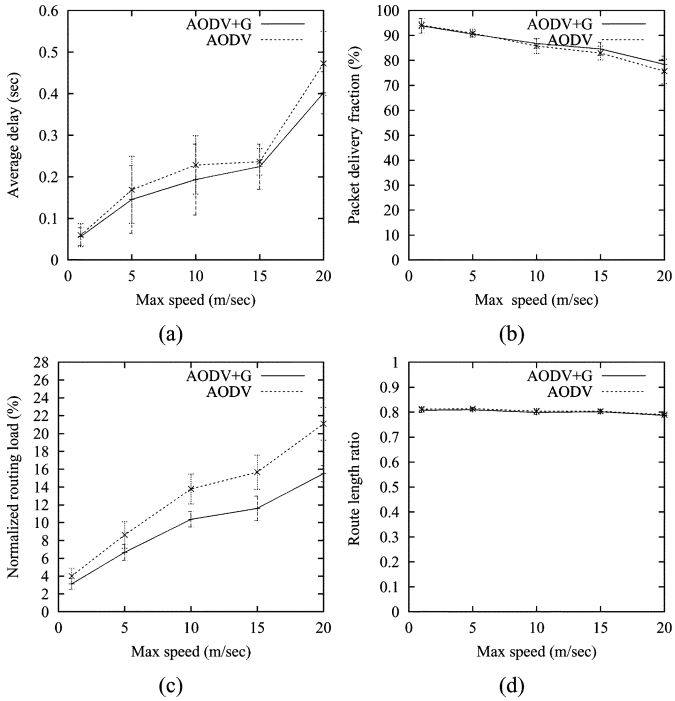

Fig. 10. AODV+G versus AODV.

We now consider the performance of AODV+G and AODV in terms of the four metrics discussed above. We plot the mean of these four metrics along with their 90 percent confidence interval using the t-distribution in Fig. 10. Fig. 10(a) shows the relative performance of AODV and AODV+G with respect to end-to-end delay; Fig. 10(b) compares them with respect to fraction of packets delivered; Fig. 10(c) compares them with respect to normalized routing load; Fig. 10(d) compares them with respect to the route length ratio. Fig. 10(a) and (b) shows that AODV+G delivers better network performance than AODV in terms of end-to-end delay and packet delivery fraction. The performance improvements correlate with the amount by which the routing load is reduced. This is not surprising, since routing load increases with mobility and constitutes a significant part of the network load, as can be seen from Fig. 10(c). At maxSpeed 20 m/s, AODV+G reduces average end-to-end delay by 15% and increases packet delivery fraction by 3%. Note that for low settings of maxSpeed, the confidence interval for end-to-end delay is quite large, although it decreases with an increase in mobility. For example, it is $\pm 56\%$ of the average delay for maxSpeed $= 5$ m/s, and drops to $\pm 13\%$ of the average delay for maxSpeed $= 20$ m/s. The reason is that local persistent congestion is more likely with low mobility than high mobility. In scenarios with local persistent congestion, a small fraction of packets incur a very high delay. For example, in one scenario with maxSpeed $= 5$ m/s and average delay 0.24 s, only 27% of the received packets had a delay of more than 0.06 s. By way

of contrast, as shown in Fig. 10(b), the confidence interval for packet delivery fraction is small and does not vary much; it is essentially $\pm 6\%$ of the average over all settings of maxSpeed. From Fig. 10(c), we see that AODV+G reduces the routing load; the reduction is from 22% to 27% in terms of the normalized routing load. Based on the confidence interval data, the expected improvement of AODV+G over AODV may not be that significant for end-to-end delay and packet delivery fraction, at least at low speeds, although AODV+G does typically perform better than AODV. We suspect that this is mainly due to the fact that, at these settings, the network is not heavily loaded (as shown by the high packet delivery fraction). On the other hand, the expected improvement of AODV+G over AODV in terms of routing load is quite significant statistically.

Finally, we consider route lengths. Note that neither gossiping nor flooding (as used by AODV) will necessarily find the shortest route. For example, suppose that (u_0, u_1, u_2, u_3) is the shortest path from u_0 to u_3, but that there is another path $(u_0, v_1, v_2, u_2, u_3)$. It is possible that after u_0 broadcasts a route request, u_2 will receive it along the path from v_2 before receiving it from u_1. Since, in AODV, u_2 would save in its routing table the information from only the first route request to arrive, AODV will not necessarily discover the shortest route. For similar reasons, with gossiping, we may not always discover the shortest routes. Our experimental results show that, in the 150-node network studied here, the length of paths found by flooding and by our gossiping algorithm are essentially indistinguishable. We considered the ratio of the shortest route found by AODV to the actual shortest route, and similarly for AODV+G. Fig. 10(d) shows that the routing length ratio for AODV+G and AODV is almost the same (and, indeed, is sometimes marginally better for AODV+G). However, this result seems to be to some extent an artifact of the particular small network and the gossip probability used here. Experimental results performed on the networks studied in Section IV show that gossiping finds routes 10%–15% longer than flooding, if gossiping is done with a probability just a little above threshold. The gap decreases as the gossiping probability increases; for sufficiently large gossip probability, the route lengths are again essentially indistinguishable.

These simulations were carried out in a network with 150 nodes. In such a small network, even if route–destination pairs are chosen at random, a great many pairs will be within 5 hops of each other and thus will be discovered by the expanding-ring search. Indeed, in our simulation, 30%–40% of the routes discovered had a length less than or equal to 5. Thus, as many as 40% of the routes are discovered by the expanding-ring search. We expect that things will be quite different in a larger network. Of course, this depends in part on the nature of route requests and the choice of the parameters for the expanding-ring search. While it is possible that many requests will be local, there are applications for which this seems unlikely. Certainly if route–destination pairs are chosen at random, then expanding-ring search is unlikely to be effective for almost any choice of parameter settings. That is, a great many source-destination pairs are likely to be far apart, so no expanding-ring search is likely to find them efficiently. Additionally, expanding-ring search may add a great deal of routing traffic and route discovery latency. By way of contrast, gossiping continues to perform well in large networks. Thus, we predict that the relative advantage of AODV+G over pure AODV will increase as the network gets larger. The graphs presented here underestimate this performance improvement.

VII. Concluding Remarks

Despite the various optimizations, with flooding-based routing many routing messages are propagated unnecessarily. We show that gossiping can reduce control traffic up to 35% when compared to flooding. Since the routes found by gossiping may be up to 10%–15% longer than those found by flooding (depending on the gossip probability), how much gossiping can save in terms of overall traffic depends on the gossip probability used, node mobility, and the type of messages sent. With high mobility, new routes will have to be found more frequently, and the savings will be relatively larger. In addition, if messages are mainly network-wide broadcasts, rather than point-to-point, gossiping may result in significant savings over flooding. (Note that with gossiping, in general, a small fraction of the nodes will not get the broadcast. However, in certain applications, such as route discovery, for example, it may suffice that almost everyone gets the message, or the contents of broadcast k can be piggybacked with broadcast $k+1$, so that the probability of missing a message altogether becomes very low.)

Our protocol is simple and easy to incorporate into existing routing protocols. When we add gossiping to AODV, simulations show significant performance improvements in all the performance metrics, even in networks as small as 150 nodes. As discussed in the Section VI, we expect this performance improvement to become even more significant in larger networks.

We have also experimented with adding gossiping to ZRP, by using gossiping to send the route request to some peripheral nodes rather than to all peripheral nodes. Again, our results show significant improvement in all performance metrics. It seems likely that gossiping can be usefully added to a number of other ad hoc routing protocols as well.

Gossiping has a number of advantages over other approaches considered in the literature. For one thing, unlike many heuristics considered in the literature, we believe that we have a very good understanding of how gossiping will perform in large networks. This understanding is supported both by analytical results and our experiments. While there are fundamental limits to the amount of nonlocal traffic that can be sent in large networks, due to problems of scaling [11], [17], gossiping should still be useful in large networks when nonlocal messages need to be sent. It is far less clear how well other optimizations considered in the literature will perform in large networks. Moreover, as our simulations with AODV have shown, gossiping can provide significant advantages even in small networks. Experience in other contexts has shown that gossiping is also quite robust and able to tolerate faults; we expect that this will be the case in ad hoc routing as well. All this suggests that gossiping can be a very useful adjunct to the arsenal of techniques in mobile computing. Of course, work needs to be done in finding good techniques to learn the appropriate gossip parameters. We have experimented with adjusting the gossiping probability of each

node according to the success/failure of route requests; it is increased if the route request failure probability is high and decreased if the route request failure probability is close to 0. To propagate the appropriate probability throughout the network, it can be embedded into the route request packet. Each intermediate node receiving the packet will gossip with the probability carried in the route request packet. Our preliminary experiments have shown that this approach does produce good results, although we have not had enough experience to determine the best way of making these adjustments to the gossip probability; we leave this for future work.

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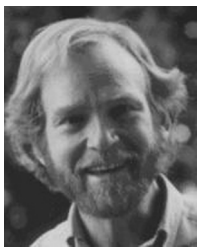

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