# Evaluating the Impact of Faults on Broadcasting Protocols for MANETs*

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***Abstract.*** *Broadcasting in* MANET*s is a fundamental building block for dealing with routing and reaching consensus. In this kind of network, faults are commonplace. In spite of this, existing broadcast protocols are not adequate to deal with failures present in a real world scenario, such as link failures, network partitions, topology change during broadcasts and momentary node failures. Moreover, the ones that are capable of dealing with faults, are not suitable for* MANET*s. In this paper, we conduct simulations in order to evaluate the impact of faults on* MANET *broadcasting protocols under various network scenarios and situations. Although previous studies show that these protocols are very mobile resilient and support well congestion and collisions, the study conducted here show that they are not capable of supporting omission faults. In presence of this type of faults, they are unable to provide a high delivery rate of messages.*

## 1. Introduction

A mobile ad hoc network (MANET) is a special kind of network where the mobile hosts (also called nodes) are capable of communication restricted to their wireless transmission range. Thus they are only able to communicate directly with neighboring nodes. The lack of fixed and wired gateways (base stations) forces cooperation between the nodes every time a packet has to be forwarded. Moreover, because of the shared transmission channels, nodes are not able to selectively transmit: whenever it sends a message, all of its neighbors receive it. Whenever messages overlap, collisions may occur preventing correct reception [Mohapatra et al. 2004, Goldsmith and Wicker 2002, Lou and Wu 2002, Ray et al. 2005]. Self-organization, full decentralization, shared transmission channels and high dynamicity are the main characteristics of these systems [Basile et al. 2003].

Because of the dynamic topology of MANETs, broadcasting is fundamental to ad hoc routing algorithms for route discovery and management [Sasson et al. 2001, Lim and Kim 2000, Wu and Dai 2005, Williams and Camp 2002]. Broadcasting is an active research topic and the most significant challenge in its development is the tradeoff between the number of messages broadcast and the number of nodes reached [Zhang and Agrawal 2005]. Since every transmission uses energy, an added challenge to any broadcasting protocol is to reduce the number of redundant transmissions while reaching all possible nodes. On one hand, a large number of re-transmissions will result in a larger number of nodes reached, but so will the chances of collisions and possibly transmission delays rise as well. On the other hand, when too small of a number of re-transmissions is chosen there is a potential risk of not all nodes being reached.

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There exists a large number of solutions for broadcasting in MANETS. They are usually classified into two approaches: *probabilistic* and *deterministic*. Both approaches select a small group of nodes, commonly called *gateway* or *forward* nodes, who are to retransmit the broadcast message. The probabilistic approach tend to offer simple solutions but at a cost of redundant messages, while the deterministic approach is capable of a better delivery rate with less redundant messages.

Yet finding these forward nodes does not guarantee a complete broadcast due to indication that mobility is the major cause of message delivery failure [Wu and Dai 2005, Pagani and Rossi 1999, Lou and Wu 2002]. If members of the MANET have high mobility, chances are that many messages will fail to be delivered. Earlier work has assumed that one way to reduce the mobility related problems is to use a link that endures communication for a longer time [Gerharz et al. 2002, Lim et al. 2002]. What has been validated from those studies is the use of past perceived behaviour as a measure of expected lifetime [Gerharz et al. 2002]. But this notion of link stability has always been related to link duration, and not necessarily to whether messages are being forwarded correctly or not.

With the number of applications for wireless ad hoc networks growing quickly, a demand for communication protocols that are able to handle frequent link failures and changing network topology will rise. As will the need for more reliable connections between two or more mobile nodes in order to guarantee a certain degree of quality of service. The few papers that exist on reliable delivery of messages by mobile nodes either assume the existence of some kind of infrastructure [Pagani and Rossi 1999, Kermarrec et al. 2003, Nett and Schemmer 2003], require constant communication adjustments [Wu and Dai 2005, Vollset and Ezhilchelvan 2003] or simply have too high of a computational burden, thus are not usable in MANETs. Indeed, most broadcast algorithms assume that during the process there happens none or very little topology change and that the network remains connected. But in a real scenario, this cannot be guaranteed. This is what motivates our work.

As we discussed, there exists protocols that offer reliability guarantees in spite of failures, but these are not suitable for MANETs. On the other hand, the protocols made for MANETs ensure weak guarantees of delivery in presence of faults. Thus, as a first step in order to develop a reliable fault tolerant broadcast protocol for MANETs, we decided to conduct a study of how current broadcasting protocols behave in a fault injected scenario.

As far as we know, no performance study about the impact of faults in broadcasting protocols has ever been done taking in consideration a real world scenario. Previous studies have limited themselves on analyzing the impact of mobility, collisions and network congestion on the delivery rate (reliability) and on the number of gateway nodes (efficiency) [Dai and Wu 2004, Williams and Camp 2002]. Although these three factors can be considered as faults, they are not sufficient to denote all the possible fault scenarios that affect MANETs such as link failures, network partitions, topology change during broadcasts and momentary node failures. This is one of the reasons we have chosen to use an omission failure model. Previous works consider fail-stop failures and most broadcasting protocols are tolerant to these types of failure. The omission failure model appropriately represents real fault scenarios.

We evaluate the impact of faults on the performance of five significant broadcasting protocols. These are: *blind flooding*, *dynamic probabilistic protocol* [Zhang and Agrawal 2005], *Wu and Li´s protocol's* with and without the application of rules [Wu and Li 1999] and *scalable broadcasting algorithm* (SBA) [Peng and Lu 2000]. They were evaluated by means of discrete event simulations, with the support of the *NS-2* simulator, under various network scenarios and situations.

Our simulation studies consists of measuring the reliability (delivery ratio), the efficiency (number of gateway nodes), the congestion and collision (dropped packets) and the end-to-end delay of the protocols when $0\%$, $5\%$, $25\%$ and $50\%$ of the nodes fail. Although previous simulated studies show that the broadcast protocols are very mobile resilient and support well congestion and collisions, the study conducted here show that these protocols are not fault tolerant when omission failures are taken into account. They are unable to provide a consistent delivery of messages when in presence of these kind of faults.

This paper is organized as follows. In Section 2, MANETs are characterized. Section 3 describes the protocols in study. Section 4 presents the metrics, explains the implementation of the omission fault model, the scenarios and the results. Section 5 concludes and presents future works.

## 2. Preliminaries

A MANET is a graph $G = (V, E)$ in which $V$ represents a set of mobile nodes and $E$ represents a set of edges. Whenever two nodes $x$ and $y$ are within their wireless transmission range, an edge $(x, y)$ is used to symbolize this, and they are considered neighbors. $N(x)$ represents all the 1-hop neighbors of $x$ and in this case $y \epsilon N(x)$. Connectivity between nodes is then clearly based on geographical distance. A node can obtain its neighborhood information by periodically sending and exchanging "hello" messages. By sending "hello" messages containing not only the node identification but also its list of neighbors, receiving nodes can learn the topology information within 2 hops. For simplicity, we will assume that all nodes are homogeneous, i.e., every node has the same wireless transmission range and the corresponding graph will be bidirectional. We also assume that nodes are battery operated, having a limited power supply. We assume no previous knowledge of mobility patterns except that movement has some upper bound $V_{max}$ on speed.

As can be seen in the network shown in figure 1(a), the transmission range of any node is indicated by a circle surrounding the node. The graph in figure 1(b) represents the network shown. If a network consisted of nodes all within each others wireless transmission ranges, broadcasting would be simple. But, take for example a message $m1$ broadcast from node $n1$. Since its only neighbor is node $n2$, in order for $m1$ to reach all nodes, the message must be retransmitted by $n2$, by $n3$ and finally by $n4$. But unless nodes $n5$ and $n6$ have knowledge of some part of the network, or are told not to, they will unnecessarily retransmit the message.

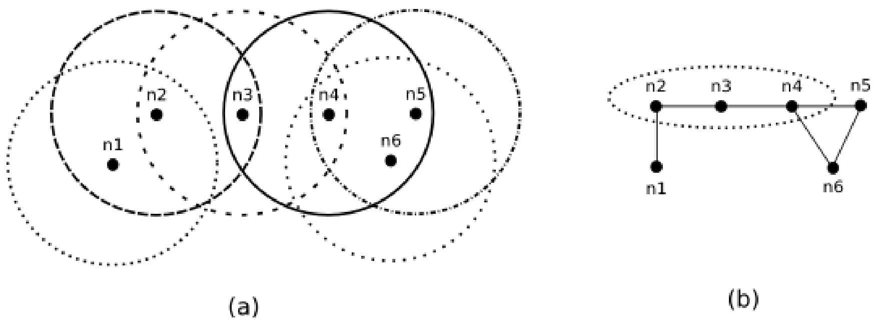


**Figure 1. An ad hoc wireless network and the corresponding graph.**

## 3. Description of Protocols

Broadcasting refers to the process by which one node sends messages to all other nodes in the network. Existing approaches aim to select a small group of nodes who are to forward the broadcast message (commonly called *gateway* nodes). If the topology of the network is known and static, the problem of finding these nodes with the smallest overhead of retransmissions is very similar to the problem of finding the minimum connected dominating set (MCDS) [Lim and Kim 2000]. An MCDS is the smallest set of forwarding nodes such that every node in the set is connected, and all nodes which are not in the set are within transmission range of at least one node in the MCDS. Once found, the process of forwarding messages can be handled by the nodes within the set. In figure 1(b), the MCDS is formed by nodes $n2$, $n3$ and $n4$.

Since the problem of finding a MCDS has been proven to be NP-complete [Zhang and Agrawal 2005, Guha and Khuller 1996, Lim and Kim 2000], the use of efficient approximation algorithms is necessary, like for example Berman's algorithm [Guha and Khuller 1996]. Unfortunately, this and many other solutions rely on global network topology information. Since MANETs are dynamic in nature, global information exchange such as link/node states and routing tables, are no longer reasonable to expect and support. Nodes must somehow limit themselves to local information on topology in order to broadcast.

The solutions for broadcasting in MANETs are usually classified in two approaches: *probabilistic* and *deterministic*. The probabilistic approach [Sasson et al. 2001, Zhang and Agrawal 2005, Luo et al. 2004] tend to offer simple solutions where each node determines whether or not it is a gateway based on a probability *r*. The value of *r* is determined individually by each node, and when well chosen, a high ratio of delivery can be obtained. Unfortunately, this approach does not guarantee message delivery to all nodes (*coverage*) and relies on the inherent redundancy to reach all nodes. Reliability and fault-tolerance is assumed because of the high redundancy [Kermarrec et al. 2003].

The deterministic approach [Lou and Wu 2002, Lim and Kim 2000, Wu and Dai 2005, Wu and Li 1999, Pagani and Rossi 1999, Huang et al. 2004, Jüttner and Magi 2004] uses knowledge of local topology to determine the gateways. By periodically sending *"hello"* messages, nodes are able to construct a local view of their neighbors. Unfortunately, this information can (and probably will) be imprecise and inconsistent, since between any two *"hello"* messages, a node may move, its neighbors may crash, a link may become unstable or many other situations may rise.

In spite of the name, the deterministic approach when applied to "real world" conditions (with mobility, contention and collision of messages), cannot guarantee complete coverage. Instead, it is capable of a better delivery rate with less redundant messages. Due to indication that mobility is the major cause of message delivery failure [Wu and Dai 2005, Pagani and Rossi 1999, Lou and Wu 2002], the existing protocols offer reliable communication by analyzing node movement and adjusting communication parameters (signal strength and transmission range, for example). As far as we know, no protocol deals with omission faults in an explicit manner. In the literature, the few proposals that concentrate on reliable message delivery by mobile nodes [Pagani and Rossi 1999, Kermarrec et al. 2003] can not be used in MANETs since they assume the existence of an infrastructure.

The protocols we analyzed will now be described. They are: blind flooding (section 3.1), dynamic probabilistic protocol (section 3.1), Wu and Li´s protocol with and without rules 1 and 2 (section 3.2) and scalable broadcasting algorithm (SBA) (section 3.3). After each description, we quickly comment on their hability (or lack of) to tolerate faults and mobility.

### 3.1. Dynamic Probabilistic Approach

One of the simplest solutions to broadcasting is blind flooding - where every node forwards every message received exactly once. It has been observed to cause serious redundancy, contention and collision problems. This has been published as the *broadcast storm* problem [Ni et al. 1999]. In order to reduce the number of forward nodes, one solution proposed in [Ni et al. 1999] is that each node be inhibited from re-transmission based on a probability $P$. Clearly, when $P = 1$ it will behave as blind flooding. Most approaches to probabilistic broadcasting assume a fixed probability [Ni et al. 1999, Williams and Camp 2002]. Another option proposed in [Ni et al. 1999] was to use a counter to keep track on the number of times a message has been received. If after a random delay the counter equals an internal counter threshold, it is assumed that the message has been received by all neighbors and the node will not re-transmit. Thus, in a dense area of the network, some nodes will not rebroadcast, while in sparse areas of the network, all nodes rebroadcast.

Zhang and Agrawal, on the other hand, proposed a dynamic probabilistic approach [Zhang and Agrawal 2005]. Their approach combines the probabilistic approach with the counter based approach and dynamically adjusts the value of $P$ according to the density of the network. The re-transmission probability $P$ is lowered whenever a node is positioned in a high-density area, while it is raised when in sparser areas. Network density is estimated by using an internal counter - the counter increases whenever a node receives a message and decreases after every time interval $t$ passes. A high counter value infers that the number of neighbors is high, while a low counter value a small number of neighbors. Their algorithm assumes that the network topology does not change drastically so that the probability calculated can be a reasonable approximation of the optional probability for the next packet transmission. This, unfortunately, is only the case for networks where movement speed is low. This and the following algorithms all assume that the nodes are uniform (omni-directional antenna and same transmission range) and that the wireless channels is shared by all nodes and can be accessed by any node at any time.

## 3.2. Wu and Li

Wu and Li [Wu and Li 1999] proposed an efficient and distributed algorithm to calculate a set of forward nodes that form a connected dominating set. Their *marking process* is simple and relies on constant neighborhood set exchange between nodes: a node is marked as a gateway if it has two neighbors that are not directly connected. It uses a constant number of rounds to calculate the connected dominating set (CDS), which is directly related to the number of neighbors each node has. Clearly, after neighborhood set exchange, each node knows its 2-hop neighbors. Additionally, they also introduce two prunning rules in order to reduce the CDS. *Rule 1* states that a gateway looses its gateway status whenever all of its neighbors are also neighbors of another gateway with a higher priority (priorities are determined based on id and node degree). The priority values are used in order to establish a total order among all nodes of the MANET. *Rule 2* affirms that whenever the neighbors of a gateway node is covered by 2 other nodes that are connected and with higher priorities, than it will become a non-gateway node.

According to the authors, the resultant dominating set includes nodes of the shortest path. But, in an ad hoc environment where the nodes are free to move, the shortest path tends to be the most unstable (prone to link failure) [Lim et al. 2002]. This is not taken into consideration by Wu and Li and no guarantees are ever made that a gateway is forwarding the messages nor is the delivery of any message ensured.

## 3.3. Scalable Broadcast Algorithm (SBA)

The main idea of the broadcasting algorithm proposed by Peng and Lu [Peng and Lu 2000] is that a node does not need to rebroadcast a message that already has been received by neighboring nodes. In order to determine this, each node needs to have knowledge of local 2-hop topology and of duplicate messages. Their algorithm is divided in 2 steps: local neighborhood discovery and data broadcasting.

The first step consists of exchanging neighborhood sets between local nodes, and, very much like the protocol proposed in [Wu and Li 1999], 2-hop topology is learned. In the second step, whenever a node $t$ receives a message $m$ from node $v$, before re-transmitting, it checks which nodes belong to $v$ neighborhood. Since $v$ transmitted, node $t$ knows all the nodes that should have received the message $m$. By looking at its own neighborhood set, $t$ can determine if there are still any other neighbors which have not received $m$. Only when there exists neighbors in this situation will $t$ schedule a re-transmission. But, if the initial transmission of $m$ already reached all the neighbors of $t$, the redundant re-transmission is unnecessary and can be canceled. Instead of immediately re-transmitting, the authors proposed a random backoff delay based on the density of the neighborhood. Nodes with more neighbors will have a higher priority and will rebroadcast earlier. Thus, a node that is waiting for the delay period to expire is able to receive the broadcast of a higher priority node and can possibly cancel re-transmission if all of its neighbors receive the message.

One drawback of SBA is that it requires up-to-date neighborhood information. Without it, unfortunately, a node that is receiving a message will erroneously calculate its forward status. But even with perfect topology information, due to mobility and failures, a node has absolutely no guarantees that the same message arrived at the other nodes. The backoff delay also has the drawback of longer overall delay to transmit messages.

### 3.4. Protocols in Study

Blind flooding and dynamic probabilistic protocol are, in our opinion, good representations of the probabilistic approach and were chosen for their high redundancy. Blind flooding seemed a natural choice for its simplicity while dynamic probabilistic for its novel approach for dynamically setting the rebroadcast probability.

The other three protocols are deterministic and were chosen for their efficient use of neighborhood information and for their good simulation results [Wu and Li 1999, Peng and Lu 2000]. Wu and Li´s protocol has been used and extended by many others [Dai and Wu 2003, Dai and Wu 2004, Wu and Dai 2004], and although the extensions themselves have better simulation results, they are more complicated to understand and implement. Finally, we chose SBA for its dynamic use of the neighborhood information.

## 4. Description of Studies

**The Metrics.** In order to evaluate the performance and behavior of the broadcast protocols when in a fault injected environment we have defined four metrics with which we have divided the simulation studies. The metrics are reliability (delivery ratio), efficiency (number of gateway nodes), congestion and collision (dropped packets) and end-to-end delay. A high delivery ratio is the primary goal of any broadcast protocol, thus reliability is the most significant metric. It will demonstrate not only if the broadcast protocol in question does what it is supposed to do, but will help to show how each protocol deals with failure.

Efficiency is given by the number of gateway nodes that re-transmit. Thus an efficient broadcast protocol is one that has the lowest number of gateways, which in turn will lead to a lower number of packets and consequently to less congestion and collision. Obviously, a congested network causes a rise in the number of collisions and, in most cases, this is the result of an increase in the broadcast rate or in the size of the broadcast packets. Naturally, we chose to measure the number of dropped packets to represent congestion and collision. End-to-end delay is a metric normally used in conjunction with the others to help understand how congestion has affected the protocols since it measures how long it takes any given packet to reach every node.

**Fault Model Implementation.** Most deterministic broadcasting protocols are resilient to fail-stop failures due to the fact that these protocols use constant neighborhood set exchange between nodes. Thus, a faulty node can only interfere for a short time during the broadcasting process. Shortly after the failure, all neighboring nodes will detect the fault and in future broadcasts, the node (which has now crashed), will no longer be involved in any broadcast. Using a fail-stop failure model is, in our opinion, inadequate to analyze faults when simulating deterministic broadcasting protocols. Thus, unlike any other work we have seen before, we have implemented an omission fault model in order to simulate a real world scenario characterized by interference introduced by the environment, link instability and transmission failure due to node movement.

In our implementation, a faulty node will always seem ok (will always reply to neighborhood set exchanges and control packets) but will not re-transmit any broadcasts. This implements the omission fault model and also helps to stress those protocols that assume a correct behavior on the reception and transmission during a broadcast by some special set of nodes, such as the gateway nodes. For each one of the metrics, we simulated a network where $0\%$ (failure free), $5\%$, $25\%$ and $50\%$ of the nodes fail.

| Simulation Parameters | |
|---|---|
| Simulator | NS-2 (2.29) |
| Network Area | 900 x 900 $m^2$ |
| Transmission Range | 250 $m$ |
| Simulation Time | 10 $s$ |
| # of Trials | 10 |
| Mobility Model | Random WayPoint |
| Broadcast Rate | 10 $packets/s$ |
| Node Speed | 1 $m/s$ |

**Table 1. Simulation Parameters**

**The Simulations.** We then simulated a MANET where the number of nodes vary from 10 to 160. Most algorithms are dependent on the density of the network - in sparse networks they are expected to act somewhat like flooding, since most nodes will have to re-transmit to reach isolated nodes, while in denser networks, less nodes re-transmit. For all simulations the parameters that remain constant can be seen in Table 1. Values used for the broadcast rate and the node speed were obtained by previous simulations.

- Broadcast Rate. To obtain the broadcast rate we first simulated a MANET where mobility was fixed at $1m/s$, but broadcast rate varied from 1 $packet/s$ to 111 $packets/s$, the number of nodes varied from 10 to 160 and node failure varied from $0\%$ to $50\%$. As expected, too high or too low of a number of rebroadcasts affect communication. 10 $packets/s$ was the value chosen since, on average, even when taking node failure in consideration, had the best overall effect on every metric measured and permitted the most stable and reliable communication.

- Node Speed. We made similar simulations to obtain the node speed, in this case fixing broadcast rate at $10packets/s$ but varying node speed between $1m/s$ and $20m/s$, and varying the other parameters with similar values. Previous studies on the impact of mobility varied the speed of the nodes between $1m/s$ and $160m/s$ and proved that mobility was a major cause of delivery failure as noted by [Wu and Dai 2005, Pagani and Rossi 1999, Lou and Wu 2002]. In our case, since we kept the speeds relatively low, the negative effects of mobility where less visible being node failure much more significant. We ended up choosing the final value of $1m/s$ - which represented the scenario where the protocols would be least impacted by mobility - but, even under these conditions broadcasting was affected by node failure. The only notable exception was the dynamic probabilistic protocol where, as noted in Section 3.1, has much better performance in a low-mobility scenario.

### 4.1. Results

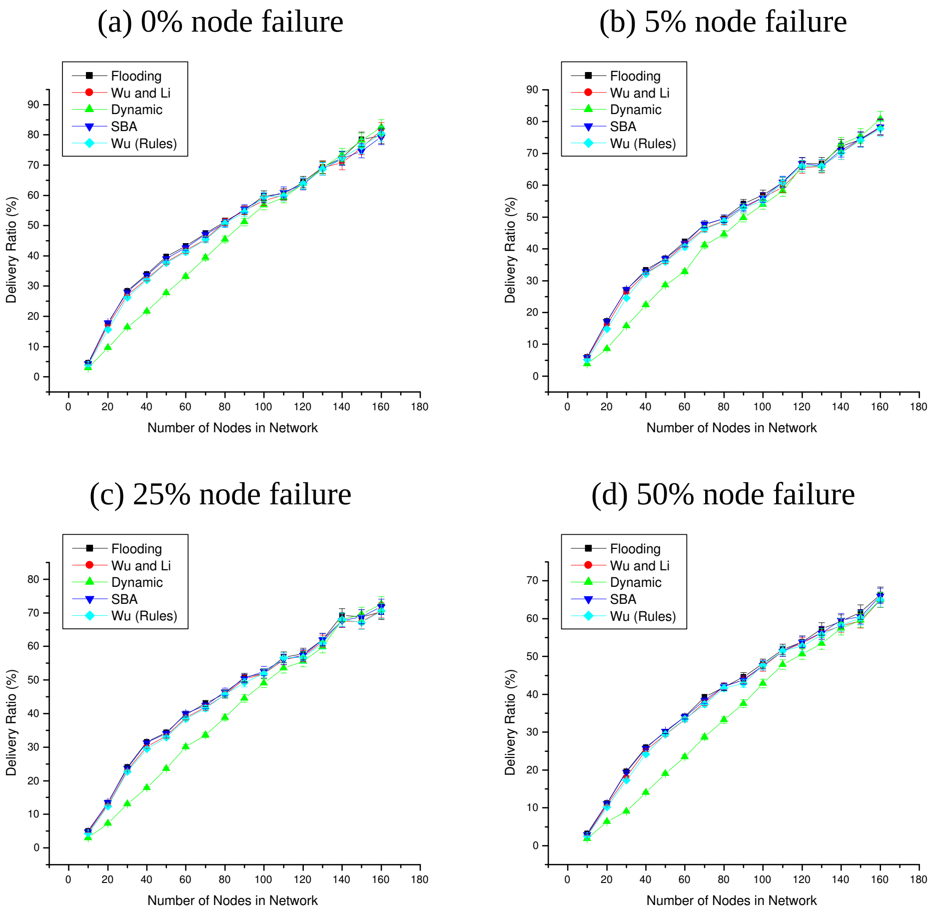


**Figure 2. The effects of node failure on reliability.**

**Reliability.** Figure 2 clearly shows what was expected: the reliability of all broadcasting protocols simulated lowers as the number of node failure increases. This conclusion is true to both deterministic and probabilistic approaches, and is independent of the number of nodes, since even in low density scenario the delivery ratio is affected. On a fail-free run ($0\%$ of node failure) the delivery ratio reached values as high as $85\%$ of nodes receiving broadcasts, but when $50\%$ of the nodes failed the delivery ratio barely reached $65\%$.

**Efficiency.** Ironically, using the fault model we proposed, the efficiency of the protocols is greater as soon as we inject more failures. This is due to the fact that the failure of any node is limited to the act of broadcasting, and does not interfere with neighborhood set and control packet exchanges. Thus, although most protocols continue to assume the same number of gateways independent of the number of node failures (since, after all, they do not know when a node is faulty or not), the *actual* number of gateways is reduced. That is why we notice in Figure 3 that

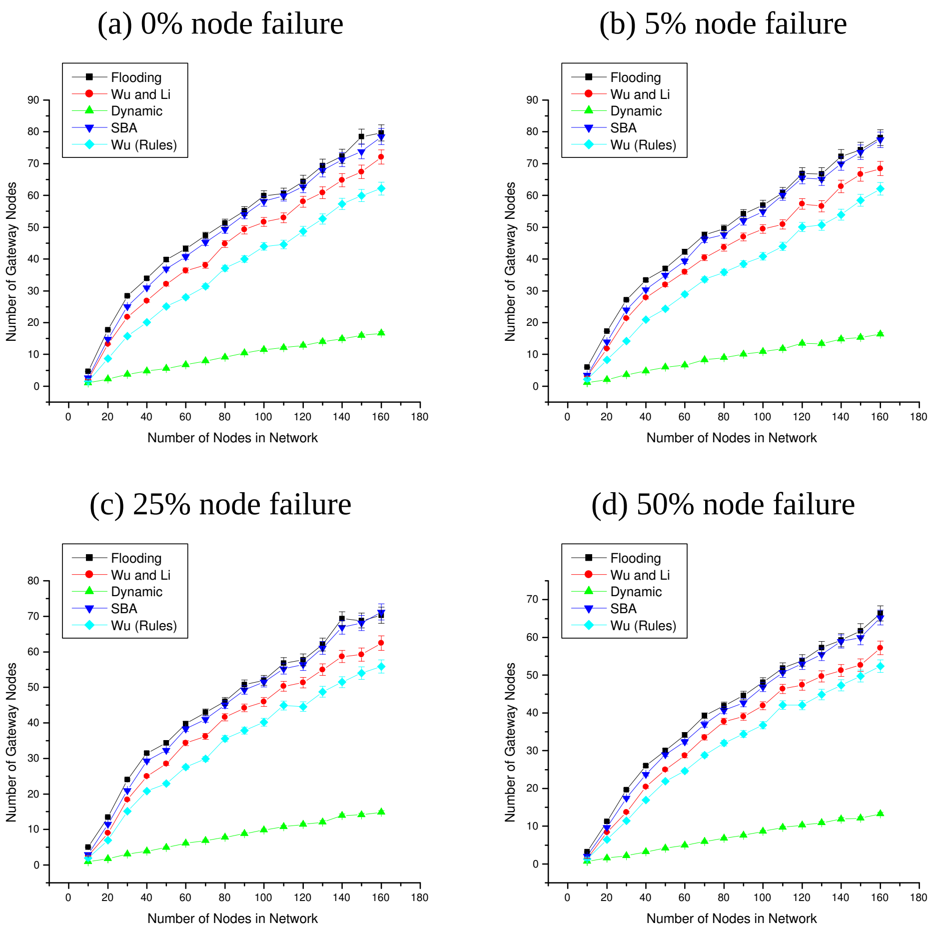


**Figure 3. The effects of node failure on efficiency.**

in a $50\%$ node failure scenario there is a smaller number of gateways then when in a fail-free scenario.

**Congestion and Collision.** Much like the efficiency metric, congestion and collisions are also lowered in a high-failure network. This is pretty obvious, since the number of transmission are also reduced as can be observed in Figure 4.

**End-to-End Delay.** As seen in Figure 5, there is a slight rise in the end-to-end delay of all protocols as more nodes failed. This was the expected behavior since the node re-transmission activity ceased on all faulty nodes. Much like previous metrics, network density does not alter the results.

## 5. Conclusion

In order to evaluate the impact of faults on the performance of significant broadcasting protocols, we have conducted simulations under various network scenarios and situations. The simulation studies consisted of measuring the reliability, the efficiency, the congestion and collision and the end-to-end delay of the protocols when in an omission fault injected environment. Thus we have simulated networks where a node seems to be functional but in reality is not. This simulates many

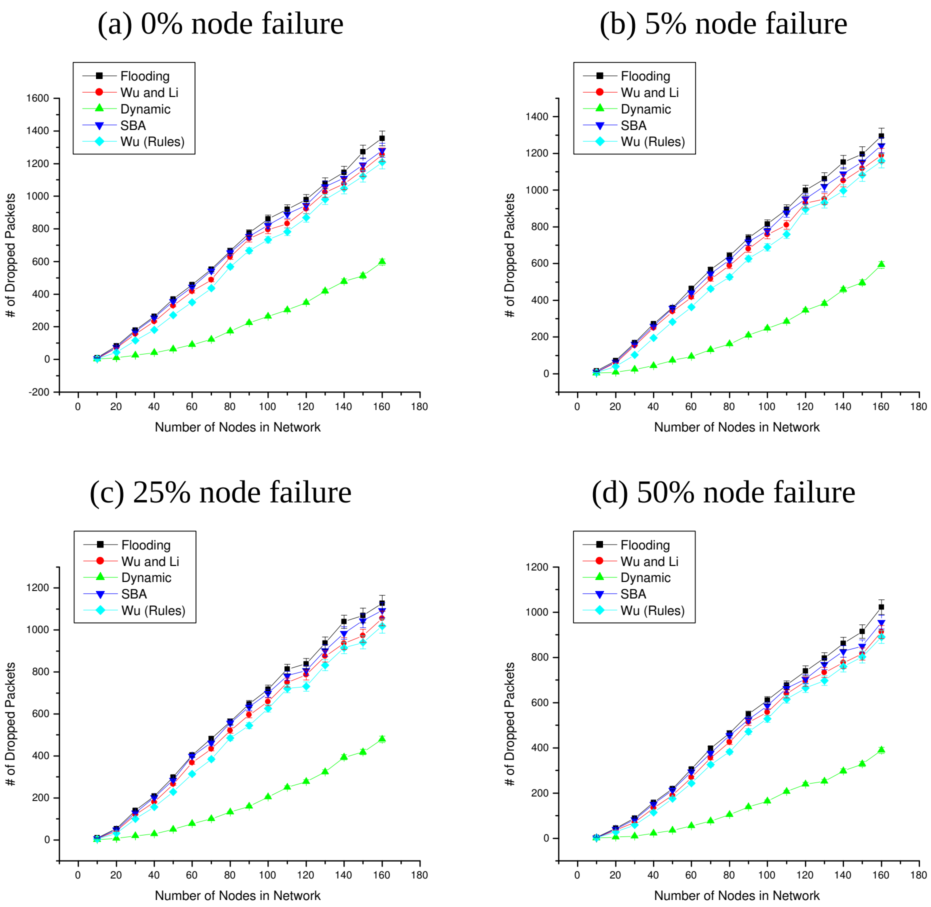


**Figure 4. The effects of node failure on collision and congestion.**

possible real world scenarios and helps stress protocols that assume correct reception by other nodes when in fact the transmission failed. It is interesting to note that the protocols are unable to cope well with failures under the realistic model proposed. Under a fail-stop model, eventually they adapt, since the faulty nodes are to be removed from the neighbors set. Our future work includes researching possible extensions to broadcasting algorithms in order to provide efficient mechanisms to deal with faults.

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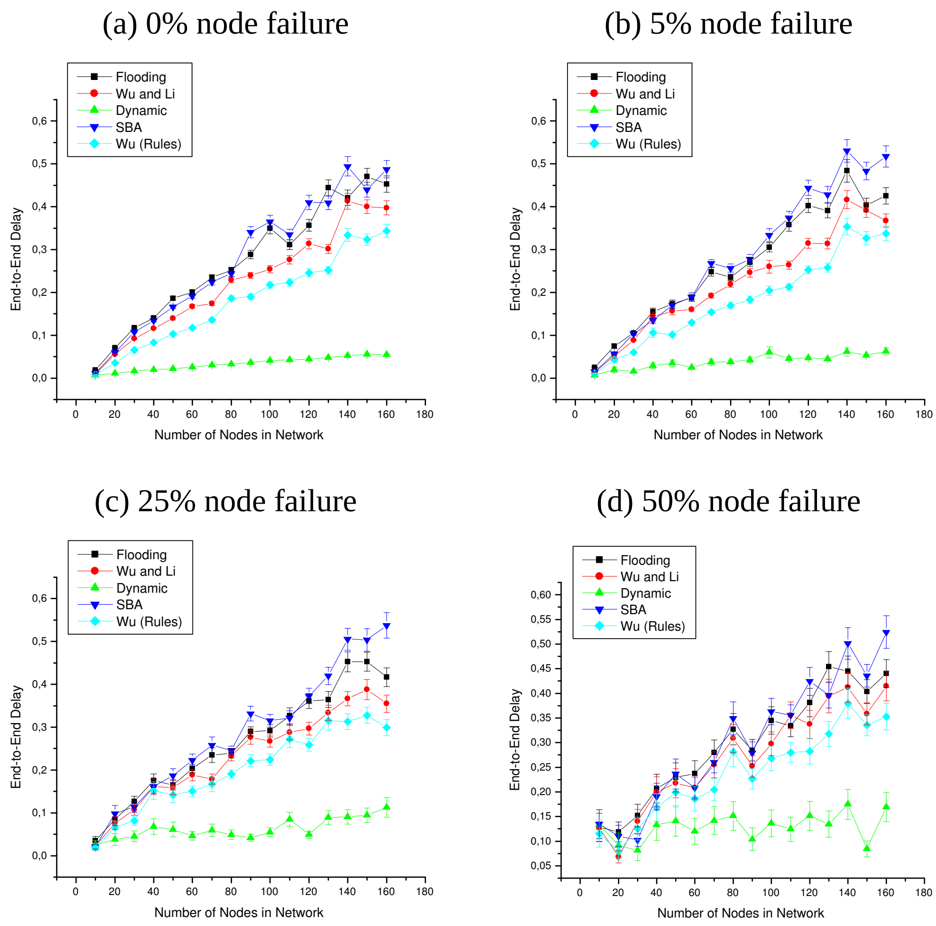


**Figure 5. The effects of node failure on end-to-end delay.**

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