

Analysis of Packet Flooding in Dense MANETs using a Probabilistic Model

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Abstract—Flooding is a decisive aspect of mobile ad hoc networks. A number of efficient flooding schemes have been proposed to suppress redundant rebroadcasts as simple flooding causes broadcast storm problem. For example, a cellular automata based flooding scheme inspired by the organ growth control in cell biology is proposed in [1]. These protocols may fail to reach all the nodes for global broadcast in the process of suppressing the redundant rebroadcasts. Though the protocols are evaluated using simulations extensively it is essential to develop a robust theoretical model to analyze and compare performance of different flooding protocols. However there is only a little work in this area. In this research, we base on Viswanath-Obraczka [2] and the underlying Wu-Varshney [3] models that theoretically analyze reachability in multihop flooding in mobile ad hoc networks. We applied the model to a sample scenario and the analysis shows that flooding fails to reach all the nodes in the network in the presence of hidden terminal problem and collisions. The reachability was found to increase asymptotically with the increasing number of retransmission and the parameters can be tuned to improve the reachability.

Index Terms—MANET, Probabilistic Model, Reachability

I. INTRODUCTION

MANETs are characterized as networks of mobile nodes that communicate in a multi-hop manner without infrastructure support. Wireless links that comprise these networks are inherently error-prone due to wireless impairments such as interference and multi path propagation. MANETs are highly dynamic in terms of topology due to limited battery life, mobility of nodes with limited transmission ranges. MANET protocols are tested mostly by simulations due to unavailability of widely spread practical or testbed implementations and these studies are subjective and specific to the particular configuration used. Therefore a theoretical model is required to validate simulation results and also to compare results of different studies.

Flooding is a decisive aspect of MANETs. Simple flooding however causes broadcast storm problem and a number of efficient flooding schemes have been proposed to suppress redundant rebroadcasts. Flooding schemes are categorized into

probabilistic, counter-based, distance-based, location-based, and cluster-based [4]. Williams [5] further categorizes them as probability-based, area-based and neighbor knowledge based. There are counter based approaches such as [6] which combines counter based scheme with probabilistic approach, [7] which incorporates a dynamic threshold depending on node densities and [4] in which threshold is adjusted using a function depending on local connectivity information. A cellular automata based flooding scheme inspired by the organ growth control found in cell biology proposed in [1] is also a threshold driven counter based mechanism.

As a result of suppressing rebroadcasts these flooding mechanisms may compromise the reachability in the MANET in disseminating the messages. Therefore it is essential to develop a mathematical model to analyze reachability in MANETs in order to tune protocol parameters and compare performance of different flooding protocols. The reachability assessment or connectivity via mathematical models are also important in characterizing a given MANET topology.

There are a few attempts to model MANETs theoretically with the aim of analyzing reachability or connectivity in MANETs. The approaches are for example, combinatorial models like evolving graphs that capture dynamic nature over time [8][9], random graph models following percolation theory [10]. Combinatorial structures are systems that consist of many locally interacting components [11]. A trust computation system in a MANET based on local interactions and node cooperation is analyzed for the availability of a secure path, using phase transition phenomena in random graphs in [11].

Viswanath and Obraczka [2] proposed an analytical model to study the performance of plain and probabilistic flooding in terms of reliability and reachability. The network model they used is same as that used by Takagi and Kleirock [12] in obtaining the optimal transmission range of a node in a multi-hop wireless network. The multi-hop communication model proposed in [2] is also based on the probability of successful transmission in CSMA derived by Wu and Varshney [3].

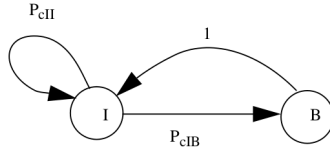


Fig. 1. Two state Markov chain model of a channel [3]

II. PRELIMINARIES

In order to understand the Viswanath-Obraczka model and the underlying Wu-Varshney model we will consider following components in this section referring to [2] and [3]:

- Physical network model with non-persistent CSMA as the multiple access technology
- Channel model of an individual node
- Transmission model from one node to another in the immediate neighborhood in the presence of hidden terminal problem
- Probability of successful transmission in multihop flooding

A. Physical network model with CSMA

a is the one way propagation delay for a wireless link. CSMA transmissions occur in time slots of a duration. A node is assumed to listen to its channel with a probability of p in a slot as a Bernoulli process. The probability of an actual transmission happening is p' . For an actual CSMA transmission to happen during a slot a node must listen to the channel and the channel must be idle during that slot. In order to assess the probability of sensing a channel to be idle a channel of an individual node is modelled as a two-state Markov chain as in figure 1.

B. Channel model of an individual node

According to figure 1 the channel of the node x , $CH(x)$ will transit from *idle* state to itself in the next time slot only if all its neighbors do not actually transmit during that slot. Hence the transition probability P_{cII} depends on the number of neighbors in the node's transmission range as follows:

$$P_{cII} = \sum_{i=0}^{\infty} (1-p)^i p(i) \quad (1)$$

where $p(i)$ is the probability of having i many neighbors in the transmission range

Steady state probability of state I is computed as follows because the only two ways that the process goes to state I is either from I to I with the probability P_{cII} or from B to I with the probability 1:

$$P_c(I) = P_c(I)P_{cII} + P_c(B)$$

Further, the following equation also holds for this two state Markov chain:

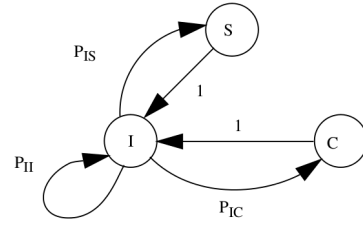


Fig. 2. Three state Markov chain model of a node [3]

$$P_c(I) + P_c(B) = 1$$

Therefore;

$$P_c(I) = \frac{1}{2 - P_{cII}}$$

According to the definition of limiting probability in Markov chains, the limiting probability of $CH(x)$ being in state I is:

$$P_{cI} = \frac{D_I P_c(I)}{D_B P_c(B) + D_I P_c(I)}$$

where D_I and D_B are the time durations that the process stays in Idle and Busy states respectively.

$$p' = pP_{cI}$$

C. Transmission model of a node

A node is also modelled as a Markov chain in transmitting a packet to any one of its immediate neighbors. The Markov chain is as in figure 2.

The three states are *idle state* (I), *successful transmission state* (S) and *collision transmission state* (C).

A node x leaves the state I with probability p' or remains in state I with probability $(1 - p')$. Therefore:

$$P_{II} = 1 - p'$$

The steady state probabilities follow the following expression:

$$P(I) = P(I)P_{II} + P(C) + P(S)$$

Following equation also holds:

$$P(I) + P(C) + P(S) = 1$$

Therefore:

$$P(I) = P(I)P_{II} + 1 - P(I)$$

$$P(I) = \frac{1}{1 + p'}$$

As shown in figure 3 $N(x)$ is the hearing region of the node x , $N(y)$ is the hearing region of node y . $C(r)$ is the

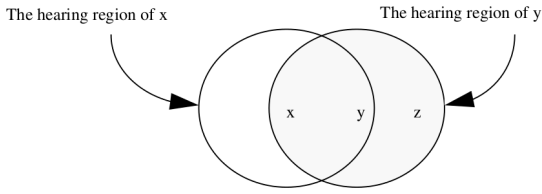


Fig. 3. Hidden terminal problem example [3]

area of the region $N(x) \cap N(y)$ and $B(r)$ is the area of the region $N(y) - N(x)$. A transmission from node x to y that are r distance apart will be successful when x transmits in a slot, y does not transmit during that slot, nodes in $C(r)$ do not transmit during that slot and nodes in $B(r)$ do not transmit for $2\tau+1$ slots according to the requirements of CSMA. Therefore the probability of node x having a transition from state I to S during a transmission from x to y (denoted by $P_{IS}(r)$) depends on all these conditions. Each probability has to be calculated according to the node distribution.

The transition probability P_{IS} for node x is:

$$P_{IS} = \int_0^R f(r) P_{IS}(r) dr \quad (2)$$

where $f(r)$ is the probability density function of the distance, r between x and y . Also,

$$P(S) = P(I) P_{IS} \quad (3)$$

Limiting probability of successful transmission:

$$P_S = \frac{D_S P(S)}{D_S P(S) + D_I P(I) + D_C P(C)} \quad (4)$$

D. Probability of successful transmission in multihop flooding

Viswanath and Obraczka [2] expand the work of Wu and Varshney [3] to determine the probability of CSMA's successful transmission in multihop flooding. They estimate the probability of successful reception of data by nodes in a MANET when the flooding wave passes through the network. The model assumes that the flooding wave terminates after each packet is retransmitted a maximum of l hops and l is determined by the diameter of the network. The *reachability* is given by the sum of nodes reached by each transmission.

According to Figure 4, S is the source. N is the average number of nodes in the S 's transmission region. Probability of successful transmission by S to any one of its neighbors is P_S given by Equation 4.

If N_S is the number of neighbors that receive the transmission from S , then the probability of successful transmissions to N_S nodes from S is:

$$P(N_S) = \binom{N}{N_S} P_S^{N_S} (1 - P_S)^{N - N_S}$$

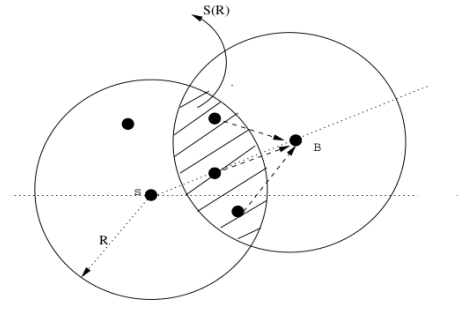


Fig. 4. Second level retransmission [2]

$$\bar{N}_S = E[N_S] = P_S N$$

$\bar{N}_S$ is the number of neighboring nodes that will retransmit the received data. Out of these $\bar{N}_S$ nodes only the retransmissions of those nodes in the region $S(R)$ will reach node B . Number of nodes in the region $S(R)$ is denoted by N_b .

$$N_b = \frac{S(R)}{\pi R^2} \bar{N}_S$$

$$\bar{N}_b = E[N_b]$$

$P_b = P(\text{B receives at least one copy of data} / \bar{N}_b \text{ nodes transmit})$

$$P_b = 1 - P(\text{B receives no copy} / \bar{N}_b)$$

$$P_b = 1 - (1 - P_S)^{\bar{N}_b}$$

The probability of successful reception at any retransmission level is P_b .

E. Reachability of Flooding:

The above analysis is then extended to l levels of retransmissions. The number of nodes reached by the transmission of the source is N_1 given by:

$$N_1 = P_S N$$

N_2 is the number of nodes newly reached by the second transmission and it is given by:

$$N_2 = \beta P_b N N_1$$

$$N_2 = \beta P_b N P_S N$$

Here β is the expected percentage increase in the coverage of nodes as the second transmission will have a significant overlap with nodes covered by the first transmission.

$$N_3 = (\beta P_b N)^2 P_S N$$

Similarly,

$$N_l = (\beta P_b N)^{l-1} P_S N$$

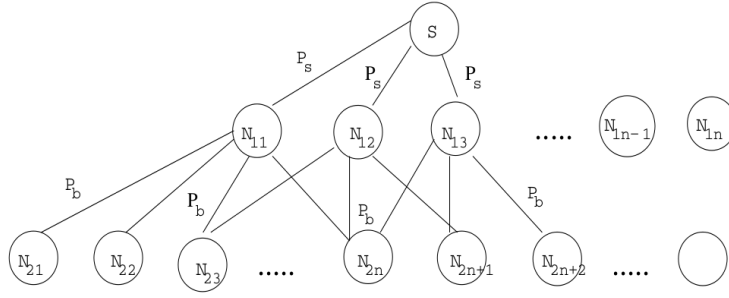


Fig. 5. First two retransmissions of flooding [2]

Therefore the reachability of flooding is:

$$N_T = \sum_{i=1}^l N_i$$

$$N_T = P_S N + P_S N \sum_{i=1}^{l-1} (\beta P_b N)^i$$

F. Notation

$CH(x)$ is the channel of the node x

$p(i)$ is the probability of having i many neighbors in the transmission range of a node

T is the packet transmission time

a is the one way propagation delay for a wireless link and is the duration of a time slot

$\tau = \frac{T}{a}$ is the number of slots required for a packet to get transmitted. Packet size is assumed to be common and fixed for all nodes.

p probability of listening to the channel during a slot by a node

p' probability of an actual transmission happening during a slot

D_j is the mean time spent in state j per cycle in a Markov chain

r is the distance between x and y

$N(x)$ is the hearing region of x 's transmission and $N(y)$ is the hearing area of y 's transmission

$C(r)$ is the area of the region $N(x) \cap N(y)$

$B(r)$ is the area of the region $N(y) - N(x)$

$|N(x)|$ is the area of the region $N(x)$

III. ANALYSIS OF SIMPLE FLOODING

We analyze simple flooding using the proposed mathematical model for the case of every node in the network having the same number of constant neighborhood. For the simplification we will consider the parameter values in Table I.

Viswanath-Obraczka model assumes heavy traffic condition so that the nodes do not idle because there are no packets to send. It is assumed that nodes always have packets to send therefore the idle periods are all mandatory idling required by CSMA.

In the heavy traffic condition considered in Viswanath-Obraczka model, all the nodes are assumed to have packets to

TABLE I
MODEL PARAMETERS

Parameter	Value	Description
Listening probability, p	0.01 to 0.02	In the simulated heavy traffic scenario it entails only 1 to 2% probability of listening with no intention to transmit
Packet transmission time, T	1	A unit time is selected
Transmission ranges, R	1	Unit disk of transmission range is selected
Slot duration, a	0.1	Packet transmission time is assumed to be divided into 10 slots of equal duration

be sent all the time. When the channel of an individual node is considered it will transit from Idle to Busy state with some probability and will stay Busy for T amount of time for the packet to be transmitted. Soon after transmitting the packet, channel must come back to Idle to allow for the propagation of last chunk of the packet for a slot period a . Therefore in this traffic model D_I is a and D_B is T . However, in flooding a single data packet the traffic model differs and the channel has to go back to Idle again and again and therefore stay Idle for more than one slot of a duration when there are no data available for sending. Therefore D_I for this case is $a + \gamma a$ where γ is a positive integer and γ varies according to the traffic model with heavy traffic condition represented by $\gamma = 0$.

$$D_I = a + \gamma a$$

$$D_B = T \quad (5)$$

A. Constant neighborhood scenario

Assume that each node in the MANET has exactly N neighbors all the time. Therefore;

$$p(i) = \begin{cases} 1, & i=N \\ 0, & \text{otherwise} \end{cases}$$

Therefore, according to Equation 1 the transition probability, P_{cII} from state I to itself is;

$$P_{cII} = (1 - p)^N$$

$$P_c(I) = \frac{1}{2 - (1 - p)^N}$$

$$P_{cI} = \frac{D_I P_c(I)}{D_B P_c(B) + D_I P_c(I)}$$

According to Equation 5;

$$P_c(I) = \frac{(a + \gamma a) P_c(I)}{T(1 - P_c(I)) + (a + \gamma a) P_c(I)}$$

$$P_c(I) = \frac{a(1 + \gamma)/(2 - (1 - p)^N)}{T(1 - 1/(2 - (1 - p)^N)) + a(1 + \gamma)/(2 - (1 - p)^N)}$$

$$P_c(I) = \frac{a(1 + \gamma)}{T(1 - (1 - p)^N) + a(1 + \gamma)}$$

$$p' = \frac{ap(1 + \gamma)}{T(1 - (1 - p)^N) + a(1 + \gamma)}$$

According to the node model in Figure 2;

$$P_{II} = 1 - p'$$

$$P(I) = \frac{1}{1 + p'}$$

$P_{IS}(r)$ is the transition probability from Idle state to Successful Transmission state in the Markov chain model of a node given in Figure 2 when a node x sends a packet to node y that are r distance apart from each other.

$$P_{IS}(r) = \frac{\text{Prob}(x \text{ transmits in a slot}). \text{Prob}(y \text{ does not transmit in the same slot} | r). \text{Prob}(\text{nodes in } C(r) \text{ region do not transmit in the same slot} | r). \text{Prob}(\text{nodes in } B(r) \text{ do not transmit in } 2\tau + 1 \text{ slots} | r)}{\text{Prob}(x \text{ transmits in a slot}). \text{Prob}(y \text{ does not transmit in the same slot} | r). \text{Prob}(\text{nodes in } C(r) \text{ region do not transmit in the same slot} | r). \text{Prob}(\text{nodes in } B(r) \text{ do not transmit in } 2\tau + 1 \text{ slots} | r)} \quad (6)$$

Neighbors are assumed to be uniformly distributed within the communication range of a node. Therefore the probability $p(i)$ of having i nodes within the $C(r)$ region;

$$p(i) = 1 \text{ where } i = \frac{NC(r)}{\pi R^2} \text{ and } 0, \text{ otherwise}$$

The probability that none of the nodes in $C(r)$ region transmits;

$$P_c(r) = (1 - p)^{\frac{NC(r)}{\pi R^2}}$$

Similarly

$$P_b(r) = (1 - p)^{\frac{NB(r)}{\pi R^2}}$$

From Equation 6;

$$P_{IS}(r) = p'(1 - p) P_c(r) (P_b(r))^{2\tau+1}$$

$$P_{IS}(r) = p'(1 - p) (1 - p)^{\frac{NC(r)}{\pi R^2}} (1 - p)^{\frac{NB(r)}{\pi R^2} (2\tau+1)}$$

Referring to [12];

$$C(r) = 2R^2 q\left(\frac{r}{2R}\right)$$

$$B(r) = \pi R^2 - 2R^2 q\left(\frac{r}{2R}\right)$$

where

$$q(t) = \arccos(t) - t\sqrt{1 - t^2}$$

Therefore;

$$P_{IS}(r) = p'(1 - p)^{(1+(2\tau+1)N - \frac{4\tau N}{\pi} q(\frac{r}{2R}))}$$

Node x can choose any of its neighbors with equal probability. Nodes are assumed to be uniformly distributed within the region $N(x)$, therefore the probability density function of the distance between x and y is given by;

$$f(r) = 2r, 0 < r < R$$

Then, the transition probability P_{IS} for node x by considering all possible locations of its neighbors according to Equation 2

$$P_{IS} = \int_0^R 2rp'(1 - p)^{(1+(2\tau+1)N - \frac{4\tau N}{\pi} q(\frac{r}{2R}))} dr$$

from Equation 3

$$P(S) = \frac{\int_0^R 2rp'(1 - p)^{(1+(2\tau+1)N - \frac{4\tau N}{\pi} q(\frac{r}{2R}))} dr}{1 + p'}$$

Equation 4 gives limiting probability of successful transmission as follows where $D_S = D_C = T$, $D_I = a$ and $P(C) + P(S) + P(I) = 1$:

$$P_S = \frac{TP(S)}{T(1 - P(I)) + aP(I)}$$

$$P_S = \frac{T \int_0^R 2rp'(1 - p)^{(1+(2\tau+1)N - \frac{4\tau N}{\pi} q(\frac{r}{2R}))} dr}{Tp' + a}$$

After solving the above equations numerically and then using the set of equations in Section II-E the reachability was calculated for a 100-node network described in Section IV.

IV. RESULTS AND DISCUSSION

Consider a grid of 10×10 nodes distributed equi-distant manner, with unit transmission range. Distance between nodes is 1 units and the neighborhood is 8 consistently for all nodes and thus results in constant neighborhood scenario. Each node is assumed to listen to the channel with a probability, p randomly chosen in the range 0.01-0.02 given in Table I. The resulting probability of successful transmission with CSMA was around 3%. A major finding of this research is that flooding fails to reach all nodes in the presence of collisions and hidden terminal problem with CSMA.

According to theoretical results in Figure 6 it is observed that the reachability has no upper bound defined in the theoretical model because the reachability definition in the model depends only on local neighborhood parameters without considering the total number of nodes.

In parallel to the theoretical model we also simulated a similar scenario in OMNET++ with the CSMA implementation of MiXiM. The simulation parameters are given in Table II. The

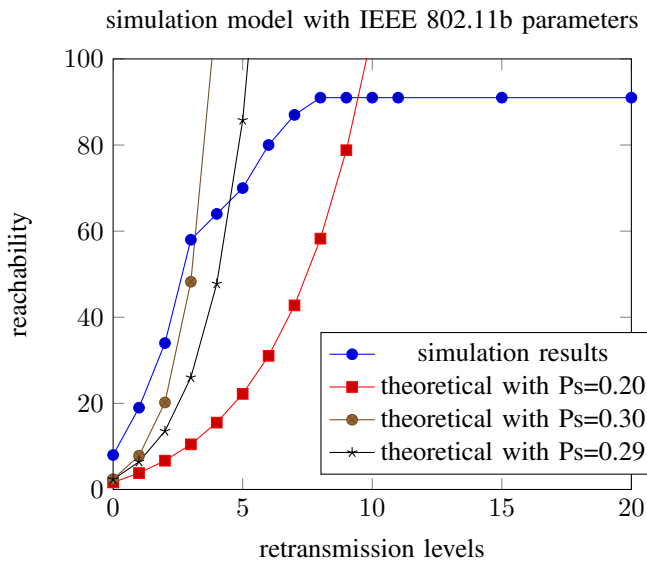


Fig. 6. Reachability with level of retransmission for a 100-node network

TABLE II
SIMULATION PARAMETERS BASED ON IEEE 802.11b

Parameter	Value
Packet length	14600 bits
Bit rate	5.6 Mbps
Maximum transmission power	100 mW
Slot duration	20 μ s

resulting reachability plot against the number of retransmission levels is in also shown in Figure 6.

The simulation results asymptotically arrives at 90 nodes with the increasing number of retransmission levels. Accordingly we can conclude that no additional nodes are reached beyond 8 retransmissions and it is advisable to inhibit retransmissions after this number. For a flooding protocol that operates with an associated retransmission inhibition mechanism, to control broadcast storm problem above threshold can be used to initiate the inhibition scheme.

The theoretical results closely follow the simulation results in the region of increasing reachability, only when the probability of successful transmission in CSMA is around 30%.

V. CONCLUSION

Flooding in MANETs requires a rigorous mathematical treatment but little work is available to fulfil this requirement. In this study, we used a probabilistic model derived in [2] and [3] and analyzed the reachability of a sample MANET scenario in a 100-node network for the case of constant neighborhood. It was observed that in the presence of hidden terminal problem and collisions around 90 nodes could be reached according to the simulation. Further, the reachability was shown to asymptotically increase with the increasing levels of retransmission and a threshold is available for a given MANET topology for optimum reachability. It is advisable

to suppress retransmissions beyond that threshold to control broadcast storm problem.

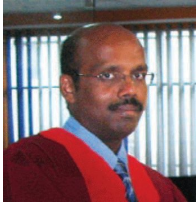
Both the theoretical and simulated studies provide a reachability behaviour of similar characteristics during the region of increasing reachability when there is a successful transmission probability of around 30% in the theoretical model. However, parameters resulted in a successful transmission probability of around 3%. This significant difference needs to be resolved through further analysis of both the theoretical model and the simulation model. For the theoretical model to be complete an upper bound for reachability must also be derived depending on the total number of nodes.

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