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Modeling and Analysis of Self-pruning based Broadcasting and a New Dynamic Probabilistic Broadcast for MANETs

by

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Dedicated to my loving parents and husband.

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Candidate's Declaration

This is hereby declared that the work titled "Modeling and Analysis of Self-pruning based Broadcasting and a New Dynamic Probabilistic Broadcast for MANETs" is the outcome of research carried out by me under the supervision of Dr. A.K.M Ashikur Rahman, in the Department of Computer Science and Engineering, Bangladesh University of Engineering and Technology, Dhaka 1205. It is also declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

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Abstract

Self-pruning broadcasting algorithm exploits neighbor knowledge to reduce redundant retransmissions in mobile ad hoc wireless networks (MANETs). Although in self-pruning, only a subset of nodes forward the message based on certain forwarding rule, it belongs to one of the reliable broadcasting algorithm category where a broadcast message is guaranteed (at least algorithmically) to reach all the nodes in the network. In this thesis, we develop an analytical model to determine expected number of forwarding nodes required to complete a broadcast in self-pruning algorithm. The derived expression is a function of various network parameters (such as, network density and distance between nodes) and radio transceiver parameters (such as transmission range). Moreover, the developed mathematical expression provides us a better understanding of the highly complex packet forwarding pattern of self-pruning algorithm and valuable insight to design a new broadcasting heuristic. The proposed new heuristic is a dynamic probabilistic broadcast where rebroadcast probability of each node is dynamically determined from a developed mathematical expression. Extensive simulation experiments have been conducted to validate the accuracy of the analytical model, as well as, to evaluate the efficiency of the proposed heuristic. Performance analysis shows that the proposed heuristic outperforms the static probabilistic broadcasting algorithm.

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Chapter 1

Introduction

A mobile ad hoc wireless network (MANET) is a collection of low power wireless mobile hosts forming a temporary network without the aid of any global topological information or infrastructure. The nodes are free to move randomly and organize themselves arbitrarily; thus, the network's wireless topology may change rapidly and unpredictably. In general, routes between nodes in an ad hoc network may include multiple hops, and hence it is appropriate to call such networks as *"multi-hop wireless ad hoc networks"*. Each node will be able to communicate directly with any other node that resides within its transmission range. For communicating with nodes that reside beyond this range, the node needs to use intermediate nodes to relay the messages hop by hop. Applications of MANETs occur in situations like battlefields or major disaster areas where networks need to be deployed immediately, but base stations or fixed network infrastructures are not available, not trusted, too expensive or unreliable. Because of their self-creating, self-organizing and self-administering capabilities, ad hoc networks can be rapidly deployed with minimum user intervention. There is no need for detailed planning of base station installation or wiring. Broadcast and unicast are two unique ways for data dissemination in MANETs. Due to the dynamic nature of MANETs, broadcasting is more frequent compared to the wired network.

1.1 Broadcasting in MANETs and its Applications

Broadcasting is a fundamental network operation. It refers to the sending of a packet from a source host to all other hosts in the network. It is a one-to-all operation in the network. Due to the limitation of radio power, a mobile host may not be within the transmission range of all other hosts. This creates a multi-hop scenario, where packets originated from the source host are relayed by several intermediate hosts before reaching the destination. Broadcasting is spontaneous that means any mobile host can issue a broadcast operation at any time.

Broadcasting is a common operation in many applications, e.g., graph-related problems and distributed computing problems. Broadcasting applications include paging a particular host, sending an error message to erase invalid routes in a mobile environment or sending an alarm signal. It is also widely used to resolve many network layer problems. It is frequently performed for route discovery process in several routing protocols such as Dynamic Source Routing (DSR) [1], Ad-hoc On-Demand Distance Vector Routing (AODV) [2], Cluster Based Routing Protocol (CBRP) [3], Location-Aided Routing (LAR) [4], Zone Routing Protocol (ZRP) [5] and so on. Some protocols even use broadcasting for actual data transmissions. Sometimes, broadcasting may also be used to provide multicast services in networks with rapid changing topologies.

1.2 Broadcast Storm Problem in Mobile Wireless Ad hoc Network

In MANETs each mobile host is equipped with a CSMA/CA (*carrier sense multiple access with collision avoidance*) [6] transceiver and there is no acknowledgment mechanism. Synchronization in such a network with mobility is unlikely, and global network topology information is unavailable to facilitate the scheduling of a broadcast. Therefore, the most naive approach for broadcasting is flooding where a broadcast packet is forwarded exactly once by every node [7] in the network. Clearly, this costs n transmissions in a network of n hosts. The only *"optimization"* applied to this solution is that nodes remember messages received from flooding, and do not act when receiving repeated copies of the same message. Although theoretically, such blind flooding ensures a complete coverage, in reality, such naive flooding may cause serious redundancy, contention and collision, with many nodes not receiving the message as a consequence.

- Redundant rebroadcast: The radio propagation is omnidirectional and a physical location of a host may be covered by the transmission ranges of several hosts. When a mobile host decides to rebroadcast a message to its neighbors and all of its neighbors already have the message then the rebroadcast is considered to be redundant.
- Contention: After receiving a broadcast message from a host, if many of its neighbors decide to rebroadcast the message then these rebroadcasts may cause serious contention in the network.
- Collision: Because of the lack of acknowledgment mechanism and the timing of rebroadcast is highly correlated, collisions are more likely to occur and cause more damage.

Fig. 1.1 represents a network scenario where the nodes indicate mobile host and the links between nodes indicate that they are within the transmission range of each other. In Fig. 1.1(a), when node B broadcasts a message nodes A, C and D will receive the packet. After receiving the packet from B, nodes C and D decide to rebroadcast the packet at the same time and they will contend for rebroadcast. And if they forward the packet at the same time it will cause collision in the network. Fig. 1.1(b) describes the situation after every node in the network forwards the packet exactly once. It will create serious redundancy in the network. For example, D receives the same message 3 times from B, C and E. Collectively, this phenomenon is known as broadcast storm problem [8] in the literature. Moreover, in wireless environment each node operates in promiscuous receive mode which often makes such blind flooding undesirable.

1.3 Broadcasting Algorithms

Therefore, a variety of broadcasting techniques have been proposed to reduce redundant packet forwarding generated by flooding [9–14]. All those techniques can be broadly

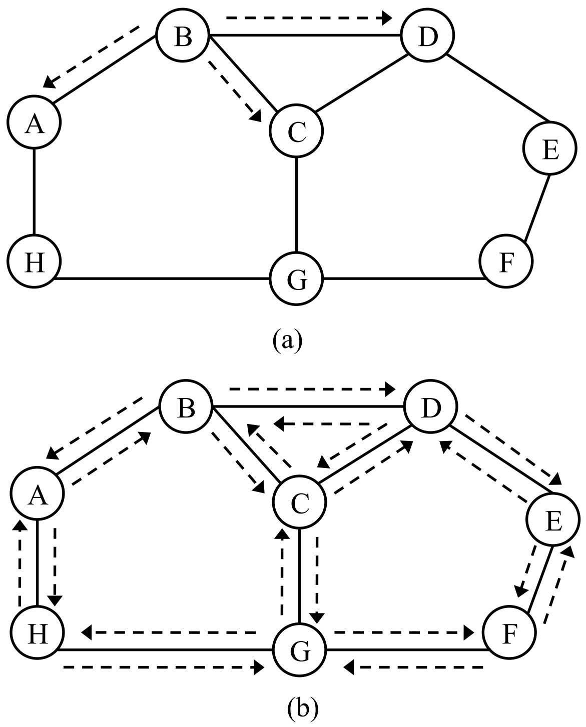

Figure 1.1: Broadcast storm problem. (a) nodes A, C and D receive a broadcast packet from B. (links between nodes indicate that they are within the transmission range of each other and the arrows indicate packet forwarding), and (b) after every node in the network forwards the broadcast packet exactly once.

classified into two categories,

1. Unreliable broadcasting and
2. Reliable broadcasting.

In an unreliable broadcasting, a node may miss a broadcast packet because the protocol (intelligently) reduces redundancy by inhibiting packet forwarding from the nodes which find themselves *"less-effective"* as intermediate forwarder. The effectiveness of a node is often measured based on some preset probability values or counter values, or based on distance and location [8]. Usually, this kind of broadcasting algorithm requires no topology information. On the contrary, the reliable protocols are based on the so-called concept of *"connected dominating sets"* (*CDS*) and ensure that every node in the network receives a broadcast. A dominating set $D(S)$ of a set S is a set of nodes such that each node from S either belongs to $D(S)$ or has a neighboring node that belongs to $D(S)$. It is easy to observe that all nodes will receive the message if it is retransmitted only by nodes that belong to a connected dominating set. Connectivity provides propagation through the whole network, whereas domination assures reachability by all nodes. The broadcasting task can therefore be solved optimally by finding a connected dominating set of minimal size. Optimality here is measured by the percentage of saved retransmissions in a reliable broadcasting scheme. Unfortunately, the problem of finding a connected dominating set of minimal size is NP-complete, even if a node has global knowledge about the network. Therefore, one must apply heuristics to flood intelligently. Reliable broadcasting algorithms usually use one or more hop neighbor information for their forwarding decision. Many reliable broadcasting algorithms have been proposed over the past decade [14–17]. Of course, the unreliable broadcasting algorithms can only be used for applications that do not require full reliability. On the other hand, full reliability often induces a cost that is too high.

1.4 Motivation of the Thesis

One of the widely used reliable broadcasting algorithms known as self-pruning uses neighborhood knowledge [14] for forwarding packets and significantly reduces redundant data transmissions. In self-pruning each node collects adjacent node information by periodically exchanging *"hello"* messages. Upon receiving a broadcast packet, the receiving node will check the neighbor list of the sender and receiver. If there is any neighbor other than the common neighbor of the sender and receiver in the neighbor list of the receiving node then the receiving node will forward the packet. Otherwise, it drops the packet and becomes a non-forward node. So far, the evaluation of self-pruning is mainly based on experiments and lacks detailed theoretical analysis. One inherent reason lies on the fact that even a simple broadcasting algorithm like self-pruning typically generates highly complex packet forwarding patterns and the existing protocols were only targeting simple heuristics. Theoretical analysis of self-pruning will help us to gain insight to the efficiency and reliability of the protocol as a function of various network parameters. We can also easily estimate the reliability and performance of a network prior to the deployment of that network.

Furthermore, based on the analysis results it is possible to design new heuristics. Therefore, the analytical modeling of self pruning will assist us to propose a new dynamic probabilistic heuristic for MANETs. Although reliable broadcasts ensure the reachability of a broadcast to every node in the network, the reliable protocols have a very high communication overhead due to their dependency on 1-hop neighborhood information and sometimes on 2-hop neighbor information. Exchanging neighborhood information is a costly operation in MANETs and incurs a high overhead. The frequency of exchanging neighborhood information increases with the increase of mobility. Consequently, unreliable protocols are more preferable in the highly mobile dynamic environment.

In highly mobile networks, a very simple but effective approach to reduce redundant rebroadcasts is the *probabilistic* broadcasting algorithm [8]. In probabilistic broadcasts, upon receiving a broadcast packet, each node in the network (except the sender and receiver) decides whether to rebroadcast it or not based on a pre-defined probability value. Mathematically speaking, instead of blindly forwarding any packet, a node in the network rebroadcasts a message with probability P and takes no action with probability $1 - P$. The performance of such protocol highly depends on the selected value of the forwarding probability P. With higher P values, more redundant transmissions take place but the chance of reaching all the nodes in the network increases as well. With lower P values the opposite thing happens. Thus, an inherent problem of this approach is to set a globally optimal probability value which is appropriate for all networking conditions and all dynamic environments. For example, in a *dense* network, a low probability value would ensure high reachability but the same low probability value would inhibit a significant number of nodes from receiving the broadcast in *sparse* networks. On the other hand, with a high probability value, high reachability can be maintained in *sparse* networks but the same value will create many redundant rebroadcasts in *dense* networks. Therefore, the probability of each node should be assigned dynamically rather than statically based on the node density, distance from the sender and other network parameters.

1.5 Contribution of the Thesis

In this thesis, we concentrate on building an analytical model for characterizing self pruning algorithm as a function of various network and transceiver parameters. The developed mathematical model gives us insight to the efficiency and reliability of this protocol. To validate the accuracy of the analytical model, we compare the analytical results with the simulation results. Another contribution of this thesis is, we propose a dynamic probabilistic broadcasting algorithm for MANETs based on the analytical results of self-pruning algorithm. We measure the efficiency and effectiveness of the proposed heuristic through extensive simulation experiments. Therefore, the main objectives of our thesis are as follows:

1. Mathematically analyze self-pruning algorithm and quantify the forwarding probability of a node located at a certain distance from the source of a broadcast.

2. Build mathematical model to estimate average fraction of neighbors forwarding/rebroadcasting the packet within a node's neighborhood when self-pruning algorithm is used.

3. Identify the effect of several network and transceiver parameters on the performance of self-pruning based broadcasting.

4. Propose a new dynamic probabilistic heuristic for wireless multi-hop networks.

1.6 Organization of the Thesis

After an introduction which is provided in this chapter, Chapter 2 provides a brief discussion of prior related research works. A brief discussion of the basic terms and concepts used throughout the thesis is presented in Chapter 3. Chapter 4 develops the analytical model to characterize the self-pruning algorithm, while Chapter 5 describes the proposed dynamic probabilistic algorithm. Chapter 6 presents simulation results to validate our model and measure effectiveness of the proposed new heuristic. Finally, Chapter 7 concludes the thesis with some pointers to possible future works.

Chapter 2

Literature Review

In this chapter, we provide an overview of broadcasting algorithms that focus on reducing broadcast storm problem. A significant amount of works have been done to alleviate the broadcast storm problem. Section 2.1 discusses some simple broadcasting algorithm. Works related to self-pruning broadcasting algorithm are presented in Section 2.2. Finally, Section 2.3 reviews some of the recent works related to probabilistic broadcasting algorithms.

2.1 Broadcasting Algorithm in Wireless Ad hoc Network

One of the earliest broadcast mechanisms is flooding. Although flooding is extremely simple and easy to implement, it can be very costly and can lead to serious problem, named as broadcast storm problem. Ni et al. [8] classified broadcasting schemes into five classes to reduce redundancy, contention, and collision: probabilistic, counter-based, distance-based, location-based and cluster-based. In probabilistic scheme on receiving a broadcast message for the first time, a mobile host will rebroadcast it with a predefined probability value, P. Clearly, when P equals 1, this scheme is equivalent to flooding. In counter-based scheme, a node determines whether it rebroadcasts a packet or not by counting how many identical packets it receives during a random delay. The expected additional coverage decreases after hearing the same message k times as k increases. When the expected additional coverage of the host's rebroadcast becomes too low that means the number of received messages exceeds a threshold value, the rebroadcast is inhibited. In distance-based scheme the decision of whether to drop a rebroadcast or not depends on the relative distance between hosts. Suppose, host A heard a broadcast message from S for the first time. If the distance, say d, between A and S is very small, there is little additional coverage A's rebroadcast can provide. If d is larger, the additional coverage will be larger. Therefore, this can be used as a metric by A to determine whether to rebroadcast or not. In location-based scheme, additional coverage concept is used to decide whether to rebroadcast a packet or not and this additional coverage is acquired by the locations of broadcasting hosts. In cluster-based scheme, MANETs is divided into clusters, which is a set of mobile hosts. There are one cluster head and several members in a cluster. Cluster head is representative of a cluster and its rebroadcast can cover all members in that cluster. A member that can communicate with other clusters and have responsibilities to propagate the broadcast message is known as gateways.

Williams et al. [18] classified the broadcasting techniques into four groups and compared their performances: simple flooding, probability-based, area-based and neighbor knowledge scheme. The algorithm for simple flooding starts with a source node broadcasting a packet to all its neighbors. Upon receiving the packet each neighbor in turn rebroadcasts the packet exactly one time and continues until all reachable network nodes have received the packet. In probability-based methods they have presented probabilistic scheme and counter-based scheme. Probabilistic scheme is a very simple approach to reduce redundancy. It is similar to flooding except nodes only rebroadcast with a predetermined probability, P. In area-based methods nodes decide whether to rebroadcast a packet or not based on the additional coverage area. Although area-based scheme works quite well, it does not know whether there is any node in the calculated coverage area. Therefore, some nodes may not receive broadcasting packets. Area-based methods include distance-based scheme and location-based scheme. Neighbor knowledge scheme maintains neighbor node information to decide whether it or the neighboring nodes have to rebroadcast. To use neighbor knowledge method, each node has to explicitly exchange neighborhood information among mobile hosts using periodic *"hello"* packets. Various neighbor-knowledge based schemes are discussed here, such as, Flooding with Self-pruning, Scalable Broadcast Algorithm (SBA), Dominant Pruning, Ad hoc

Broadcast Protocol, CDS-based Broadcast Algorithm and so on.

2.2 Self-pruning Algorithm

Lim and Kim [14] proposed one of the simplest neighbor-knowledge based flooding approach dubbed as self-pruning which reduces the number of retransmission by selecting a small set of forward nodes. In this approach, when a node receives a broadcast packet and all of its neighbors already have the packet then it refrains itself from rebroadcast. Otherwise, it is selected as a forwarding node.

Wu and Dai [15] proposed a general framework for broadcasting based on self-pruning in ad hoc networks. In this approach, each node builds its k-hop information by exchanging periodical *"hello"* messages. The *"hello"* message also includes the *priority* of each node. Each node makes its forwarding decision based on two coverage conditions and these coverage conditions depend on the k-hop topology, priority, and visited node information. The forward node set can be constructed by either a dynamic or static approach. If the protocol use visited node information then it is dynamic otherwise it is static.

Wu and Dai [19] focused on the performance evaluation of existing self-pruning algorithms and also described an enhanced version of the generic protocol proposed by Wu and Dai [15]. In their work they have observed the efficiency and reliability of various protocols which have used different self-pruning conditions as a function of various network parameters. They have also evaluated the performance of the generic protocol under various network environments. But their analysis lacks theoretical details.

Wu and Dai [20] proposed a mobility management method based on two transmission ranges, r_1 and r_2, where $r_1 < r_2$. r_1 is used to collect neighbor set and k-hop information through *"hello"* messages, whereas r_2 is used to perform actual transmission. Specifically, the proposed method consists of two stages: (a) forward node selection, followed by (b) forwarding process. They have also extended Wu and Dai's coverage condition to a dynamic environment where network topology is allowed to change, even during the broadcast process. In addition, connectivity, link availability, and consistency issues related to neighborhood information of different nodes have also been addressed.

Woon and Yeung [21] proposed two protocols namely, E-SBA and E-SBA+ which use a simple idea of delay timer to ensure that nodes with more uncovered neighbors rebroadcast first. These approaches solve the problems of an existing self-pruning protocol named SBA. They also introduced a timer suppression mechanism where a node upon receiving a rebroadcast message set a lower priority and reset the timer.

Huang et al. [22] developed an analytical model for self-pruning. They have evaluated their model based on expected broadcast cost and scalability. The analysis of the effect of various network parameters, as well as, transceiver parameters was not considered in their work. It also lacks proper analysis and evaluation of the mathematical model.

2.3 Probabilistic Broadcasting Algorithm

Reliable broadcasting algorithms use more specific information like neighbor list to reduce redundant rebroadcast. However, this kind of information requires the large message overhead to keep the exact neighbor node list. Thus the methods those do not require exact topology information in their forwarding decision can be used in broadcasting.

Haas et al. [23] proposed a gossip-based approach, where each node forwards a packet with a probability. They showed that gossip-based approach can save up to 35 percent overhead compared to the flooding. However, when the network density is high or the traffic load is heavy, the improvement of the gossip-based approach is limited.

Kim et al. [24] developed a dynamic probabilistic broadcasting approach with coverage area and neighbor confirmation. Based on the coverage area of a node, probability is set. If it has small additional coverage area then a low probability is set and in case of large additional coverage, a high probability is set. The additional coverage is estimated by the distance from the sender. They have divided the coverage area of the sender into three sub area A_1, A_2 and A_3 with radii r_1, r_2 and r_3 respectively. A node can determine its coverage ratio depending on this three sub area. And by multiplying a sensitivity parameter, α with the coverage ratio rebroadcast probability is determined. They have also applied neighbor confirmation to prevent the early die out of a packet. But authors did not introduce any optimal value for the sensitivity parameter α.

Yassein et al. [25] presented a new probabilistic approach that dynamically adjusts the rebroadcast probability as per the node distribution and node movement. It used one-hop neighbor information to adjust probability of a node. If the message is received for the first time and the number of neighbors is less than the average number of neighbor then the node rebroadcast the message with a high probability value. Otherwise, if the node has a high degree neighbors its probability is set to low value.

Bahadili [26] proposed a new probability adjusting model in which the number of first hop neighbors of the transmitting node is divided into three ranges (low, medium and high). And the rebroadcasting probability is adjusted according to three distribution functions ($f_{low}(k), f_{med}(k)$ and $f_{hig}(k)$) where k is the number of first hop neighbors. Depending on the neighborhood density one of the three distribution function is selected and it returns one of the three rebroadcasting probability P_{max}, P_{med} or P_{min}. The main drawback of this approach is that the estimation of the optimum values of the variables P_{max}, P_{med} or P_{min} and the appropriate value for the three ranges (low, medium and high) of neighbors. They have also ignored the investigation of the effect of nodes density, nodes radio transmission range etc. on the performance of the new model.

Zhang et al. [27] proposed a neighbor coverage-based probabilistic rebroadcast (NCPR) protocol for reducing routing overhead in MANETs. In their approach, they have calculated a novel rebroadcast delay to effectively exploit the neighbor coverage knowledge and also define a connectivity factor to provide the node density adaptation. By combining the neighbor coverage knowledge and connectivity factor, a reasonable rebroadcast probability is set. But using of neighbor coverage knowledge to keep the exact neighbor node list will cause large message overhead in a highly mobile network.

In this section we have discussed various broadcasting algorithms. The goal of all the above approaches is to minimize the number of rebroadcast in the network and to minimize broadcast storm problem. Among these approaches one of the simplest neighbor-knowledge based approaches is self-pruning broadcasting algorithm. To get a better perception of the self-pruning algorithm, we develop an mathematical model for it. We also propose a new dynamic probabilistic algorithm which uses a simple expression to calculate the rebroadcast probability of a node based on the existence of any node in the additional coverage area.

Chapter 3

Preliminaries

In this chapter we discuss some basic terms and concepts which are used throughout the thesis. Section 3.1 presents the network model used to model a wireless ad hoc network and the assumptions we made in this thesis. Section 3.2 illustrates the concept of connected dominating set and in Section 3.3 we briefly describe self-pruning algorithm. The idea of additional coverage area is covered in Section 3.4. Section 3.5 presents the probabilistic broadcasting algorithm. Finally, Section 3.6, Section 3.7 and Section 3.8 describe the Binomial distribution, Poisson distribution and Simpson's 3/8 rule respectively which are used in the mathematical modeling of self-pruning algorithm.

3.1 Network Model

We can use an unweighted graph $G = (V, E)$ to represent an ad hoc wireless network, where each node in a wireless network corresponds to a vertex $v \in V$ and each edge $e \in E$ corresponds to a bidirectional link between the neighboring nodes in ad hoc networks. In this thesis node and vertex have been used interchangeably. Two nodes are considered neighbors if and only if their geographic distance is less than the transmission radius, r. The circle around a node u corresponds to the transmission range of node u. All the nodes within the circle are considered as the neighbors of node u. A node can obtain its neighborhood information by periodically sending an update message. Another efficient way uses the piggyback technique; that is, when a node needs to send a packet, it attaches its neighborhood information along with the packet. We use $N(u)$ to represent

Table 3.1: Summary of notations.

Notation	Description
A	Network area
n	Total node in the network
μ	Node density
r	Transmission radius
$N(u)$	Set of neighbors of node u
$N(v)$	Set of neighbors of node v
S_u	Circle areas covered by u's transmission range
S_v	Circle areas covered by v's transmission range
S_{v-u}	Additional cover region of v
x	Distance between a node pair (u, v)
$C(u)$	Cover region of node u with radius r
$P_F(x)$	Forwarding probability of node v at distance x from node u
E_F	Expected number of neighbors forwarded
F_F	Average fraction of neighbors forwarded
P_{rand}	Some random number between 0 and 1

the neighbor set of u. Notations used in our model are listed in Table 3.1.

3.1.1 Assumptions

In our network model n nodes are uniformly distributed over a rectangular deployment area A and the resulting network is connected. The average node density is: $\mu = n/A$. The maximum transmission radius of each node is r. We assume a homogeneous system where every node in the network has the same transmission range (TX). Each node has the same probability to initiate a broadcast. In our model node mobility, packet loss and node failure are not considered.

3.2 Connected Dominating Set

Neighbor-knowledge-based methods are based on the following idea: To avoid flooding the whole network, a small set of forward nodes is selected. Basically, the forward node set forms a connected dominating set (CDS) [14]. CDS is to find connected subset S of V in which all elements in $V - S$ is adjacent to at least one element of S, given graph $G = (V, E)$. For example, in the graph of Fig. 3.1, all the nodes except $\{B, C, D, G\}$ is

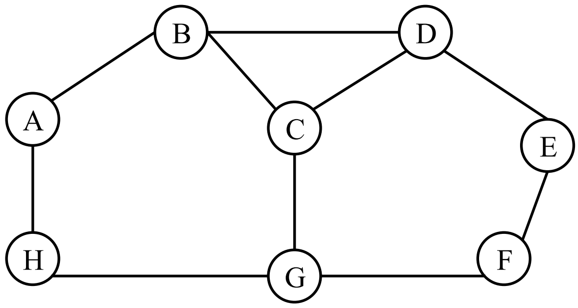

Figure 3.1: Connected Dominating Set (CDS).

linked to at least one element of $\{B, C, D, G\}$, and $\{B, C, D, G\}$ is connected. Therefore, $\{B, C, D, G\}$ is a Connected Dominating Set. Again, $\{A, B, C, D, E\}$ is also a CDS because every node not in this subset is adjacent to at least one node in the subset. It is easy to observe that all nodes will receive the message if it is retransmitted only by the nodes that belong to a connected dominating set. Connectivity provides propagation through the whole network, whereas domination assures reachability by all nodes.

3.3 Self-pruning Algorithm

Self-pruning is a simple broadcasting algorithm which helps in reducing the redundant rebroadcast in flooding and minimizes the effect of broadcast storm problem. The self-pruning algorithm [14] exploits the knowledge of directly connected neighborhood information only. A node does not need to rebroadcast a packet if all its neighbors have been covered by the previous transmission. Each node collects adjacent node information by periodically exchanging *"hello"* messages. Therefore, it requires extra transmission overhead of exchanging neighbor information. Suppose, node u forwards a packet and v receives the packet. Node u piggybacks its neighbor list, $N(u)$ in the packet. Upon receiving the packet from u, node v checks whether $N(v) - N(u) - \{u\}$ is empty where $N(v)$ is the neighbor list of node v. If it is empty, node v is set as a non-forwarding node and refrains itself from forwarding. Otherwise, it is added to the forward list. These forward nodes, including the source node form a connected dominating set (CDS).

We can explain self-pruning algorithm with a simple example shown in Fig. 3.2. Fig. 3.2 shows a sample network of eight nodes with source node A. Neighborhood

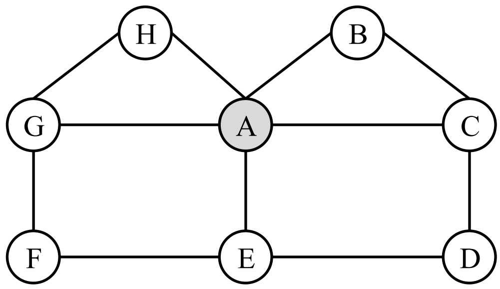

Figure 3.2: Example of self-pruning method. Connectivity between nodes is represented by links. Here, A is the source node.

Table 3.2: Neighbors within 1-hop.

v	$N(v)$
A	B,C,E,G,H
B	A,C
C	A,B,D
D	C,E
E	A,D,F
F	E,G
G	A,F,H
H	A,G

information of each node is shown in Table 3.2. Blind flooding needs eight packet forwarding because all the nodes that receive the packet should forward the packet. For self-pruning algorithm, node A broadcasts the packet and $N(A)$ will receive the packet directly. Neighbor set $\{B, C, E, G, H\}$ receive the packet and decide whether to rebroadcast the packet or not. Based on self-pruning algorithm, node C will be selected as a forwarding node because $N(C) - N(A) - \{A\} = \{D\}$, which is not empty. Again, node E and G also rebroadcast the packet. But the nodes B and H need not to forward the packet. Because, both $N(B) - N(A) - \{A\}$ and $N(H) - N(A) - \{A\}$ is empty. Therefore, total number of packet forwarding is six when self-pruning algorithm is used.

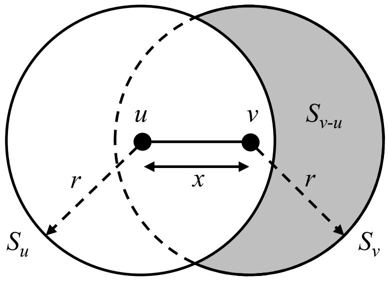

Figure 3.3: Additional area that can be benefited from a rebroadcast is the shaded region. Node u sends a broadcast packet and node v receives the packet.

3.4 Additional Coverage Area

The area that can be actually benefited from node *v's* transmission after receiving the packet from node u is denoted as the additional coverage area of v [8]. Based on self-pruning approach, a node v is eligible for forwarding if it has one or more nodes in its additional coverage area. If there is no node in the additional coverage area, then all neighbors of v have already received the packet from *u's* transmission. Therefore, node v does not need to rebroadcast. Consequently the node v will be marked as a non-forwarding node.

Consider the simple scenario in Fig. 3.3 where an arbitrary node u sends a broadcast message and upon receiving the message node v decides whether to rebroadcast it or not. The distance between node u and node v is x. Let, S_u and S_v denote the circular areas covered by node *u's* and node *v's* transmission range, respectively. The *additional coverage* area that can be benefited from *v's* rebroadcast is the shaded region and denoted as S_{v-u}. A node located in this shaded region will become the neighbor of node v only. The common neighbors of node u and node v are located in the intersection region of the two circles centered at node u and node v. Therefore, if there is at least one node in this additional coverage area then the list $N(v) - N(u) - \{u\}$ will not be empty. Based on this result we can determine whether a node in self-pruning broadcast will forward the message or not.

3.5 Probabilistic Broadcasting Algorithm

Probabilistic broadcasting algorithm [8] is a simple approach for broadcasting which also reduces redundant rebroadcasts. In the probabilistic scheme each node rebroadcasts with a predefined probability P. That means it assigns all nodes in the network the same probability P for forwarding the message. Suppose, node v receive a broadcast packet from node u. Node v will then generate a random probability (a random number between 0 to 1). If this random probability is less than or equal to the predefined probability P of the network then node v will forward the packet. Otherwise, it will drop the packet.

When $P = 1$, it simply becomes blind flooding. The blind flooding is a straightforward approach that can guarantee reliable propagation over all regions of the network but it generates high number of redundant messages. When P is set to a low value, the number of redundant messages decreases but the scheme cannot guarantee message dissemination over the network. Probability P must be high enough to propagate the message all over the network and also low enough to minimize the redundant messages in the network.

3.6 Binomial Distribution

In probability theory and statistics, the binomial distribution [28] is the discrete probability distribution of the number of successes in a sequence of n independent trials, each of which yields success with probability P. Therewith the probability of an event is defined by its binomial distribution. The random variable X that counts the number of successes, k, in the n trials is said to have a binomial distribution with parameters n and P, written $bin(k; n, P)$.

$$f(k) = P(X = k) = \binom{n}{k} P^k \times (1 - P)^{n-k} \tag{3.1}$$

For $k = 0, 1, 2, 3, \ldots\ldots, n$; $\binom{n}{k}$ counts the number of outcomes that include exactly k successes and $n - k$ failures.

3.7 Poisson Distribution

In probability theory and statistics, the Poisson distribution [29] expresses the probability of a given number of events occurring in a fixed interval of time and/or space if these events occur with a known average rate and independently of the time since the last event. The Poisson distribution can also be used for the number of events in other specified intervals such as distance, area or volume. If we let X equals the number of events in a given interval and if the mean number of events per interval is λ then the probability of observing k events in a given interval is given by:

$$f(k;\lambda) = P(X = k) = \frac{\lambda^k \times e^{-\lambda}}{k!} \tag{3.2}$$

Where e is Euler's number ($e = 2.71828...$)

3.8 Simpson's 3/8 Rule

In numerical analysis, numerical integration [30] constitutes a broad family of algorithms for calculating the numerical value of a definite integral, and by extension, the term is also sometimes used to describe the numerical solution of differential equations. The basic problem in numerical integration is to compute an approximate solution to a definite integral to a given degree of accuracy.

$$\int_a^b f(x)\,dx \tag{3.3}$$

If $f(x)$ is a smooth function integrated over a small number of dimensions, and the domain of integration is bounded, there are many methods for approximating the integral to the desired precision.

Simpson's 3/8 rule [31] is a method for numerical integration proposed by Thomas Simpson. It is based upon a cubic interpolation rather than a quadratic interpolation.

Simpson's 3/8 rule is as follows:

$$\begin{aligned}\int_a^b f(x)\,dx &\approx \frac{3h}{8}[f(a) + 3f(\frac{2a+b}{3}) + 3f(\frac{a+2b}{3}) + f(b)] \\ &= \frac{b-a}{8}[f(a) + 3f(\frac{2a+b}{3}) + 3f(\frac{a+2b}{3}) + f(b)] \end{aligned} \tag{3.4}$$

where $b - a = 3h$. The error of this method is:

$$\left|\frac{(b-a)^5}{6480} f^{(4)}(\xi)\right| \tag{3.5}$$

where ξ is some number between a and b.

And for Simpson's 3/8 rule (for n intervals) we can define,

$$h = \frac{b-a}{n}, \qquad x_i = a + ih$$

And we have

$$\begin{aligned}\int_a^b f(x)\,dx \approx \frac{3h}{8}[&f(x_0) + 3f(x_1) + 3f(x_2) + 2f(x_3) + 3f(x_4) \\ &+ 3f(x_5) + 2f(x_6) + \ldots + f(x_n)] \end{aligned} \tag{3.6}$$

We can only use this if n is a multiple of three.

In this chapter, we discuss several basic terms which are used in mathematical modeling of self-pruning algorithm and proposed dynamic probabilistic algorithm. We have also introduced the basic mechanism of the self-pruning algorithm and static probabilistic algorithm in Section 3.3 and Section 3.5 respectively.

Chapter 4

Mathematical Modeling of Self-pruning

Self-pruning is a simple neighbor-knowledge based broadcasting algorithm which helps in reducing the redundant rebroadcast in flooding and minimizes the effect of broadcast storm problem. In this chapter, we mathematically analyze self-pruning algorithm and develop mathematical model for determining average fraction of neighbors forwarding/rebroadcasting the packet within a node's neighborhood. In Section 4.1 we define the problem. And Section 4.2 presents the derivation of our mathematical model for quantifying average fraction of neighbors forwarding/rebroadcasting within a node's neighborhood. In this literature, the two terms analytical model and mathematical model are used interchangeably.

4.1 Problem Definition

In this section we provide the formal definition of the problem. As discussed in Section 3.1 we use an unweighted graph $G = (V, E)$ to represent an ad hoc wireless network, where V represents a set of wireless mobile nodes and E represents a set of bidirectional links between the neighboring nodes. Two nodes are considered as neighbor if and only if their geographic distance is less than the transmission range, r. The circle around a node u corresponds to the transmission range of node u. All the nodes within the circle

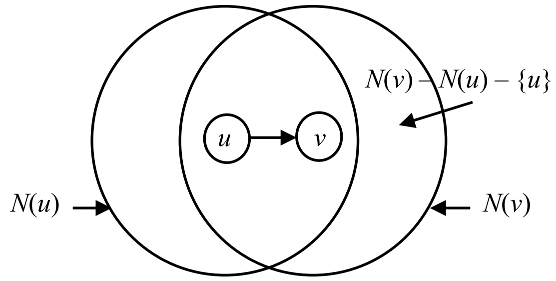

Figure 4.1: Self-pruning method.

are considered as the neighbors of node u.

In self-pruning broadcasting approach, each node collects adjacent node information by periodically exchanging *"hello"* messages. In Fig. 4.1, node u forwards a packet and v receives the packet. Node u piggybacks its neighbor list, $N(u)$ in the packet. Upon receiving the packet from u, node v checks whether $N(v) - N(u) - \{u\}$ is empty. If it is empty, node v is set as a non-forwarding node and refrains from forwarding. Otherwise, it is added to the forward list. In this thesis we focus on mathematically analyzing self-pruning algorithm and quantify the forwarding probability of a node located at a certain distance from the source of a broadcast. Due to the omnidirectional nature of radio transmission, when a node in the wireless ad hoc network broadcasts, every neighbor of it receives the packet. Thus, *redundancy* is used as a key performance metric in the performance evaluation of any broadcasting algorithm. Therefore, we build mathematical model for determining *redundancy* when self-pruning broadcasting algorithm is used.

4.2 Derivation of the Mathematical Model

In this section, we mathematically analyze self-pruning algorithm and develop mathematical model for determining *redundancy*. At first we will discuss *redundancy*.

We use an example to demonstrate how much *redundancy* could be generated in a network. In Fig. 4.2(a), node B is the source node. It initiates a broadcast and nodes C, D and G are relay nodes which will propagate the message all over the network. In this scenario, it only takes four transmissions for node B to complete a broadcast, whereas

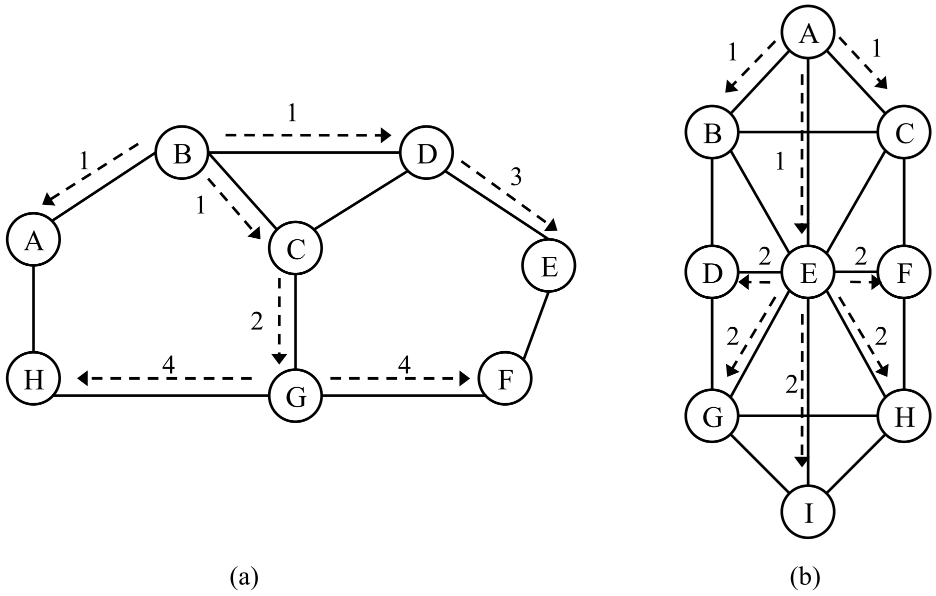

Figure 4.2: Optimal broadcasting schedules in MANETs. Connectivity between nodes is represented by links. And the arrow represents message transmission (a) Node B is the source node, and nodes C, D and G are relay nodes. (b) Node A is the source node, and node E is the relay node.

eight transmissions will be carried out if no attempt is made to reduce redundancy. Fig. 4.2(b) shows an even serious scenario: only two transmissions are sufficient to broadcast a message as opposed to nine transmissions caused by flooding.

Therefore, we can formally define *redundancy* as follows:

Redundancy. The average fraction of 1-hop neighbors rebroadcasting/forwarding from a node's neighborhood is called redundancy. Mathematically:

$$\begin{aligned} Redundancy &= Average\,fraction\,of\,neighbors\,rebroadcasting \\ &= \frac{Average\,number\,of\,neighbors\,rebroadcasting}{Number\,of\,nodes\,in\,a\,node's\,TX\,area} \end{aligned} \tag{4.1}$$

While estimating redundancy, we have to calculate the value for average/expected number of neighbors rebroadcasting from a node's neighborhood. To find out the average number of neighbor rebroadcasting first we have to find the probability of a node to be considered as a rebroadcasting node. This probability value can be quantified by multiplying two probability values: the probability of the node to be a neighbor and

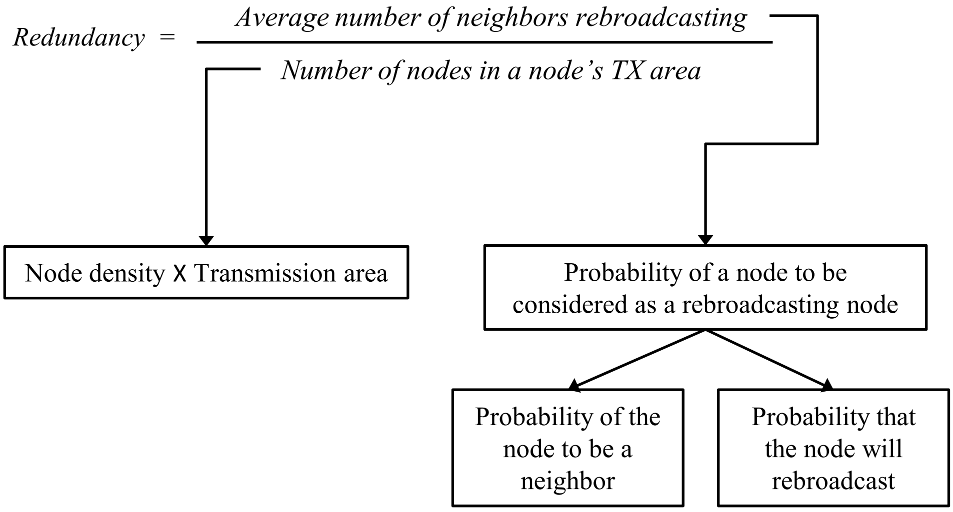

Figure 4.3: *Redundancy*

the probability that the node will rebroadcast. And we can find the number of nodes in a node's transmission area simply by multiplying node density in the network with the transmission area of the node. And finally dividing average number of neighbor's rebroadcasting by number of nodes in a node's TX area we can get redundancy. The whole process is shown in Fig. 4.3.

Now we will discuss in detail the derivation of the expression for redundancy when self-pruning algorithm is used. First in Section 4.2.1 we calculate number of nodes in a node's TX area. In Section 4.2.2 the average number of neighbors rebroadcasting is estimated and finally in Section 4.2.3 we derive the expression for quantifying redundancy.

4.2.1 Number of Nodes in a Node's TX Area

To determine *redundancy* first we will find the number of nodes in a node's TX area. In our network model n nodes are uniformly distributed over a rectangular deployment area A and having homogeneous transmission range r. Therefore, the average node density is: $\mu = n/A$. As the node distribution is assumed to be uniform, it is easy to determine the number of nodes present in a node's transmission (TX) area (in Equation 4.1) if the node density is known a priori. To see how, let us observe an arbitrary node u within the deployment area. The average number of nodes located in the communication region of node u is:

$$N_R = Node\, density \times Transmission\, Area = \mu \times \pi r^2 = \pi \mu r^2 \quad (4.2)$$

Our next step is to calculate average number of neighbors rebroadcasting from a node's neighborhood.

4.2.2 Average Number of Neighbors Rebroadcasting

Now, let us find the average number of neighbors rebroadcasting in Equation 4.1. As stated in Fig. 4.3 to determine this quantity, first we have to find the probability of any node v to be considered as a rebroadcasting node from u's neighbor set, denoted by $P_E(x)$. It can be derived simply by multiplying the probability that there exists a neighbor v at distance x from u denoted by $P_N(x)$ with its rebroadcasting/forwarding probability $P_F(x)$. Therefore, $P_E(x)$ is:

$$P_E(x) = P_N(x) \times P_F(x) \quad (4.3)$$

Finally, the expected number of rebroadcasting neighbors of node u denoted by E_F is found by integrating $P_E(x)$ from 0 to maximum transmission radius r within which node u possibly can communicate:

$$E_F = \int_0^r P_N(x) \times P_F(x) dx \quad (4.4)$$

We derive the expression for the expected number of rebroadcasting neighbors of node u in a bottom up manner. First we derive $P_N(x)$, the probability that there exists a neighbor v at distance x from u. Then we calculate rebroadcasting/forwarding probability $P_F(x)$ of that node. By multiplying these two probabilities we get $P_E(x)$, the probability of any node v to be considered as a rebroadcasting node from u's neighbor set. Finally, integrating $P_E(x)$ from 0 to maximum transmission radius r we get E_F, the expected number of rebroadcasting neighbors of node u.

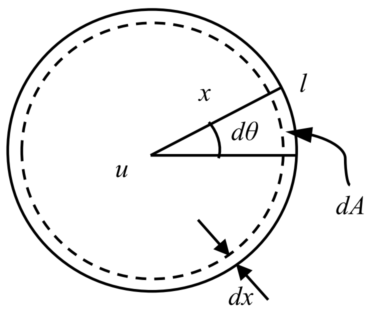

Figure 4.4: A circle strip at distance x.

4.2.2.1 $P_N(x)$: Probability of a Node's Existence at Distance x

Now let us derive $P_N(x)$, the probability that there exists a neighbor v at distance x from u. Clearly $P_N(x) = 0$ if $x > r$. For $x \leq r$, consider a small area strip defined by dx at the perimeter of the circle with radius x and centered at u. Also, consider a small angle $d\theta$ measured from an arbitrary but fixed axis as shown in Fig. 4.4. The length of the arc $l = xd\theta$ and the area of the small region dA within this small strip can be approximated as, $dA = ldx = xdxd\theta$. Therefore, the area of the entire small strip denoted by A_{strip} becomes,

$$A_{strip} = \int_0^{2\pi} dA = \int_0^{2\pi} ldx = \int_0^{2\pi} xdxd\theta = 2\pi xdx \qquad (4.5)$$

We can determine $P_N(x)$ by multiplying the area of the strip from Equation 4.5 with the node density of the network. That is:

$$\begin{aligned} P_N(x) &= Area\,of\,the\,strip \times Node\,density \\ &= A_{strip} \times \mu = 2\pi xdx \times \mu = 2\pi\mu xdx \qquad (4.6) \end{aligned}$$

4.2.2.2 $P_F(x)$: Forwarding/Rebroadcasting Probability of a node

Once we find the probability of a node's existence at distance x, the next thing is to find the probability that the node will rebroadcast upon receiving a message from node u. Based on self-pruning approach, a node v is eligible for forwarding after receiving a broadcast packet from node u, if it has one or more nodes in its *additional coverage* area. The area that can be actually benefited from node *v's* transmission after receiv-

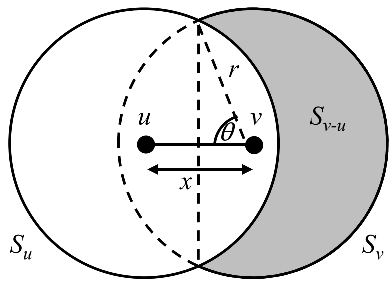

Figure 4.5: Intersection area of the two circles centered at two nodes u and v separated by distance x.

ing the packet from u is denoted as the additional coverage area of v. If there is no node in the additional coverage area, then all neighbors of v have already received the packet from *u's* transmission. Therefore, node v does not need to rebroadcast. Thus, forwarding/rebroadcasting probability of node v, $P_F(x)$ becomes the probability that there exist at least one node in the additional coverage area $A.C.(x)$ of node pair u and v where x is the distance between two nodes.

Now, to find the forwarding probability $P_F(x)$, first we have to determine the additional coverage area $A.C.(x)$. We can define $A.C.(x)$ by this simple equation:

$$|S_{v-u}| = |S_v| - |S_{u\cap v}| = \pi r^2 - INTC(x) \tag{4.7}$$

Here, S_v denotes the circular area covered by node *v's* transmission range and $S_{u\cap v}$ is the intersection area of the two circles S_u and S_v centered at two nodes u and v separated by distance x. S_{v-u} is the *additional coverage* area that can be benefited from the transmission of node v. This scenario is illustrated in Fig. 4.5. In this figure the shaded region is the additional coverage area, $A.C.(x)$ of node v. Let us derive the equation for the intersection area, $INTC(x)$ of node pair u and v:

$$INTC(x) = 4\int_{x/2}^{r} \sqrt{r^2 - x^2}dx \tag{4.8}$$

Converting Cartesian co-ordinate of Equation 4.8 in polar co-ordinate by using trigonometric functions we get,

$$
\begin{aligned}
INTC(x) &= 4\int_{\sin^{-1}(x/2r)}^{\pi/2} \sqrt{r^2 - r^2\sin^2\theta}\, r\cos\theta d\theta \\
&= 4\int_{\sin^{-1}(x/2r)}^{\pi/2} r^2\cos^2\theta d\theta \\
&= 4r^2\int_{\sin^{-1}(x/2r)}^{\pi/2} \frac{1}{2}(1+\cos 2\theta)d\theta \\
&= 2r^2 \times \left[\theta + \frac{\sin 2\theta}{2}\right]_{\sin^{-1}(x/2r)}^{\pi/2} \\
&= 2r^2 \times \left[\frac{\pi}{2} - \sin^{-1}\left(\frac{x}{2r}\right) + \frac{\sin\pi}{2} - \frac{\sin 2\sin^{-1}\left(\frac{x}{2r}\right)}{2}\right] \\
&= r^2 \times \left[\pi - 2\sin^{-1}\left(\frac{x}{2r}\right) - \sin 2\sin^{-1}\left(\frac{x}{2r}\right)\right] \qquad (4.9)
\end{aligned}
$$

Therefore, by plugging Equation 4.9 into Equation 4.7, we can find the additional coverage area which is:

$$
\begin{aligned}
A.C.(x) &= \pi r^2 - INTC(x) \\
&= \pi r^2 - r^2 \times \left[\pi - 2\sin^{-1}\left(\frac{x}{2r}\right) - \sin 2\sin^{-1}\left(\frac{x}{2r}\right)\right] \\
&= \pi r^2 - \pi r^2 + r^2\left[2\sin^{-1}\left(\frac{x}{2r}\right) + \sin 2\sin^{-1}\left(\frac{x}{2r}\right)\right] \\
&= r^2\left[2\sin^{-1}\left(\frac{x}{2r}\right) + \sin 2\sin^{-1}\left(\frac{x}{2r}\right)\right] \\
&= r^2\left[2\sin^{-1}\left(\frac{x}{2r}\right) + 2\sin\sin^{-1}\left(\frac{x}{2r}\right)\cos\sin^{-1}\left(\frac{x}{2r}\right)\right] \\
&= r^2\left[2\sin^{-1}\left(\frac{x}{2r}\right) + \frac{x}{r}\sqrt{\cos^2\sin^{-1}\left(\frac{x}{2r}\right)}\right] \\
&= r^2\left[2\sin^{-1}\left(\frac{x}{2r}\right) + \frac{x}{r}\sqrt{1-\sin^2\sin^{-1}\left(\frac{x}{2r}\right)}\right] \\
&= r^2\left[2\sin^{-1}\left(\frac{x}{2r}\right) + \frac{x}{r}\sqrt{1-\left(\sin\sin^{-1}\left(\frac{x}{2r}\right)\right)^2}\right] \\
&= r^2\left[2\sin^{-1}\left(\frac{x}{2r}\right) + \frac{x}{r}\sqrt{1-\frac{x^2}{4r^2}}\right] \\
&= r^2\left[2\sin^{-1}\left(\frac{x}{2r}\right) + \frac{x}{2r^2}\sqrt{4r^2-x^2}\right] \qquad (4.10)
\end{aligned}
$$

Finally from Equation 4.10 we get the expression for the additional coverage area $A.C.(x)$ of node v. Our next target is to find the probability that a node exists in this additional coverage area $A.C.(x)$ within the deployment area A where $A = n/\mu$. The probability is denoted by P_Δ and it becomes:

$$P_\Delta = \frac{A.C.(x)}{A} = \frac{A.C.(x) \times \mu}{n} \tag{4.11}$$

The probability $P_k\left(A.C.(x)\right)$ that exactly k nodes are located in the additional coverage area can be estimated using binomial distribution and it is:

$$P_k\left(A.C.(x)\right) = \binom{n-2}{k} P_\Delta^k \times (1 - P_\Delta)^{n-2-k} \tag{4.12}$$

Note that in Equation 4.12, $n - 2$ is used rather than n, because we exclude node u and node v from consideration. For large n and small P_Δ, the binomial distribution can be approximated using poisson distribution. Therefore,

$$P_k\left(A.C.(x)\right) = \frac{(nP_\Delta)^k \times e^{-nP_\Delta}}{k!} \tag{4.13}$$

Now, the forwarding probability $P_F(x)$ becomes the probability that there exist one or more nodes in the additional coverage area, $A.C.(x)$. Thus, we have to take the summation of probability of Equation 4.13 from 1 to n where n is the total number of nodes in the network.

$$\begin{aligned} P_F(x) &= \sum_{k=1}^{n} P_k\left(A.C.(x)\right) \\ &= \sum_{k=1}^{\infty} \frac{(nP_\Delta)^k \times e^{-nP_\Delta}}{k!} \\ &= e^{-nP_\Delta} \left(\sum_{k=0}^{\infty} \frac{(nP_\Delta)^k}{k!} - \frac{(nP_\Delta)^0}{0!} \right) \\ &= e^{-nP_\Delta}\left(e^{nP_\Delta} - 1\right) \\ &= 1 - e^{-nP_\Delta} \end{aligned} \tag{4.14}$$

Now, by plugging the expression of forwarding probability $P_F(x)$ from Equation 4.14 and expression of probability of a node's existence at distance x from Equation 4.6 into Equation 4.3 we will get $P_E(x)$, the probability of any node v to be considered as a rebroadcasting node from u's neighbor set.

$$\begin{aligned} P_E(x) &= P_N(x) \times P_F(x) \\ &= 2\pi\mu x dx \times \left(1 - e^{-nP_\Delta}\right) \end{aligned} \tag{4.15}$$

And from Equation 4.4 and 4.15 we get,

$$E_F = \int_0^r 2\pi\mu x \times \left(1 - e^{-nP_\Delta}\right) dx \tag{4.16}$$

4.2.3 Redundancy

Finally, the average fraction of nodes rebroadcasting, denoted by F_F, can be found if we divide expected number of neighbors rebroadcasting from a node's neighborhood, E_F by the number of nodes located in the communication region of that node, N_R. Mathematically:

$$Redundancy = F_F = \frac{E_F}{N_R} \tag{4.17}$$

By plugging the value of E_F and N_R into Equation 4.17 we get,

$$Redundancy = F_F = \frac{\int_0^r 2\pi\mu x \times \left(1 - e^{-nP_\Delta}\right) dx}{\pi\mu r^2} \tag{4.18}$$

Finally using Equation 4.10, 4.11 and 4.18 we get the expression for *redundancy*,

$$\begin{aligned} Redundancy = F_F &= \frac{\int_0^r 2\pi\mu x \times \left(1 - e^{-n\frac{A.C.(x)\times\mu}{n}}\right) dx}{\pi\mu r^2} \\ &= \frac{\int_0^r 2\pi\mu x \times \left(1 - e^{-A.C.(x)\times\mu}\right) dx}{\pi\mu r^2} \\ &= \frac{\int_0^r 2\pi\mu x \times \left(1 - e^{-r^2\left[2\sin^{-1}\left(\frac{x}{2r}\right) + \frac{x}{2r^2}\sqrt{4r^2 - x^2}\right]\times\mu}\right) dx}{\pi\mu r^2} \\ &= \frac{2\int_0^r \left(x - xe^{-r^2\left[2\sin^{-1}\left(\frac{x}{2r}\right) + \frac{x}{2r^2}\sqrt{4r^2 - x^2}\right]\times\mu}\right) dx}{r^2} \end{aligned} \tag{4.19}$$

According to Equation 4.19, the *redundancy*, F_F is a function of network parameters namely, distance between two nodes x, transmission range r, and node density μ. But this expression has no anti-derivative. By using numerical integration we can approximate a definite integral to any degree of accuracy. Numerical integration is used to evaluate definite integrals when the integrand has no simple anti-derivative. Therefore, we use Simpson's 3/8 rule for the numerical integration of Equation 4.19. To achieve high accuracy of the mathematical result the step size h is set to a very small value (i.e., 0.001). From this equation, we can estimate average fraction of neighbors within a node's neighborhood rebroadcasting the packet. Also, the effect of various network parameters on the efficiency and reliability of the self-pruning algorithm can be easily determined by some simple analysis.

Chapter 5

Proposed Dynamic Probabilistic Algorithm

In highly mobile networks, a very simple but effective approach to reduce redundant rebroadcasts is the *probabilistic* broadcasting algorithm. In this chapter we propose our dynamic probabilistic broadcasting algorithm. In Section 5.1 we define the problem of static probabilistic algorithm. And Section 5.2 presents our proposed dynamic probabilistic algorithm which uses a simple expression to calculate the rebroadcast probability of a node based on the existence of any node in the additional coverage area.

5.1 Probabilistic Broadcasting

In probabilistic broadcasts, upon receiving a broadcast packet, each node in the network (except the sender and receiver) decides whether to rebroadcast it or not based on a pre-defined probability value P. Mathematically speaking, instead of blindly forwarding any packet, a node in the network rebroadcasts a message with probability P and takes no action with probability $1 - P$. The performance of such protocol highly depends on the selected value of the forwarding probability P. With higher P values, more redundant transmissions take place but the chance of reaching all the nodes in the network increases. With lower P values the opposite thing happens. Thus, an inherent problem of this approach is to set a globally optimal probability value which is appropriate for all networking conditions and all dynamic environments. For example, in a *dense* network, a low probability value would ensure high reachability but the same low probability value would inhibit a significant number of nodes from receiving the broadcast in *sparse* networks. On the other hand, with a high probability value, high reachability can be maintained in *sparse* networks but the same value will create many redundant rebroadcasts in *dense* networks. Therefore, the probability of each node should be assigned dynamically rather than statically based on the node density, distance from the sender and other network parameters. Therefore, in this thesis we propose a dynamic probabilistic algorithm where every node dynamically calculates its rebroadcast probability by using a simple expression.

5.2 Dynamic Probabilistic Broadcasting

In this section we present our proposed algorithm. Let us first determine the rebroadcast probability of a node. From Equation 4.14, we get the forwarding probability of a node v at distance x from node u, if there exist one or more nodes in the additional coverage area of v, $A.C.(x)$. Using Equation 4.10, 4.11 into Equation 4.14, we get

$$\begin{aligned} P_F(x) &= 1 - e^{-nP_\Delta} \\ &= 1 - e^{-n\frac{A.C.(x)\times\mu}{n}} \\ &= 1 - e^{-A.C.(x)\times\mu} \\ &= 1 - e^{-r^2\left[2\sin^{-1}\left(\frac{x}{2r}\right)+\frac{x}{2r^2}\sqrt{4r^2-x^2}\right]\times\mu} \end{aligned} \quad (5.1)$$

We use Equation 5.1 in dynamic probabilistic algorithm to find out the forwarding/ rebroadcasting probability of a node. That means instead of a predefined probability for all the nodes in the network, every node will dynamically calculate its own rebroadcast probability based on the probability of existing at least one node in the additional coverage area. That is, with higher $A.C.(x)$ the rebroadcast probability becomes larger and with lower $A.C.(x)$ the probability value becomes smaller. Note that, the equation is a function of distance between the sending node and the receiving node (x), node density (μ) and transmission range (r).

Algorithm 5.1 Dynamic Probabilistic Broadcasting

if $Retrans(v, message) = 0$ **then** ▷ The node has not seen the message before.
  $p_{rand} = rand()$
  Calculate $P_F(x)$ ▷ By using Equation 5.1.
  if $p_{rand} \leq P_F(x)$ **then**
    Retransmit message
  end if
end if

The proposed algorithm is described in Algorithm 5.1. Here, $rand()$ is a function which generates a random number between 0 and 1 and the value is stored in p_{rand}. And $P_F(x)$, rebroadcast probability of a certain node v located at distance x from node u is calculated using Equation 5.1. If a node receives the message for the first time and the rebroadcast probability is greater than the generated random number then the node v rebroadcasts the message. Otherwise node v refrains itself from forwarding.

We can use a simple example to illustrate the proposed algorithm. Fig. 5.1 shows a sample network scenario. Suppose, 100 nodes are scattered in a deployment area of $10000m^2$ and the homogeneous transmission range, r is $15m$. Here, node u is the source node. Node u broadcast a message and neighbors of node u receive the broadcast

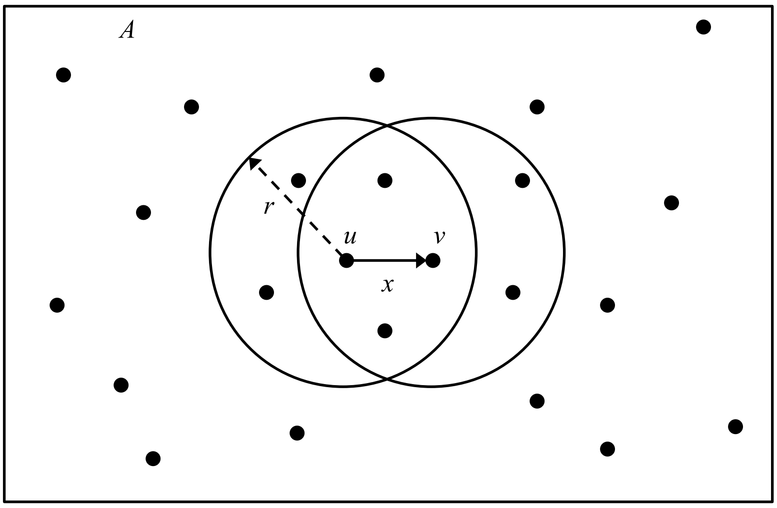

Figure 5.1: Illustration of proposed dynamic probabilistic algorithm. Some nodes are scattered in the deployment area A. Node u is the source node and v is another node at x distance from u.

message. Node v is a node in the neighborhood of node u and the distance between these two nodes, $x = 8m$. Now, using the expression for rebroadcast probability in Equation 5.1 we can determine the rebroadcast probability of node v. The node density of the network can be calculated by $\mu = n/A$. That means, $\mu = 100/10000 = 0.01$. Therefore, the rebroadcast probability becomes:

$$
\begin{aligned}
P_F(x) &= 1 - e^{-r^2\left[2\sin^{-1}\left(\frac{x}{2r}\right)+\frac{x}{2r^2}\sqrt{4r^2-x^2}\right]\times\mu} \\
&= 1 - e^{-(15)^2\left[2\sin^{-1}\left(\frac{8}{2\times 15}\right)+\frac{8}{2\times(15)^2}\sqrt{4\times(15)^2-(8)^2}\right]\times 0.01} \\
&= 1 - e^{-2.3712} \\
&= 0.90
\end{aligned}
$$

Again, if the distance between node u and node v becomes $5m$ then the rebroadcast probability becomes: $P_F(x) = 0.77$. In this way, every node will dynamically calculates its own rebroadcast probability using the distance between sender and receiver x, node density μ and transmission range r.

After calculating the rebroadcast probability node v will generate a random number between 0 to 1. If this random number is less than or equal to the rebroadcast probability of node v then it will rebroadcast the message. Otherwise it will drop the message.

Chapter 6

Simulations and Experiments

To validate the correctness of our analytical model, extensive simulation experiments have been conducted. We simulate the self-pruning algorithm and perform a comparative analysis based on the simulation results and the results derived from the analytical models. We also implement our proposed dynamic probabilistic algorithm and compare the performance of the algorithm with the static probabilistic algorithm. We build the simulation program using C/C++. The simulation is basically implemented in Network Layer. From Chapter 4 and Chapter 5 we can see that, all mathematical expressions are function of three network parameters, (1) transmission range (2) node density, and (3) node distribution. We can observe their impacts on the protocols, assuming ideal Medium Access Control (MAC) or Physical Layers. If the expressions would depend on the Physical Layer or Data Link Layer parameters such as, collision probability, bit error rate etc. then a simulation with more realistic environments (like ns-2) could be justified. However considering those event's effects on the mathematical model are beyond the scope of this work.

In this chapter, we describe the experimental setup and results in brief. Section 6.1 discusses about the simulation scenario that has been used to run the experiments. In Section 6.2 we provide an overview of our implementation of self-pruning algorithm and proposed dynamic probabilistic broadcasting. Performance metrics that are important to evaluate our mathematical model and quantify the performance of our proposed algorithm are discussed in Section 6.3. The simulation results and comment on various

Table 6.1: Summary of simulation parameters.

Parameter Name	Value
Area of deployment	$100m \times 100m$
Maximum Transmission range	$30m$
Node Distribution	Uniform
Node Number	70-200

aspects of performance measures of our analytical model of self-pruning is presented in Section 6.4. Finally, Section 6.5 presents the simulation results to evaluate the performance of our proposed dynamic probabilistic broadcasting algorithm.

6.1 Simulation Scenario

We simulate a network where all nodes are randomly scattered in a $100m \times 100m$ square area. The density of node is varied by varying the number of nodes from 70 to 200 nodes in the fixed deployment area. To analyze the effect of transmission range we vary the transmission range from $12m$ to $30m$. We only consider the connected networks for the simulation results. For the simulation experiments of self-pruning algorithm the results are averaged over 1000 random scenarios considering the source node can be anywhere in the network. And for the dynamic probabilistic algorithm we generate 100 random scenarios. For each scenario, experiment is conducted considering each node as a source node and for each node in the network rebroadcast decision is calculated. Performance measures are reported as an average of these random samples. Table 6.1 summarizes the simulation parameters.

6.2 Implementation

This section describes the implementation of self-pruning broadcasting and our proposed dynamic probabilistic broadcasting algorithm. Here, we describe the different module of the implementation process and their functionality.

6.2.1 Implementation of Self-pruning Broadcasting

Inputs: The main parameters for the self-pruning algorithm are transmission range (r), distance between two nodes (x) and node density (μ).

Outputs: The output is average fraction of neighbors rebroadcasting.

Scenarios: The topology considered describes a rectangular deployment area (A) where n nodes are randomly scattered. We variated the nodes generation to create different network scenario.

We have created an object named node. Every node has an x and y-coordinate. And it has a field to store the broadcast identifier. Our implementation has different modules and they are:

1. $rand\_node\_generation(n)$: This module takes as input the number of nodes (n) and create n random nodes in the deployment area (A).

2. $connected\_network()$: In the mathematical modeling of self-pruning algorithm we consider only the connected network. So this module checks the connectivity of the network generated from the $rand\_node\_generation(n)$ module.

3. $neighbor\_find(u)$: The input is a single node. This module finds the neighbors of this node. Two nodes are neighbor if the euclidean distance is less than or equal to the transmission radius (r) of the nodes.

4. $self\_prune(u, v)$: After any node v receives a broadcast from node u, it will check the neighbor list of node u and v. If there is any neighbor other than the common neighbors of node u and v, then node v will set as a forwarding node. Otherwise it will set as a non-forwarding node.

5. $self\_pruning\_algo()$: In this module by calling $rand\_node\_generation(n)$ and $connected\_network()$ we first create a connected network with randomly scattered n nodes in the deployment area (A). After that, a source node initiates the broadcast and all the neighbors of the source node get the broadcast. And every neighbors of the source node will check whether it is a forwarding node or not by calling $self\_prune(u, v)$. If it is a forwarding node then it will rebroadcast. After receiving any broadcast node v also stores the broadcast identifier and does

not act on receiving repeated copies of the same broadcast. This process will be continued until all the nodes in the network get the broadcast as we consider only connected networks. We use *queue* data structure to propagate the broadcast all over the network.

6.2.2 Implementation of Dynamic Probabilistic Broadcasting

Inputs: The parameters for dynamic probabilistic broadcasting are transmission range (r), distance between two nodes (x) and node density (μ).

Outputs: The outputs are average fraction of neighbors rebroadcasting, average fraction of neighbors receiving the broadcast and the saved rebroadcast.

Scenarios: The topology considered describes a rectangular deployment area (A) where n nodes are randomly scattered. We variated the nodes generation to create different network scenario.

The node object is also used in this implementation. The three modules used in self-pruning implementation: $rand\_node\_generation\,(n)$, $connected\_network\,()$ and $neighbor\_find\,(u)$ are also used here having the same functionality. The other two modules are:

1. $rebroadcast\_prob(u, v)$: This module calculates the distance (x) between two nodes, source node (u) and the receiving node (v). It determines the rebroadcast probability of node v using Equation 5.1 in Chapter 5. This equation is a function of network parameters transmission range (r), distance between two nodes (x) and node density (μ).

2. $dynamic\_prob\_algo()$: In this module by calling $rand\_node\_generation(n)$ and $connected\_network()$ we first create a connected network with randomly scattered n nodes in the deployment area (A). After that, a source node initiates the broadcast and all the neighbors of the source node get the broadcast. And every neighbors of the source node will determine its own rebroadcast probability by calling $rebroadcast\_prob(u, v)$ and also generate a random number between 0 and 1. If this generated random number is less than or equal to the calculated rebroadcast probability then the node will rebroadcast otherwise it will drop the

broadcast. Every node upon receiving any broadcast stores the broadcast identifier and does not act on receiving repeated copies of the same broadcast. In this way the broadcast will propagate all over the network. We use *queue* data structure to propagate the broadcast.

6.3 Performance Metric

In this section we define the performance metrics used to quantify our mathematical model and proposed algorithm. We analyze the performance of self-pruning using *redundancy* as a metric. On the other hand, in order to evaluate the performance of the proposed dynamic probabilistic broadcasting algorithm, we use three kinds of measures: *redundancy*, *reachability* and *saved rebroadcast*.

6.3.1 Redundancy

As mentioned earlier in Chapter 4, redundancy is defined as the average fraction of one-hop neighbors rebroadcasting/forwarding from a node's neighborhood. Formally:

$$\begin{aligned} Redundancy &= Average\, fraction\, of\, neighbors\, rebroadcasting \\ &= \frac{Average\, number\, of\, neighbors\, rebroadcasting}{Number\, of\, nodes\, in\, a\, node's\, TX\, area} \end{aligned} \tag{6.1}$$

The main goal of every broadcasting algorithm is to reduce the *redundancy*. The less *redundancy* in the network the better it is.

6.3.2 Reachability

The average fraction of the number of nodes receiving the broadcast packets to the total number of nodes in the network is defined as reachability. Mathematically:

$$\begin{aligned} Reachability &= Average\, fraction\, of\, nodes\, receiving \\ &= \frac{Number\, of\, nodes\, receiving}{Number\, of\, nodes\, in\, the\, network\, area} \end{aligned} \tag{6.2}$$

Higher *reachability* ensures high coverage in the network that means more nodes in the network will receive the packet. The goal of every broadcasting algorithm is to ensure high *reachability*.

6.3.3 Saved Rebroadcast

Saved rebroadcast can be defined as $(r - t)/r = r$, where r is the number of nodes receiving the broadcast message, and t is the number of nodes actually transmitted the message.

6.4 Analytical Model of Self-pruning

To validate the correctness of our analytical model we compare the analytical result with our simulation result. Measurements from both simulation experiments and analytical expressions are plotted in the same graph. In this section we present the effect of distance between two nodes (x), node density (μ) and transmission range (r) on the forwarding probability of a node located at x distance from the sender. And also the performance of the mathematical model is compared with the simulation results based on *redundancy*.

6.4.1 Effect of Distance between Nodes on Forwarding Probability

Effect of distance between two nodes (x) on the forwarding probability is shown in Fig. 6.1. Distance between two nodes (x) has clear effects on the additional coverage region S_{v-u} and thereby changes the forwarding probability. For a homogeneous transmission range r, additional coverage area increases with the increase of distance x and it reaches the highest value when $x = r$. Experiments are conducted for 150 nodes in the network and transmission range is set to r equals $12m$ and r equals $18m$. We vary the distance between nodes from 0 to maximum transmission range, r with an increment of $1m$ at each step. As can be seen from Fig. 6.1, the forwarding probability $P_F(x)$ exponentially increases with the increase of distance between two nodes and the forwarding probability gets the maximum value of 1 when x is equal to the transmission range r. Also for all scenarios, the results of analytical expressions are close to the simulation results. The discrepancy between the analytical results and the simulation results are

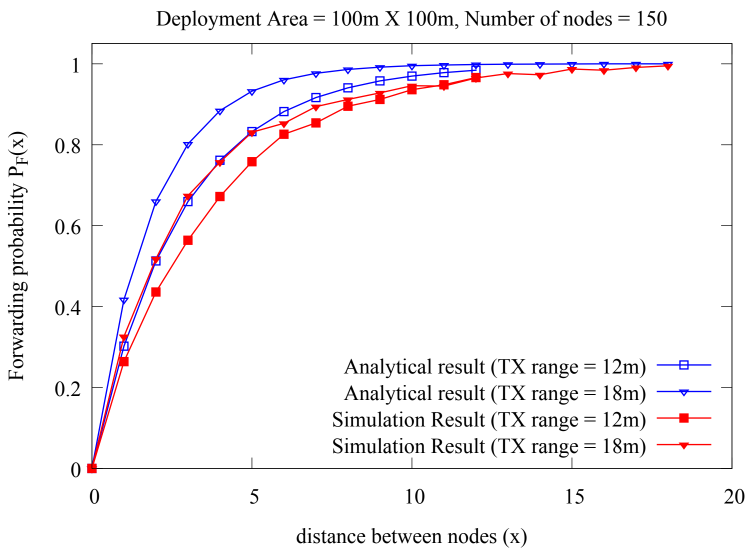

Figure 6.1: Effect of distance between nodes, x on $P_F(x)$.

very small, maximal being around 8% when r is $12m$ and 12% when r is $18m$.

6.4.2 Effect of Node Density on Forwarding Probability

We have presented the effect of node density (μ) on the forwarding probability in Fig. 6.2. With the increase of number of nodes in the network, the probability of existing nodes in the additional coverage region S_{v-u} also increases. Experiments are conducted for different values of x such as $5m$, $8m$ and $12m$ where x is the distance between two nodes and the value for transmission range (r) is set to $15m$. We vary the number of nodes (n) in the network from 70 to 200 with an increment of 10 nodes at each step. As can be seen from Fig. 6.2, the forwarding probability $P_F(x)$ increases with the increase in node density. Also for all scenarios, the results of analytical expressions are close to the simulation results. The discrepancy between the analytical results and simulation results are very small, maximal being around 11% when distance between two nodes, x is $5m$, 8% when x is $8m$ and 6% when x is $12m$.

6.4.3 Effect of Node Density on *Redundancy*

We present the effect of node density on the average fraction of neighbors forwarding the packet with various transmission ranges while keeping the deployment area constant.

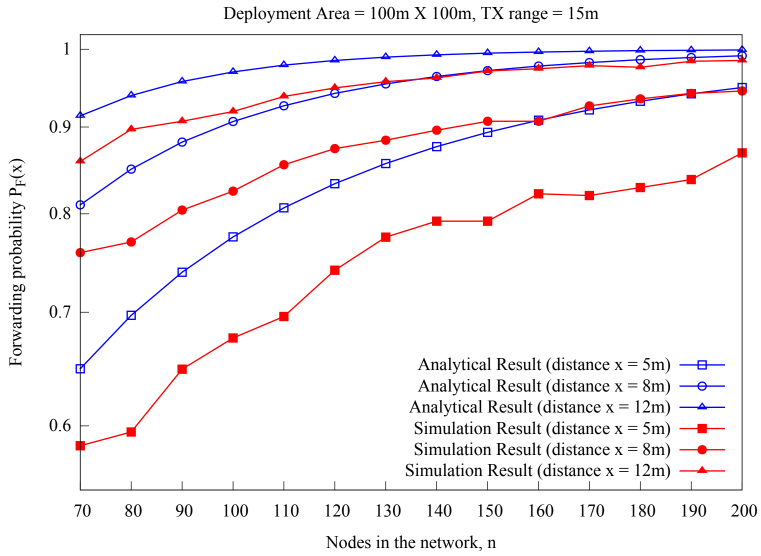

Figure 6.2: Effect of node density, μ on $P_F(x)$.

The node density is varied by increasing 10 nodes in the network per step, starting from 70 to 200 and we examine the result for transmission ranges $15m$, $18m$ and $21m$. The node density, μ affects the number of nodes located in the additional coverage region $S_{(v-u)}$. With larger node densities, it is highly probable that at least one node exists in the additional coverage area of v which makes it an eligible forwarding node. We present both the analytical results and results from simulation in Fig. 6.3. From the figure, we can see that average fraction of neighbors rebroadcasting, F_F is increased with the increase in node density, μ in the network. That is, a higher fraction of neighbors is set as a forwarding node in more dense networks for all transmission ranges. The maximum difference between analytical results and simulation result is around 8%.

6.4.4 Effect of Transmission Range on *Redundancy*

To determine the effect of various transmission ranges on the average fraction of neighbors rebroadcasting, we measure F_F with different node densities. Transmission range is varied between $12m$ to $30m$ with an increment of $3m$ at each step. We verify the result for $n = 90$, $n = 120$ and $n = 180$ where, n is the number of nodes in the network and the deployment area is constant. When the transmission range r changes the circular regions S_u and S_v also change. Thus, the additional coverage region changes

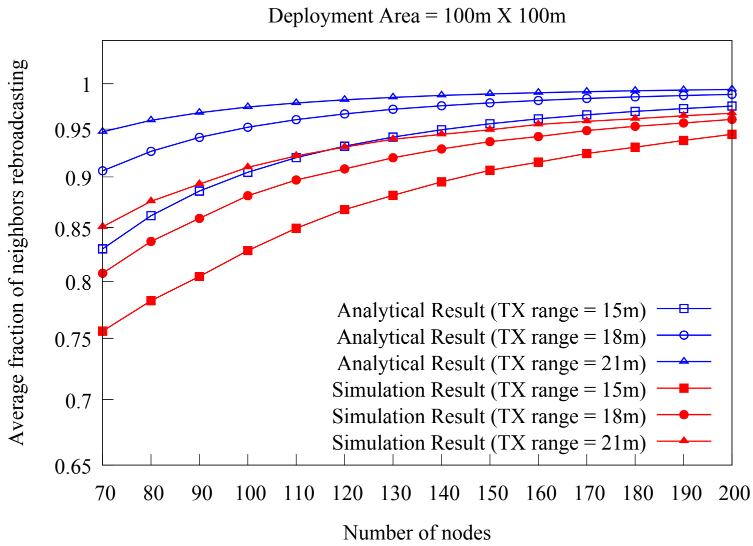

Figure 6.3: Effect of node density, μ on F_F.

which results in changing of forwarding probability of a node. The result is presented in Fig. 6.4. From the figure, it is clear that average fraction of nodes rebroadcasting (i.e. F_F) increases with the increase of transmission range r. The analytical results and simulation results are very close. The small inaccuracy arises from the nodes located close to the perimeter of the deployment area. The nodes in the perimeter are more likely to have overlapping neighbors than the nodes in the center because their communication area is restricted.

6.5 Proposed Dynamic Probabilistic Algorithm

The simulation result of our proposed dynamic probabilistic algorithm is compared with the static probabilistic algorithm and plotted on the same graph for a clear comparison.

6.5.1 *Reachability*

We present the effect of node density on the reachability in Fig. 6.5. To analyze the performance of our proposed dynamic probabilistic algorithm we plot the result of both static and dynamic probabilistic algorithm in the same graph. The number of nodes in the network is varied from 70 to 200 and transmission range is set to $15m$. Probabilities

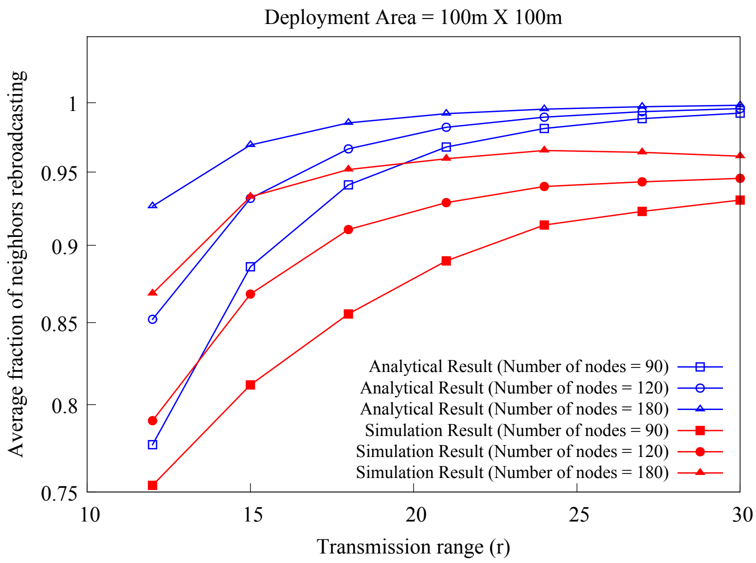

Figure 6.4: Effect of transmission range, r on F_F.

of values 0.5, 0.6, 0.7, 0.8 and 0.9 are considered for static probabilistic algorithm. As can be seen from the figure, in the dynamic probabilistic algorithm average fraction of nodes in the network receiving the packet is high, compared to the static probabilistic algorithm of values 0.5, 0.6, 0.7 and 0.8. The static values of 0.5, 0.6, 0.7 and 0.8 have a very low *reachability* in case of sparse networks. But our proposed scheme ensures high *reachability* for sparse, as well as, dense networks compared to the existing heuristic.

6.5.2 *Redundancy*

The effect of node density on the *redundancy*, i.e., on the average fraction of rebroadcast for both static and dynamic probabilistic algorithms is presented in Fig. 6.6. Node density is varied by varying the number of nodes between 70 to 200 while keeping the deployment area constant at $100m \times 100m$ square regions. The transmission range is set to $15m$. For the static probabilistic algorithm we vary the probability values from 0.5 to 0.9 with an increment of 0.1 at each step. As can be seen from the figure, the redundancy of the proposed dynamic probabilistic broadcasting is lower than the static probabilistic broadcasting with probability value of 0.9. Although the redundancy of the dynamic probabilistic broadcasting is higher compared to the static probabilistic broadcasting with other probability values (i.e., $P = 0.5,\ 0.6,\ 0.7,\ 0.8$), ultimately, the dynamic

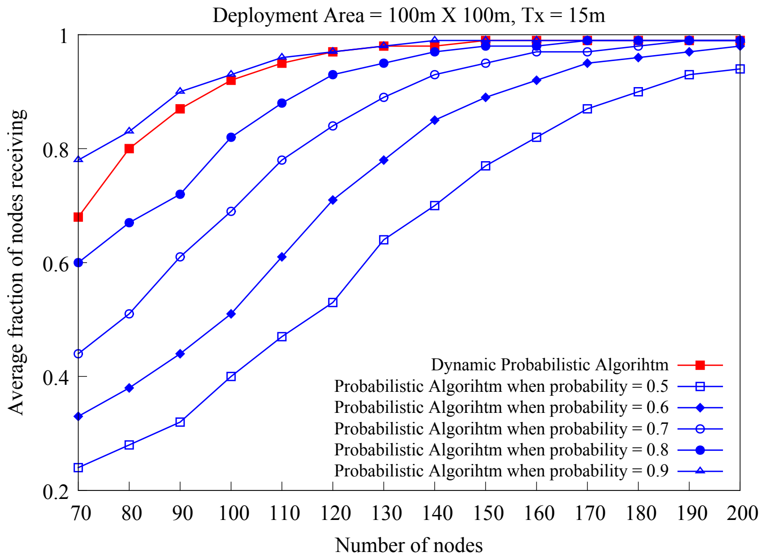

Figure 6.5: Measurement of *reachability* in dynamic probabilistic algorithm and static probabilistic algorithm.

probabilistic broadcasting turns up the clear winner when we look at Fig. 6.5 and Fig. 6.6 together. Our proposed dynamic probabilistic algorithm provides high reachability in case of sparse network as well as dense network. As the goal of every broadcasting algorithm is to maximize the reachability while minimizing the redundancy, the dynamic probabilistic algorithm incurs more redundancy simply to improve reachability.

6.5.3 Ratio of *Redundancy* and *Reachability*

The ratio of *redundancy* and *reachability* is shown in Fig. 6.7. Node density is varied by varying the number of nodes from 70 to 200 while keeping the deployment area constant. The transmission range is set to 15m. For the static probabilistic algorithm we vary the probability values from 0.5 to 0.9 with an increment of 0.1 at each step. We can see that the ratio of *redundancy* and *reachability* of proposed dynamic algorithm is less than the fixed probability value 0.9. To properly interpret the graphs in Fig. 6.7, we should realize that the spectacularly low ratio of redundancy and reachability of static probabilistic algorithm with probability values in the range of 0.5-0.8 results from the fact that the *reachability* of static probabilistic broadcasting in that probability range is also very poor (cf. Fig. 6.5).

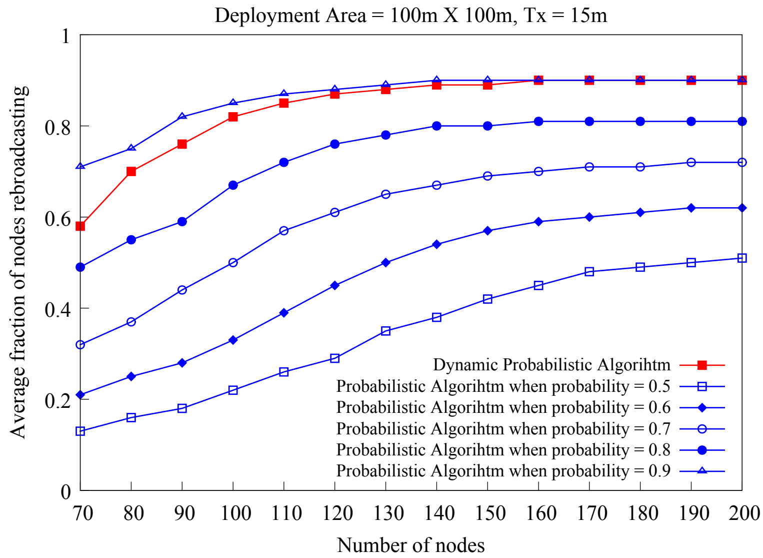

Figure 6.6: Measurement of *redundancy* in dynamic probabilistic algorithm and static probabilistic algorithm.

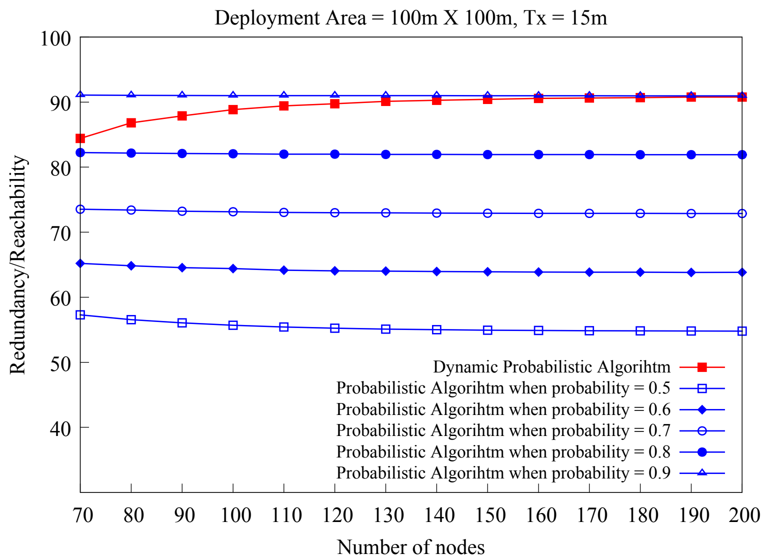

Figure 6.7: Measurement of ratio of *redundancy* and *reachability* in dynamic probabilistic algorithm and static probabilistic algorithm.

6.5.4 Saved Rebroadcast

The effect of node density on the *saved rebroadcast* for both static and dynamic probabilistic algorithms is presented in Fig. 6.8. Node density is varied by varying the number of nodes between 70 to 200 while keeping the deployment area constant at $100m \times 100m$

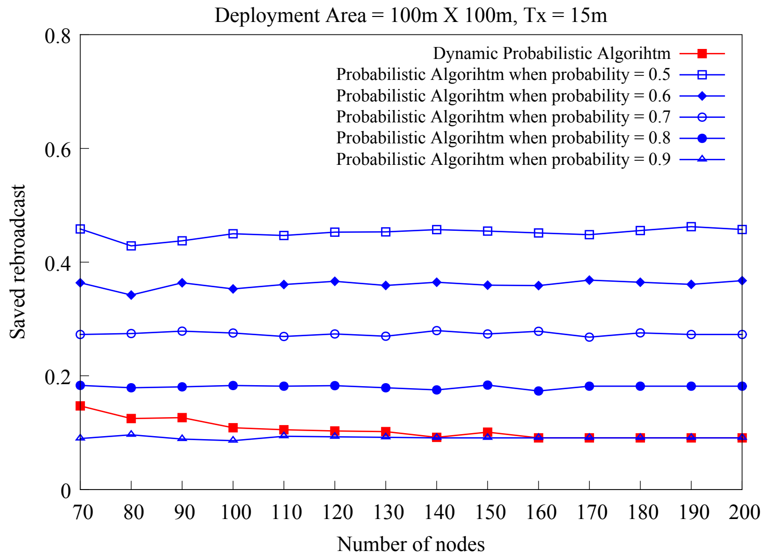

Figure 6.8: Measurement of *saved rebroadcast* in dynamic probabilistic algorithm and static probabilistic algorithm.

square regions. The transmission range is set to $15m$. For the static probabilistic algorithm we vary the probability values from 0.5 to 0.9 with an increment of 0.1 at each step. As can be seen from the figure, the saved rebroadcast of the proposed dynamic probabilistic broadcasting is higher than the static probabilistic broadcasting with probability value of 0.9. The saved rebroadcast of the dynamic probabilistic broadcasting is lower compared to the static broadcasting with probability values 0.5, 0.6, 0.7 and 0.8. It is because, the dynamic probabilistic broadcasting ensures high reachability for sparse, as well as dense network. On the other hand, static broadcasting with probability values 0.5, 0.6, 0.7 and 0.8 shows low reachability compared to the dynamic probabilistic broadcasting.

From the analytical results and simulation results of self-pruning it is clear that our analytical model efficiently characterize self-pruning algorithm. The small discrepancy between the analytical results and simulation results arise from the nodes located close to the perimeter of the deployment area. The comparison of simulation results of dynamic probabilistic algorithm and static probabilistic algorithm shows that our proposed scheme performs better.

Chapter 7

Conclusion

In this thesis, we have presented an analytical model for characterizing self-pruning algorithm as a function of various network and transceiver parameters and get a better perception of the complex mechanism of the algorithm. With the help of this model, we can easily estimate the reliability and performance of the network prior to the network deployment. Moreover, the analysis helps us to design new heuristics for broadcasting in wireless ad hoc networks. In this thesis, we have also introduced a dynamic probabilistic broadcasting algorithm based on the rebroadcasting probability of a node. The rebroadcast probability is calculated using the expression of forwarding probability of a node derived during the modeling of self-pruning algorithm. Simulation results show that, the proposed dynamic probabilistic algorithm performs better than the static probabilistic algorithm.

The work of this thesis can be extended in various ways. Here, we discuss some future works:

1. Self-pruning approach is based on selecting a small subset of hosts (also called nodes) to form a forward node set to carry out a broadcast process. Each node, upon receiving a broadcast packet, determines whether to forward the packet based on neighborhood knowledge. It can use 1-, 2- or more-hop neighbor information for the forwarding decision, though self-pruning based on 2- or 3-hop neighborhood information is relatively costly. Based on our analytical model it is possible to develop mathematical model for broadcasting algorithm where 2- or more-hop

neighbor information is used for forwarding decision.

2. We can also extend our mathematical model to analyze other broadcasting algorithms.

3. Again, our proposed dynamic probabilistic broadcasting algorithm performs well compare to blind flooding and static probabilistic broadcasting algorithm. We can design a more adjustable dynamic probabilistic algorithm which will be able to achieve more saved rebroadcast and higher reachability in the network.

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