Modeling the Performance of Flooding in Wireless Multi-Hop Ad Hoc Networks

Kumar Viswanath and Katia Obraczka
1156 High Street, Baskin Engineering Bldg,
University of California, Santa Cruz
Santa Cruz, CA 95064
email: {kumarv,katia}@cse.ucsc.edu

Abstract

One feature common to most existing routing protocols for wireless mobile ad hoc networks, or MANETs, is the need to flood control messages network-wide during the route acquisition and maintenance process. Flooding of control messages may result in redundant broadcasts and cause serious contention and collision problems in MANETs. In this paper, we develop an analytical model to study the performance of plain- and probabilistic flooding in terms of its *reliability* and *reachability* in delivering packets. *Reliability* is a measure of the total number of packets received by network nodes whereas *reachability* refers to the total number of unique nodes reached by the flooding process. We also provide simulation results to validate the model.

Keywords: Wireless, Ad-hoc networks, broadcast, flooding, multi-hop , analytical model

1 Introduction

Wireless mobile ad hoc networks, or MANETs, operate without any fixed infrastructure. Nodes communicate with one another through wireless packet radios. Because of the limited radio propagation range, routes can often be multi-hop. Hence, every host may act as a packet forwarder as well as a traffic source or destination. Due to their ease of deployment, MANETs are an attractive choice for scenarios where the fixed network infrastructure is non-existent or unusable. Example applications include search and rescue, disaster recovery, digital battlefield, and covert military operations.

MANETs can exhibit very diverse characteristics. Nodes may differ in terms of their communication, processing, storage, and power capabilities. Because of this diversity, routing in MANETs raises serious challenges and has been an active area of research over the past five years. As a result, several approaches to routing in MANETs have been proposed and evaluated. These approaches can be grouped into two main categories: proactive and on-demand. Protocols of the former variety maintain routing state for all network nodes, while on-demand protocols reduce the impact of frequent topology changes due to mobility, link failures, etc. by acquiring routes on demand. One feature common to on-demand protocols like DSR [1], AODV [2] and ODMRP [3] is the need to broadcast control messages during the *Route Request Phase* in order to obtain routes to reach potential receivers. *Route Request* is typically carried out by using a broadcast mechanism such as flooding. Broadcast in MANETs is also necessary for applications such as

- Sending commands to a group of nodes (e.g., alarm signals).
- Paging Mobile Hosts
- Sending location updates for routing.

The most common mechanism for broadcast is through flooding. However, one drawback of flooding is that it may result in redundant broadcasts. These re-broadcasts can cause serious contention and collision problems, especially in resource-constrained (e.g., power, bandwidth) MANETs. One of our longer-term goals is to (1) propose variants of flooding that achieve delivery ratios similar to flooding at considerably lower overhead and (2) characterize their performance analytically and through simulations. This paper takes a first step toward these goals by introducing an analytical model to evaluate the performance of flooding in MANETs. More specifically, we characterize flooding's reliability and reachability.

In order to reduce the overhead incurred by flooding, several optimizations and efficient broadcasting schemes based on neighbor information have been proposed in [4], [5] and [6]. In [7], the authors have proposed a new medium access control (MAC) architecture for providing efficient and reliable broadcast services in ad hoc networks. However, none of the above mechanisms provide an analytical discussion on the reliability and reachability of the broadcasting schemes.

We should point out that significant work has been done in analyzing the performance of packet radio networks [8] in terms of its delay characteristics, optimum transmission radius (e.g., [9]), etc. However, to our knowledge, little work has been done in characterizing the reliability of routing protocols based on analytical models. We also use simulations to validate our model.

The rest of this paper is organized as follows. In Section 2 we derive the probability of successful transmissions given hidden terminals and collisions. Sections 3 and 4 study the reliability and reachability of plain- and probabilistic flooding mechanisms. Section 5 presents our simulation setup and compares results from our model against simulation results. Finally, Section 6 presents our concluding remarks and directions for future work.

2 Probability of Successful Transmissions

In MANETs, packet loss can occur either due to node mobility or collisions arising from exposed sources and hidden terminals. It should be noted that since we are using flooding, we assume that data is broadcast at the MAC layer and there is no RTS-CTS exchange to prevent exposed sources from transmitting at the same time. Thus, the behavior of the MAC layer is essentially similar to CSMA for broadcast. Given this similarity, the analysis of CSMA's successful transmission probability can be extended to determine the probability of successful reception by nodes in the flooding regime. However, the difference is that in flooding, nodes can possibly receive the same packet multiple times.

In the remainder of this section, we revisit the CSMA analysis presented by Varshney and Wu [10] including their network model, assumptions, and key results. These results are then used in Section 3 to derive the probability of successful reception by nodes in flooding.

Network Model and Assumptions

Figure 1 shows the hearing regions of nodes A and B, where r is the distance between A and B, and R is their transmission radius. The network model used in the analysis is described below. This network model is essentially the same as used by Takagi and Kleinrock in [11] to obtain the optimal transmission range of a node in a multi-hop wireless network.

- The node distribution within the topology is a two-dimensional Poisson point process with parameter λ, i.e,

$$\begin{aligned} &\mathrm{P}(k \textit{ nodes within Tx region of radius } R) \\ &\qquad = \exp(-\lambda\pi R^2)\frac{(\lambda\pi R^2)^k}{k!} \end{aligned} \tag{2.1}$$

- The transmission time T (or packet length) is assumed to be the same for all nodes. Transmission time is divided in slots of duration α, where α is the one way propagation delay. τ is defined to be $\frac{T}{\alpha}$. Nodes can transmit only at the beginning of each slot.

- All nodes always have packets waiting to be transmitted and nodes transmit at the beginning of a slot according to a Bernoulli process with parameter p, where $0 < p < 1$. Although the probability of a node transmitting varies from slot to slot, the model assumes a steady state probability p. This assumption has also been used by Kleinrock and Takagi [11] in deriving the optimum transmission range for packet radio networks.

- The receiver is chosen randomly from any one of the transmitter's neighbors.
- The system is independent from slot to slot during the idle period, i.e., whenever there is a packet waiting to be sent, it is equally likely that this packet will be destined to any node no matter whether it is a new– or retransmitted packet.
- The re-transmission of a packet by neighbor nodes is assumed to be independent of one another.

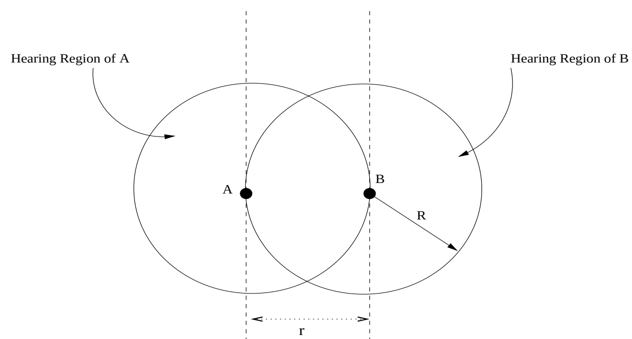


Figure 1: Hearing Region

CSMA Probability of Successful Transmission

Even though a node may be ready to transmit, the actual transmission in a slot depends on collision avoidance and also on the state of the channel. In [10], the authors have shown that the probability p' that a node actually transmits in a time slot is given as

$$\begin{aligned} p' &= p * \mathrm{P}(\textit{channel is idle in given slot}) \\ &= \frac{\alpha p}{1+\alpha-e^{p'N}} \end{aligned} \tag{2.2}$$

where α is the one way propagation delay and N is number of nodes within transmission region of radius R.

Using the assumptions and network model described in section 2, it has also been shown in [10] that the probability of a successful transmission from a A to B is given as

$$P_s = \frac{2p'(1-p')}{\alpha+p'} e^{-(2\tau+1)p'N} \int_0^1 e^{\frac{4p'N\tau}{\pi} q(\frac{r}{2})} r dr \tag{2.3}$$

where $q(r) = \arccos(r) - r\sqrt{1-r^2}$ and $\mathrm{N} = \lambda\pi R^2$

3 Reliability and Reachability Analysis of Flooding

In this section, we build upon the results from Section 2 to compute flooding's reachability and reliability in MANETs. We also analyze the reliability and reachability of probabilistic flooding. We first start by defining these metrics.

Definitions

- **Reachability** is the number of nodes in the network that can receive at least one copy of a source's transmission.
- **Reliability** is the ratio of number of nodes that receive the source's transmission to the total number of nodes in the network.

Note that these are important metrics when studying the performance of MANET routing mechanisms. In fact, these performance metrics are key to achieve our goal of designing protocols that are as reliable as flooding but incur less overhead (e.g., in terms of number of retransmissions).

3.1 Flooding's Probability of Successful Reception

We extend the analysis presented in Section 2 for determining CSMA's probability of success in the case of multi-hop transmissions via flooding. Our approach is to estimate the probability of successful reception by nodes as the flooding wave passes through the network. If we assume that the flooding wave terminates after each packet has been retransmitted a maximum of l hops (which can be determined from the network diameter), we can sum the number of nodes reached by each retransmission to obtain flooding's *reachability*.

In Figure 2, S is the source of the flooding packet. The average number of nodes within S's transmission region is N. The probability of a successful transmission from source S to any of its neighbors is P_s, as given by Equation 2.3.

Let N_s be the number of neighbors that receive the transmission from source S.

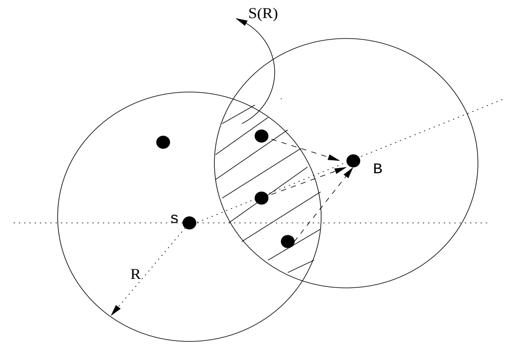


Figure 2: Intersection region for second level retransmissions

$$P(N_s) = \begin{pmatrix} N \\ N_s \end{pmatrix} {P_s}^{N_s}(1-P_s)^{N-N_s} \tag{3.1}$$

$$\bar{N_s} = E[N_s] = P_s N \tag{3.2}$$

Each of these $\bar{N_s}$ neighbors will further retransmit the packet. As shown in Figure 2, at the second level of re-transmission, nodes in the $S(R)$ region are the ones which can forward the packet to node B. The number of nodes in region $S(R)$ is given by

$$\begin{aligned} N_b &= \frac{S(R)}{\pi R^2}\bar{N_s} \\ &= \frac{P_s N}{\pi R^2}\left(2R^2 \text{acos}(\frac{r}{2R}) - r\sqrt{R^2 - \frac{r^2}{4}}\right) \end{aligned} \tag{3.3}$$

The expected value of the number of nodes in region $S(R)$ can be obtained by unconditioning on r and θ (θ is the angle made by the line joining the centers of node S and B with the X axis).

$$\begin{aligned} E[N_b] &= \bar{N_b} \\ &= \int_0^{2\pi}\int_0^R \frac{PsN}{\pi R^2}\frac{rdrd\theta}{\pi R^2}\left(2R^2 \text{acos}(\frac{r}{2R}) - r\sqrt{R^2 - \frac{r^2}{4}}\right) \\ &= P_s N \frac{2}{\pi R^2}\int_0^R \left(2\text{acos}(\frac{r}{2R}) - \frac{r}{R^2}\sqrt{R^2 - \frac{r^2}{4}}\right) rdr \end{aligned} \tag{3.4}$$

The probability that any node B at the second level of retransmission receives at least one copy of the source's packet successfully is

$$
\begin{aligned}
P_b &= \mathrm{P}\ (B\ receives\ at\ least\ 1\ copy/\ \bar{N}_b\ nodes\ Tx\ ) \\
&= 1 - \mathrm{P}\ (B\ receives\ no\ copy/\ \bar{N}_b\ ) \\
&= 1 - (1 - P_s)^{\bar{N}_b} \qquad (3.5)
\end{aligned}
$$

Similarly, the probability of successful reception at any retransmission level is also P_b.

3.2 Determining Flooding's Reachability

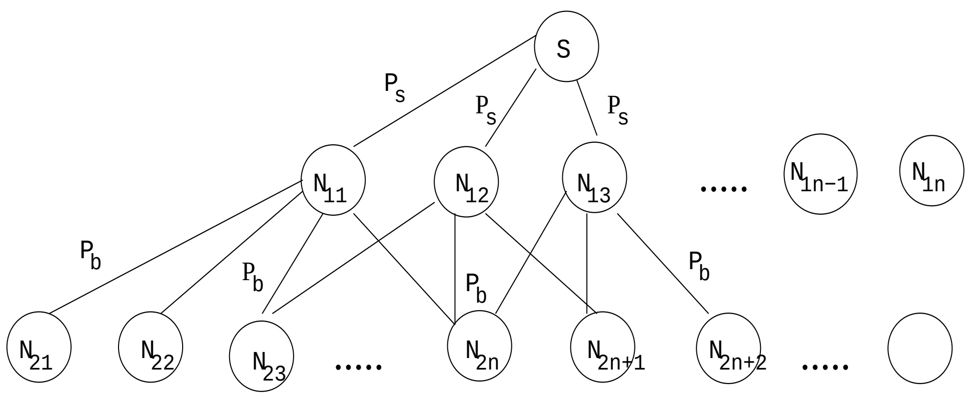


Figure 3: Reachability of flooding

We generalize the previous analysis to l retransmission levels (assuming each packet is retransmitted a maximum of l hops). Figure 3.2 schematically represents the first two retransmission levels, where S is the source of transmissions. At the first level, the number of nodes reached, or N_1 is given by

$$N_1 = P_s N \qquad (3.6)$$

In [12], it was shown that the area of coverage from the second retransmission significantly overlaps with the original transmission area. The expected increase in the coverage area achieved by the second retransmission (β) is around 41% of the original transmission. Hence, the number of nodes reached by the second level, N_2, is

$$
\begin{aligned}
N_2 &= \beta P_s N P_b N \\
&= \beta P_s N \left(1 - (1 - P_s)^{\bar{N}_b}\right) N \qquad (3.7)
\end{aligned}
$$

where β is the percentage increase in the coverage area. Similarly, at retransmission level l, N_l is

$$
\begin{aligned}
N_l &= P_s N (P_b N)^{l-1} \beta^{l-1} \\
&= P_s N \left(\left(1 - (1 - P_s)^{\bar{N_b}} \right) N \right)^{l-1} \beta^{l-1}
\end{aligned}
\tag{3.8}
$$

Assuming the flooding wave terminates after l hops, then flooding's reachability is measured by the total number of nodes receiving S's transmission N_T and is given as

$$
\begin{aligned}
N_T &= P_s N + P_s N \sum_{i=1}^{l-1} {P_b}^i N^i \beta^i \\
&= P_s N + P_s N \left(\sum_{i=0}^{l-1} {P_b}^i N^i \beta^i - 1 \right) \\
&= P_s N \frac{(P_b N \beta)^l - 1}{P_b N \beta - 1}
\end{aligned}
\tag{3.9}
$$

3.3 Determining Flooding's Reliability

If N_R is the total number of nodes in the network, then reliability of flooding can be estimated as

$$
\begin{aligned}
\text{Reliability factor} &= \frac{N_T}{N_R} \\
&= \frac{1}{N_R} \left(P_s N \frac{(P_b N \beta)^l - 1}{P_b N \beta - 1} \right)
\end{aligned}
\tag{3.10}
$$

4 Reliability and Reachability Analysis for Probabilistic Flooding

Recall that in plain flooding, each node always forwards packets it receives to all its neighbors. In probabilistic flooding, however, a node forwards packets according to some probability $p \leq 1$ (when $p = 1$ probabilistic flooding behaves exactly similar to plain flooding). By varying p, we can control the degree of redundant transmissions while maintaining network connectivity and thus ensuring data can get through. However, the main challenge in probabilistic flooding is to determine the critical probability

p_c which ensures that the network is statistically connected. For instance, in [13], the phase transition phenomena from percolation theory was used to determine p_c. Our premise is that, by adjusting p as a function of the conditions of the underlying network, we can achieve reliability similar to flooding at lower overhead.

4.1 Determining Probabilistic Flooding's Reachability

We consider that all nodes receiving the packet retransmit it with probability P_{tx} where $P_{tx} \leq 1$. With reference to Figure 2, in case of probabilistic flooding, out of the $\bar{N}_s$ neighbors that receive the packet from source S, only $\bar{N}_s P_{tx}$ will further retransmit the packet. Hence by similar analysis to equation 3.5, we can determine the probability that any node B at the second level of retransmission receives at least one copy of the source's packet successfully is

$$\begin{aligned} P_b &= \text{P}\ (\textit{B receives at least 1 copy/ } \bar{N}_b P_{tx} \textit{ nodes Tx}\ ) \\ &= 1 - \text{P}\ (\textit{B receives no copy/ } \bar{N}_b P_{tx}\ ) \\ &= 1 - (1 - P_s)^{\bar{N}_b P_{tx}} \end{aligned} \tag{4.1}$$

With reference to Figure 3, we assume each packet is retransmitted a maximum of l hops. At the first level, the number of nodes reached, or N_1 is given by

$$N_1 = P_s N \tag{4.2}$$

Out of the $P_s N$ nodes reached only $P_{tx} P_s N$ will retransmit the packet. Hence, the number of nodes reached by the second level of transmission, N_2, is

$$\begin{aligned} N_2 &= \beta P_{tx} P_s N P_b N \\ &= \beta P_{tx} P_s N \left(1 - (1 - P_s)^{\bar{N}_b P_{tx}}\right) N \end{aligned} \tag{4.3}$$

where β is the percentage increase in the coverage area as explained in section 3.2. Similarly, at retransmission level l, N_l is

$$
\begin{aligned}
N_l &= P_s N (P_b N P_{tx})^{l-1} \beta^{l-1} \\
&= P_s N \left(\left(1 - (1 - P_s)^{\bar{N}_b P_{tx}}\right) N P_{tx} \right)^{l-1} \beta^{l-1} \qquad (4.4)
\end{aligned}
$$

Hence for probabilistic flooding, the total number of nodes receiving S's transmission is N_T and is given as

$$
\begin{aligned}
N_T &= P_s N + P_s N \sum_{i=1}^{l-1} {P_{tx}}^i {P_b}^i N^i \beta^i \\
&= P_s N + P_s N \left(\sum_{i=0}^{l-1} {P_{tx}}^i {P_b}^i N^i \beta^i - 1 \right) \\
&= P_s N \frac{(P_{tx} P_b N \beta)^l - 1}{P_{tx} P_b N \beta - 1} \qquad (4.5)
\end{aligned}
$$

4.2 Determining Probabilistic Flooding's Reliability

If N_R is the total number of nodes in the network, then reliability of probabilistic flooding can be estimated as

$$
\begin{aligned}
\text{Reliability factor} &= \frac{N_T}{N_R} \\
&= \frac{1}{N_R} \left(P_s N \frac{(P_{tx} P_b N \beta)^l - 1}{P_{tx} P_b N \beta - 1} \right) \qquad (4.6)
\end{aligned}
$$

5 Validation and Simulation Results

In this section we validate our model using results obtained from a network simulator. We used `ns-2` as the simulation platform. `ns-2` is a popular discrete-event simulator which was originally designed for wired networks and has been subsequently extended to support simulations in mobile wireless (and MANET) settings. In particular, we use the CMU Monarch group's extensions that enable `ns-2` to simulate multi-hop MANETs [14]. Table 1 summarizes the simulation parameters used.

In our simulations, 10 nodes are selected as data sources. The mobility model chosen was a modified

Parameter	**Value**	**Description**
num-packets	250	packets sent by a node
bandwidth	2 Mbit/s	node's bandwidth
simulation-time	500 s	simulation duration
node-placement	random	node placement policy
propagation-func	Free-Space	propagation function
mac-protocol	802.11	MAC layer
transport-protocol	UDP	transport layer

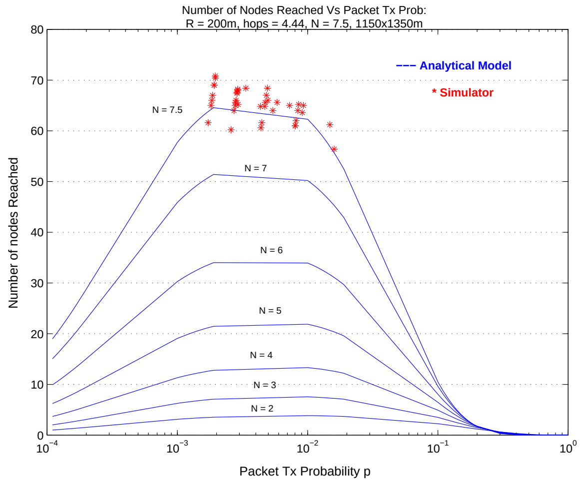
Table 1: Simulation parameters

version of the random waypoint model referred to as the bouncing ball model. In this mobility model, nodes start off at random positions within the field. Each node then chooses a random direction and keeps moving in that direction till it hits the terrain boundary. Once the node reaches the boundary it chooses another random direction and keeps moving in that direction till it hits the boundary again. All nodes moved with speeds between $v\_min = 2m/sec$ and $v\_max = 5m/sec$.

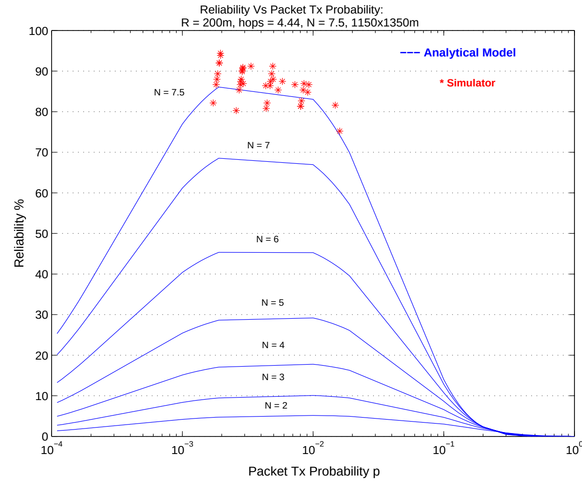
While in our analytical model, we assume that nodes are constantly transmitting, in the simulations we do not require that all nodes be traffic sources. Recall that in the flooding regime, all nodes re-broadcast data packets that they receive for the first time. If we assume that re-broadcasts by neighboring nodes are independent, we can treat these re-broadcasts as data transmissions. The assumption of independence can be somewhat justified by introducing a random jitter value between the time the nodes receive a data packet and the time they re-broadcast the packet.

A CBR traffic generator was attached to the sources and the data rate was varied from 0.5Kb/s to 10Kb/s. We implemented a simple *hello* message scheme to compute the average node neighborhood for each node. The average neighbor information and the average number of hops from the simulator were then used in the analytical model for comparison. Each point in the graph represents the average of 10 different seed values. We used 50 different traffic patterns to generate data points from the simulator.

It should be noted that the field size and total number of network nodes were chosen to ensure that the model and the simulator setup were matched as closely as possible. In the case of the simulator, fixing the total number of network nodes places an arbitrary upper bound on the reachability. However, this upper-bound may not necessarily be the same as reported by the model. Hence the total number of nodes and field size for the simulations are chosen to match the upper-bound on the total nodes reached, as obtained from the model for a particular field size.



(a) Reachability



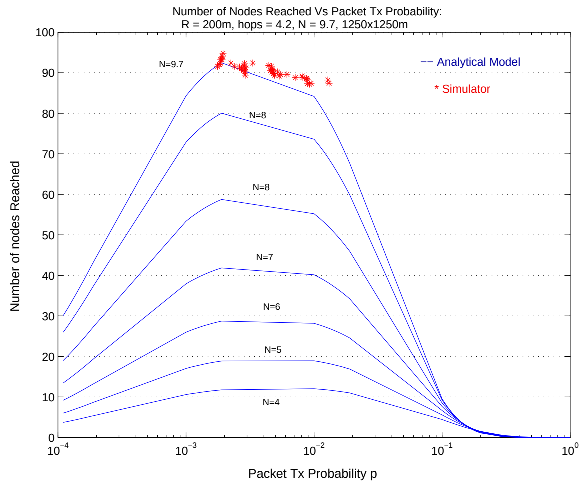
(b) Reliability

Figure 4: Flooding's reliability and reachability: 75 Nodes, 1150x1350m^2

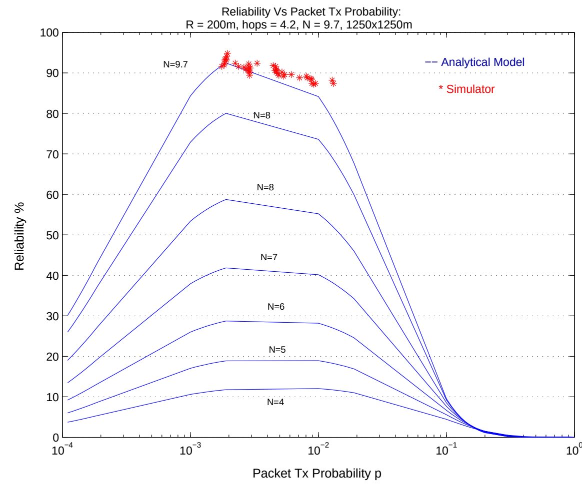
5.1 Results for Plain Flooding

Figure 4 shows the results obtained for a field size of 1150x1350m^2 comprising of 75 nodes, Figure 5 shows results for a field size of 1250x1250m^2 containing 100 nodes and Figure 6 shows results obtained for 150 nodes in a field size of 1500x1750m^2. The field sizes and the node speeds considered in the simulations could be typical of collaborative computing in an airport concourse environment or in emergency/disaster rescue scenarios. Although, we tried to vary the packet transmission probability p' by varying the packet size and the traffic rate, it is seen that typically the operating region for the simulator lies between 10^{-3} and 10^{-2}. This can be explained by the fact that the packet transmission probability is dependent on the rate at which traffic is being sourced into the network and also on the behavior of the 802.11 [15] MAC layer. As the traffic rate increases, the increased contention causes the back-off behavior of the MAC layer to reduce the actual transmission probability. From our simulations we observed that the normal operating region was between 10^{-3} and 10^{-2}.

From Figures 4(a), 5(a) and 6(a), it is observed that the simulated values for *reachability* seem to correspond to values obtained from the model. One difference between the simulator and the model is that in our implementation of flooding, we use a jitter mechanism to stagger re-broadcasts to prevent unnecessary collisions. However, the model assumes that after nodes receive a data packet they re-broadcast the packet immediately. This can result in the model having a conservative estimate of the probability of successful reception (P_b) as compared to the simulator.



(a) Reachability



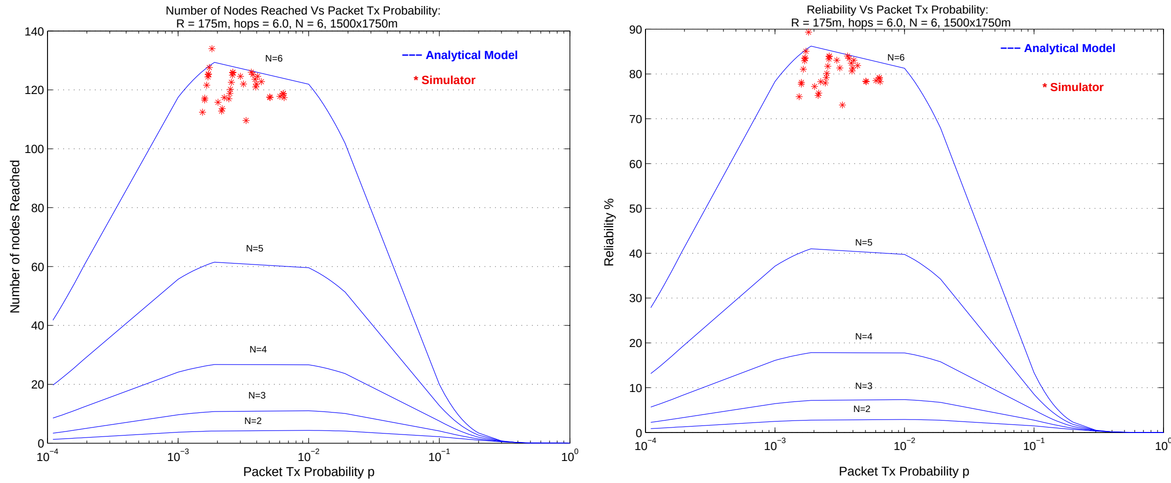
(b) Reliability

Figure 5: Flooding's Reliability and Reachability: 100 Nodes, 1250x1250m^2

Figures 4(b), 5(b) and 6(b) plot *reliability* as a function of the packet transmission probability.

The results from the simulator and model suggest that the reliability of flooding is dependent on the number of network nodes and total number of hops. In general as number of hops increases, the reliability of flooding decreases. This result is quite intuitive since data packets that are dropped at each hop on account of contention or collision are not propagated further. The downstream neighboring nodes may never receive a copy of the data packet and hence cannot forward it to their own downstream neighbors, reducing the inherent redundancy of the flooding mechanism. This effect accumulates over multiple hops, causing nodes which are farthest away from sources to receive a smaller number of packets as compared to nodes which are closer.

Another observation from the results is that reliability increases as number of neighbors increases, since nodes can potentially receive each packet from a larger set of neighbors. From the model it is seen that the maximum value of reliability is obtained when the packet transmission probability is between 0.01 and 0.001. The reliability starts decreasing with further increase in the packet transmission probability p'. As packet transmission rate increases there is a greater chance for contention and collision among nodes, reducing the probability of successful reception and also the total number of nodes that can be reached.



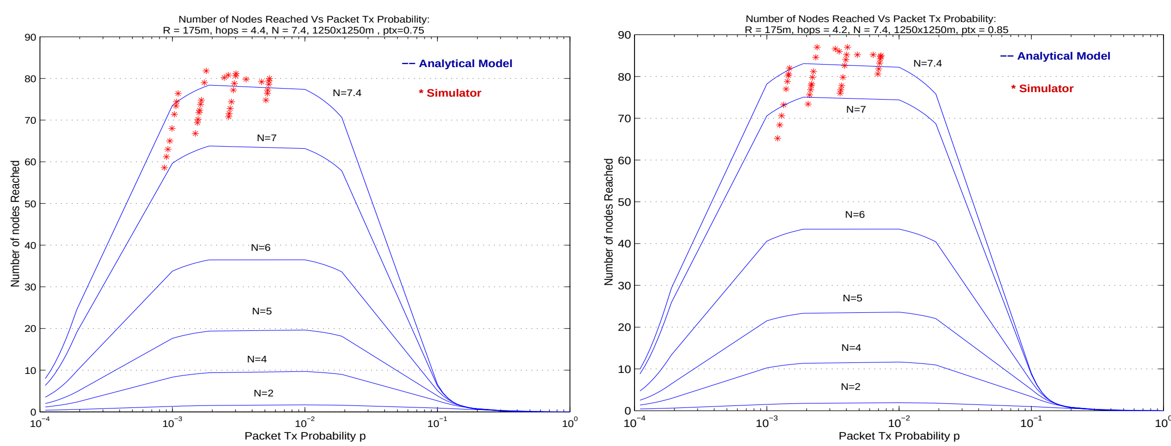
(a) Reachability

(b) Reliability

Figure 6: Flooding's Reliability and Reachability: 150 Nodes, 1500x1750m^2

5.2 Results for Probabilistic Flooding

The simulation setup for this set of experiments was similar to that of normal flooding. However, in this set of experiments the packet transmission probability p_{tx} was varied between 0.5 and 1 We present results for $p_{tx} = 0.75$ and $p_{tx} = 0.85$.



(a) Reliability: $p_{tx} = 0.75$

(b) Reliability: $p_{tx} = 0.85$

Figure 7: Reachability of Probabilistic Flooding : 100 Nodes, 1250x1250m^2

Figures 7(a) and 7(b) show the results obtained for a field size of 1250x1250m^2 comprising of 100 nodes for $p_{tx} = 0.75$ and $p_{tx} = 0.85$ respectively. Similar to the results from section 5.1, it is observed that the simulated values for *reachability* seem to correspond to values obtained from the model. One interesting observation from the results was that the average number of hops decreased slightly with the increase in the transmission probability p_{tx}. As p_{tx} increases, a greater number of intermediate nodes re-transmit packets. Hence it is more likely that packets reach destinations through more optimal paths resulting in a decrease in the average hop-count. Comparing the results of probabilistic flooding with normal flooding we see that the reachability of probabilistic flooding is quite similar to that of plain flooding. However, it should be noted that this reliability is obtained at a lower overhead. An interesting extension to this study would be to characterize this overhead in terms of the number of saved re-broadcasts and we are currently working on this aspect.

6 Conclusions and Future Work

In this paper, we have developed an analytical model for determining the *reachability* and *reliability* of flooding protocols in MANETs. We also extended the basic CSMA analysis presented in [10] to derive the probability of successful reception in multi-hop flooding. A network simulator was also used to provide some preliminary simulation results to validate the model. Our tests so far seem to indicate that the results for the analytical model correspond quite closely to those obtained from the simulator.

As mentioned previously, most MANET routing protocols have to flood network-wide during the route acquisition phase. Flooding is also used for signaling purposes such as paging mobile hosts, sending alarm signals and for location updates in routing. One major drawback of flooding is that it results in redundant broadcasts causing serious contention and collision problems and increasing routing overhead. This is especially harmful in resource-constrained MANETs. One technique to reduce the impact of network-wide flooding is to use scoped flooding [16] or probabilistic flooding [13]. In this paper we also proposed an analytical model for determining the reachability and reliability of probabilistic flooding. Our preliminary simulation results indicate that probabilistic flooding can provide similar reliability and reachability guarantees as plain flooding at a lower overhead (saved re-broadcasts). One interesting extension to this paper would be to characterize the lower overhead of probabilistic flooding in terms of the saved re-broadcasts compared to plain flooding. We are currently investigating this aspect. Scoped flooding [16] is another technique to reduce the number of re-broadcasts based on neighbor discovery. In [13] Sasson et al. have proposed a probabilistic form of flooding based on percolation theory. These flooding variants are the subject of our further analytical work.

One possible direction for future work is to develop a statistical approach for validation of our analytical model. We first plan to formulate a statistical model based on the assumptions of the analytical model, and fit it to data generated from the simulator. A bayesian approach to model fitting can be employed that captures the uncertainty due to unknown parameters of the model. The resulting posterior predictive distributions of quantities of interest (e.g., number of neighbors that receive the transmission from a source) can be used to formally address the fit of the statistical model and hence the validity of the analytical model.

References

[1] D. Johnson and D. Maltz, "Dynamic source routing in ad hoc wireless networks," in *Mobile Computing*, T. Imielinski and H. Korth, Eds. Kluwer Academic Publishers, 1996, ch. 5.

[2] C. Perkins and E. Royer, "Ad-hoc on demand distance vector routing," *Proceedings of the IEEE Workshop on Mobile Computing Systems and Applications (WMCSA)*, pp. 90–100, February 1999.

[3] M. Gerla and S. Lee, "On-demand multicast routing protocol for mobile ad-hoc networks," available from http://www.cs.ucla.edu/NRL/wireless/.

[4] W. Peng and X. Lu, "Ahbp: An efficient broadcast protocol for mobile ad hoc networks," *Journal of Science and Technology - Beijing, China*, vol. 16, no. 2, March 2001.

[5] H. Lim and C. Kim, "Flooding in wireless ad hoc networks," *Computer Communications*, vol. 24, no. 3-4, pp. 353–363, February 2001.

[6] T. J. Kwon and M. Gerla, "Efficient flooding with passive clustering (pc) in ad hoc networks," *ACM Computer Communication Review*, vol. 32, no. 1, January 2002.

[7] F. Borgonovo, A. Capone, M. Cesana, and L. Fratta, "Adhoc mac: a new mac architecture for ad hoc networks providing efficient and reliable point-to-point and broadcast services," *Wireless Networks (WINET)*, vol. 10, no. 4, pp. 359–366, July 2004.

[8] F. Tobagi, "Modeling and performance analysis of multihop packet radio networks," *Proceedings of the IEEE*, vol. 75, no. 1, pp. 135–155, August 1987.

[9] V. Li and T. Hou, "Transmission range control in packet radio networks," *IEEE Transactions on Communications*, vol. 34, no. 1, pp. 38–44, January 1986.

[10] L. Wu and P. Varshney, "Performance analysis of csma and btma protocols in multihop networks: Part 1–single channel case," *Information Sciences*, vol. 120, no. 14, pp. 159–177, 1999.

[11] H. Takagi and L. Kleinrock, "Optimal transmission range for randomly distributed packet radio terminals," *IEEE Transactions on Communications*, vol. Com-32, pp. 246–257, March 1984.

[12] S. Ni, Y. Tseng, Y. Chen, and J. Sheu, "The broadcast storm problem in a mobile ad hoc network," in *ACM MOBICOM '99*, August 1999.

[13] A. S. Yoav Sasson, David Cavin, "Probabilistic broadcast for flooding in wireless mobile," July 2002, technical Report 200254, Department of Computer and Communication Sciences, EPFL Lusanne.

[14] *Mobility Extensions to ns-2*, CMU Monarch Project, 1999, available from http://www.monarch.cs.cmu.edu/.

[15] I. C. S. L. M. S. Committee, "Wireless lan medium access control (mac) and physical layer (phy) specifications," IEEE Standard 802.11, 1997.

[16] K. Viswanath and K. Obraczka, "An adaptive integrated approach to group communications in multi-hop ad hoc networks," *IEEE Symposium on Computers and Communications (ISCC)*, 2002.