Probabilistic Broadcast for Flooding in Wireless Mobile Ad hoc Networks

Yoav Sasson David Cavin André Schiper
{yoav.sasson,david.cavin,andre.schiper}@epfl.ch

École Polytechnique Fédérale de Lausanne (EPFL)
1015 Lausanne, Switzerland

***Abstract*— Although far from optimal, flooding is an indispensable message dissemination technique for network-wide broadcast within *mobile ad hoc networks* (MANETs). As such, the plain flooding algorithm provokes a high number of unnecessary packet rebroadcasts, causing contention, packet collisions and ultimately wasting precious limited bandwidth. We explore the phase transition phenomenon observed in percolation theory and random graphs as a basis for defining probabilistic flooding algorithms.**

By considering *ideal* and *realistic* models, we acquire a better understanding of the factors that determine phase transition, the consequences of the passage to realistic MANET conditions and to what extent we may benefit from probabilistic flooding in real MANET networks.

I. Introduction

Mobile ad hoc networks (MANETs) are self-organizing mobile wireless networks that do not rely on a preexisting infrastructure to communicate. Nodes of such networks have limited transmission range, and packets may need to traverse multiple other nodes before reaching their destination. Research in MANETs was initiated 20 years ago by DARPA for packet radio projects [13], but has regained popularity nowadays due to the widespread availability of portable wireless devices such as cell phones, PDAs and WiFi / Bluetooth enabled laptops.

Because of the ever-changing topology of MANETs, broadcasting [19] is a fundamental communication primitive, essential to ad hoc routing algorithms (e.g., [20], [5]) for route discovery. The usual approach for broadcasting is through flooding. Flooding is well suited for MANETs as it requires no topological knowledge. It consists in each node rebroadcasting a message to its neighbors upon receiving it for the first time.

Although straightforward, flooding is far from optimal and generates a high number of redundant messages, wasting valuable limited resources such as bandwidth and energy supplies. Besides research mentioned in Section II, more effort has been devoted to defining MAC and routing algorithms adapted to MANETs, than to flooding. Since flooding is a low-level primitive, optimizing it will drastically improve the overall performance of MANETs.

One direction to optimize flooding is to take a probabilistic approach. In order to flood, a node in the network broadcasts a message with probability p and takes no action with probability $1-p$. In our paper we explore the possibility of applying a phenomenon well studied in percolation theory and random graphs, *phase transition*, as a basis for selecting p. Above a certain threshold for p, in graphs of a certain size for random graphs and lattices of a certain density for percolation, an *infinite spanning cluster* abruptly appears instead of a set of finite clusters. An *infinite spanning cluster* is a unbounded connected component, which if transposed to a MANET would translate in the very high probability of the existence of a multi-hop path between any two nodes within the network.

To the best of our knowledge, besides [12], previous publications having studied probabilistic broadcast for flooding in MANETs [6], [16] have not done so within the context of phase transition. This paper contributes in a first stage to a better understanding of the various factors that influence phase transition in ideal MANET environments (no packet collisions). By opposition to traditional theoretical phase transition analysis and simulation, we specifically consider factors that would typically intervene within probabilistic algorithms deployed on MANETs. In a second stage, we illustrate the consequences of considering realistic effects such as packet collisions and node mobility. To the contrary of [12], we concentrate on pure flooding in order to understand the variations in performance due solely to the parameters simulating realistic MANET environments. Our results therefore provide a general understanding of the behavior to be expected from probabilistic flooding.

The remainder of the paper is organized as follows. Section II gives an overview of other works that seek to reduce the overhead of flooding in MANETs. In Section III we introduce the *phase transition* phenomenon, known results, and how it may benefit flooding in MANETs. In Section IV we present two models for which we study the phase transition behavior. Section V contains simulations and results of our algorithms. Finally, we conclude and describe future work in Section VI.

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II. Related Work

In this section we examine related work which directly or indirectly aims at reducing the number of broadcast packets generated by the flooding algorithm.

The high number of redundant broadcast packets due to flooding in MANETs has been referred to as the *Broadcast Storm Problem* in [16]. The paper proposes several schemes, of which one probabilistic, in order to reduce the number of broadcast packets while maintaining high reliability. More recently, [6] provides a comparative study of broadcasting algorithms, including probability based methods. Given the scenarios and results in these two papers, it is difficult to make any statement regarding phase transition (Section III).

As for deterministic studies of the problem, [18] and [15] make use of local topology knowledge in order to avoid unnecessary rebroadcasts by comparing the added coverage between the rebroadcast of a destination node to that of the source node at each hop. [18] enhances the algorithm by taking into consideration statistical information about broadcast duplicates, whereas [15] enhances the algorithm by taking into account two-hop coverage. [21] restricts flooding to a subset of nodes ("multipoint relays") by selecting for each node a minimum number of one-hop neighbors covering all second-hop neighbors. [17][1] and more recently [23] (with an optimized approach) explore the idea of superimposing a communications graph — a *cluster* — over the network so that only particular nodes rebroadcast the packets. Albeit reducing the number of rebroadcast packets, constructing and maintaining the clusters introduce a new source of overhead in a mobile network.

Other fields such as *percolation theory* and *random graphs* have recently been a source of inspiration for designing solutions within MANETs. Both are based on a probabilistic model and exhibit an interesting phenomenon called *phase transition*. They will be presented in more detail in Section III.

Phase transition has been applied to reduce traffic for multicast in wired networks [2], to study optimum power ranges for connectivity [3], [11] and for enhancing connectivity in hybrid MANET/Wired networks [7]. Only recently however, and in parallel with our research, have characteristics from these fields been applied to reduce flooding in MANETs:

- [14] points out that the phase transition phenomenon also occurs in MANETs and may be taken advantage for the elaboration of probabilistic algorithms such as flooding and routing within such networks.
- [12] studies a gossip-based approach to flooding. Through simulations the authors show that for large networks, a simple gossiping uses up to 35% fewer messages than flooding, and that the performance of AODV routing [20] relying on gossip-based flooding is improved even in small networks of 150 nodes.

This paper is based on the same inspiration as [14] and [12], yet we obtain different results and gain a better understanding of the phase transition behavior.

[1]The goal of this paper is primarily to provide *reliable* broadcast delivery.

III. The Phase Transition Phenomenon

A *phase transition* is a phenomenon where a system undergoes a sudden change of state: small changes of a given parameter in the system induces a great shift in the system's global behavior. This abrupt transition occurs at a specific value p_c called the *critical point* or *critical threshold*. Below p_c the system is said to be in a *subcritical phase* — the global behavior is non-existent. Above p_c the system is in a *supercritical phase* and the global property may be almost surely observed. Figure 1 illustrates the phase transition probability θ given the probability p of a problem specific parameter λ. L denotes the size of the system considered.

It would be extremely cost-efficient to observe phase transition in a probabilistic flooding algorithm within all or known subsets of MANET topologies. The implication within such cases would be that there exists a certain probability threshold $p_c < 1$ at which the flooded message will almost surely reach all nodes within multihop broadcast reach. Broadcasting with a probability $p > p_c$ will not provide any significant improvement. We now present two areas of research where phase transition applies in order to extract models for MANETS in Section IV and study their phase transition properties.

A. Percolation Theory

Percolation theory studies the flow of fluid in random media and has been generally credited as being introduced in 1957 by Broadbent and Hammersley [4]. Two main two-dimensional lattice square percolation models are studied, *site* percolation and *bond* percolation. In the bond percolation model (Figure 2(a)), each edge of the lattice is said to be *open* with probability p and *closed* with probability $1-p$. The fluid flows through the open edges of the lattice. The site percolation model on the other hand considers the lattice squares or sites to be the relevant entities (Figure 2(b)): A lattice site is open with probability p and closed with probability $1-p$, and the fluid flows from open site to open site across the lattice. Figure 2(b) illustrates an example of site percolation with $p \simeq 0.55$.

Phase transition in percolation models is observed as the change of state between having a *finite* number of clusters and having one *infinite* cluster. A cluster is a set of connected entities (edges for bond percolation and sites for site percolation). A cluster that reaches from one side of the lattice to the other is said to be an *infinite cluster*. Percolation theory

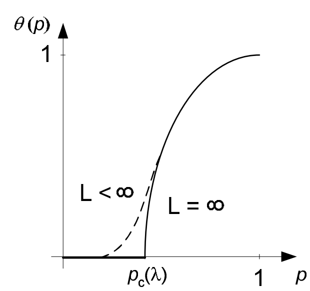


Fig. 1. Phase Transition

studies the existence and value p_c for which phase transition occurs, as well as cluster numbers, sizes and structures.

Percolation theory has numerous interesting applications to cases which involve some form of propagation or connectivity such as the spreading of infectious diseases with regard to population density or the spreading of forest fires. The question is whether results may also be derived for message propagation within real-world MANETs.

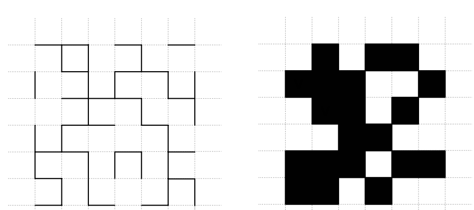
Great effort within percolation theory has been devoted to finding the exact value of p_c at which the phase transition occurs. Unfortunately, p_c is not universal but specific to each lattice geometry. Besides a few distinct cases, there is no general analytical formula to obtain p_c, which is usually computed case by case through Monte Carlo simulations.

B. Random Graphs

Another predominant area of research for phase transition is *Random Graphs*. A random graph G is a graph where the number of nodes, edges and connections between them are determined in some random manner. The phase transition property has been well studied in the context of random graphs. Erdős and Rényi [8] have shown that the probability of a random graph being connected tends to 1 if the number of edges E is greater than $p_c(E) = \frac{N\,logN}{2}$. Although the results of Erdős and Rényi are for large values of N, Frank and Martel have shown by simulation in [9] that phase transition occurs also in graphs of moderate size (between 30 to 480 vertices). In other words, we may view $p_c(E)$ as a critical value for the number of edges above which a phase transition will occur, resulting in a quick convergence for obtaining a connected graph. As such, we are not able to use random graphs to represent MANETs: In random graphs, an edge may connect any two vertices's in the euclidean plane. In MANETs however, communication links connect nodes that are within communication range only. In Section IV-B we describe the *Fixed Radius Model* which is an ideal representation of MANET topologies. It remains a question whether results as in [8], [9] may be observed in the fixed radius model.

C. Discussion

Phase transition properties depend greatly on the graph geometry. There is no general theoretical result that enables us to determine the critical threshold p_c at which the transition will take place, if at all. Therefore p_c will have to somehow be approximated. Furthermore, the few results we have from percolation theory are for *infinite* lattices ($L = \infty$). As we take smaller configurations ($L \ll \infty$), the transition from the subcritical to the supercritical state becomes less abrupt. The dashed tail of the graph in Figure 1 illustrates that in non infinite lattice configurations, the probability of percolation taking place becomes linear. We must therefore determine graph characteristics for which border effects are not significant.



(a) Bond Percolation (open edges are in bold) (b) Site Percolation (open sites are in black)

Fig. 2. Bond and Site Percolation

IV. Applying Phase Transition to Flooding

Similarly to wired networks, we may model a MANET by a graph. Let $G = (V, E)$ be an undirected graph. A vertex $v_i \in V$ represents a mobile node, and an edge $e_{ij} \in E$ means that the nodes i and j are within communication range of each other. Within this paper we assume that all mobile nodes possess the same constant transmission range, and do not consider other properties such as energy levels or consumption.

Given a broadcast source node S, let G_B be the connected subgraph of G representing all nodes that will receive the broadcast message by flooding ($S \in G_B$) (Figure 3). Since the message reaches all the nodes in the graph, G_B may be thought of as an *infinite open cluster* as defined in Section III-A. An efficient probabilistic algorithm will remove edges from G_B while still remaining above G_B's percolation threshold p_c, thus maintaining the infinite open cluster. By remaining in the supercritical phase, we expect to observe a significant reduction of message traffic due to flooding while minimizing the loss of reachability.

We must however ultimately take into consideration that real-world MANETs differ from mathematical graphs on several points. The differences that impact phase transition properties are:

1) Typical real-world MANETs as we see them are not infinite but may be composed of a few tens to a few thousand nodes. Border effects may therefore eventually impact the system's behavior.
2) Nodes may join or leave the network for various reasons, constantly modifying the network's density over time. This directly affects the network's phase transition properties.
3) Packet loss: Packets within a MANET are lost due to packet collisions and contention as well as node

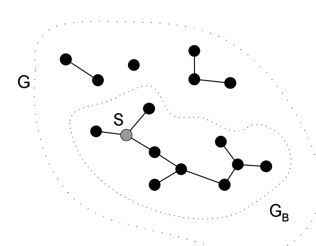


Fig. 3. G_B Subgraph

mobility. In percolation theory there is no loss of "fluid".

We now consider two models as a basis for studying the above points. The first model is quite simplistic but is nonetheless useful for extracting best-case results for a specific MANET topology, as we show that it may be reduced to a well studied percolation case with known theoretical results. Through the second and more realistic model any MANET topology may be represented.

A. Square Grid Model

We define the square grid model as follows. Consider a $m \times m$ square grid with nodes placed at each intersection as illustrated in Figure 4(a). Each node communicates with is direct vertical and horizontal neighbors, such that each node has exactly four neighbors. We broadcast one message from a single source positioned at the center of the grid. Using the regular algorithm for flooding in order to achieve our broadcast, a total of m^2 messages will be transmitted (Algorithm 1).

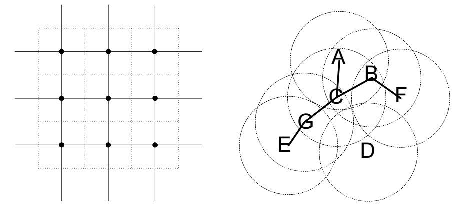
Let's now consider a probabilistic approach. Instead of systematically rebroadcasting a message upon receiving it for the first time, we slightly modify Algorithm 1 in order to rebroadcast the message with a probability p (Algorithm 2). The exception is the source that broadcasts always ($p = 1$) to initiate the flooding. With Algorithm 2 and besides the non-probabilistic broadcast source, our case becomes equivalent to the site percolation on the plane square lattice as described in Section III-A. Indeed, since p is constant throughout the flooding operation, and has the same value at all nodes, it is like saying that we initially decide to remove links from the graph with probability p, and then executing a regular non-probabilistic flooding operation. The threshold value for percolation in such a case is known to be $p_c \simeq 0.59$ [22]. We furthermore note that there has been no loss of generality by assuming that all sites are populated, as flooding with probability p_f on a grid of occupation probability p_o is equivalent to site percolation on the square lattice of occupation probability $p_f * p_o$. By choosing $p > p_c$ for Algorithm 2, we expect to observe an infinite open cluster, translating in our flooding reaching nearly all nodes in the graph.

Algorithm 1 flood(m)

upon reception of message m at node n:
if message m received for the first time **then**
  broadcast(m) {this is the basic local broadcast primitive to nodes within range only}
end if

Algorithm 2 p-flood(m,p)

upon reception of message m at node n:
if message m received for the first time **then**
  broadcast(m) with probability p {this is the basic local broadcast primitive to nodes within range only}
end if



(a) Square Grid Model (b) Fixed Radius Model

Fig. 4. Models

B. Fixed Radius Model

The previous model is useful for reducing a particular MANET configuration to a well studied percolation model in order to compare results. Unfortunately, the model only enables us to consider particular graphs of maximum node degree 4. A general model adapted to MANETs may be defined as follows. Let R be the nodes' communication range. The nodes are randomly placed on an $m \times n$ area according to a probability distribution such as *Poisson*. A link l_{ij} connecting nodes i and j is added to the graph if the Euclidean distance between the nodes is less than R. We have thus obtained *fixed radius random graph* as described in [14] and illustrated in Figure 4(b). We must however note an that probabilistic flooding in such a model implies that a node may choose not to broadcast a message to all its neighbors within range with probability $1 - p$, resulting in the "fluid" not flowing in *any* of the links attached to the node using percolation terminology. In random graph models, edges are added or removed independently.

V. Simulation and Results

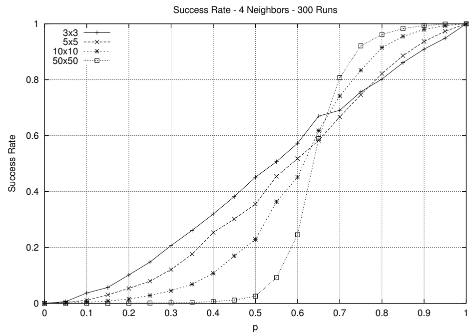
Given the two models presented in Section IV, we are interested in analyzing the phase transition properties of probabilistic flooding as defined in Algorithm 2. Throughout the cases, we define the *success rate SR* as the ratio of distinct packets received at each node by the total number of distinct packets broadcast in the network, averaged across all nodes.

A. Probabilistic Flooding with Ideal Network Conditions

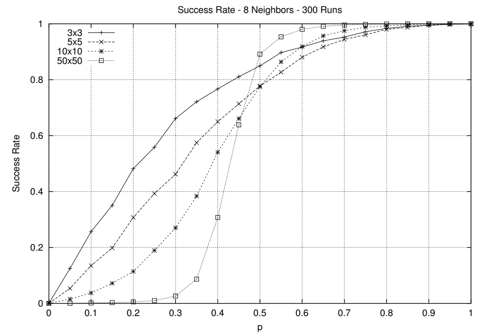
The motivation behind our first series of simulations is to obtain best case results. We have written a discrete event simulator in Java to simulate the Square Grid Model described in Section IV-A. Mobility is not considered, and the wireless medium is collision-free. We measure the success rate of probabilistic flooding for a single packet broadcast at the center of 3×3, 5×5, 10×10 and 50×50 size square lattices. The center broadcasts with probability $p = 1$, and we consider lattices of average node degrees 4 and 8. Figure 5 presents the results for simulations averaged over 10 and 300 runs.

We conclude from the results in Figure 5 that there are three factors that affect the phase transition properties in our chosen scenarios: network size, average node degree, and the number of simulation runs over which the success rate is averaged.

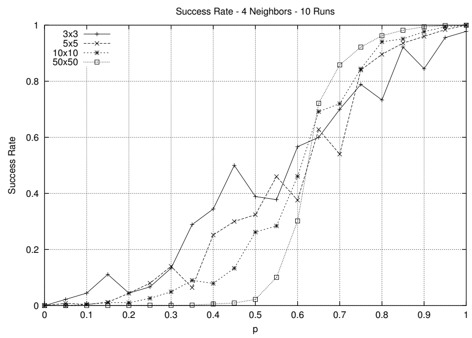
Network Size: In all four graphs phase transition becomes apparent as of 100 nodes (10×10 lattices). The success rate



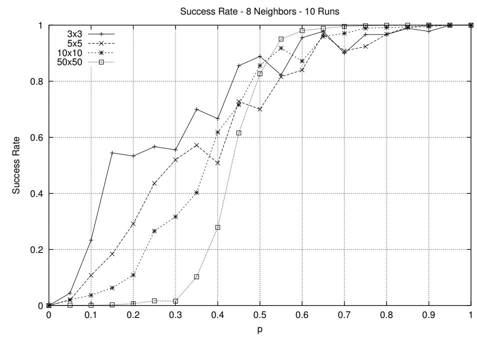
(a) 4 Neighbors



(b) 8 Neighbors



(c) 4 Neighbors



(d) 8 Neighbors

Fig. 5. Ideal network (no collisions): success rate for probabilistic flooding in $n \times n$ square lattice configurations with no collisions as a function of the broadcast probability p

graphs tend to become linear as the number of nodes in the network decreases, due to boundary effects.

Average Node Degree: Higher success rate values are obtained for lower values of p when the average node degree is of 8 instead of 4. A potentially interesting and exploitable result is that success rates of over 90% are achieved as "early" as $p \geq 0.65$ for small networks in absence of phase transition (linear success rate curves).

Number of Simulation Runs: The success rate average curves become less robust to the number of simulation runs as the number of nodes considered decreases. We observe nonetheless in Figure 5(d) that in this case likewise a high average node degree compensates for a small number of simulation runs, even for small networks.

The main result of this series of simulations is that for higher average node degrees, probabilistic flooding may be used to significantly reduce the amount of broadcast packets *even* for small size networks and in absence of phase transition. This result is obtained in an ideal case of a perfectly symmetrical topology, no packet collisions and an absence of node mobility. The question is whether and how is the success rate and phase transition affected by network conditions of realistic MANETs.

B. Probabilistic Flooding with Realistic Network Conditions

We now examine node distribution and topology corresponding to the Fixed Radius Model described in Section IV-B. We have used the ns2 network simulator [1] to simulate various scenarios for probabilistic flooding. We have considered small to medium-sized networks of 9, 25 and 100 nodes with little to no mobility using the 802.11b MAC layer [10] in DCF mode. Due to the large number of simulations conducted and ns2's limited scalability, simulation duration for potentially significant larger networks would have been prohibitive. Node transmission ranges of 150 and 250 meters and simulation areas of $0.25km^2$ and $1km^2$ were chosen to vary network density. Note that the 802.11b MAC layer specification uses CSMA/CA and enforces RTS/CTS/ACK control frames for unicast communication only. Collision control for broadcast is limited to basic collision avoidance carrier sensing and broadcast is therefore extremely prone to packet collisions. A straightforward tweak to reduce collisions is to have nodes wait for a random small amount of time before rebroadcasting (*JITTER*). We had $\sqrt{N}$ broadcast sources emit a maximum of one hundred 64 byte packets at constant bit rate with an interval of 0.05 second, where N is the total number of nodes in the network. The radio model is ns2's default, which simulates Lucent's WaveLAN wireless card with a 2Mb/sec bit rate. Simulation duration is of 30 seconds. Figures 6 and 7 present the success rate for the various scenarios while varying the probabilistic flooding probability p. In order to evaluate the MANET connectivity, we have displayed the upper bound for success rate when relevant. This upper bound was obtained by running the simulations with regular flooding ($p = 1$) over a collision-free *ideal* MAC layer. The ideal success rate is of 1.0 in the highly dense networks represented by Figure 7, and has therefore been omitted from the plots.

We observe that probabilistic flooding behaves differently for low density and high density networks. For low density networks as illustrated in Figure 6 the success rate varies linearly with regard to p, regardless of the number of nodes and packet rate considered. A purely probabilistic approach for flooding is therefore inefficient.

Upon augmenting the network density by raising the power range from 150m to 250m, we notice that the success rate graph resembles a bell curve, with the maxima reached for lower values of p as the network becomes more dense (Figure 7). The observation is explained by the fact that a sufficiently high value for p is necessary to perpetuate the flooding. Beyond an ideal value p_{ideal} for p however, packet collisions become more frequent and the overall network performance degrades from this point onward. The value p_{ideal} is as low as 0.1 in Figure 7. In all scenarios, a mobility of $5m/s$ has little effect on the success rate.

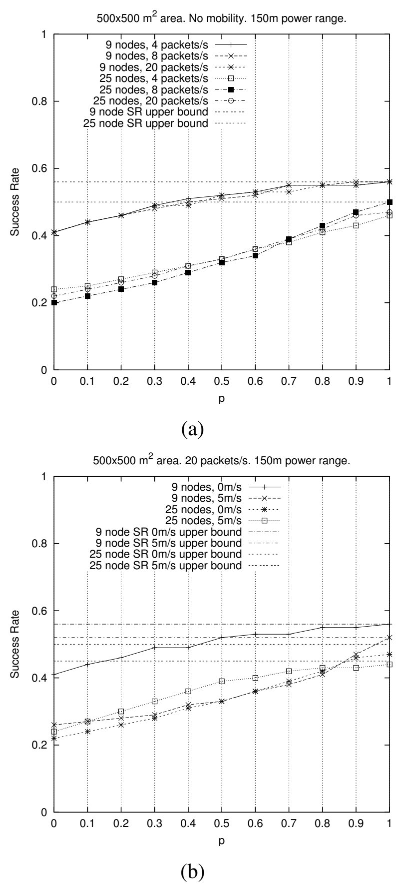


Fig. 6. Realistic network: probabilistic flooding success rate for 9 and 25 nodes of 150m power range

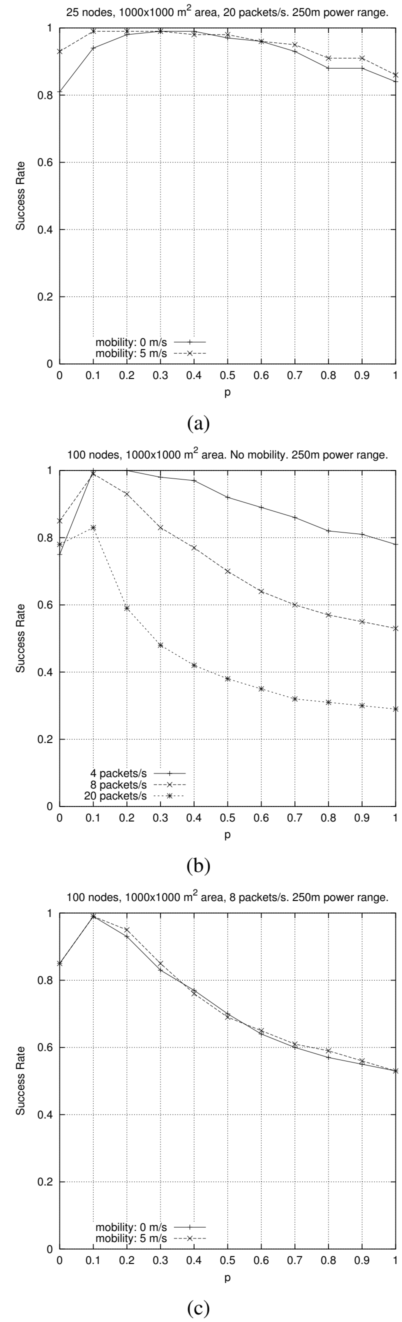


Fig. 7. Realistic network: probabilistic flooding success rate for 25 and 100 nodes of 250m power range

VI. Summary and Future Work

We have studied a purely probabilistic approach to flooding attempting to exploit the phase transition phenomenon. Our results show that there is a major difference between the behavior obtained in ideal situations inspired from random graphs and percolation theory and simulations undertaken in MANETs prone to packet collisions. For the latter, the success rate for probabilistic flooding does not exhibit a bimodal behavior as percolation theory and random graphs would suggest. The success rate curve for probabilistic flooding tends to become linear for MANETs of low average node degree, and resembles a bell curve for MANETs of high average node degree. Although phase transition is not observed, probabilistic flooding nonetheless greatly enhances the successful delivery of packets in dense networks.

For future work, it would be interesting to explore algorithms in which nodes would dynamically adjust the probability p for probabilistic flooding based on local graph topology information. In our paper we have made the assumption that all nodes possess the same transmission range. Another potential area for study would be to understand within probabilistic flooding the combined effects on MANETs performance of modifying the nodes' transmission range r with regard to p.

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