5-2016

Development of an efficient Ad Hoc broadcasting scheme for critical networking environments

Ahmed Ghulam Mustafa Saber Karam

UAEU

جامعة الإمارات العربية المتحدة
United Arab Emirates University

United Arab Emirates University

College of Information Technology

DEVELOPMENT OF AN EFFICIENT AD HOC BROADCASTING SCHEME FOR CRITICAL NETWORKING ENVIRONMENTS

Ahmed Ghulam Mustafa Saber Karam

This dissertation is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

Under the Supervision of Professor Liren Zhang

May 2016

Declaration of Original Work

I, Ahmed Ghulam Mustafa Saber Karam, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this dissertation entitled "*Development of an Efficient Ad Hoc Broadcasting Scheme for Critical Networking Environments*", hereby, solemnly declare that this dissertation is my own original research work that has been done and prepared by me under the supervision of Professor Liren Zhang, in the College of Information Technology, UAEU. This work has not previously been presented or published, or formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my dissertation have been properly cited and acknowledged in accordance with appropriate academic conventions. I declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation and/or publication of this dissertation.

Student's Signature: __________________________ Date: ________________

Advisory Committee

1) Advisor: Dr. Liren Zhang

Title: Professor

Networking Track

College of Information Technology

2) Member: Dr. Abderrahmane Lakas

Title: Associate Professor

Networking Track

College of Information Technology

3) Member: Dr. Ezedin Barka

Title: Associate Professor

Information Security Track

College of Information Technology

Approval of the Doctorate Dissertation

This Doctorate Dissertation is approved by the following Examining Committee Members:

1) Advisor (Committee Chair): Dr. Liren Zhang
   Title: Professor
   Department of Networking
   College of Information Technology
   Signature ______________________ Date 9/5/2016

2) Member: Dr. Hesham El-Sayed
   Title: Associate Professor
   Department of Networking
   College of Information Technology
   Signature ______________________ Date 9/5/2016

3) Member: Dr. Mohammad Hayajneh
   Title: Associate Professor
   Department of Computer Systems Design
   College of Information Technology
   Signature ______________________ Date 9/5/2016

4) Member (External Examiner): Dr. Azzeddine Boukerche
   Title: Professor
   School of Electrical Engineering and Computer Science
   Institution: University of Ottawa, Canada
   Signature ______________________ Date 9/15/2016

This Doctorate Dissertation is accepted by:

Dean of the College of Information Technology: Professor Omar El-Gayar

Signature ______________________ Date 9/5/16

Dean of the College of the Graduate Studies: Professor Nagi T. Wakim

Signature Nagi Wakim Date 26/5/2016

Copy 11 of 13

Abstract

Mobile ad hoc network has been widely deployed in support of the communications in hostile environment without conventional networking infrastructure, especially in the environments with critical conditions such as emergency rescue activities in burning building or earth quick evacuation. However, most of the existing ad hoc based broadcasting schemes either rely on GPS location or topology information or angle-of-arrival (AoA) calculation or combination of some or all to achieve high reachability. Therefore, these broadcasting schemes cannot be directly used in critical environments such as battlefield, sensor networks and natural disasters due to lack of node location and topology information in such critical environments. This research work first begins by analyzing the broadcast coverage problem and node displacement form ideal locations problem in ad hoc networks using theoretical analysis. Then, this research work proposes an efficient broadcast relaying scheme, called Random Directional Broadcasting Relay (RDBR), which greatly reduces the number of retransmitting nodes and end-to-end delay while achieving high reachability. This is done by selecting a subset of neighboring nodes to relay the packet using directional antennas without relying on node location, network topology and complex angle-of-arrival (AoA) calculations. To further improve the performance of the RDBR scheme in complex environments with high node density, high node mobility and high traffic rate, an improved RDBR scheme is proposed. The improved RDBR scheme utilizes the concept of gaps between neighboring sectors to minimize the overlap between selected relaying nodes in high density environments. The concept of gaps greatly reduces both contention and collision and at the same time achieves high reachability. The performance of the proposed RDBR schemes has been evaluated by comparing them against flooding and Distance-based schemes. Simulation results show that both proposed RDBR schemes achieve high reachability while reducing the number of retransmitting nodes and end-to-end delay especially in high density environments. Furthermore, the improved RDBR scheme achieves better performance than RDBR in high density and high traffic environment in terms of reachability, end-to-end delay and the number of retransmitting nodes.

Keywords: Mobile Ad hoc Networks (MANETs), Data Dissemination, Node Density, Data Redundancy, Performance Modeling, Probabilistic Broadcast, Distance-based Broadcast, Directional Antenna.

Title and Abstract (in Arabic)

تطوير نظام كفء لنشر المعلومات في بيئة ذات مواصفات استثنائية

الملخص

يستخدم شبكة (ad hoc) النقالة على نطاق واسع لدعم الاتصالات في بيئة ذات مواصفات استثنائية التي تعاني من عدم وجود البنية التحتية للشبكات التقليدية، وخاصة في البيئات ذات الظروف الحرجة مثل أنشطة الإنقاذ في حالات الطوارئ عند احتراق مبنى أو عملية إخلاء في حالة حدوث زلزال. ولكن، معظم الحلول المقترحة لنشر المعلومات في هذه البيئات تعتمد إما على موقع (GPS) أو مخطط الشبكة أو حساب زاوية وصول الاشارة أو مزيج من بعض أو جميع هذه المميزات لتحقيق قابلية الوصول الى اكبر عدد من (Nodes). لذلك، هذه الحلول المقترحة لنشر المعلومات لا يمكن استخدامها مباشرة في بيئات حرجة مثل ساحة المعركة، شبكات الاستشعار والكوارث الطبيعية نظرا لعدم وجود نظام تحديد المواقع و مخطط الشبكة في مثل هذه البيئات الحرجة.

الخطوة الاولى في هذه الأطروحة لحل المشكلة المذكورة اعلى، هي تحليل نظري لمشكلة تغطية البث ومشكلة تحرك ال(Nodes) من مواقعها المثالية في شبكات ذات ظروف استثنائية. ثم، يقترح هذا البحث نظام كفء لنشر المعلومات، يسمى نظام عشوائي موجه لنشر المعلومات (RDBR)، حيث يقوم النظام المقترح في تقليل من عدد (Nodes) المستخدمة في عملية النشر وايضا تقليل زمن نشر المعلومة الى جميع (Nodes) في الشبكة مع تحقيق قابلية الوصول عالية. ويتم ذلك عن طريق اختيار مجموعة فرعية من (Nodes) المجاورة لنقل الحزمة باستخدام هوائيات الاتجاه الموجهة (Directional Antennas) دون الاعتماد على موقع ال(Node)، و مخطط الشبكة والعمليات الحسابية المعقدة مثل حساب زاوية وصول الاشارة.

لزيادة تحسين أداء نظام (RDBR) في بيئات معقدة ذات كثافة (Nodes) عالية، وسرعة (Nodes) عالية وارتفاع معدل المعلومات المنشورة، تم اقتراح نظام (RDBR) محسن. يستخدم نظام (RDBR) المحسن مفهوم الفجوات بين القطاعات المجاورة لهوائيات الموجة (Directional Antennas) للحد من التداخل بين (Nodes) التي تم اختيارهم لعملية نشر المعلومات. مفهوم الفجوات بين القطاعات المجاورة تقلل كثيرا حالات التصادم والمنافسة على استخدام سعة النشر، وفي الوقت نفسه تحقق قابلية الوصول عالية. وقد تم تقييم أداء أنظمة (RDBR) التي تم اقتراحها في هذه الأطروحة بمقارنتها مع انظمة نشر اخرى مثل

(Flooding) و (Distance-based scheme). وتبين نتائج المحاكاة أن كل من أنظمة (RDBR) المقترحة حققت قابلية وصول عالية مع تقليل في عدد (Nodes) المستخدمة في عملية النشر وتقليل زمن نشر المعلومات لا سيما في البيئات ذات الكثافة العالية. وعلاوة على ذلك، حقق نظام (RDBR) المحسن أداء أفضل من نظام (RDBR) التقليدي من حيث تحقيق قابلية وصول عالية و استخدام عدد اقل من (Nodes) لعملية النشر وتقليل زمن نشر المعلومات خصوصا في بيئة ذات كثافة (Nodes) عالية و كمية معلومات كبيرة.

مفاهيم البحث الرئيسية: شبكات (Ad hoc) متنقلة، نشر البيانات، كثافة (Nodes)، تكرار البيانات، نمذجة الأداء، البث الاحتمالي، البث القائم على المسافة، الهوائيات الموجة.

Acknowledgements

This thesis would not have been possible without the generous help and encouragement of many individuals. I would like to express my gratitude to everyone who has contributed to the process leading to my PhD dissertation. Here I would like to mention a few of these people.

First and foremost, I would like to thank my supervisor Professor Liren Zhang for his tremendous help and guidance in every phase and aspect of my doctorate study. The flexibility and freedom he has provided me in deciding and evolving my research focus has been an invaluable asset in my quest to acquire, generate, and disseminate new knowledge. He has set the perfect example of being inspiring researcher for me. His example has been very influential in shaping this work and will undoubtedly continue to light my way in my future career.

I would like to thank all my teachers and my friends for being the colors of my life. Lastly and most importantly, I would like to thank my parent, my uncle, my wife, sisters, brothers, children and my whole family for their everlasting love and gratuitous support for me. To them I dedicate this thesis.

Dedication

To my beloved parents, my uncle, my wife, my children and my family

Table of Contents

List of Tables

List of Figures

List of Abbreviations

NS-2	Network Simulator Version 2
RWP	Random Waypoint Mobility Model
RDBR	Random Directional Broadcasting Relay
MANET	Mobile Ad hoc Network
GPS	Global Positioning System
TTL	Time To Live
RAD	Random Assessment Delay
MAC	Medium Access Control

Chapter 1: Introduction

The first chapter of this dissertation provides a brief introduction to Mobile Ad hoc Networks, broadcasting in MANETs and broadcast storm problem, followed by motivation of the research, problem statement, aims and objectives, and the main contributions of this work. The chapter is concluded by describing the structure of the thesis.

1.1 Background

Mobile ad hoc network (MANET) has been rapidly developed and widely deployed in support of the communications in hostile environment without conventional networking infrastructure, especially in the environments with critical conditions such as emergency rescue activities in burning building or earth quick evacuation [1], [2], [3] [4], [5], [6], [7]. In MANET, nodes act both as user and router at the same time. The nodes communicate with each other over a shared medium [8][9]. Broadcasting forms the basis to many critical ad hoc networks such as sensor networks and battlefield communications. One fundamental requirement of such critical networks is power-conservation because it determines the life of the ad hoc network. However, broadcasting is a power consuming process which can threaten and shorten the life span of the ad hoc network. Sensor networks heavily depend on broadcasting to disseminate information in the network. Sensor networks are battery operated and has limited bandwidth. Furthermore, sensor networks may not contain GPS device due to several reasons such as cost, size and limited energy. Therefore, efficient ad hoc based broadcasting schemes are required which do not rely on GPS location, topology information and complex calculations while achieving high reachability in the network.

Military is another important field which relies on broadcasting as the basis for data dissemination. Even though both sensor networks and military applications have some common limitations, however, military applications face some more critical conditions. For example, the military communications in battlefield are usually performed in random ad hoc mode on demand basis. Due to the use of electronic warfare, the radio communications between different military nodes can be extremely critical [6]. First of all, the electronic warfare system is able to effectively detect the frequency and position of the radio transmission station and further block the radio frequency or destroy the station [10]. To avoid this, the communications between nodes are usually performed on-demand basis in a random burst mode [11]. Second, the electronic warfare system is also able to interrupt the GPS signals so that the positioning and target tracking of military personnel become extremely difficult. In this critical environment, to create and maintain an effective network topology, even on ad hoc basis, becomes extremely difficult. In this dissertation, the battlefield environment will be used as a case study of a critical ad hoc environment. However, the proposed schemes are not exclusively designed for battlefield environments and can work in any similar critical environment such as sensor networks and disaster environments.

Broadcasting relay may be the only effective packet delivering scheme in battlefield environment, especially when packets need to be delivered to multiple nodes in the network [8][9]. In this case, how to search suitable forwarding nodes in order to increase the successful delivery ratio and reduce the number of broadcasting hops for end-to-end communication are critical challenging problems. Blind flooding is the conventional broadcasting approach in wireless networks. However, the blind flooding generates a large number of redundant packets that waste valuable resources such as bandwidth and energy supplies. Blind flooding is very expensive because all nodes in the network take part in the broadcast which is expensive and eventually will lead to the broadcast storm problem [12][13][14][15][16]. Current approaches on optimizing broadcasting relay in ad hoc networks have been focusing on minimizing the number of rebroadcast and increasing successful packet delivery rate.

1.2 Ad hoc Based Broadcasting

The existing broadcasting protocols for the ad hoc networks can be divided into two broad categories, i.e. protocols that depend on network topology information and protocols that depend on geometric location of nodes in the network.

The topology-based broadcast protocols [17][19] are based on a 1- or 2-hop network topology to select the forwarding nodes, so that the redundant rebroadcasts can be significantly reduced while the high successful packet delivery ratio is maintained comparing to the blind flooding. However, the process of establishing the 2-hop topology has some problems such as large amount of overhead and high convergence time, especially in ad hoc environment with critical limits on point-to-point communication duration. Furthermore, to avoid the radio channel blockage by electronic warfare system in the battlefield environment, the communications between nodes are usually performed in short-burst mode and on-demand basis that makes the maintenance of the topology even more difficult [11]. Hence, the topology-based broadcast relay schemes cannot be easily deployed in a critical battlefield environment.

In contrast, the geometry-based broadcast schemes [12][13][15][16][21][25] search the forwarding nodes by their geometric locations, which are obtained either by the built-in Global Positioning System (GPS) receiver [22][23] or by measuring signal strengths and calculating relative coordinates [1][2][12][24]. The positioning information is exchanged among the directly connected neighboring nodes through periodical beacons, which use much less bandwidth than that are used by the topology-based protocols. Hence, the geometry-based protocols usually have much shorter convergence time comparing to topology-based protocols. From this point of view, the geometry-based protocols are more efficient in terms of drastic node mobility. However, considering the critical battlefield conditions, to create and maintain an effective large scale network topology using GPS positioning information is difficult due to high and arbitrarily node mobility. Thus, this positioning based topology is usually limited within a single hop. Hence, the performance of geometry-based protocols is usually not as good as that of topology-based protocols.

Furthermore, when the position tracking of military vehicles becomes extremely difficult due to electromagnetic warfare interference in the critical battlefield environment, in this case, the geometry-based protocols are performed as blind flooding. To overcome the weakness of topology-based approaches and geometry-based approaches in terms of generating large amount of overheads for creating and maintaining network topology, the distance-based approach [12] and the angle-based approach [13][21] have been developed. The advantage of distance-based approach over topology and geometric based schemes is the ability of distance-based schemes to reduce the redundant broadcasts by limiting the broadcasting range. In contrast, the angle-based approach generates massive rebroadcasts to increase the reachability without changing the broadcasting range. From the performance point of view, the angle-based approach has a better reachability comparing to the distance-based approach [13]. However, when the positioning information of node is unknown, the angle-based approach is performed as blind flooding. Therefore, the angle-based approach is not suitable to be deployed in critical ad hoc environments such as battlefield and sensor networks.

First, this dissertation presents and proves a Lemma which defines the conditions to achieve the upper bound of broadcasting coverage for both single-hop and multi-hop broadcast relay communications in ad hoc network. Second, a new Lemma is presented and proven which analyses the effect of nodes displacement form ideal locations on the performance from both distance and transmission angle point of view. The second Lemma was proposed to solve the problems faced when applying the conditions presented in first Lemma. The conditions presented in both Lemmas can be used as the basis for designing effective broadcast relaying schemes in critical ad hoc networking environments. Third, this dissertation presents a novel broadcast relay scheme, called Random Directional Broadcasting Relay (RDBR) scheme, based on the conditions presented in first Lemma in order to provide efficient broadcasting in critical ad hoc environment. This proposed scheme effectively selects the most suitable forwarding nodes from the direct neighboring nodes of the source node, which are located inside the predefined relaying areas without any requirement on the transmission angle, topology information and node position. Fourth, an improved RDBR scheme was presented based on the conditions presented in second Lemma to achieve high reachability while reducing both contention and collision in the network.

The numerical results obtained by both theoretical analysis and simulations demonstrate that the proposed RDBR schemes are able to improve the performance of ad hoc based communications by reducing the number of broadcasting hops and increasing delivery rate, especially in critical battlefield environment suffering from electronic warfare and relies on burst transmission. The novelty of the proposed schemes, compared with the conventional ad hoc broadcasting schemes, lies in providing ad hoc communications in critical environments without the need for location, topology and complex calculations. The overhead and computing load associated with selecting suitable forwarding nodes to relay broadcast messages by using the proposed schemes is much less than that in the conventional broadcasting schemes, in which both topology information and node position are essential to ensure correct operation of the protocols. The numerical results obtained from both theoretical analysis and simulations are able to demonstrate that the proposed RDBR schemes associated with conditions presented in Lemma 3.1 and Lemma 4.2 are able to significantly increase the successful packet delivery rate and reduce the number of rebroadcasting messages and end-to-end delay.

1.3 Motivation

Mobile ad hoc networks have drawn a lot of attention over last decade by academia and industry, especially in applications for supporting emergency evacuation, sensor networks and mission-based military activities in critical environments. This is not surprising, given the ability of ad hoc networks to construct effective networks without requiring any pre-configurations in terms of network infrastructure and also due to the flexibility of ad hoc networks to meet the critical conditions in natural disaster environments. The performance of ad hoc networks greatly depends on the message dissemination technique being used. To date, many broadcasting schemes have been proposed in the literature to alleviate the broadcast storm problem. However, the majority of existing broadcasting schemes use the available host node positioning information and topology information as a comprehensive condition. Furthermore, these broadcasting schemes lack solid modeling and theoretical analysis and are mainly validated through simulation results. It is clear that the host node positioning information and topology information required by the majority of existing broadcasting schemes are not always available in hostile environments such as disaster recovery, military operations and environmental monitoring. In this research effort, a systematic analysis to identify the problems faced while deploying ad hoc networks in hostile environments is performed. Based on this analysis, both proven theories and practical formulas are used as guideline to develop efficient broadcast relaying schemes without the requirement of host node positioning, topology information and complex AoA calculations to make it more suitable to the applications in critical ad hoc environments. The proposed efficient practical broadcasting schemes are able to greatly reduce the number of forwarding nodes and end-to-end delay while achieving high reachability.

1.4 Problem Statement

Efficient broadcasting in mobile ad hoc network (MANET) is a challenging problem due to the unique characteristics of such an environment in terms of rapidly changing network topology, nodes mobility, and network partitioning. Until now, the majority of research on broadcasting in MANET has been focusing on mitigating the problem of the broadcast storm in an ad hoc network relying on node location, topology information and AoA information [55]. A broadcast storm may occur in an ad hoc network with high nodes density and high number of rebroadcasting nodes. The direct impact of the broadcast storm problem on network performance is a long end-to-end delay, high power consumption and bandwidth wastage. On the other hand, the major impact of the broadcast storm in ad hoc network, however, is the low packet delivery ratio and high packet loss ratio which can have a serious negative impact on network performance [12]. Therefore, in order to increase the delivery ratio and decrease packet loss, it is crucial to design efficient broadcasting schemes that can suppress the broadcast redundancy significantly while maintaining high reachability.

An important issue related to ad hoc based broadcasting scheme is how to minimize the number of redundant rebroadcasts while maintaining low rebroadcasting latency and high packets reachability [15][16]. It is worth noting that a large number of rebroadcasts are able to guarantee high reachability. However, it greatly consumes limited network bandwidth and causes contention and packets collisions. On the other hand, a small number of message rebroadcasts reduce the chance of contention and collision among the neighboring nodes and hence reduce the bandwidth consumption. However, the drawback of this scheme is the low reachability in low density networks due to the large distances between nodes which may eventually lead to network partitioning. Majority of existing ad hoc broadcasting schemes use omni-directional antennas for transmission and assume a uniformly distributed network where the network is connected [37]. However, the problem of frequent network partitioning can occur in MANET due to sparse distribution of nodes and also due to node mobility.

1.5 Research Aim and Objectives

The major focus of this dissertation is to design and implement efficient ad hoc based broadcast relaying schemes for critical environments using directional antennas without relying on node location information, network topology and AoA calculations, in order to achieve high reachability while reducing both the number of relaying nodes and end-to-end delay. The objectives of this dissertation are the following:

- To analyze in depth the broadcast storm problem in a critical MANETs environment using theoretical analysis.

- To study and analyze the factors that causes node displacement form ideal locations and their effect on the performance.
- To investigate the performance impact of a number of important network parameters in MANETs, including node density, node mobility and traffic load on reachability, number of relaying nodes and end-to-end delay, using extensive simulations.
- To develop an efficient ad hoc based broadcasting scheme called Random Directional Broadcasting Relay (RDBR) for critical MANET environment in order to achieve high reachability while reducing the number of redundant retransmissions.
- To evaluate the performance of the proposed RDBR scheme in critical MANETs environment using the widely adopted Random Waypoint (RWP) mobility model using different mobility parameters in the dynamic network environment.
- To develop an improved RDBR scheme to increase the reachability while reducing redundant retransmission, contentions and collisions in extreme and complex scenarios.
- To compare the performance of the proposed RDBR schemes with existing broadcasting schemes to demonstrate their efficiencies and capabilities.

1.6 Research Contribution

The contributions of this dissertation are the following:

(1) Comprehensive literature review on existing state of the art broadcasting schemes in mobile ad hoc networks. The review covers broadcasting schemes

that use omni-directional antenna for transmission and schemes that use directional antenna for transmission.

(2) Investigation of the efficiency of broadcasting relay in critical ad hoc network environment using theoretical modeling and analysis. Note that most of the existing research works in this field are evaluated by simulations. The theoretical model and analytical evaluations presented in this dissertation are able to provide an alternative approach for future research works in the field.

(3) Investigation of the impact of host node location and broadcasting angle displacement from ideal locations on the efficiency of broadcasting relay in critical ad hoc environment.

(4) Propose a novel scheme, called Random Directional Broadcasting Relay (RDBR), in ad hoc network without any requirement on node positioning and topology information. The proposed scheme is more suitable to be deployed in hostile environment such as disaster evacuation, sensor networks and battlefield.

(5) The performance evaluations have been investigated in terms of end-to-end delay, node reachability and broadcasting efficiency in terms of number of relaying nodes using theoretical modeling and analysis. Furthermore, simulations are also used to confirm the efficiency of the proposed schemes.

1.7 Outline of the Dissertation

The rest of this dissertation is structured as follows. Chapter 2 reviews and categorizes existing broadcasting schemes in MANETs. Specifically, existing ad hoc based broadcasting schemes are reviewed in this chapter which includes broadcasting schemes that use omni-directional antennas for transmission and broadcasting schemes that use directional antennas for transmission. Chapter 3 presents a Lemma to achieve the maximum coverage area while utilizing the minimum number of relaying nodes. Specifically, this chapter theoretically analyses the broadcast storm problem and then presents the conditions that need to be met in order to solve the broadcast storm problem. Chapter 4 theoretically analyses the effect of nodes displacement from ideal locations on the total coverage area from both distance and angle point of view. Basically, this chapter presents the situations in which the conditions presented in Chapter 3 are not fulfilled and then discusses the effect of that on the coverage area. Chapter 5 introduces the Random Directional Broadcasting Relay (RDBR) scheme and the improved variant of the RDBR scheme to solve the broadcast storm problem in MANETs. Furthermore, the directional antenna model which is used in the RDBR and improved RDBR schemes is also presented in this chapter. In Chapter 6, a comprehensive simulation based performance evaluation of the proposed schemes against existing broadcasting schemes under different network parameters is presented. Chapter 7 concludes the dissertation and gives directions and suggestions for future research.

Chapter 2: Related Work

This chapter reviews most of state-of-the-art ad hoc based broadcasting schemes that are related to the research topic presented in this dissertation. The following technical reviews focus on research works that have been published based on the best of our knowledge, including omni-directional antennas based broadcasting schemes and directional antennas based broadcasting schemes. The remaining of this chapter is organized as follows. In Section 2.1, an overview of basic broadcasting schemes and existing classification of broadcasting schemes are discussed. In Section 2.2, the ad hoc based broadcasting schemes that utilize omni-directional antenna for broadcasting are discussed. Section 2.3 presents the limitations of existing omni-directional antenna based broadcasting schemes. Section 2.4, an overview of directional antennas is presented. In Section 2.5, the ad hoc based broadcasting schemes that utilize directional antennas for communication are discussed. Section 2.6, discusses the limitation of the existing ad hoc based broadcasting schemes.

2.1 Broadcasting Relay

Simple flooding is one of the earliest schemes for broadcasting relay in ad hoc networks since many routing protocols proposed for ad hoc networking environment in the early stage are based on flooding algorithm [26][27][28][29][30]. The reason is that the flooding mechanism is considered as a simple broadcasting scheme and guarantees high reachability in certain scenarios, but it can be very costly in terms of bandwidth and energy consumption due to large redundant retransmissions are involved [15]. The approach to overcome this weakness was focused on how to reduce the redundant retransmissions so that network nodes need to keep track of every received packet and drop the duplicate packet. Several studies have been conducted by researchers to investigate and alleviate this problem through both theoretical analysis and simulations [29][31]. In [12], Ni *et al*. investigated the flooding approach using theoretical modeling and simulation evaluations. The numerical results show that one rebroadcast is able to create an increment of transmission redundancy up to 61% for each additional coverage area and also an increment of up to 41% in terms of additional coverage area in average over that already covered by the previous transmission. This research paper has concluded that rebroadcasts on flooding basis are very costly and able to degrade the performance of the network greatly. Therefore, flooding based rebroadcasts as a technical solution should be used carefully although high reachability is achievable due to the highly costs in terms of bandwidth and energy consumption.

Under simple flooding mechanism, a source node broadcasts packets to all its one-hop neighbors. Then, each one of receiving nodes would rebroadcast the packets to all their one-hop neighbors. This process continues until all nodes receive the packets or the TTL expires. In low density network environments, flooding mechanism has the advantage of achieving better reachability than other existing schemes [12][15][32]. However, the price for such a high reachability is paid by the costs in terms of network bandwidth and energy consumptions. On the other hand, the major problem of flooding mechanism occurs in dense network environment, in which redundant retransmission is able to lead to serious problems such as broadcast storm problem. The broadcast storm occurs when several nodes within the transmission coverage of each other are trying to retransmit the received packets at the same time. Therefore, the flooding mechanism is not recommended in high density network environments with scarce resources due to the three factors:

- Redundant retransmissions: a node rebroadcasts a packet that was already received by all of its one hop neighbors.

- Contention: multiple retransmitting nodes are trying to access the shared channel at the same time.
- Collision: multiple nodes are trying to retransmit the packet at the same time which results in either packet corruption or packet loss.

The main approach towards solving the broadcast storm problem in MANET has focused on how to reduce the amount of redundant retransmissions. This can be basically achieved by selecting a subset of the network nodes to act as relaying nodes. There are several existing broadcasting schemes utilizing this concept to mitigate the broadcast storm problem [1][12][15][41][45][49][50]. Ad hoc based broadcasting schemes can be classified into several categories based on different factors. There are several classifications of ad hoc based broadcasting schemes have been considered [12][32][33][34][35]. Two classifications proposed by Ni *et al.* [12] and Williams *et al.* [32], respectively, have been widely adopted.

Ni *et al.* [12] classified the existing ad hoc based broadcasting schemes into five different categories: counter-based, location-based, distance-based, probabilistic and cluster-based. In counter-based broadcasting scheme, a node decides whether to broadcast a packet or not based on the number of duplicated packets received. Every node keeps the track of redundant received packets during a random time interval. If the number of duplicate packets exceeds some predetermined threshold the packet will simply be dropped otherwise the node will rebroadcast the packet. In location-based broadcasting scheme, a node decides whether to broadcast or not based on the percentage of additional coverage area achieved when a packet is rebroadcasted. This is done by calculating the additional coverage area that can be achieved by the broadcasting nodes using location information of nodes which can be acquired using GPS devices.

In distance-based broadcasting scheme, the nodes use a different concept other than that used in location-based broadcasting scheme. Instead of relying on exact location information as was the case in location-based schemes, distance-based schemes use the relative distance between the source node and the relaying node to decide whether to rebroadcast or not. Specifically, the relative distance can be estimated using received signal strength [1][2][12][24][36] between the sender and relaying node. Upon expiry of the waiting time, every relaying node checks whether the distance between itself and the sender is equal to or beyond a predetermined threshold, if yes the relaying node will rebroadcast, otherwise it will simply drop the packet.

In probabilistic broadcasting schemes, a node rebroadcasts a packet using a certain fixed probability. In cluster-based scheme, the ad hoc network is divided into several clusters. Each cluster consists of a cluster head, cluster members and several gateways. Cluster head is responsible for managing the cluster and acts as central controller. Each cluster head rebroadcast a packet received from its members and this rebroadcast can reach all nodes within that particular cluster. Furthermore, every cluster head selects a subset of its member to act as gateways. Only gateways are allowed to communicate with members of other clusters and they are responsible for propagating the broadcast packet.

Williams *et al.* [32] classified the ad hoc based broadcasting schemes into four main categories: flooding, probability-based, area-based and neighbor knowledge method. The probability-based schemes consist of both probabilistic scheme and counter-based scheme. On the other hand, the area based broadcasting schemes consist of both distance-based and location-based broadcasting schemes. In neighbor knowledge method, each node maintains its neighbor's information and based on the neighbor information the node decides whether to rebroadcast the packet or not. The neighborhood information is collected by periodically exchanging hello packets. The shorter period will result in collisions and contentions because it is very frequent while the longer period will result in inaccurate and outdated neighborhood information due to mobility.

Recently, a comprehensive classification of ad hoc based broadcasting schemes is proposed by Ruiz and Bouvry [37]. The authors classified existing broadcasting schemes using four criteria's: centralized and decentralized systems, global or local knowledge, deterministic and stochastic processes, source dependent and source independent techniques. The classification is done by considering several features such as the existence of a central management entity, the location of the forwarding decision, the network information and the use of random variables in the algorithm. In a central system, a central node is responsible for managing the whole system. The central node can make decision based on its own information or information obtained from different nodes in the system. However, central system based schemes suffer from overhead and delay due to signification coordination between nodes. Moreover, this system is subject to the single point of failure problem if the central node fails. On the other hand, in a decentralized system, nodes can make decisions based on their local information and also can change their behavior without relying on central units. In global or local knowledge based systems, if a node's decision of rebroadcasting a packet requires information about the whole network (e.g., location information of all nodes in the network) then this scheme is considered as global knowledge based system. On the contrary, if a node's decision of rebroadcasting a packet relies on locally obtained data, then this scheme is considered as local knowledge based systems. Furthermore, local knowledge based systems, not only rely on information about the node itself, but may also require information from the node's neighbor which can be obtained either through using beacons or eavesdropping.

In deterministic or stochastic process features, a process is called deterministic if no random decisions are involved, i.e. a given particular input can always generate the same result [34]. On the other hand, a process is called stochastic when there are random choices and the execution of the same process several times under the same conditions can result in different outcomes [34]. Regarding to source-dependent technique, the broadcasting scheme relies on a source node to select the next forwarding nodes from its direct 1-hop neighbors. On the other hand, in the source-independent technique, the receiving node decides the next forward

In next section, a comprehensive review of existing omni-directional antenna based broadcasting schemes is provided.

2.2 Omni-directional Antenna Based Broadcasting Schemes

Several Omni-directional antenna based broadcasting schemes can be found in the literature and can be classified into different categories based on several criteria's as discussed above. In this section, two most important and widely used probabilistic broadcasting schemes are reviewed. Furthermore, these schemes serve the same objective as of this work and also can operate under similar critical environment conditions as of this work. The two selected categories of probabilistic based broadcasting schemes are counter-based [12] and distance-based broadcasting schemes [9].

2.2.1 Counter-based Broadcasting Schemes

In the counter-based scheme proposed by Ni et al. [12], the node cancels rebroadcasting and drops the packet in case it receives multiple copies of the same message. Upon receiving a broadcast message for the first time, the node starts waiting for a random time interval called RAD (Random Assessment Delay) before rebroadcasting the packet. If a node receives multiple copies of the same packet during the random time interval and the number of duplicated packets received is greater than some threshold, the rebroadcasting will be cancelled.

Tseng *et al.* [16] proposed an adaptive counter-based scheme to tackle the problem of fixed counter threshold value. The counter threshold can be described as the maximum number of copies of the same message allowed before rebroadcasting the message. A low threshold value can greatly reduce the number of retransmitting nodes; however, the performance of the system in terms of reachability greatly degrades in sparse networks. On the other hand, a high threshold value can guarantee high reachability but at the cost of large number of retransmitting nodes. To tackle the above problem, the authors introduced an adaptive counter threshold function which takes into consideration the number of neighboring nodes i.e. the value of counter threshold varies based on the number of neighboring nodes surrounded by each source node. One simple way to calculate the number of neighbors of each node is done by periodically exchanging hello packets among mobile nodes.

Keshavarz-Haddad *et. al.* [38] introduced a variant of the counter-based scheme called the color-based broadcast scheme. The main concept of this scheme is to assign color to each broadcast packet. In this scheme, every message has a color field which is used to differentiate between different colors. The basic idea of the color-based scheme is to color all broadcast messages. Then, after a random time interval all nodes rebroadcast the message unless they received *n* messages with same color during the random time interval.

In Chen *et. al.* [39], the authors integrated the concept of distance-based scheme into the counter-based scheme. They proposed a scheme called *DIS RAD* which assigns shorter waiting time to relaying nodes located at the transmission boundary. Specifically, relaying nodes closer to the transmission boundary of the source node have higher probability of rebroadcasting than relaying nodes located at small distance away from to the source node. The farthest the relaying node form the source node the shorter RAD time is assigned to that node. However, the authors did not specify how the relaying nodes can estimate the distance to the source node.

Al-Humoud *et. al.* [40] introduced an adaptive counter-based scheme that uses different threshold values based on the node density in the network. The proposed scheme assigns high threshold values to dense networks and low threshold values for sparse networks. The node density is estimated by comparing the existing active number of neighbors to the average threshold. If the current number of neighbors is greater than a threshold it is considered dense otherwise it is considered sparse. However, the authors did not specify how to calculate the average number of neighbors in the networks.

Liarokapis and Shahrabi [41] proposed an adaptive probabilistic counter-based scheme called *ProbA*. In this scheme, a node receiving a message counts the number of times it received a duplicate copy of the same message during a random time interval. Then, the proposed scheme assigns different probability based on the number of duplicated packets received. Nodes with large number of duplicate received packets will be assigned lower probabilities than a node received fewer numbers of duplicate packets.

Mohammed *et. al.* [42] developed an efficient counter-based scheme which combines the properties of probability-based scheme and counter-based scheme. They proposed to use a probability value of approximately 0.65 which was previously proposed in [43] to achieve better reachability while reducing both end-to-end delay and redundant retransmissions. To further improve the performance of the proposed scheme, they conducted another research in which they found that the better probability value is approximately 0.5. They showed through experiments that the improved scheme with probability value of 0.5 achieves better performance that the previous scheme. In both the proposed schemes the authors considered sparse network environments. However, in dense networks, nodes always drop their rebroadcast packets. This can greatly affect the reachability and saved-rebroadcast for both the proposed schemes.

In Mohammed *et. al.* [43], the authors proposed an efficient counter-based scheme in which different probability values used for dense and sparse networks. Specifically, the proposed scheme is called an adjusted counter-based scheme (ACBS) and it is a combination of both counter-based scheme and probability-based scheme. In this scheme, a high rebroadcast probability is used in sparse areas of the network and a low rebroadcast probability is used in dense areas. The main idea is to assign a low rebroadcast probability value in dense network instead of just dropping the packet as was the case in previous schemes. The rebroadcast probability value is assigned based on the network density which is estimated as follows: if the number of duplicate packets received during a time interval is less than a threshold, the network area is sparse and therefore a high probability value is used. Otherwise, the network area is considered dense and a lower probability value is used. Based on simulation evaluations, the authors selected a high rebroadcast probability value of 0.5 and a low rebroadcast probability value of 0.25.

Mohammed *et. al.* [44] proposed to investigate the effect of adapting RAD value to network congestion on the performance of their earlier counter-based scheme [45]. The main ideas of this work is to improve the original RAD mechanism used in [45] by utilizing network information in terms of network congestion. In a congested network, using a higher RAD value can ensure high delivery ratio. On the contrary, a lower RAD value is required in non-congested network. To obtain network congestion level, every node keeps track of the number of packets received per second. If the number of received packets are more than or less than some threshold, then the value of RAD T_{max} is set accordingly. The authors proposed to increase the packet generating rate to estimate the network congestion. They generate broadcast packets as control packets which obviously are small in size and do not consume the bandwidth.

2.2.2 Distance-based Broadcasting Schemes

In Ni *et. al*. [12], the authors introduced the Distance-Based (DB) broadcasting scheme. DB scheme relies on the distance between the nodes to decide whether to rebroadcast the packet or not. The distance between sender and received can be calculated using GPS or received signal strength. The DB scheme works as follows: upon reception of a broadcasting packet, the DB scheme initiates a random waiting time. During the waiting time, if the node receives a packet and the distance between the sender and receiver is less than some threshold, the retransmission is cancelled. Otherwise, the node keeps waiting until the timer expires.

In Chen *et. al.* [1], the authors proposed two variants of the distance-based scheme to improve the efficiency of broadcasting in MANET. The main idea of this work is to utilize both the neighborhood density information and the relative distance between the source node and its neighboring nodes to select the forwarding nodes. Basically, every node maintains both neighborhood size and signal information in a table. The table entries are sorted descending depending on neighborhood distances from the source node starting from the highest distance. The neighborhood information can be collected through exchanging periodic hello packets or by receiving a packet transmission. On the other hand, the distance between the nodes can be estimated used received signal strength. The reason behind maintaining the distance information is to select the outmost neighboring nodes as forwarding nodes. The first proposed Distance-ADaptive scheme is called DAD-NUM, in this scheme the number of forwarding nodes is already predefined i.e. certain number of outmost nodes are only allowed to rebroadcast the packet. The second proposed scheme is called DAD-PER in which a percentage of nodes are selected as forwarding nodes. In this scheme a percentage of the outmost nodes are allowed to rebroadcast the packet.

Sun and Lai [21] proposed a distance-based defer time scheme to effectively select forwarding nodes. The basic concept of the proposed scheme is that instead of randomly selecting forwarding nodes, it is more plausible to select forwarding nodes located far away from the source nodes. The idea is to select nodes which cover more new areas and these nodes are those which located close to the transmission boundary of the nodes. Therefore, the authors proposed to incorporate the distance between nodes into the traditional random defer time scheme to select outmost nodes as forwarding nodes. The authors also proposed an angle based scheme to eliminate redundant retransmissions. This scheme works as follows: when a node receives multiple retransmissions of the same message during random waiting time, it then calculates the area covered by each node based on coverage angle. After that, the scheme will retransmit the packets only in uncovered directions given that the other areas are already covered by other nodes.

In Cartigny and Simplot [46], the authors combined the advantages of distance-based schemes and probability-based schemes to achieve better reachability. In the proposed broadcasting algorithm, each node maintains 1-hop neighbor information which is obtained by exchanging periodic hello packets. The proposed scheme relies on the local node density and does not require any positioning information. Furthermore, the proposed scheme utilizes the distance to the source node to give high probability to nodes located at transmission boundary of the source node. In addition to probability and distance based schemes combination, the proposed scheme also uses neighbor elimination scheme to drop packets retransmission that already covered by previous nodes. The proposed scheme works as follows: the neighbor information is embedded in the header of the broadcast packet which basically contains the ID of the sender. The receiving node uses the neighbors list of the sender to identify nodes that have been covered by the previous transmissions. Then, the already covered nodes will be eliminated and the receiving node adds its list of neighbor node and deduces the probability accordingly. Based on the estimated distances between nodes, higher probability is assigned to node located far away from the sender. The distance between nodes is estimated using some mathematical formals which use the neighbor lists of both sender and receiver to approximate distance between them.

Cao, Ji, and Hu [2] introduced an energy-aware broadcast scheme for WSN which is a combination of both counter-based and distance-based schemes. The main objective of this work is to solve the problem of hot spots and prolong the lifetime of sensor networks. This problem is tackled by balancing the energy level among nodes which is done by considering the remaining energy level of the nodes in the design of the proposed scheme. Furthermore, the proposed scheme is based on border-aware scheme and aims at improving the interest dissemination in Directed Diffusion (DD) of sensor networks. The proposed scheme works as follows: upon reception of a broadcast packet, the node calculates the distance to its neighboring node using received signal strength. Then each received packet is assigned a time slot considering both the distance and remaining-energy level. During the waiting time, each node keeps track of the number of times it received the same packet and also records the minimum distance from the sender. When a duplicate packet is received by the node, it compares the counter to some threshold C and the distance to some threshold D. if the counter is greater the C or the minimum distance is less than the D, the packet is dropped otherwise the packet is rebroadcasted. The value of C and D are determined using simulation.

Kasamatsu *et. al.* [47] proposed a new distance-based broadcasting scheme called BMBD (Broadcasting Method Considering battery and Distance). The proposed scheme takes into consideration the remaining energy level of node before rebroadcasting the packet. The main idea of the BMBD scheme is to increase the lifetime of the network by selected forwarding nodes with higher residual battery level. This scheme will help reduce the number of dead nodes in the network which increases with time lapse. The proposed scheme assigns weighting times that are inversely proportional to the distance between two nodes and the battery level of potential forwarding node. The BMBD scheme works as follows: upon reception of a broadcast packet, the node is assigned a waiting time using the combination of distance and residual battery level. Nodes with higher distance from the source node and higher residual battery level will be assigned a lower delay. During the waiting time, if the node receives the same message again, the rebroadcasting will be cancelled. The proposed scheme relies on GPS devices to calculate the distance and for proper operation of the proposed algorithm.

In Kokuti and Simon [48], the authors proposed three different adaptive broadcast schemes, namely, *Distance-Based Handshake Gossiping* (DBHG), *Valency-Based Handshake Gossiping* (VBHG) and *Average Valency-Based Handshake Gossiping* (AVBHG). All three protocols are based on Gossiping algorithm [12] in which every receiving node forwards the received packet with a predetermined probability. The proposed schemes rely on both location information and 3-phase handshaking process before selection of the forwarding nodes. During the 3-phase handshaking, the source node collects information such as distance, density, and possibility of both collisions and contentions. In DBHG scheme, the source node assigns the forwarding probability to its neighboring nodes based on the distance between them. Whereas in AVBHG scheme, instead of relying only on the distance between neighboring nodes to assign probabilities. The source node also considers the degree of nodes surrounded by each neighboring node. Basically, the VBHG scheme is an enhancement of the DBHG scheme in which nodes are only selected based on the distance and this sometimes leads in selection of nodes without or with very small neighboring nodes. The AVBHG scheme is a combination of the above two schemes. In this scheme the proposed scheme considers past decisions for estimating forwarding nodes probability. The AVBHG scheme uses the average valency and average distance as parameters to calculate the forwarding probabilities using some mathematical formulas.

Liarokapis *et. al.* [49] developed an adaptive distance-based scheme (DibA) which dynamically changes the distance threshold value based on the number of redundant retransmission received. DibA is a combination of distance-based and counter-based schemes. In the proposed scheme, each node locally estimates network density without relying on GPS or hello packets. The authors argue that a fixed distance threshold value is not appropriate for all network topologies as the density and distribution of nodes differs in different topologies. The basic ideas is to assign low density networks, a low distance threshold value whereas a high distance threshold values are assigned to high density networks. The proposed scheme works as follows: every node maintains a table of predetermined distance threshold value associated with predetermined counter values. During the waiting time, every node keeps the track of the number of times it receives a duplicate packet. Then, it selects the appropriate distance threshold value based on the counter value.

Leng *et. al.* [50] introduced a relative position-based scheme called RPBR which is basically a combination of location-based and distanced-based scheme. Each node in the proposed scheme maintains the location information of the neighboring node. The location information is obtained through GPS and exchanged between neighboring nodes by periodic hello packets. Furthermore, the proposed scheme also uses forward angle information to select forwarding nodes. The key idea is to select forwarding nodes from circular areas at the transmission boundary of the nodes. The circular areas are referred to as symmetric areas and each of them is located at 120 degree away from each other. There are three dedicated symmetric areas and one forwarding node is selected from each symmetric area. To select outmost nodes from each symmetric area, they proposed to use defer time which is a distance based random time. This allows nodes located farther away from the source node to be selected as forwarding nodes. However, in case there are no nodes located in symmetric areas, a node will be selected from each non-symmetric area. To differentiate between nodes located inside and outside symmetric areas, they proposed to assign nodes located inside symmetric areas a shorter differ time than nodes located outside symmetric area. This will ensure that the node located inside a symmetric area has a higher priority to rebroadcast than other nodes. The size of symmetric area is fixed and it doesn't change automatically.

In Liarokapis *et. al.* [51], the authors proposed an improved version of the distance based scheme called Constant-Width Zone (CWZ). Unlike the distance based scheme where the distance threshold is fixed, in the CWZ scheme, the node calculate a new distance threshold at every round of rebroadcast. The CWZ scheme uses a constant upper bound for the width of all rebroadcast zones. The CWZ scheme works as follows: when a node receives a rebroadcast packet, it sets the waiting time on. Upon the expiry of the waiting time, if the node decides to rebroadcast the packet, it will then calculate a new distance threshold value based on some mathematical formulas and then replace the old threshold value. The new distance threshold value is then embedded in the message and will be used for the next round of rebroadcasting.

Kim *et. al.* [52] proposed a dynamic broadcasting scheme which is a combination of both probabilistic and area-based schemes. The proposed scheme is based on coverage area and neighbor confirmation. It utilizes coverage area to determine nodes rebroadcast probabilities. The key idea of the proposed scheme is to divide the transmission coverage area of nodes into inner and outer areas. Nodes located in outer areas area assigned higher probabilities than nodes located in inner areas. This is due to the fact that nodes located in outer areas are able to reach additional coverage areas and therefore cover more nodes. Nodes are allowed to choose different probabilities based on their distances from the sender. The distance between nodes can be calculated using either GPS or received signal strength. To solve the problem of early die-out of rebroadcast, the authors proposed to use neighbor confirmation. Early die-out occurs when a non-redundant packet retransmission is cancelled due to the non-uniform nodes distribution in the network. The concept of the neighbor confirmation scheme is to retransmit a packet for the second time if one of the neighbors of the node does not receive the packet due to the early die-out problem. This process is only performed by the nodes which did not participate in retransmitting the packet. The idea is that after a given waiting time, a node verifies if all its one-hop neighbors have received the rebroadcast packet. If not, the node rebroadcast the packet.

Table 2.1 shows a summary of remaining omni-directional antenna based broadcasting scheme. A common problem among these broadcasting scheme is that all of them rely on neighbor information to function properly.

Table 2.1: Summary of omni-directional antenna based schemes

Reference	Shortcomings
D. Scott and A. Yasinac, 2004	Dynamically adjust the probability of retransmission nodes by relying on node density which is collected through ping mechanism. This scheme cannot be directly used in critical ad hoc environment because the node density cannot be calculated. Furthermore, this scheme does not specify the minimum no. of relaying nodes required to achieve high reachability. It achieve better performance than Flooding but as DB scheme, it will still have large redundancy.
W. Peng and X. Lu, 2002	Proposed an Ad hoc broadcast protocol which relies on two-hop neighbor information to select one-hop neighbors to rebroadcast the packet. The two-hop neighbor information is collected by exchanging hello packets. The scheme is based of Connected Dominating Set (CDS) and it outperforms Flooding scheme. However, since this scheme relies on network topology, it cannot be used in the critical ad hoc environment. Furthermore, this scheme is not resilient to the high mobility due to topology links.
W. Lou and J. Wu, 2004	The authors proposed a scheme called Double-Covered Broadcast (DCB). It is a CDS-based scheme which relies on exchanging hello packets. The idea of this scheme is to overcome the problem of packet loss during transmission by using the concept of double-coverage. The proposed scheme introduces a fixed redundant in the network to achieve the double coverage. However, the proposed scheme has some deficiencies, first, it can be used in critical ad hoc network due to topology information. Second, it is not resilient to mobility. Third, even though it generates fixed redundant. However, under severe network conditions, this scheme result in collision and contention due to broadcast storm problem.
P. Ruiz and P. Bouvry. 2010	In this work, the authors proposed an enhanced distance based broadcasting scheme called EDB. The proposed scheme is an energy saving version of DB scheme in which transmission range of nodes is adjusted to reduce energy consumption. The EDB scheme reduces its transmission power in order to reach its furthest neighbor. However, this scheme has some limitations: first, it relies on the 1-hop neighboring information. Second, it suffers from high end-to-end delay due to large number of relaying nodes.
P. Ruiz and P. Bouvry. 2010b	In this paper, the authors proposed a new broadcasting scheme called AEDB which is an extension of their previous EDB algorithm. The proposed AEDB algorithm adjusts its transmission power in terms of the number of one hop neighboring in order to decrease the energy consumption. The AEDB scheme allows each device to locally manage the transmission power to save energy in high density networks. The main idea of this scheme is to reduce the transmission range of the nodes even if it leads to the loss of some neighbors. The notion behind this mechanism is that the network connectivity does not really gets affected in high density environments due to the availability of alterative nodes. However, this scheme has some shortcomings: first, it relies on the 1-hop neighboring information. Second, it suffers from high end-to-end delay.

2.3 Limitations of Omni-directional Antenna Based Broadcasting Schemes

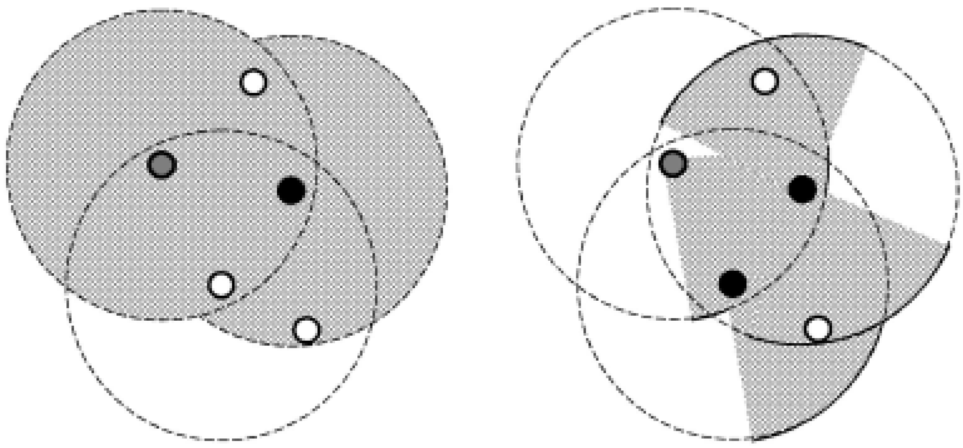
Most of the existing omni-directional antenna based broadcasting schemes for MANETS in general have the following limitations:

1. They rely on GPS providing location in order to function properly i.e. exact positioning information is required.
2. They maintain topology information by exchanging hello packets. Some schemes require 1-hop neighbor information where as other require 2-hop neighbor information.
3. They generate a lot of redundant retransmission to achieve high reachability.
4. High consumption of scare network resources such bandwidth and energy. The main reason behind both bandwidth and energy consumption is due to large number of redundant retransmissions.
5. They are not scalable in high density environments. The main reason behind scalability problem is maintaining of network topology and neighbor information.
6. They suffer from performance degradation in high mobility and high density environments.
7. They suffer from interference, collision and contention which are caused by simultaneous retransmission of packets.

Due to the above reasons, the existing omni-directional antenna based schemes cannot be directly deployed in the critical environments. Therefore, a novel ad hoc broadcasting scheme is needed for critical ad hoc environments without relying on GPS location, topology, hello-packets and complex AoA calculations. Furthermore, the new schemes must be scalable, can operate in high mobility environments and does not generate extra overhead. In next section, directional antenna based broadcasting schemes are reviewed to investigate their applicability in critical ad hoc environments.

2.4 An Overview of Directional Antenna

Omni-directional antennas restrict the ad hoc network capability for reaching suitable rebroadcasting nodes and suffer from increasing interference and energy consumption. This is because that the omni-directional antennas distribute the energy in all directions which not only decreases the potential transmission range but also causes unnecessary interference. Replacing omni-directional antennas with directional antennas to mitigate the broadcast storm problem in ad hoc networks is becoming a popular research topic in both academia and industry [53][54][55][56]. Directional antennas have the ability to radiate their energy out to form a beam in a particular direction. Figure 2.1 shows a comparison between omni-directional broadcasting and directional broadcasting.



(a) Omni-directional broadcast (b) Directional broadcast

Figure 2.1: Omni-directional vs. Directional broadcast

There are two main types of switched beam directional antennas, single beam directional antennas and multi-beam directional antennas [53][55][56][58][59]. In switched single beam directional antenna model, there is only a single beam active at any given time. Furthermore, each node in switched single beam antenna model is equipped with a single transceiver. Therefore, multiple transmission and reception is not possible at the same time. Broadcasting can be achieved in such a case by sequentially steering the antenna beam across all pre-defined directions. On the other hand, in switched beam antenna model, multiple beams can be activated at the same time using multi-beam directional antenna model. Furthermore, this antenna model has multiple transceivers and therefore can forms multiple beams in multiple directions at the same time. However, it worth nothing that even though multi-beam antenna model allows transmission in multiple direction at the same time, it is not possible that some beams transmit while others beam receive at the same time [53][55][56].

Unlike omni-directional antennas, broadcasting is not directly supported by directional antennas. There are basically two ways to achieve broadcasting using multi beam directional antennas [53][56] [55] 52]. The first solution to broadcasting using directional antennas as mentioned earlier is to sequentially sweep across all antenna beams. However, this method of transmission results in sweeping delay due to the sequential transmission of packets. The second solution to broadcasting using directional antennas is to switch on all the beams of a node at the same time. This will result in transmitting packets in all directions simultaneously. Though this method of transmission does not result in sweeping delay, it does not achieve higher coverage area. This is due to the fact that the transmission power will be distributed over the entire beam instead of concentrating it on a single beam at a time. Achieving a good trade-off between these two methods of transmission is basically depending on the type and quality of directional antenna being used. For example, military uses the most advanced and high quality directional antennas. Therefore, they can achieve a better coverage while minimizing if not eliminating sweeping delay completely.

Directional antennas have many benefits over omni-directional antennas in ad hoc networks. Unlike omni-directional antennas, directional antennas can control their radiation patterns to form directional beams in specific direction to reduce broadcast redundancy. This capability of directional antennas also reduces the consumption of both bandwidth and energy by reducing interference among neighboring nodes. Furthermore, they provide much longer transmission range and maintain the stability of links due to increased signal strength. The advantages of directional antennas over omni-directional antennas are many [53][55][56]. However, the most important features of directional antennas are:

1. Larger transmission ranges
2. Stable transmission links (Higher network connectivity)
3. Less interference
4. Less collisions
5. Increased spatial reuse

Another reason for using directional antennas is due to less power consumption. Power consumption is another problem facing some ad hoc networks such as sensor networks because in these networks the antennas are battery operated. This is even more sophisticated when the batteries cannot be recharged frequently due to the nature of the environment. Directional antennas increase spatial reuse which allows multiple directional antennas to send data at the same time. The slow adoption of directional antennas in ad hoc networks in the past was due to many factors. The most important factors were: (1) the size of directional antennas was big (2) directional antennas were expensive (3) directional antennas were complex. However, according to the literature [53][55], the size of directional antennas is decreasing tremendously. Furthermore, cheaper and high quality directional antennas are now available [53]. As for the complexity, several improvements have been made on directional antennas which make specific type of directional antennas less complex. However, omni-directional antennas remain to be less complex that directional antennas due to their simplicity.

Several ad hoc based broadcasting schemes have been proposed in the literature which uses directional antennas for transmission. However, most of these works focus either on physical layer (directional antenna technology) [61], the MAC layer [62][63][64][65][66] or routing algorithm [67][68][69][70], and studies which utilize directional antennas to mitigate the broadcast storm problem in ad hoc network are very limited. Furthermore, most of the existing ad hoc based broadcasting schemes which utilize directional antennas assume specific directional antenna models and rely on node location, network topology and AoA information. In the next section, a review of the existing directional antenna based broadcasting schemes which are relevant to this work are reviewed.

2.5 Directional Antenna Based Broadcasting Schemes

Research works that utilize directional antennas to provide efficient broadcasting in ad hoc networks are limited in the literature. This section reviews state of the art ad hoc based broadcasting schemes which utilize directional antennas for efficient broadcasting. In Hu *et. al.* [56], the authors proposed three schemes to mitigate the broadcast storm problem in ad hoc networks. The authors assume that each node is embedded with four beams directional antennas. The first scheme is called on/off directional broadcast, in this scheme each node when receiving a broadcast packet for the first time forwards the packet in three directions other than the direction from which the packet received. This is done by switching off the directional antenna beams towards the direction from which the packet was received. In the second scheme which is called relay node based directional broadcast, each forwarding node can have only one relaying node in each direction i.e. four relaying nodes per forwarding nodes. This scheme is based on 1-hop neighbor information which is collected by exchanging frequent hello packets. Each forwarding node selects the farthest node in each direction where the distance is estimated using received signal strength. In the third scheme which is called Location-Based Directional Broadcast, the authors assume the existence of a GPS device embedded in each node. Unlike in scheme two in which the nodes are assigned uniform waiting time, in scheme three each node is assigned a different waiting time. The waiting is proportional to the extra coverage area the node can reach i.e. the more the new coverage area the shorter waiting time is assigned to the node. However, this scheme requires some mathematical calculations to calculate the new coverage area and the calculation has to be precise in order for the scheme to function properly.

In Joshi *et. al.* [57], the authors extended the directional broadcasting schemes proposed in [56] to solve the problem of network partitioning and to further reduce redundancy in the network. Unlike the schemes proposed in [56] which uses switched multi beam directional antenna, the authors in this work propose to use switched single beam directional antenna. This antenna model guarantees large coverage in specific direction by concentrating the power in that direction and therefore covering more nodes. However, this antenna model suffers from what is known as sweeping delay incurred by sequentially steering the antenna beam across all pre-defined sectors. To overcome this problem, the authors proposed two directional broadcasting schemes which minimize the sweeping delay and also reduce redundancy. The basic idea is to use some of the pre-defined sectors of directional antenna which will eventually minimize the overall waiting time while reaching more nodes in each sweep. The main concept is that the rebroadcasting will happen on vertically opposite beams to the beam from which the packet received followed by the beams that are adjacent to vertically opposite beams. On the other hand, the beam with no nodes and busy sectors will be neglected. As was the case in [56], the proposed schemes in this work rely on 1-hop neighbor information to eliminate sectors.

In Shen *et. al.* [59], the authors proposed several directional antenna-based broadcasting schemes. Basically, they extended the omni-directional broadcasting schemes introduced in [16] by introducing directional antenna versions of them. They proposed to use directional antenna along with percolation theory to achieve the same coverage area of omni-directional antenna while reducing the number of duplicate packets in the network. They proposed to map proposed schemes to site and bond percolations. Based on the mapping, the authors' shows the proposed schemes using directional antennas incur lower overhead than omni-directional antennas in terms of the number of duplicate received packets. They found out that probability based broadcasting schemes embedded with directional antennas resembles bond percolation which has lower thresholds than site percolation. They applied these ideas to proposed directional broadcasting schemes. The authors assume an ideally sectorized switched beam directional antenna model without side lobes. Each sector of directional antenna will be assigned a different probability unlike omni-directional antenna in which the same probability is used in all directions. This helps reduce the number of redundant retransmissions while achieving the same coverage area and less overhead.

Dai and Wu [55] proposed a novel broadcasting scheme for ad hoc networks using directional antennas. The authors extended the existing omni-directional antenna based self-pruning algorithm and introduced the directional-self pruning algorithm (DSP). The proposed scheme is based on 2-hop neighborhood information and it does not on AoA calculation or node location. The 2-hop neighborhood information is collected via two round of hello packet exchange between neighboring nodes. Furthermore, the direction information which is used to form directional beams is also included in 2-hop neighborhood information. Unlike conventional omni-directional antenna based self-pruning algorithm, the number of forward directions used by each forward node in the DSP scheme is much less compared with the conventional scheme. As a result, the proposed DSP scheme algorithm is more efficient in terms of bandwidth and energy consumption due to reduction in broadcast redundancy. However, the number of forward nodes utilized in both schemes remains the same. The authors consider a general directional antenna model where every node is equipped with four beams directional antennas. Furthermore, the authors also introduced two variants of the proposed scheme: the first variant is used for shortest path routing while the second variant is used in directional reception mode. Other directional antenna based schemes which rely on 2-hop neighbor information include the works in [71][72].

Yang *et. al.* [73] introduced an efficient broadcasting scheme to reduce the total number of retransmissions in the ad hoc network by using both network coding and directional antennas. Network coding is used to combine some of received messages into a single message before forwarding using XOR operation. This scheme reduces the number of transmissions a selected forwarding node sends. The directional antenna is used to further reduce energy consumption by sending the message on selected beams. In their, scheme the forwarding nodes are selected locally based on 2-hop neighbor information. Furthermore, they piggyback broadcast state information generated from 2-hop topology information in encoded message.

Garg and Garg [58] proposed a localized directional antenna based broadcasting scheme using the concept of network coding. Network coding allows each forwarding node to combine some of the received messages before forwarding them. As a result, the number of retransmission performed by each forwarding node is greatly reduced. The authors extended the already existing omni-directional antenna based broadcasting scheme i.e. the CDS (connected dominating set) approach by integrating it with directional antennas and network coding. In this scheme, each node performs directional neighborhood discovery by sending hello packets via all sectors of the directional antenna. This process continues for *h* rounds after which each node constructs its *h*-hop neighborhood information. The *h*-hop neighborhood information of each node therefore contains information about its 1-hop neighbors and the locations of the sectors each neighbor belong to. Based on the collected information, each node determines its status whether it is a forwarding node or not. If it is yes, then it piggybacks the forwarding edges information in the broadcast message. Therefore, the forwarding node only transmits messages on restricted sectors by forwarding the messages only toward their corresponding forwarding edges. However, the proposed scheme suffers from mobility as the performance of the proposed schemes degrades with increasing node mobility. In similar work by Yang *et. al.* [74], the authors proposed to construct an energy efficient virtual network backbone using directional antennas. The proposed scheme is combination of connected dominating sets and directional antennas.

2.6 Discussion

Although there are few directional antenna based broadcasting schemes proposed to resolve the broadcast storm problem [56], none of them considering the critical environment conditions. While most of the ad hoc based broadcasting schemes achieve high reachability, however, the increment in reachability comes at the cost of high data redundancy. The existing directional antenna based schemes also suffer from mobility problem and some schemes assume specific directional antenna model. Therefore, it seems that there is still an important research area available in critical ad hoc environments as far as the problem of location, topology and AoA calculations is concerned, since different directional antenna based broadcasting scheme to solve the above problem may yield even better results.

In summary, to best of my knowledge, there is no directional antenna based broadcasting scheme that has been proposed yet for providing efficient broadcasting in critical ad hoc environments. Unlike existing directional antenna based broadcasting scheme which utilize directional antennas to achieve large transmission coverage by taking advantage of larger transmission range capabilities of directional antennas. In this research work, an efficient directional antenna based broadcasting scheme in MANET is proposed which uses directional antennas only to overcome the absence of GPS location. The main objective of the proposed scheme is to utilize directional antennas only to provide omni-directional coverage in critical ad hoc networks.

The proposed schemes combine the advantages of distance-based scheme and directional antenna to provide efficient broadcasting in critical ad hoc environment without relying on topology, location, hello-packets and complex AoA calculations. The design of the proposed RDBR schemes is based on theoretical analysis which helped to discover the minimum number of relaying nodes and directional antenna beams required to achieve high broadcasting coverage. The proposed RDBR schemes are able to achieve high reachability while reducing both the number of redundant retransmissions and end-to-end delay. The proposed schemes are highly scalable and more energy efficient. The high scalability capability comes from the lack of any coordination among neighboring nodes. Whereas energy efficiency comes from the huge reduction of the number of relaying nodes and the usage of distance based waiting time. Furthermore, the RDBR schemes are not affected by high node mobility which is an important feature of flooding based schemes.

Chapter 3: Broadcasting Upper Bound Analysis

This chapter analyses the broadcast coverage problem and presents conditions to achieve the upper bound of coverage for broadcasting relay for both single-hop and multi-hop broadcast relay. The conditions to achieve the upper bound coverage can be used as guidance for designing effective broadcast relaying schemes in critical environment. The remaining of this chapter is organized as follows. In Section 3.1, an overview of basic broadcasting schemes and existing classification of broadcasting schemes are discussed. Section 3.2 presents the performance analysis and the conditions to achieve the maximum coverage area for broadcasting relay in case of single hop broadcast relay. Section 3.3 presents the performance analysis and the conditions to achieve the maximum coverage area for broadcasting relay in case of multi-hop broadcast relay. In Section 3.4, a summary of the findings of this chapter is presented.

3.1 The Efficiency of Broadcasting Relay

In order to improve the efficiency of broadcasting relay in ad hoc networking environment, one of the most effective approaches is to reduce the number of redundant retransmissions. Therefore, the forwarding nodes must be carefully selected such that the distance between the source node and forwarding nodes must be the farthest among all one-hop neighboring nodes. This section investigates the lemma to achieve an optimized broadcasting coverage area as well as the condition to achieve this goal. It is assumed that the ad hoc network is modeled by a unit-disk graph [75], in which each node has the same transmission range, donated as radius r = 1. All host nodes in the network can move arbitrarily with random direction and speed, which is called Random Waypoint Mobility Model [76][77].

Host nodes make their own decision independently based solely on the local information. The nodes can communicate with each other directly or indirectly through one or more intermediates nodes using wireless transmission only without any fixed network infrastructure. Therefore, nodes in ad hoc network can act as sender, receiver and repeater at the same time. Note that host nodes in a critical environment may fail at any time due to lack of energy or be destroyed. Thus, network topology may dynamically change with time in an unpredictable manner. The current neighborhood of a node changes due to nodes mobility, neighboring nodes move into each other's transmission coverage ranges or moves out of each other's transmission coverage ranges. Whenever a node moves out of transmission coverage range of all nodes in the network, the node becomes isolated from the network and becomes orphaned.

This section focuses on the conditions to achieve high coverage area while utilizing minimum number of relaying nodes for both single-hop and multi-hop ad hoc networks [50]. As shown in Figure 3.1, two nodes are considered neighboring nodes if the Euclidean distance between them is less than or equal to the transmission range r. Packets can be directly transmitted between these two nodes. On the other hand, packets can be indirectly transmitted by a node through intermediate nodes in multi-hop fashion when the nodes are outside the transmission coverage range of the source node, i.e. when $r>1$. A node can also use short range transmission ($r \leq 1$) for transmitting packets to one-hop neighbors and for transmitting control messages. Without loss of generality, let $TA_{(k,n)}$ represent the total broadcasting coverage area of $m(k,n)$, where k is the index of rebroadcasting hop, n is the number of broadcasting nodes around each node, $m(k,n)$ is the total number of broadcasting nodes in the k-hop broadcast and $AS_{(k,n)}$ represents the average coverage area of each broadcasting node in the area.

As shown in Figure 3.1, a source node $Y_{o,1}$ has a forwarding node $Y_{1,n}$ located inside of coverage area, where n indicates node id and it is equal to 1. It is assumed that both node $Y_{o,1}$ and $Y_{1,n}$ have the same coverage range with an initialized radius $r=1$ and the distance between $Y_{o,1}$ and $Y_{1,n}$ is $x \le 1$. Let $A_{Y_{o,1}}$ represent the broadcasting coverage area provided by $Y_{1,n}$ as the shaded area indicated in Figure 3.1. Then we have that $A_{Y_{o,1}} = \pi r^2 - A_{Y_o}$, where A_{Y_o} is the duplicated area between $Y_{o,1}$ and $Y_{1,n}$.

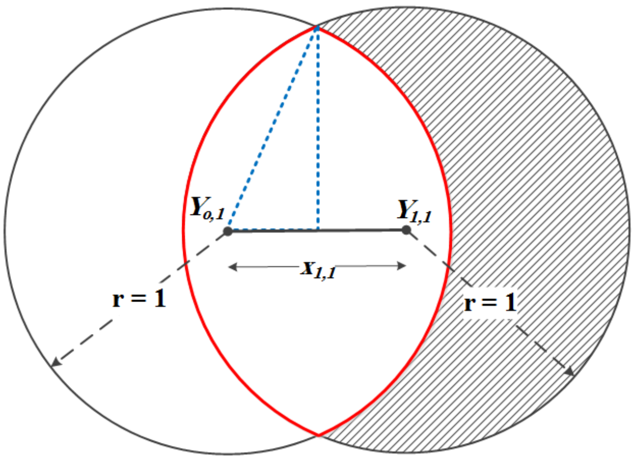


Figure 3.1: Calculating the overlapping area of two nodes $Y_{o,1}$ and , $Y_{1,1}$ while the shaded area is the extra coverage area that can be obtained from node $Y_{1,1}$

As shown in Figure 3.1, the duplicated area between $Y_{o,1}$ and $Y_{1,n}$ denoted as A_{Y_o}, can be calculated as follows:

$$A_{Y_o} = 4 \times \left[\frac{r^2}{2} \arccos\left(\frac{x}{2r}\right) - \frac{x}{4}\sqrt{r^2 - \left(\frac{x}{2}\right)^2} \right]$$

$$= 2r^2 \arccos\left(\frac{x}{2r}\right) - x\sqrt{r^2 - \left(\frac{x}{2}\right)^2}$$

Therefore, we have

$$SV(x) = 2r^2 \arccos\left(\frac{x}{2r}\right) - d_{Y_{o,1}}\sqrt{r^2 - \left(\frac{x}{2}\right)^2} \tag{3.1}$$

For $r = 1$, equation (1) can be simplifies as

$$SV(x) = 2\arccos\left(\frac{x_{Y_{o,1}}}{2}\right) - x_{Y_{o,1}}\sqrt{1 - \left(\frac{x_{Y_{o,1}}}{2}\right)^2} \tag{3.2}$$

Hence, the broadcasting coverage area provided by node $Y_{1,n}$ is given by

$$A_{Y_{1,n}} = \pi - 2\arccos\left(\frac{x_{Y_{1,n}}}{2}\right) + x_{Y_{1,n}}\sqrt{1 - \left(\frac{x_{Y_{1,n}}}{2}\right)^2} \qquad (\text{for } r = 1) \tag{3.3}$$

Lemma 3.1. A source node $Y_{o,1}$ deploys *k*-hop random directional broadcasting, where the *k*th broadcasting hop has $Y_{k,j}$ $(j = 1,2,...,n)$, $(n \geq 3)$ forwarding nodes, *k* is the index of broadcasting hop and *j* is the index of forwarding broadcast node in the *k*th broadcasting hop. The condition to achieve the best broadcasting efficiency in terms of minimum rebroadcasting nodes is when $n = 3 \times 2^{k-1}$ in the *k*th broadcasting hop and all the forwarding nodes $Y_{k,j}$ $(j = 1,2,...,n)$ are ideally located on the border of transmission range with the forwarding angle $\alpha_{1,j} = \frac{2\pi}{3}$, $(j = 1,2,3)$. The total number of broadcasting nodes is $m(k,n) = 3 \times 2^k - 2$.

Proof.

In the following analysis, it is assumed that all nodes, including the source node and all forward broadcasting nodes have the same coverage range with an initialized radius $r = 1$.

First of all, the first hop broadcasting case is considered as shown in Figure 3.2.

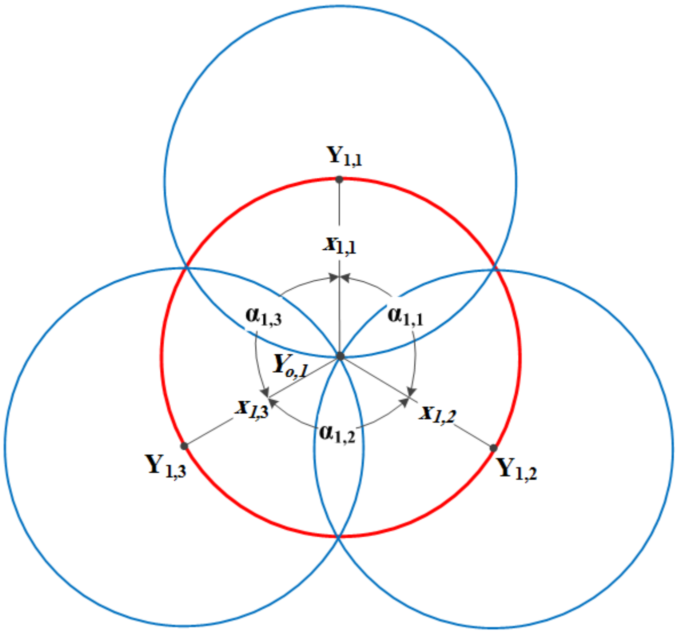


Figure 3.2: Single-hop broadcasting relay, *n* = 3

Let $A_{Y_{1,j}}\left(x_{1,j}\right)$ represent the broadcasting coverage area provided by $Y_{1,j}$. Recall equation (3.3), we can obtain

$$A_{Y_{1,j}}(x_{1,j}) = \pi - 2\arccos\left(\frac{x_{1,j}}{2}\right) + x_{1,j}\sqrt{1-\left(\frac{x_{1,j}}{2}\right)^2} \tag{3.4}$$

The differential of equation (3.4) is obtained as

$$\frac{d\left[A_{Y_{1,j}}(x_{1,j})\right]}{dx_{1,j}} = 2\sqrt{1-\left(\frac{x_{1,j}}{2}\right)^2} \geq 0,$$

It is clear that $A_{Y_{1,j}}(x_{1,j})$ is able to reach its maximum value when $x_{1,j} = 1$, that is

$$Max\left(A_{Y_{1,j}}(x_{1,j})\right)=\frac{\pi}{3}+\frac{\sqrt{3}}{2}, \quad \left(x_{1,j}=1\right) \tag{3.5}$$

Therefore, the total broadcasting coverage area provided by the all nodes, including the original source node $Y_{o,1}$ and $Y_{k,j}$ $(j=1,2,\ldots,n)$, is given by

$$Max\left(TA_{Y_{o,1},n}\right)=\pi+n\times\left(\frac{\pi}{3}+\frac{\sqrt{3}}{2}\right)-\sum_{j=1}^{n}SV_{1,j}\left(\alpha_{1,j}\right), \quad \left(x_{1,j}=1, n\geq 3 \text{ and } \sum_{j=1}^{n}\alpha_{1,j}=2\pi\right) \tag{3.6}$$

where $\alpha_{1,j}$ is defined as the angle $\angle Y_{1,j}Y_{o,1}Y_{1,j+1}$, and $j=(j+1)\bmod n$, and $SV_{1,j}(\alpha_{1,j})$ is the duplicated broadcasting area of two adjacent forwarding nodes. From equation (3.6), it can be seen that for a given *n*, the total broadcasting coverage area can reach its maximum value when $\sum_{j=1}^{n}SV_{1,j}\left(\alpha_{1,j}\right)$ is minimum.

By using Lagrange relaxation technique [78][79], we have

$$L\left(\alpha_{1,1},\alpha_{1,2},\cdots,\alpha_{1,n}\right)=\sum_{j=1}^{n}\alpha_{1,j}-2\pi$$

Therefore, the term $\sum_{j=1}^{n}SV_{1,j}\left(\alpha_{1,j}\right)$ in equation (3.6) can be presented as

$$F=\sum_{j=1}^{n}SV_{1,j}\left(\alpha_{1,j}\right)+\beta L\left(\alpha_{1,1},\alpha_{1,2},\cdots,\alpha_{1,n}\right)=\sum_{j=1}^{n}SV_{1,j}\left(\alpha_{1,j}\right)+\beta\left(\sum_{j=1}^{n}\alpha_{1,j}-2\pi\right)$$

where β is the Lagrange multiplier. The minimum value of F can be achieved under the following conditions:

$$\begin{cases} \dfrac{\partial F}{\partial\alpha_{1,1}}=\dfrac{\partial SV_{1,1}\left(\alpha_{1,1}\right)}{\partial\alpha_{1,1}}+\beta \\ \dfrac{\partial F}{\partial\alpha_{1,2}}=\dfrac{\partial SV_{1,2}\left(\alpha_{1,2}\right)}{\partial\alpha_{1,2}}+\beta \\ \qquad\vdots \\ \dfrac{\partial F}{\partial\alpha_{1,n}}=\dfrac{\partial SV_{1,n}\left(\alpha_{1,n}\right)}{\partial\alpha_{1,n}}+\beta \end{cases} \tag{3.7}$$

and

$$\frac{\partial F}{\partial\beta}=\sum_{j=1}^{n}\alpha_{1,j}-2\pi \tag{3.8}$$

From equation (3.6), we can obtain that

$$\frac{\partial SV_{1,1}(\alpha_{1,1})}{\partial \alpha_{1,1}} = \frac{\partial SV_{1,2}(\alpha_{1,2})}{\partial \alpha_{1,2}} = \cdots = \frac{\partial SV_{1,n}(\alpha_{1,n})}{\partial \alpha_{1,n}} \tag{3.9}$$

Thus, combining equation (3.7) and (3.8), it gives that

$$\alpha_{1,1} = \alpha_{1,2} = \cdots \alpha_{1,n} \text{ and } \sum_{j=1}^{n} \alpha_{1,j} = 2\pi$$

Hence, we can obtain that

$$SV_{1,1}(\alpha_{1,1}) = SV_{1,2}(\alpha_{1,2}) = \cdots = SV_{1,n}(\alpha_{1,n}) \tag{3.10}$$

Therefore, it can be concluded that the total broadcasting coverage area is able to achieve its maximum value

$$Max\left(\overbrace{TA}_{1,n}\right) = \pi + n \times \left(\frac{\pi}{3} + \frac{\sqrt{3}}{2}\right) - n \times SV_{1,j}(\alpha_{1,j}) \tag{3.11}$$

under the condition as if and only if

$$\begin{cases} x_{1,j} = 1 \\ \alpha_{1,j} = \dfrac{2\pi}{n} \end{cases} \quad \text{for } j = 1,2,\cdots,n \tag{3.12}$$

Applying the proved result in equation (3.12) to general multiple hop broadcasting case, Figure 3.4 shows an example of a multi-hop broadcasting relay with k = 2. It is clear that the first hop has 3 forwarding nodes, the second hop has 6 forwarding nodes and the third hop has 12 forwarding nodes. Likewise, it is clear that the k^{th} hop relay has $n = 3 \times 2^{k-1}$ forwarding nodes, denoted as $Y_{k,j}$, ($j = 1,2,...n$ and $n = 3 \times 2^{k-1}$). Hence, the total number of nodes involving in the k-hop broadcasting relay including the original source node and all forward broadcasting nodes is given by

$$m(k,n) = 1 + 3\sum_{i=2}^{k} 2^{i-1} = 1 + 3\left(1 + 2 + 4 + 8 + \cdots + 2^{k-1}\right) = 1 + 3 \times \frac{2^k - 1}{2 - 1} = 3 \times 2^k - 2 \tag{3.13}$$

3.2 Performance Analysis of Single-hop Broadcast Relay

As shown in Figure 3.2 that the source node $Y_{o,1}$ has three forwarding nodes in the first broadcasting hop, denoted as $Y_{1,j}$ $(j=1,2,3)$ which are symmetrically located on the border of $Y_{o,1}$ transmission range (i.e., $x_{1,j}=1)$) and the forwarding angle $\alpha_{1,j}=\frac{2\pi}{3}$. According to Lemma 3.1, the total broadcasting coverage area by the all nodes, including $Y_{o,1}$ and $Y_{1,j}$ can achieve the maximum value as equation (3.11), that is

$$Max\left(\overbrace{TA}_{1,3}\right)=\pi+3\times\left(\frac{\pi}{3}+\frac{\sqrt{3}}{2}\right)-3\times SV_{1,3}\left(\frac{2\pi}{3}\right)$$

Figure 3.2 shows the distance between two adjacent nodes $Y_{1,j}$ and $Y_{1,j+1}$, $(j=(j+1)\text{mod } 3)$. Hence, we obtain that

$$SV_{1,j}\left(\frac{2\pi}{3}\right)=0$$

Therefore, we obtain that

$$Max\left(\overbrace{TA}_{1,3}\right)=\pi+3\times\left(\frac{\pi}{3}+\frac{\sqrt{3}}{2}\right)\approx 2.827\pi \tag{3.14}$$

Table 3.1 shows the effects of forwarding angle $\alpha_{1,j}$, $(j=1,2,3)$ on the average broadcasting coverage area for each node, where $x_{1,j}=1$ and $\sum_{j=1}^{3}\alpha_{1,j}=2\pi$. From Table 3.1, it can be seen that only when the conditions of $x_{1,j}=1$ and $\alpha_{1,1}=\alpha_{1,2}=\alpha_{1,3}=\frac{2\pi}{3}$ are satisfied, the broadcasting coverage for each node reaches its maximum value of 0.706π.

Table 3.1: The impact of forwarding angles on the broadcasting coverage area

$\alpha_1 = \alpha_2$	0.5π	0.66π	0.7π	0.8π	0.9π
$\lvert x \rvert = 1$	0.686	0.706	0.705	0.680	0.593
$\lvert x \rvert = 0.8$	0.594	0.613	0.612	0.599	0.533

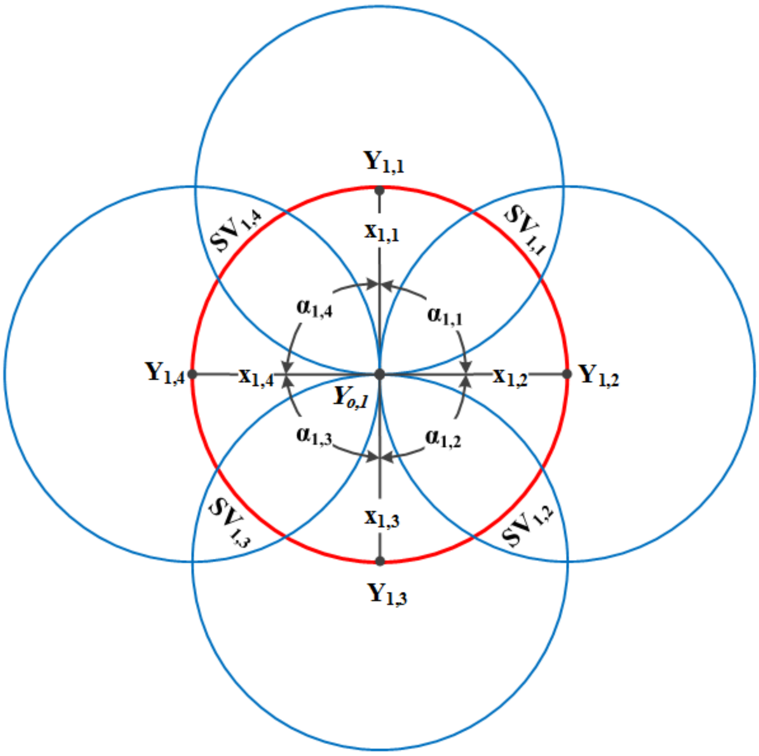


Figure 3.3: Single-hop broadcasting relay for n = 4

As a comparison, a single hop broadcasting replay with n = 4 forward broadcasting node is considered as shown in Figure 3.3, the total broadcasting coverage area provided by the all nodes, including the source node $Y_{o,1}$ and $Y_{1,j}$ $(j = 1,2,3,4)$ can achieve a value as

$$Max\left(\overbrace{TA}_{1,4}\right) = \pi + 4\times\left(\frac{\pi}{3}+\frac{\sqrt{3}}{2}\right) - 4\times SV_{1,4}\left(\frac{\pi}{2}\right) \tag{3.15}$$

From Figure 3.3, we obtain that the distance between two adjacent nodes $Y_{1,j}$ and $Y_{1,j+1}$ ($j = (j+1) \bmod 4$), so that

$$SV_{1,4}\left(\frac{\pi}{2}\right) = \frac{\sqrt{3}}{2} + \frac{\pi}{12} - 1.$$

Hence,

$$Max\left(\overbrace{TA}_{1,4}\right) = \pi + 4 \times \left(\frac{\pi}{3} + \frac{\sqrt{3}}{2}\right) - 4 \times \left(\frac{\sqrt{3}}{2} + \frac{\pi}{12} - 1\right) \approx 3.272\pi \tag{3.16}$$

The average broadcasting coverage area for each node is given by

$$Max\left(\overbrace{AS}_{1,4}\right) = \frac{Max\left(\overbrace{TA}_{1,4}\right)}{5} \approx 0.655\pi \tag{3.17}$$

A comparison of the equation (3.14) and (3.16) demonstrates that single-hop broadcasting relay with $n = 3$ has the best efficiency in terms of average broadcasting coverage area per node. Note that this comparison is under the conditions presented by Lemma 3.1.

3.3 Performance Analysis of Multi-hop Broadcast Relay

Let $Max\left(\overbrace{TA}_{m_{k,n}}\right)$ and $Max\left(\overbrace{AS}_{m_{k,n}}\right)$ represent the total broadcasting coverage area and average broadcasting coverage area per node, respectively, where $m_{k,n}$ is the total number of the nodes which are involving in the broadcasting relay.

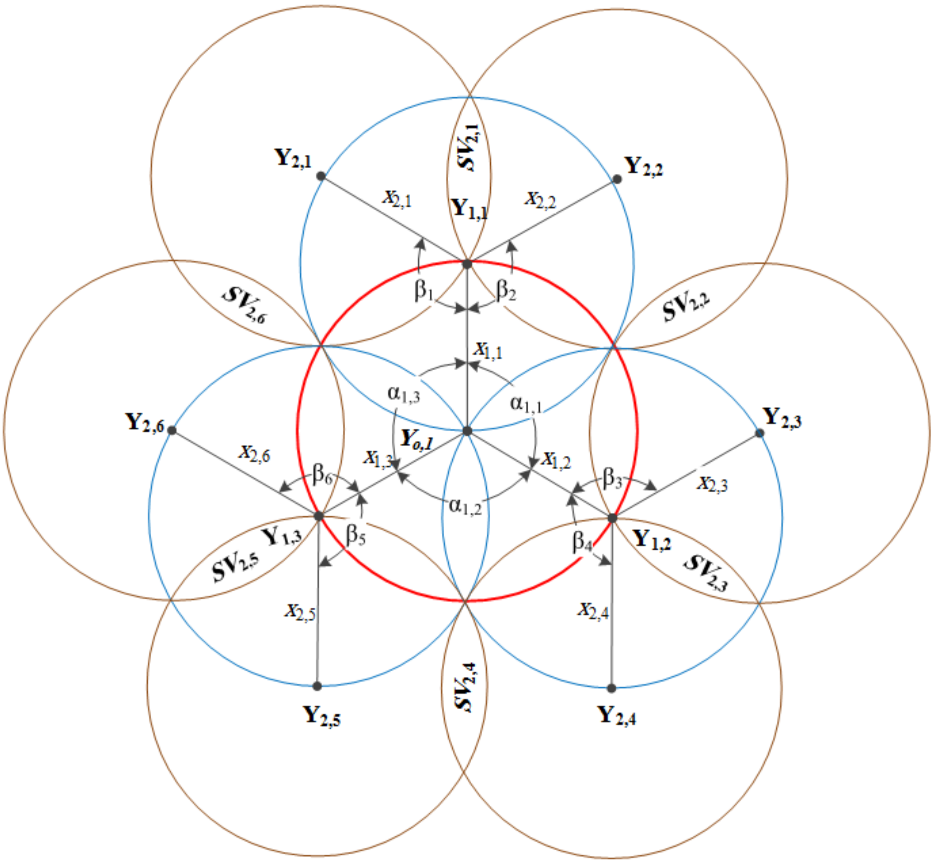


Figure 3.4: Multi-hop broadcasting relay with k = 2

Figure 3.4 shows a $k-\text{hop}$ broadcasting relay with $n=3$, where all the nodes are assumed to have the same radio transmission range (i.e., $r_{k,i_k}=1$). In order to achieve the best efficiency in terms of the average broadcasting coverage area per node, the rules of Lemma 3.1 are deployed.

In this case, the k^{th} hop broadcasting $(k \geq 1)$ has $3\times 2^{k\text{-}1}$ forwarding nodes, denoted as $Y_{k,j_k}, (j_k = 1,2,\cdots,3\times 2^{k-1})$, which are symmetrically located on the border of transmission range (i.e., $x_{k,j_k}=1$) with the forwarding angle $\alpha_{k,j_k}=\dfrac{2\pi}{3}$. Therefore, the total number of forwarding nodes in this $k-$hop broadcasting is given by

$$m_{k,n} = 1+3+3\times 2+\cdots+3\times 2^{k-1} = 3\times 2^{k}-2 \tag{3.18}$$

For $k=1$, $Max\left(\widetilde{TA}_{M_{1,3}}\right)$ is the same as that of single-broadcasting relay, which can be calculated using equation (3.14) as

$$Max\left(\widetilde{TA}_{M_{1,3}}\right)=\pi+3\times\left(\frac{\pi}{3}+\frac{\sqrt{3}}{2}\right)$$

Likewise, the total broadcasting coverage area for $k=2$ is given by

$$Max\left(\widetilde{TA}_{M_{2,3}}\right)=Max\left(\widetilde{TA}_{M_{1,3}}\right)+6\left[\left(\frac{\pi}{3}+\frac{\sqrt{3}}{2}\right)-SV_{Y_{2,i_2}}\left(\frac{2\pi}{3}\right)\right]$$

where $SV_{Y_{2,j_2},}\left(\frac{2\pi}{3}\right)$ is the duplicated coverage area between two adjacent nodes Y_{2,i_2} and Y_{2,j_2}, $(i_2=(1,2,\ldots,2\times 3)$ and $j_2=(i_2+1)\bmod 6)$. As shown in Figure 3.4, the distance between two adjacent nodes Y_{2,j_2} and Y_{2,j_2+1} can be calculated as $x_{Y_{2,i_{j2}},Y_{2,j_2+1}}=\sqrt{3}$. Therefore, submitting $x_{Y_{2,i_{j2}},Y_{2,j_2+1}}=\sqrt{3}$ to equation (3.2), that is

$$SV_{Y_{2,i_{j2}}}\left(\frac{2\pi}{3}\right)=2\arccos\left(\frac{x_{Y_{2,j_2}Y_{2,j_2+1}}}{2}\right)-x_{Y_{2,j_2}Y_{2,j_2+1}}\sqrt{1-\left(\frac{x_{Y_{2,j_2}Y_{2,j_2+1}}}{2}\right)^2}=\frac{\pi}{3}-\frac{\sqrt{3}}{2}$$

Therefore, we finally obtain

$$Max\left(\widetilde{TA}_{M_{2,3}}\right)=2\pi+\frac{\sqrt{3}}{2}+6\times\left[\left(\frac{\pi}{3}+\frac{\sqrt{3}}{2}\right)-\left(\frac{\pi}{3}-\frac{\sqrt{3}}{2}\right)\right]=2\pi+\frac{\sqrt{3}}{2}+6\sqrt{3}$$

In general, the total broadcasting coverage area for $k-\mathrm{hop}$ broadcasting relay of $n=3$ with $r_{k,j_k}=1, x_{k,j_k}=1$ and $\alpha_{k,j_k}=\frac{2\pi}{3}$ is given by

$$Max\left(\widetilde{TA}_{M_{k,3}}\right)=2\pi+\frac{\sqrt{3}}{2}+6\sqrt{3}+9\sqrt{3}+\cdots+3k\sqrt{3}=2\pi+\frac{3\sqrt{3}}{2}\left(k^2+k-1\right)\quad(k\geq 1)\tag{3.19}$$

Therefore, the average broadcasting coverage per node for $k-\mathrm{hop}$ broadcasting relay of $n=3$ with $r=1, x_{i_k}=1$ and $\alpha_{i_k}=\frac{2\pi}{3}$ is given by

$$Max\left(\widehat{AS}_{M_{k,3}}\right)=\frac{Max\left(\widehat{TA}_{M_{k,3}}\right)}{M_{k,3}}=\frac{2\pi+\frac{3\sqrt{3}}{2}\left(k^2+k-1\right)}{3\times 2^k-2} \tag{3.20}$$

Now the $k-\mathrm{hop}$ broadcasting relay of $n=4$ is considered which has $4\times 3^{k-1}$ forwarding nodes, denoted as $Y_{k,j_k}, (j_k=1,2,\cdots,4\times 3^{k-1})$ in the k^{th} $(k\geq 1)$ hop broadcasting relay. It is assumed that all forwarding nodes are symmetrically located on the border of transmission range (i.e., $x_{k,j_k}=1$) with the forwarding angle $\alpha_{k,j_k}=\frac{\pi}{2}$ in order to achieve the maximum coverage area. In this case, the total number of forwarding nodes is given by

$$M_{k,4}=1+4+4\times 3+\cdots+4\times 3^{k-1}=1+4\times\sum_{p=2}^{k}3^{p-1}=2\times 3^k-1 \tag{3.21}$$

Recall equation (3.16), the total broadcasting coverage area for $k=1$ is given by

$$Max\left(\widehat{TA}_{M_{1,4}}\right)=\pi+4\times\left(\frac{\pi}{3}+\frac{\sqrt{3}}{2}\right)-4\times\left(\frac{\sqrt{3}}{2}+\frac{\pi}{12}-1\right)$$

Likewise, the total broadcasting coverage area for $k=2$ is given by

$$Max\left(\widehat{TA}_{M_{2,4}}\right)=Max\left(\widehat{TA}_{M_{1,4}}\right)+8\left[\left(\frac{\pi}{3}+\frac{\sqrt{3}}{2}\right)-\left(SV_{2,Y_{i_2}}\left(\frac{\pi}{2}\right)\right)\right]$$

Recall equation (3.15), $SV_{2,Y_{i_2}}\left(\frac{\pi}{2}\right)=\frac{\sqrt{3}}{2}-\frac{\pi}{12}+1$. Therefore, we have

$$Max\left(\widehat{TA}_{M_{2,4}}\right)=\pi+\left[\left(\frac{\pi}{3}+\frac{\sqrt{3}}{2}\right)-\left(\frac{\sqrt{3}}{2}+\frac{\pi}{12}-1\right)\right]\times(4+12)$$

In general, the total broadcasting coverage area for $k-\text{hop}$ broadcasting relay of $n=4$ with $r=1, x_{j_k}=1$ and $\alpha_{k,j_k}=\frac{\pi}{2}$ is given by

$$
\begin{aligned}
Max\left(\overbrace{TA}_{M_{k,4}}\right) &= \pi+\left[\left(\frac{\pi}{3}+\frac{\sqrt{3}}{2}\right)-\left(\frac{\sqrt{3}}{2}+\frac{\pi}{12}-1\right)\right]\times(4+12+36+\cdots+4\times 3^{k-1}) \\
&= \pi+\left[\left(\frac{\pi}{3}+\frac{\sqrt{3}}{2}\right)-\left(\frac{\sqrt{3}}{2}+\frac{\pi}{12}-1\right)\right]\times\left(4\times 3^{k}-4\right) \\
&= \pi+\left(\frac{\pi}{4}+1\right)\times\left(4\times 3^{k}-4\right)
\end{aligned}
\tag{3.22}
$$

The average broadcasting coverage for $k-\text{hop}$ broadcasting relay for $n=4$ is given by

$$
Max\left(\overbrace{AS}_{M_{k,4}}\right)=\frac{Max\left(\overbrace{TA}_{M_{k,4}}\right)}{m_{k,4}}=\frac{\pi}{4}+1+\frac{\pi}{4\left(3^{k}-1\right)} \quad (k\geq 1) \tag{3.23}
$$

Figure 3.5 shows the number of relaying nodes required by a source node with three neighbors referred to as cases 1 versus a source node with four neighbors referred to as case 2. The number of relaying nodes required in case 1 is calculated by equation (3.18). Likewise, the number of relaying nodes required in case 2 is calculated by equation (3.21). A comparison of case 1 and 2 shown in Figure 3.5 illustrates that the number of relaying nodes required by both cases increase with increasing number of hops. Initially, there is a slight difference between two cases when broadcasting is in a range of 2 to 4 hops. However, the main observation is that the number of relaying nodes required by case 1 is much less than the number of relaying nodes required by case 2 especially when broadcasting relays are 5 hops and onward. This is because that the case 1 has three relaying nodes are required whereas the case 2 has four relaying nodes are required. This indicates that case 1 is scalable whereas case 2 is not scalable due to large redundancy. Furthermore, case 2 may also suffer from contention and collusion due to large amount of redundancy.

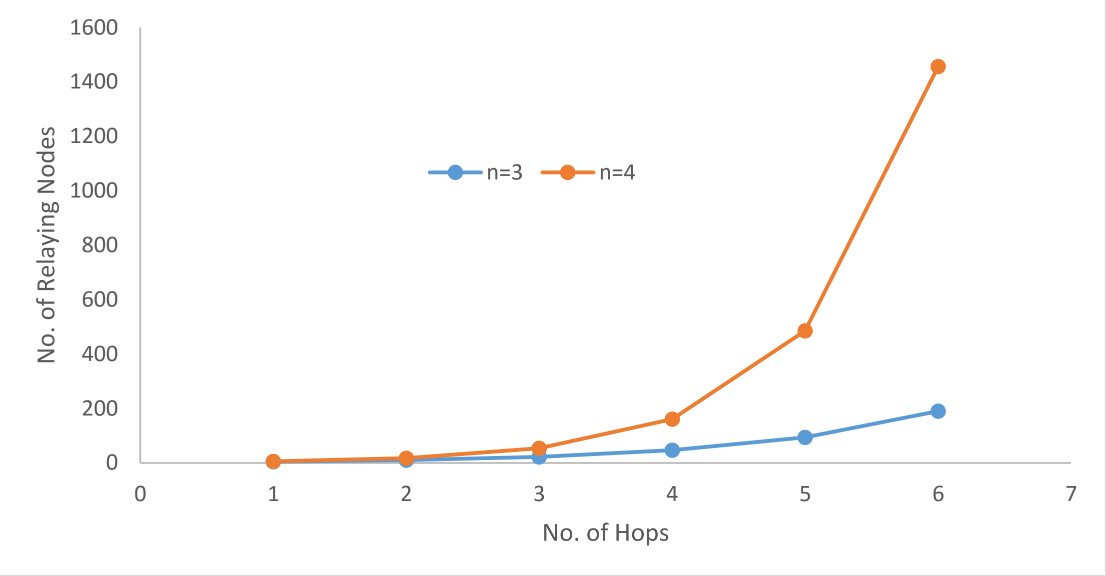


Figure 3.5: The relationship between no. of hops and no. of relaying nodes

Case Study

In single-hop broadcasting scenario, where $k=1$ and $n=3$, the maximum broadcasting coverage area is $3\times\left(\frac{\pi}{3}+\frac{\sqrt{3}}{2}\right)\approx 5.74$. The overall broadcasting coverage area after the 1st hop of broadcasting is $\pi+3\times\left(\frac{\pi}{3}+\frac{\sqrt{3}}{2}\right)\approx 8.88$. Likewise, the maximum broadcasting coverage area for $k=2$ and $n=6$ is $6\times\left(\frac{\pi}{3}+\frac{\sqrt{3}}{2}\right)\approx 11.48$ and the overall broadcasting coverage area after the 2nd hop of broadcasting is

$\pi + 6 \times \left(\frac{\pi}{3} + \frac{\sqrt{3}}{2} \right) \approx 14.62$. Table 3.2 shows the maximum multiple hop broadcasting coverage for r = 1 and n = 3.

Table 3.2: Maximum broadcasting coverage for multiple hop relay

k	**n**	**Total number of forwarding nodes**	**Maximum broadcasting coverage area (π)**
1	3	4	1.83
5	48	94	29.23
10	1536	3070	935.42
15	49152	98302	29933.46
20	1572864	3145726	957870.69

Figure 3.6 and 3.7 show the total coverage area $Max\left(\widehat{TA}_{M_{k,n}}\right)$ and the average coverage area per forwarding node $Max\left(\widehat{TA}_{M_{k,n}}\right)$ versus the number of rebroadcast hops for $n = 3$ and $n = 4$, respectively. Figure 3.6 shows that both of $Max\left(\widehat{TA}_{k,3}\right)$ and $Max\left(\widehat{TA}_{M_{k,4}}\right)$ increase exponentially when k increases. However, the increase of $Max\left(\widehat{TA}_{M_{k,3}}\right)$ is faster than $Max\left(\widehat{TA}_{M_{k,4}}\right)$ does, especially when $k \geq 5$. Likewise, as shown in Figure 3.7, the average broadcasting area $Max\left(\widehat{AS}_{M_{k,3}}\right)$ is much higher than

$Max\left(\overbrace{AS}_{M_{k,4}}\right)$. This is because that the duplicated area between two adjacent forwarding nodes for $n=3$ is smaller than that for $n=4$ that can be proved by Lemma 3.1.

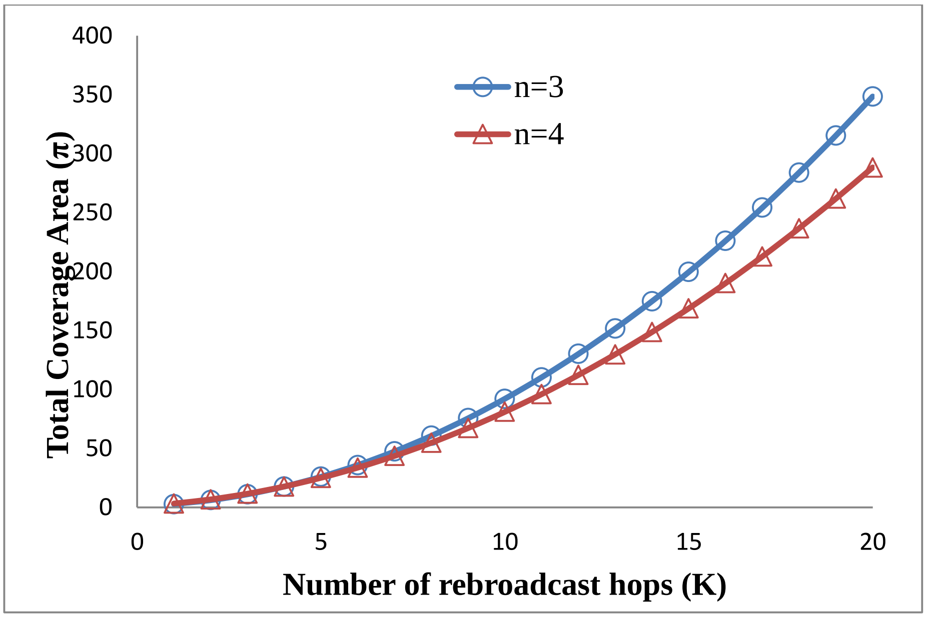


Figure 3.6: Total coverage area versus number of rebroadcast hops

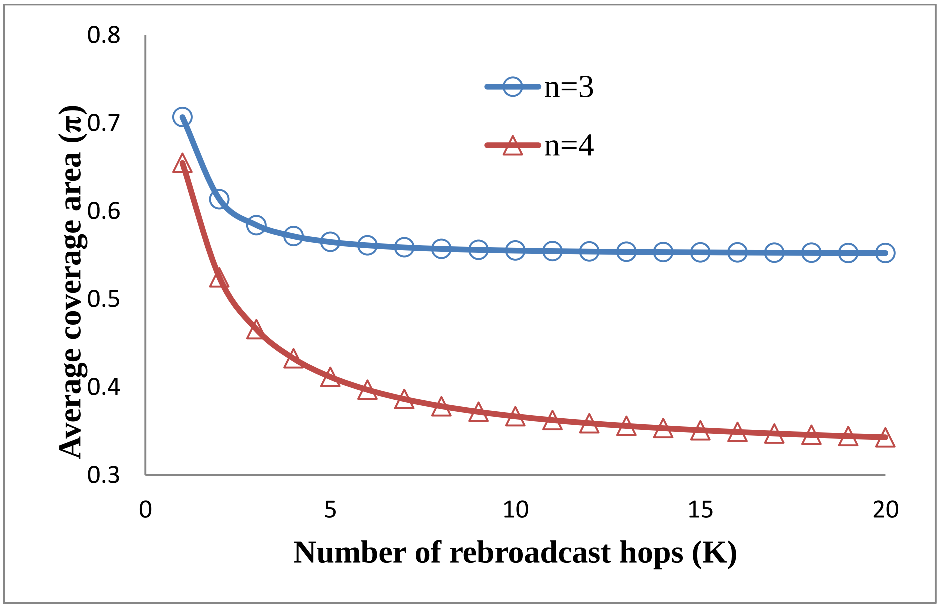


Figure 3.7: Average coverage area versus number of rebroadcast hops

3.4 Summary

This chapter presents a theorem, named as Lemma 3.1, to achieve the maximum coverage area for broadcasting relay while utilizing the least number of relaying nodes. To achieve maximum coverage area, each host node requires only three relaying nodes which must be located at the idealized locations. The nodes are located at ideal locations if and only if when angle between each relaying node is $\frac{2\pi}{3}$ and the distance between the source node and each relaying node is equal to the transmission range of the source node i.e. every node is located at the transmission boundary of the source node. To validate the findings of this chapter, several theoretical evaluation have been conducted using the formulas generated from the Lemma 3.1.

The first evaluation shows a comparison of coverage areas for n=3 and n=4. The results indicate that a source node with three relaying nodes located at the idealized locations is able to achieve optimum coverage comparing to a source node with four relaying nodes. Specifically, a source node with three relaying nodes achieved an average coverage area of 0.706π while a source node with four relaying nodes achieved an average coverage area of 0.655π. The second evaluation focuses on the comparison of number of relaying nodes required for a source node with three relaying nodes and four relaying node, respectively. The results of the evaluation indicate that a source node with three relaying node requires less relaying nodes compared with a source node with four relaying node especially when the number of broadcasting relay hops increases. In specific, a source node with three relaying nodes requires only about 200 relaying node to achieve high coverage area for six hops while a source node with four relaying nodes requires about 1500 relaying nodes to achieve high coverage. Hence, the best conditions to achieve higher coverage area using less number of relaying nodes is when a source node has three relaying nodes and these node area located at ideal locations as stated above.

Chapter 4: The Effects of Relaying Areas on the Performance of Broadcasting Relay

This chapter presents and proves two new Lemmas to overcome the shortcomings of Lemma 3.1 presented in Chapter 3. The findings and conditions presented in this chapter can be used as a guidance to develop efficient ad hoc based broadcast relaying schemes in critical environment under extreme conditions. This chapter discusses the problem of nodes displacement form ideal locations from both distance and angle point of view. Then, this chapter presents conditions to mitigate the node displacement problem. The remaining of this chapter is organized as follows. In Section 4.1, an overview of the factors that cause the problem of nodes displacement from ideal locations is presented. Section 4.2 analyses the effect of forwarding angle on the coverage area. Section 4.3 analyses the effect of the distance between the source node and the forwarding nodes on the coverage area. In Section 4.4, an overview of the worst case scenarios of the node displacement from ideal location is presented. Section 4.5 presents conditions and guidelines to mitigate the node displacement from ideal locations problem. In Section 4.6, a summary of the findings of this chapter is presented.

4.1 Overview

The limited transmission range of nodes, limited energy and high nodes mobility makes delivering packets directly from source nodes to destination nodes challenging. It is, therefore, necessary to select intermediate nodes, which act as relaying nodes to deliver the packets to the intended destinations. As discussed in Chapter 3, in order to reduce the number of redundant retransmissions, relaying nodes must be carefully selected. Therefore, a Lemma was presented in Chapter 3 for achieving high coverage while utilizing the least number of retransmitting nodes under the conditions that every source node has equal number of relaying nodes, the forwarding angle between each pair of forwarding nodes is $\frac{2\pi}{3}$ and the relaying nodes are located on the transmission boundary of the source node [50].

Ideally, as shown in Figure 4.1, the minimum requirement is that packet is relayed by three neighboring nodes in three different directions where the angle between each pair of relaying nodes is 120 degrees. And all three relaying nodes are located at the boundary of the transmission coverage of the source node which is called ideal locations. Basically, the conditions presented in Lemma 3.1 can be fulfilled if and only if the selected relaying nodes are located exactly on ideal locations.

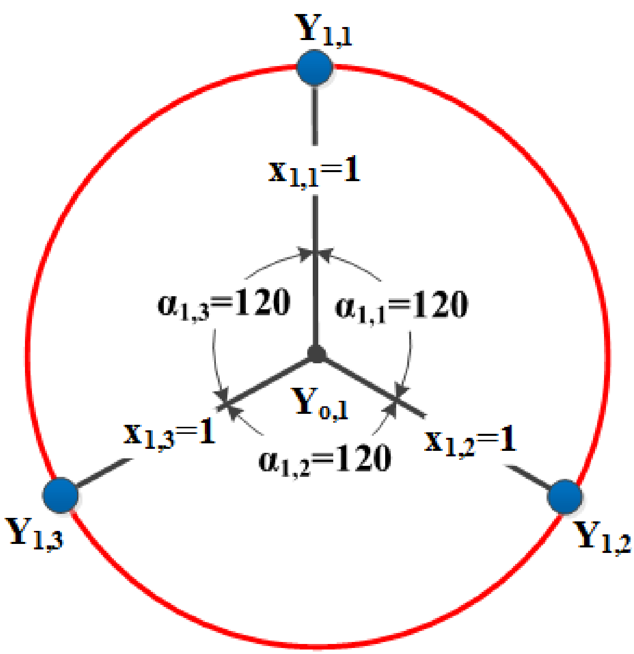


Figure 4.1: Relaying nodes at ideal locations

However, to find relaying nodes located on the ideal locations is critical from practical application point of view. This is due to the fact that in many practical situations, neighboring nodes may not be located at ideal locations. There are several factors that cause nodes displacement from their ideal locations. Random nodes deployment, low nodes density and high nodes mobility are the three most important factors. Nodes can be deployed in the critical environments such as battlefield in three different ways: predetermined, random and hybrid manner depending on the level of accessibility to the environment. The predetermined deployment is applicable to environments that are easy to access in which all nodes are placed on specific locations according to some strategy. Whereas hybrid deployment is applicable to environments that area not as easy as predetermined deployment environments in which some of nodes are placed on specific locations and the remaining nodes are deployed randomly. In both the above cases, the maximum transmission coverage is achievable because nodes can be placed on ideal locations as stated in the Lemma 3.1.

On the other hand, random deployment is not only applicable to inaccessible and critical environments such as battlefield but also applicable to less critical environment as well. This is probably due to the fact that many scenarios prefer random deployment over predetermined deployment due to practical reasons such as deployment time and cost. However, random deployment of nodes may not be able to guarantee the optimum transmission coverage as nodes may not be located at ideal locations. Furthermore, nodes density may also have an important role in achieving the optimum coverage especially in random deployment environment. In low density environments, every node has few neighbors and these neighbors may not be located on ideal positions. However, in this case, achieving the optimum transmission coverage is still possible if predetermined or hybrid nodes deployment strategies are adopted. By contrast, high density environments are more likely to achieve the optimum transmission coverage since there are more available neighbor nodes inside of the dedicated areas or close to transmission boundary and the probability of the finding neighboring nodes at the ideal locations is higher comparing to the low density environment. However, even in high density environment, nodes may still be arbitrary distributed due to high and random nodes mobility. High density environments usually adopt random nodes deployment strategy as high cost of deployment is associated with both predetermined and hybrid nodes deployment strategies.

Based on the above discussion, nodes can be found on ideal locations in few scenarios using the conditions and strategies described above. Hence, it is worth noting that even initially some nodes were found at ideal locations, nodes in the critical environment such as battlefield are vulnerable to displacement from their initial ideal locations. Dynamic topology changing and high node mobility are two major factors that cause nodes displacement form their initial ideal locations. In critical environments, for example, nodes move from one location to other location by random direction and speed. As the result, maintaining the neighbor information in such environment is nearly impossible due to high cost and overhead associated with updating the links. These challenges occur due to the absence of GPS positioning and lack of information about 1-hop neighbors. Other inevitable factors that affect ideal relaying nodes selections include weak signal at the transmission boundary, existence of obstacles that either block or divert the signal, battery drainage, node destruction by enemy and non-circular transmission ranges. One approach to reducing the effect of nodes displacement is to select relaying nodes with minimum node displacement error.

Taking the above approach into consideration, the concept of relaying areas is developed in which the neighboring nodes are located inside of dedicated areas and are only allowed nodes to be selected as relaying nodes. The size of relaying area is adjustable based on several factors, one of which is local nodes density in the network. The relaying area allows the source node to select relevant-ideal locations, i.e. the neighboring nodes closest to the ideal points are selected as relaying nodes. This approach assumes the presence of GPS positioning system. The positioning information of these neighboring nodes can be used to calculate the distance between nodes and selected neighboring nodes which are closet to the ideal points. However, the GPS positioning information is not always available in critical ad hoc environments. This means that the calculation of the neighboring nodes displacement from the ideal locations becomes almost impossible since the precise location of neighboring nodes cannot be determined. Instead, the received signal strength can be used to calculate the distances between neighboring nodes. However, this scheme only provides estimated distances and therefore makes the process of selecting relaying nodes at ideal locations very difficult and nearly impossible without using complex approaches to rectify the calculation errors.

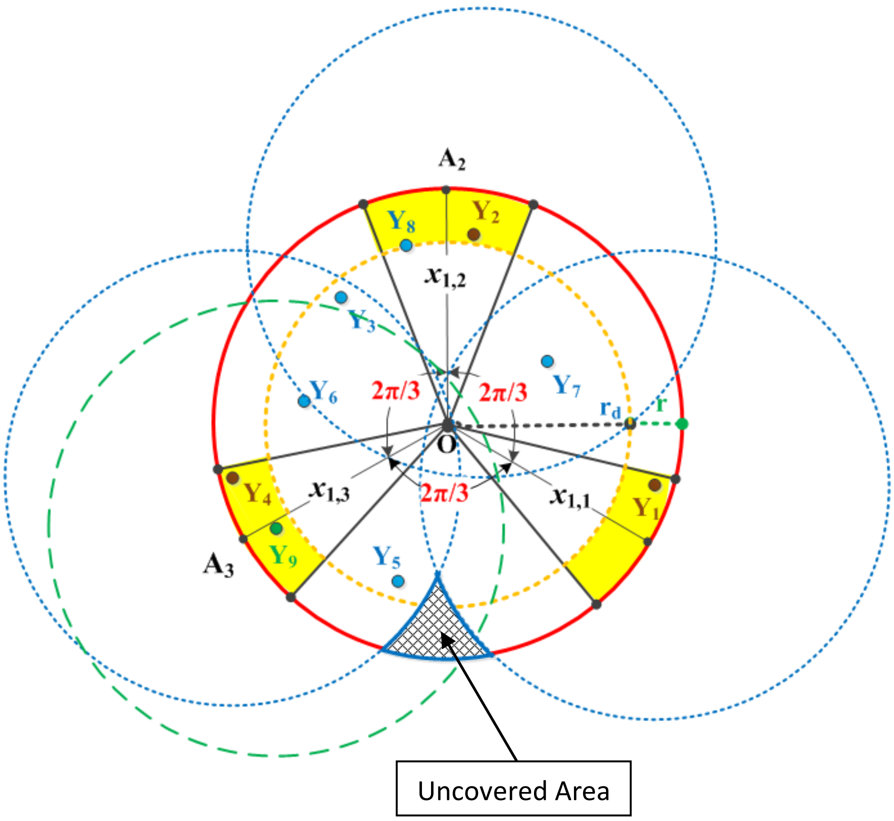


Figure 4.2: Nodes displacement from ideal locations

Figure 4.2 shows an example of a scenario where nodes are randomly distributed and there are no nodes located on ideal locations. Obviously, in this scenario the optimum transmission coverage cannot be achieved. In this case, the broadcasting relay scheme must select nodes close to ideal locations as the rebroadcasting nodes in order to be able to achieve a higher transmission coverage area. Furthermore, Figure 4.2 also shows a possible scenario in which the proposed scheme randomly selects nodes Y_1, Y_2 and Y_4 as relaying nodes. However, this selection may increase the overlapping area between the relaying nodes Y_1, Y_2 and Y_2, Y_4 but at the same time it may decrease the overlapping area between the relaying nodes Y_1, Y_4. The second selection causes a gap in coverage area where the dashed area is uncovered by either node. Therefore, a better choice would be selecting the node Y_9 as relaying node instead of Y_4. However, the source node is unaware of the location of nodes within its transmission coverage due to absence of GPS location and at the same time it is unaware of its 1-hop neighbor's information due to nodes mobility. As a result, the source node cannot make the correct decision of selecting the relaying nodes that are closet to the ideal locations.

In this Chapter, a theoretical analysis is conducted to investigate the impact of different factors that affect the performance of the network in terms of total coverage area and delivery ratio. Particular attention is paid to the investigation under what conditions these parameters can have negative effect on the total coverage area. Then, it is followed by a set of conditions and guidelines for the selection of relaying nodes in such a way to achieve higher coverage area. To the best of our knowledge, there has been no study that thoroughly investigates this problem, examine how the parameters in terms of distance and angle effect the total coverage area in the critical environment where host node positioning information is not available and consequently propose efficient schemes to mitigate this problem. Therefore, the aim of this chapter is to investigate the effect of nodes displacement from their ideal locations on the overall performance of the network. In particular, the investigation focuses on the impact of nodes displacement from their ideal locations on the total coverage area and transmission failures. In order to evaluate the effect of factors in terms of distance and angle on total coverage area, two lemmas are presented to help understand the influence of each of above factors on overall performance in terms of delivery ratio.

4.2 Effect of Forwarding Angle

This section focuses on the investigation of the effect of nodes displacement from ideal locations on forwarding angle basis.

Lemma 4.1. The effect of forwarding angle error on directional broadcasting efficiency. The effect of angle error due to the position of $Y_{x_o(t),i_0}$ $(i_o = 1,2,3)$ in the relaying areas is that $d_{Y_1,Y_2} \neq d_{Y_1,Y_3} \neq d_{Y_2,Y_3}$.

Proof:

As shown in Figure 4.3, a source node O has $Y_{x_{i_o(t)},i_o}$ $(i_o = 1,2,3)$ forwarding nodes located on ideal locations $S_{r_o,x_{i_o}(t)}(t)$ $(i_o = 1,2,3)$, respectively, where x_{i_o}(t) $(i_o = 1,2,3)$ is the forwarding direction from the source node O. The angle between the node $Y_{x_{i_o(t)},i_o}$ $(i_o = 1,2,3)$ and the forwarding direction x_{i_o}(t) $(i_o = 1,2,3)$ from the source node O is $\alpha_{Y_{i_o}}$ (t) $(i_o = 1,2,3)$. Therefore, the angle between the forwarding nodes $Y_{x_{i_o(t)},i_o}$ and $Y_{x_{i_o(t)},i_o+1}$ is $\alpha_{Y_{i_o},Y_{i_o+1}} = \frac{2\pi}{3} + \alpha_{Y_{i_o}}\text{(t)} + \alpha_{Y_{i_o+1}}\text{(t)}$. The condition to achieve the best broadcasting efficiency in terms of maximum average broadcasting coverage per node is when $n = 3$ and all these forwarding nodes Y_{i_o} $(i_o = 1,2,3)$ are ideally located on the border of O 's transmission range with the forwarding angle $\sum_{i_o=1}^{3} \alpha_{Y_{i_o},Y_{i_o+1}} = 2\pi$.

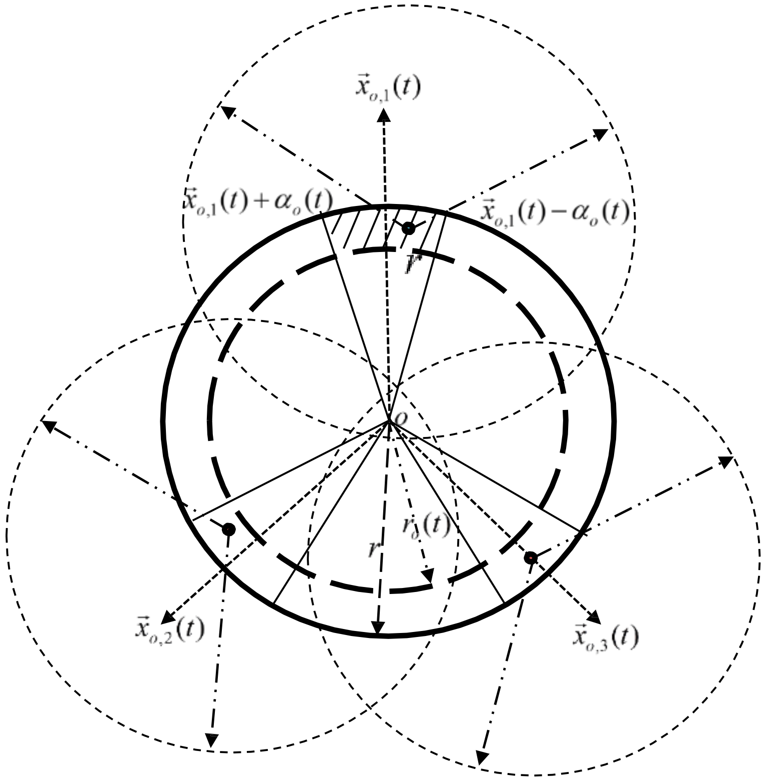


Figure 4.3: Node displacement from angle perspective

As shown in Figure 4.4, the distance d_{Y_1,Y_2} between forwarding nodes Y_1 and Y_2 is determined by the angle α_1 . Hence, the duplicated area between Y_1 and Y_2, denoted as A_{Y_1,Y_2}, can be calculated

$$SV(d_{Y_1,Y_2}) = 2r^2 \arccos\left(\frac{d_{Y_1,Y_2}}{2r}\right) - d_{Y_1,Y_2}\sqrt{r^2 - \left(\frac{d_{Y_1,Y_2}}{2}\right)^2} \tag{4.1}$$

For $r = 1$, the equation (4.1) can be simplified as

$$SV(d_{Y_1,Y_2}) = 2\arccos\left(\frac{d_{Y_1,Y_2}}{2}\right) - d_{Y_1,Y_2}\sqrt{1 - \left(\frac{d_{Y_1,Y_2}}{2}\right)^2} \tag{4.2}$$

Hence, the broadcasting coverage area provided by node Y_1 is given by

$$A_{Y_1} = \pi - 2\arccos\left(\frac{d_{Y_1,Y_2}}{2}\right) + d_{Y_1,Y_2}\sqrt{1-\left(\frac{d_{Y_1,Y_2}}{2}\right)^2} \qquad \text{(for } r = 1\text{)} \qquad (4.3)$$

Note that d_{Y_1,Y_2} can be calculated from Figure 4.4 as

$$d_{Y_1,Y_2} = 2r \times \sin\left(\frac{\alpha_{Y_{i_o,i_o+1}}}{2}\right) \qquad (4.4)$$

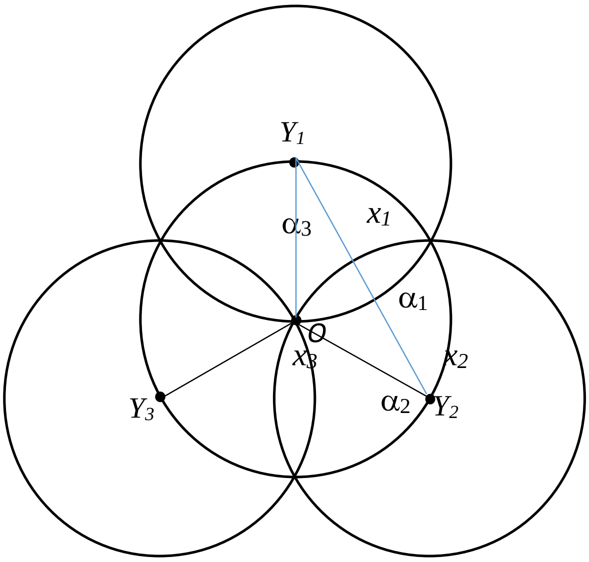


Figure 4.4: Coverage area calculation from angle perspective

Likewise, the duplicated area between Y_1 and Y_3 can be obtained as well as that between the forwarding nodes Y_2 and Y_3, that is

$$SV(d_{Y_1,Y_3}) = 2\arccos\left(\frac{d_{Y_1,Y_3}}{2}\right) - d_{Y_1,Y_3}\sqrt{1-\left(\frac{d_{Y_1,Y_3}}{2}\right)^2} \qquad (4.5)$$

$$A_{Y_3} = \pi - 2\arccos\left(\frac{d_{Y_1,Y_3}}{2}\right) + d_{Y_1,Y_3}\sqrt{1-\left(\frac{d_{Y_1,Y_3}}{2}\right)^2} \qquad (\text{for } r = 1) \tag{4.6}$$

$$SV(d_{Y_2,Y_3}) = 2\arccos\left(\frac{d_{Y_2,Y_3}}{2}\right) - d_{Y_2,Y_3}\sqrt{1-\left(\frac{d_{Y_2,Y_3}}{2}\right)^2} \tag{4.7}$$

$$A_{Y_2} = \pi - 2\arccos\left(\frac{d_{Y_2,Y_3}}{2}\right) + d_{Y_2,Y_3}\sqrt{1-\left(\frac{d_{Y_2,Y_3}}{2}\right)^2} \qquad (\text{for } r = 1) \tag{4.8}$$

Hence, the total broadcasting coverage area can be expressed as

$$A_Y = \sum_{i_o=1}^{3} A_{Y_{i_o}} = 3\pi - \sum_{i_o=1}^{3} 2\arccos\left(\frac{d_{Y_{i_o},Y_{i_o+1}}}{2}\right) - d_{Y_{i_o},Y_{i_o+1}}\sqrt{1-\left(\frac{d_{Y_{i_o},Y_{i_o+1}}}{2}\right)^2} \qquad (\text{for } r = 1) \tag{4.9}$$

Recall, the idealized case, where the forwarding nodes are exactly located on ideal locations without any angle errors. In this case,

$$d_{Y_1,Y_2} = d_{Y_1,Y_3} = d_{Y_2,Y_3} = 2r \times \sin\left(\frac{\pi}{3}\right) = \sqrt{3}r$$

By contrast, the effects of angle error due to the position of $Y_{x_o(t),i_0}$ $(i_o = 1,2,3)$ in the relaying area is that

$$d_{Y_1,Y_2} \neq d_{Y_1,Y_3} \neq d_{Y_2,Y_3}\,. \tag{4.10}$$

4.3 Effect of the Distance between the Source node and Forwarding Node

This section focuses on the investigation of the effect of nodes displacement from ideal locations in terms of displacement from ideal distance as stated in Lemma 3.1.

Lemma 4.2. The effect of distance between the forwarding node and the source node on directional broadcasting efficiency. The effect of distance error due to the position of $Y_{x_o(t),i_0}$ $(i_o = 1,2,3)$ in the relaying area is that $d_{Y_1,Y_2} \neq d_{Y_1,Y_3} \neq d_{Y_2,Y_3}$.

Proof:

As shown in Figure 4.5, a source node O has $Y_{x_{i_o(t),i_o}}$ $(i_o = 1,2,3)$ forwarding nodes located inside of the relaying area $S_{r_o,x_{i_o}(t)}(t)$ $(i_o = 1,2,3)$, respectively, where x_{i_o}(t) $(i_o = 1,2,3)$ is the forwarding direction from the source node O. The distance from the source node O to the forwarding node $Y_{x_{i_o(t),i_o}}$ $(i_o = 1,2,3)$ is $r_{Y_{i_o}}$(t) $(i_o = 1,2,3)$. Therefore, the angle between the forwarding nodes $Y_{x_{i_o(t),i_o}}$ and $Y_{x_{i_o(t),i_o+1}}$ is $\alpha_{Y_{i_o},Y_{i_o+1}} = \dfrac{2\pi}{3}$ and. $r_{i_o}(t) \leq r_{Y_{i_o}}(t) \leq r, (i_o = 1,2,3)$. The condition to achieve the best broadcasting efficiency in terms of maximum average broadcasting coverage per node is $n = 3$ and all these forwarding nodes Y_{i_o} $(i_o = 1,2,3)$ are symmetrically located on the border of O's transmission range with the forwarding angle $\sum_{i_o=1}^{3} \alpha_{Y_{i_o},Y_{i_o+1}} = 2\pi$.

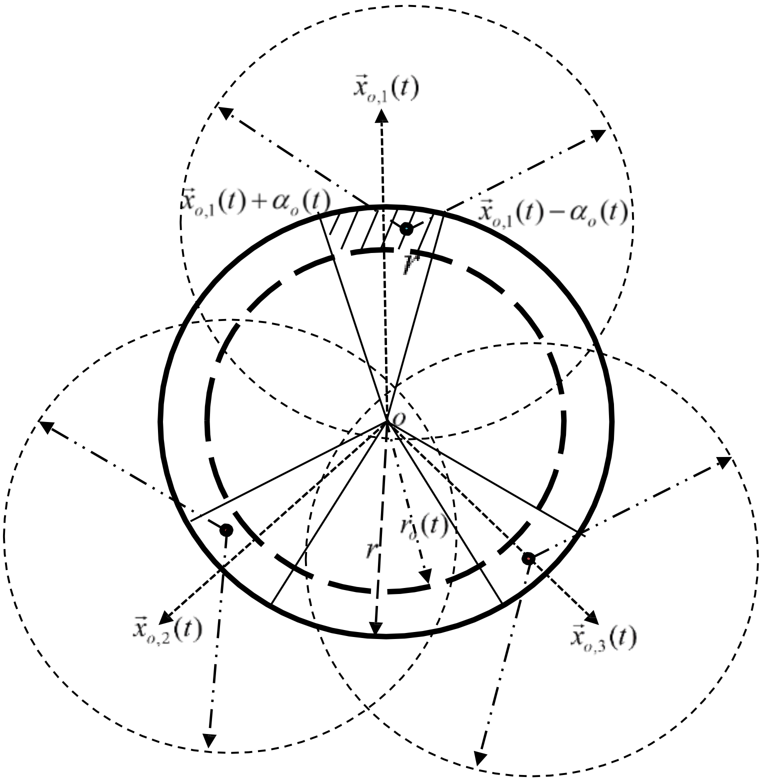


Figure 4.5: Node displacement from distance perspective

As shown in Figure 4.6, the distance d_{Y_1,Y_2} between forwarding nodes Y_1 and Y_2 is determined by the distance $r_{Y_{i_o}}$ (t) $(i_o = 1,2,3)$ and $r_{Y_{i_o+1}}$ (t) $(i_o = 1,2,3)$. Hence, the duplicated area between Y_1 and Y_2, denoted as A_{Y_1,Y_2}, can be calculated

$$SV(d_{Y_1,Y_2}) = 2r^2 \arccos\left(\frac{d_{Y_1,Y_2}}{2r}\right) - d_{Y_1,Y_2}\sqrt{r^2 - \left(\frac{d_{Y_1,Y_2}}{2}\right)^2} \tag{4.11}$$

For $r = 1$, the equation (1) can be simplified as

$$SV(d_{Y_1,Y_2}) = 2\arccos\left(\frac{d_{Y_1,Y_2}}{2}\right) - d_{Y_1,Y_2}\sqrt{1 - \left(\frac{d_{Y_1,Y_2}}{2}\right)^2} \tag{4.12}$$

Hence, the broadcasting coverage area provided by node Y_1 is given by

$$A_{Y_1} = \pi - 2\arccos\left(\frac{d_{Y_1,Y_2}}{2}\right) + d_{Y_1,Y_2}\sqrt{1-\left(\frac{d_{Y_1,Y_2}}{2}\right)^2} \qquad \text{(for } r=1\text{)} \qquad (4.13)$$

Note that d_{Y_1,Y_2} can be calculated from Figure 4.6 as

$$d_{Y_1,Y_2} = \left(r_{Y_1}(t) + r_{Y_2}(t)\right)\times\sin\left(\frac{\pi}{3}\right) = \frac{\sqrt{3}}{2}\left(r_{Y_1}(t) + r_{Y_2}(t)\right) \qquad (4.14)$$

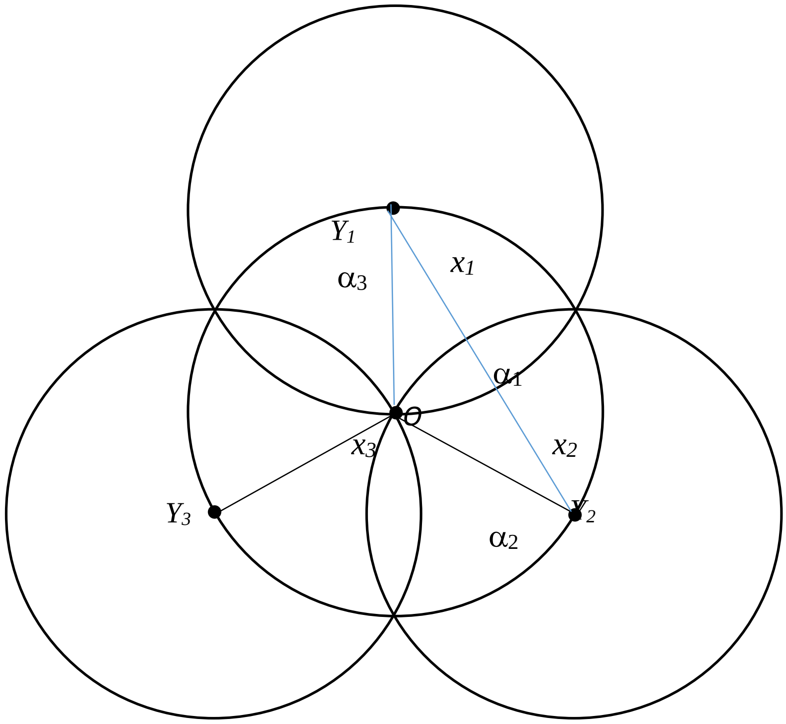


Figure 4.6: Coverage area calculation from distance perspective

Likewise, the duplicated area between Y_1 and Y_3 can be obtained as well as that between the forwarding nodes Y_2 and Y_3, that is

$$SV(d_{Y_1,Y_3}) = 2\arccos\left(\frac{d_{Y_1,Y_3}}{2}\right) - d_{Y_1,Y_3}\sqrt{1-\left(\frac{d_{Y_1,Y_3}}{2}\right)^2}$$

$$A_{Y_3} = \pi - 2\arccos\left(\frac{d_{Y_1,Y_3}}{2}\right) + d_{Y_1,Y_3}\sqrt{1-\left(\frac{d_{Y_1,Y_3}}{2}\right)^2} \qquad \text{(for } r=1\text{)}$$

$$SV(d_{Y_2,Y_3}) = 2\arccos\left(\frac{d_{Y_2,Y_3}}{2}\right) - d_{Y_2,Y_3}\sqrt{1-\left(\frac{d_{Y_2,Y_3}}{2}\right)^2}$$

$$A_{Y_2} = \pi - 2\arccos\left(\frac{d_{Y_2,Y_3}}{2}\right) + d_{Y_2,Y_3}\sqrt{1-\left(\frac{d_{Y_2,Y_3}}{2}\right)^2} \qquad (\text{for } r=1)$$

Hence, the total broadcasting coverage area can be expressed as

$$A_Y = \sum_{i_o=1}^{3} A_{Y_{i_o}} = 3\pi - \sum_{i_o=1}^{3} 2\arccos\left(\frac{d_{Y_{i_o},Y_{i_o+1}}}{2}\right) - d_{Y_{i_o},Y_{i_o+1}}\sqrt{1-\left(\frac{d_{Y_{i_o},Y_{i_o+1}}}{2}\right)^2} \qquad (\text{for } r=1)$$

Recall, the idealized case, where the forwarding nodes are exactly located in relaying areas without any angle errors. In this case,

$$d_{Y_1,Y_2} = d_{Y_1,Y_3} = d_{Y_2,Y_3} = \sqrt{3}r$$

By contrast, the effects of distance error due to the position of $Y_{x_o(t),i_0}$ $(i_o = 1,2,3)$ in the relaying area is that

$$d_{Y_1,Y_2} \neq d_{Y_1,Y_3} \neq d_{Y_2,Y_3}\,.$$

4.4 Node Displacement Worst Case Scenario

This section presents the worst-case scenario of nodes displacement from ideal location. Furthermore, the effect of such node displacement on the overall performance is investigated. Figure 4.7 shows the worst case scenario of relaying nodes selection. The transmission area is divided into three sectors where the middle line of each sector represents 120 angle i.e. the middle line of first sector is at $\frac{2\pi}{3}$, the middle line of second sector is at $\frac{4\pi}{3}$ and the middle line of third sector is at 360 degrees. Therefore, the ideal location for each sector is at transmission boundary of each middle line i.e. r=1.

As stated in Lemma 3.1, each sector can have only one relaying node. Due to the lack of GPS based host node positioning information, the three relaying nodes are selected randomly. From Figure 4.7, if the nodes Y_1, Y_2 and Y_3 are selected as relaying nodes, then this represents the worst-case scenario of nodes displacement from ideal location in terms of horizontal displacement. From the figure, it can be seen that there are two major problems. The first problem is that the transmission range of relaying nodes in sector 1 and sector 3 are overlapping such that each node is almost covering most of the other nodes transmission range. This obviously results in severe contention and collision in the network especially in the high density network. Furthermore, this may also result in both redundant retransmissions and transmission failures. The second problem is the uncovered area between sector 1 and sector 2. This may badly affect reachability as the relaying nodes are located in uncovered area so that the packet relay is failure. In practice, such problem may not seems to be severe within the first few hops but as the number of hops increase the gap increases and it results large number of nodes uncovered. To overcome these two problems, some specific conditions and guidelines are discussed in the following section to resolve these problems.

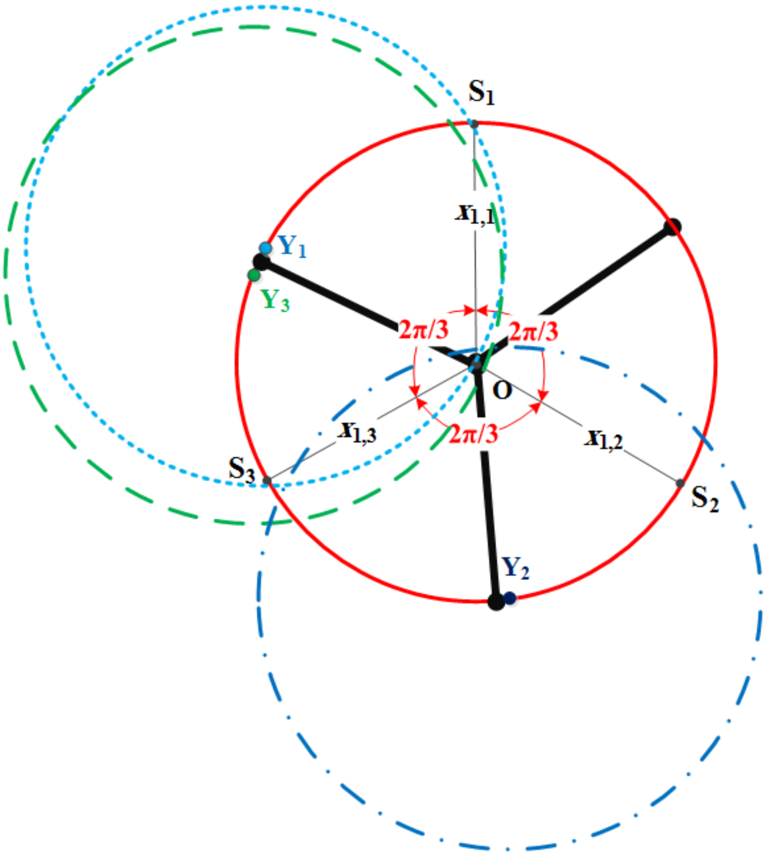


Figure 4.7: Node displacement worst case scenario

4.5 Node Displacement Error Mitigation

This section discusses conditions to mitigate the problems listed in Section 4.4. The major problem is the random selection of relaying nodes especially in worst-case scenario in which selected relaying nodes are close to transmission boundary of neighboring sector. In order to resolve this problem, this section introduces a new concept called gaps. The main idea of this concept is to introduce a gap between each neighboring sectors under the condition that nodes located inside a gap will not act as relaying nodes. The gaps between neighboring sectors are able to reduce the relaying area sizes and in turn to reduce the overlap between relaying nodes. Figure 4.8 shows the proposed solution to overcome the problems listed in Section 4.4. From Figure 4.8, it can be seen that the new concept of gap is able to greatly reduce the overlap between the nodes Y_1 and Y_3. Furthermore, it is also able to reduce the uncovered area as compared with the worst-case discussed in Section 4.4. To further reduce the overlap and reduce uncovered area it can be done by increasing the gap between relaying sectors. However, this scheme has also some drawbacks. Increasing the gap between sectors will decrease the relaying area size and which in turn reduce the probability of finding a node in relaying areas. This means that as the gap increases the node density should also increase in order to ensure some nodes can be found in relaying area. This issue will be discussed in details in the following chapter.

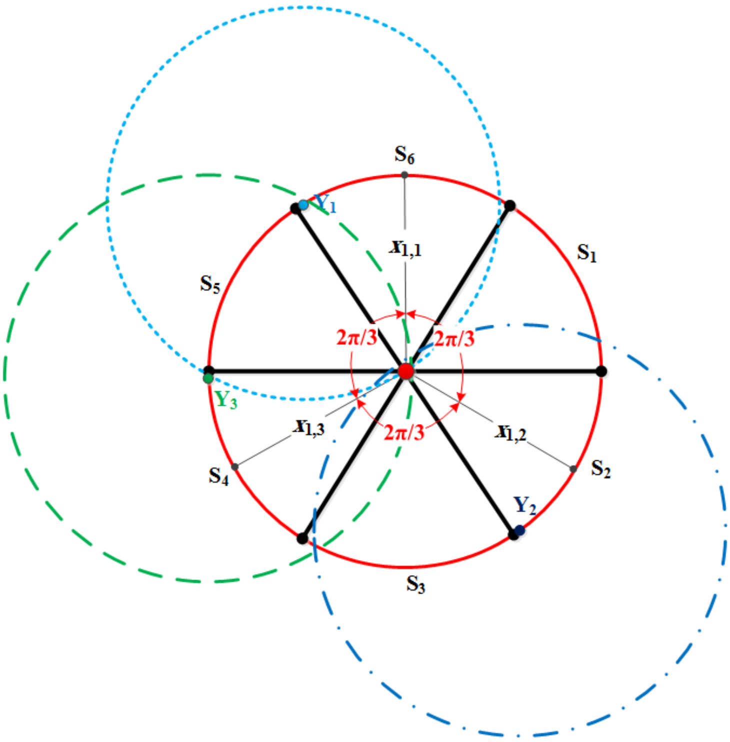


Figure 4.8: Node displacement error rectification

4.6 Summary

This chapter presents a theoretical analysis regarding the problem of node displacement from ideal location. It has discussed some of the major factors that lead to nodes displacement from ideal locations. The discussion has been under the following three topics, including the nodes deployment strategy, the low nodes density and high nodes mobility, which are known as the three most important factors. Nodes displacement form ideal location can be viewed from two different perspective: the distance from the source node and the angle. The analysis has shown the effect of these two factors on total coverage which are presented by Lemma 4.1 and Lemma 4.2, respectively. Furthermore, the worst case scenario of node displacement from ideal locations is also discussed by focusing on two major problems. The first problem is that the transmission range of relaying nodes located in two neighboring is greatly overlapping. This obviously leads to contention, collision and eventually results in transmission failure. The second problem is the uncovered area caused by nodes displacement from ideal locations. This problem will also greatly affect nodes reachability as many nodes will be uncovered. To overcome these two problems, some specific conditions and guidelines are presented which help reduce the node displacement effect on overall performance in terms of reachability. Finally, this chapter proposed to introduce gap between every neighboring sectors so that to shrink the relaying areas size. This approach is able to greatly reduce the overlap between the relaying nodes located in neighboring sectors and also reduce the uncovered area.

Chapter 5: Protocol Development for the Broadcasting Relay in Ad hoc Network without Node Positioning

First, this chapter proposes an efficient ad hoc based broadcasting scheme called Random Directional Broadcasting Relay (RDBR) scheme based on the conditions presented in Lemma 3.1. The proposed scheme utilizes directional antennas to provide efficient broadcasting without relying on node position, network topology and complex AoA calculations. Then, this chapter presents an improved version of the proposed RDBR scheme which utilizes the conditions presented in Chapter4 to mitigate the node displacement problem. The proposed RDBR schemes use ideally sectorized multi-beam directional antenna model for transmission which is widely used model in the literature. Furthermore, this chapter also discusses the shortcomings of the RDBR scheme and the advantages of the improved RDBR scheme over RDBR scheme.

5.1 Overview

The main challenge related to broadcasting relay in critical ad hoc networking environment is how to minimize the number of relaying nodes and reduce end-to-end delay while achieving high delivery ratio [1][15][16]. This is due to the fact that broadcast relay schemes usually utilize a large number of relaying nodes to guarantee high reachability. However, such schemes consume a large portion of network bandwidth that may lead to severe contention and collisions in the network due to redundant rebroadcasts [15]. From this point of view, broadcasting schemes need to utilize less number of relaying nodes in order to reduce the contention and collision in the network and hence reduce the bandwidth consumption. However, the shortcoming of such schemes is the low delivery ratio due to the large distances between neighboring nodes which eventually leads to network partitioning.

Majority of existing broadcasting approaches in ad hoc network are based omni-directional antennas. However, the problem of frequent network partitioning occurs in MANET due to sparse distribution of nodes as well as the node mobility. Network partitioning can significantly affect the performance of the network in terms of delivery ratio due to failures and therefore should be taken into consideration while designing any efficient broadcasting scheme. First, this chapter presents a novel broadcasting scheme, called Random Directional Broadcasting Relay (RDBR) scheme that mitigates the problem of node position information unavailability in critical environments. Second, an improved RDBR scheme is presented to overcome the shortcomings of the RDBR scheme to resolve the problem of nodes displacement from idealized positions which was discussed in Chapter 4. These proposed schemes focus on selecting the most suitable forwarding nodes by considering the impact of forwarding angle and distance from the source node on the selection of relaying nodes without the requirement on network topology and nodes position. The proposed schemes are evaluated in terms of the ability to reduce the number of broadcasting hops and to increase delivery ratio in support of end-to-end broadcasting relay, especially in critical ad hoc environment suffering from the absence of location and topology information. In the proposed schemes, source nodes utilize forwarding nodes located inside relaying areas to retransmit the packet. Then the distance based defer time is used to select the farthest nodes from the source node and also to reduce both contention and collision by reducing simultaneous retransmissions of neighboring nodes.

The novelty of the proposed schemes, when compared with existing broadcasting schemes, lies in providing ad hoc communications in critical ad hoc environments without the need for location, network topology, and node orientation and transmission angle information. The overhead and computing load associated with selecting suitable forwarding nodes to relay broadcast messages using the proposed schemes are much less than that in the existing broadcasting schemes, in which both node position and network topology are essential to ensure correct operation of the protocol. The ideally sectorized switched beam directional antenna model is deployed with assumption of omni-directional transmission and reception of signal.

The remaining of this chapter is organized as follows: in Section 5.2 the system model of the proposed schemes is described followed by the description of the directional antenna model in Section 5.3. In Section 5.4, the proposed RDBR scheme for efficient broadcasting in critical MANET environments is introduced. Section 5.5 describes the distance based waiting time technique used in the proposed RDBR schemes. After that, in Section 5.6 the shortcomings of the RDBR scheme are discussed. Then, in Section 5.7 the improved RDBR scheme to overcome the shortcoming of RDBR scheme is introduced and finally Section 5.8 summarizes the main points of this chapter.

5.2 System Model

This section presents a novel broadcasting protocol based on the conditions presented in Lemma 3.1, in which the neighboring nodes are only allowed to relay packets in restricted areas. The novelty of the proposed scheme lies in providing ad hoc communication in critical environments without the location and topology information. The following assumptions are used in the design of the proposed schemes. Nodes are randomly located on a two-dimensional plane. Nodes are homogeneous in terms of wireless transmission range, processing power and energy. A high density ad hoc network is considered in this study.

Furthermore, this ad hoc network considers deterministic broadcasting in which nodes do not have any a priori knowledge of the network topology or any global parameters such as synchronization information. In such a multi-hop ad hoc network, host nodes are assumed to be able to compute the distance between themselves and other nodes located inside of their transmission range. Since host nodes may not be able to receive GPS signals due to the effect of electronic warfare in battlefield environment for example, the proposed schemes use the received signal strength instead of GPS information to calculate the distance between nodes [1][2][12][24][36]. Note that the received signal strength can only provide estimated distance between the source node and neighboring node because of multipath fading. However, the proposed schemes do not rely on exact distance between the source node and neighboring node. Furthermore, the ad hoc network under consideration in this study assumes that all nodes are equipped with directional antennas, which are modeled as a circular sector model where the transmission coverage area of the each node is divided into sectors.

Specifically, the transmission coverage area of each node is equally partitioned into M number of adjacent and non-overlapping sectors where each sector covers a fraction total coverage area. Finally, it is assumed that the time taken by the source node to select relaying nodes is less than the time required by neighboring nodes to significantly change their positions. This assumption is valid due to the speed of transmission compared with the mobility of nodes.

5.3 Antenna Model

This section considers a multi-hop ad hoc network with *Y* mobile nodes equipped with directional antennas. Specifically, each node is equipped with a single radio transceiver and *M* switched-beam directional antennas as shown in Figure 5.1. Each beam is covering a partial area around the transmitter and together they cover the entire area. The multi-beam directional antenna model is widely used in the literature [53][56][57][59][74][73]. It is assumed that every node is capable of switching any or all the beams to active or passive mode, in which only selective beams are allowed to communicate whereas the remaining beams are set to idle state. Note that if all beams of a node are turned on at the same time, it can transmit and receive signal in all directions like omni-directional antenna. This means that the directional antennas can be used as omni-directional antennas if and only if all the beams of a node are active. However, turning all the beams of a node on at the same time will result in distributing the signal power evenly across all sectors and as a result the antenna gain will be reduced.

In this study, it assumed that the transmission range for both directional and omni-directional antennas is the same. The reason behind this assumption is two-fold: first, this assumption simplified the calculation of the coverage area. Second, this assumption guarantees a fair comparison between broadcasting schemes that use directional antennas like the proposed schemes and other schemes that use omni-directional antennas. Otherwise, it would be unfair to compare broadcasting schemes with larger transmission range (i.e. based on directional antenna) with broadcasting schemes with shorter transmission range (i.e. based on omni-directional antenna). This is due to the fact that the directional antenna based schemes tend to have a longer transmission range which enables them to achieve a better coverage. It is worth noting that in order for the existing directional antenna based broadcasting schemes to function properly, they need to maintain the orientation of their beams at all time and especially during mobility. This could be achieved with the aid of a direction finding device such as a compass. However, it is not possible to maintain the orientation of directional antennas all the time in critical environments such as battlefield due to the interference caused by electronic warfare. Compass devices might not work properly in such a critical environment and therefore new techniques have to be used to overcome this problem.

In the following proposed approach, the ideally sectorized switched beam with directional antenna model is used. As shown in Figure 5.1, each node is associated with *M* antennas (each beam has an azimuthal beamwidth of 360°/*M*). Figure 5.1 shows the ideally sectorized directional antenna model.

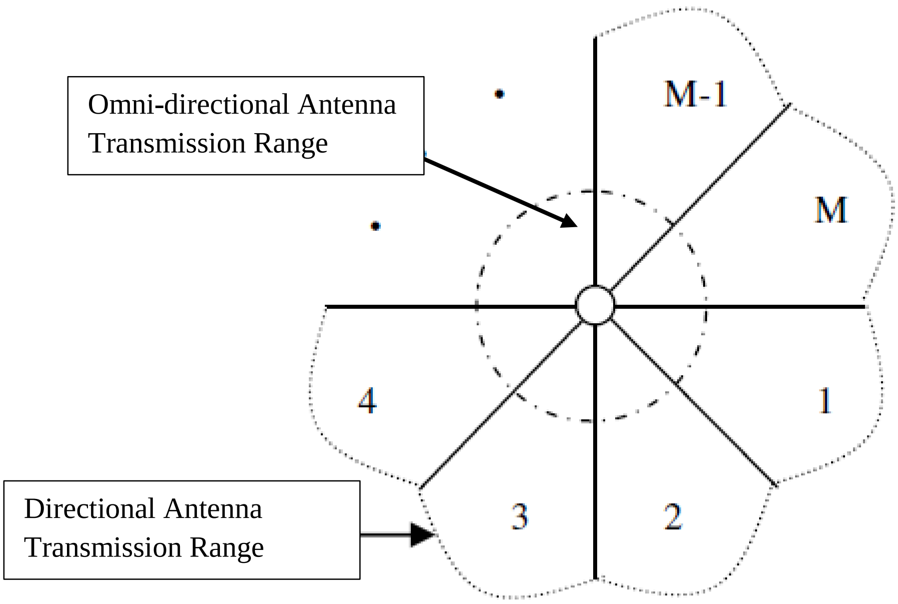


Figure 5.1: *M* Beams Directional Broadcasting Model

5.4 Random Directional Broadcasting Relay (RDBR) Scheme Using Directional Antenna

In order to provide efficient broadcasting in a critical ad hoc environment in which both the topology and location information are not available, a novel broadcasting scheme called Random Directional Broadcasting Relay (RDBR) scheme is proposed. In the proposed RDBR scheme, a source node O has Y_m ($m = 1, 2, \ldots, M$) where M is the index of directional antenna associated with the source node O) neighboring nodes located inside of coverage area by a specific sector of directional antenna which has the an azimuthal beamwidth of $360^o/M$. The source node O is searching one suitable neighboring node Y_m among Y nodes inside of the coverage area of each directional antenna beam, respectively to relay the data packets. Thus the problem is how to select only one node as the relaying node. On the other hand, the RDBR scheme needs to select the node located farthest away from the source node in order to reduce the number of rebroadcasts. In the following description, it is assumed that all nodes are equipped with 3-beam directional antennas with equally azimuthal beamwidth of 120^o per direction beam. The reason to select 3-beams directional antenna is that only three relaying nodes are required to achieve the upper bound of transmission coverage as discussed by Lemma 3.1 in Chapter 3. In the RDBR scheme, the relaying node is selected on distance - delaying mechanism. That is, each potential relaying node is assigned a waiting time inversely proportional to the distance between the potential relaying node and the source node. The proposed random directional broadcasting scheme is described by the following flow-chart diagram as shown in Figure 5.2

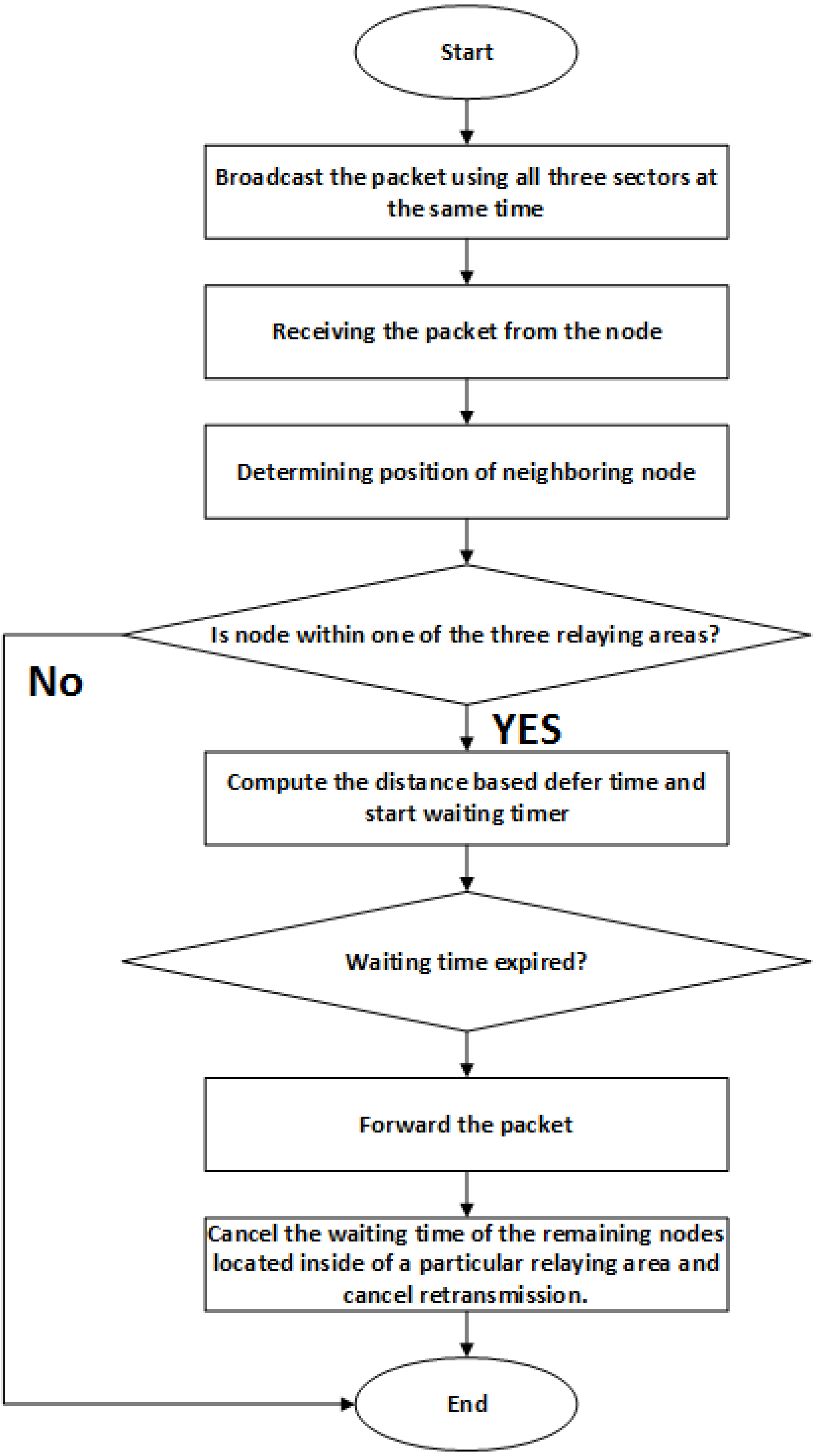


Figure 5.2: Flowchart of RDBR Scheme

Step 1: Packet Broadcasting

Based on the steps described in Figure 5.2, a source node O randomly selects a direction as reference point $\vec{\theta}_o(t)$ and broadcasts a packet at time t by three directional antenna beams simultaneously. All Y_m ($m = 1, 2, 3, \ldots, M$) nodes located inside of the transmission range of directional antenna beams receive the packet. The header of the packet sent by the source node O, as shown in Figure 5.3, consists of the following parameters:

a. Packet ID is a unique identifier attached to each data packet which is created by the source node. Packet ID is used to detect and drop duplicate packets.
b. Timestamp specifies the time of packet creation by the source node, and it remains unchanged through broadcasting process. Timestamp is used to calculate the data dissemination delay.
c. Source ID is a unique ID that identifies the source node that created the message. A source ID can be represented by unique identifier such as the MAC address of the source node. The Source ID remains unchanged throughout data dissemination process and is not changed by relaying nodes. The combination of Source ID and Packet ID are used by the potential relaying nodes to distinguish between different messages.
d. Sender ID is a unique ID that identifies the selected relaying node. The value of this field changes every time a message is forwarded by a relaying node. As was the case with the source ID, the sender ID can also be represented by the MAC address of the relaying node.
e. *Th* is a distance threshold to indicate the distance from O beyond which the nodes are allowed to rebroadcast the packet where $Th \leq d \leq r$. the symbol *d* represent the distance

between the source node and the receiving node and r is the transmission range of the node.

f. k indicates the id of the beam from which the packet was sent where k = 1,2 or 3. This parameter is used to eliminate redundant retransmissions received from other relaying areas.

g. Time-To-Live (TTL) indicates the maximum number of relaying hops a packet can travel. The value of TTL decreases as the number of hops increases.

Packet ID	Timestamp	Source ID	Relay ID	*Th*	*k*	TTL

Figure 5.3: The format layout of packet header for broadcasting

Step 2: Packet Relaying

Upon receiving the packet, node Y inspects the received packet with the following procedures:

a. If the packet has been received more than one time, the packet is discarded. This is done by checking the id of the received packet.

b. If TTL of the received packet is equal to zero, the packet is discarded.

c. If the distance between Y and O, denoted as d is less than Th, then the packet is discarded. Note that d, can be obtained using received signal strength.

d. If and only if when $d \leq Th$ then the node Y is located inside of one of three relaying areas where S_k indicates the relaying areas.

e. Each potential relaying node will set a distance based waiting time using the following formula:

$$\text{waitTime} = \text{maxWait}.(R^2\text{-}|d|)/R^2 + \text{jitter}$$

where maxWait is the maximum waiting time a potential relaying node waits before retransmitting the packet, R is the transmission range of the source node, d is the distance between the sender and receiver and jitter is a small random waiting time used to prevent nodes located at similar distance from the source node to transmit concurrently.

f. When waiting time of a potential relaying node Y expires, the node Y broadcasts the packet in three directions using three beams simultaneously. All nodes within the transmission range of the node will receive the packet including the remaining potential relaying nodes.

g. Each potential relaying node will examine the received packet. Since the received packet is a duplicate packet, each potential relaying node checks the beam number k of the packet along with the packet id, if the beam number and packet id are the same, all potential relaying nodes within that particular beam will simply drop the packet and cancel the waiting process.

h. If the beam number is not the same then the potential relaying node will simply ignore the packet and continue waiting until the timer of one of the potential relaying nodes in that particular beam expires.

Step 3: Failure of Recovery

After the source node O sends out a packet, it should receive the same packet from each relaying node within a time of T_Y $(0 \leq T_Y \leq 2t_{prop})$ as the acknowledgement of broadcasting success [50]. Otherwise, the source node needs to rebroadcast the packet using the beam from which it does not receive a relaying packet.

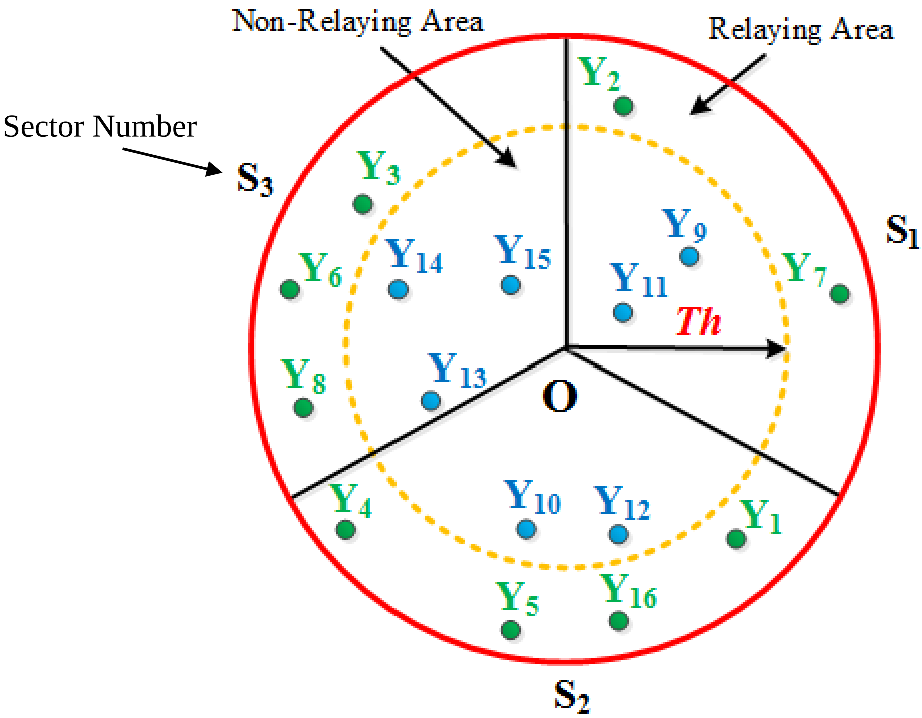


Figure 5.4: Random Directional Broadcasting Relay Scheme (RDBR)

Figure 5.4 shows an example of the proposed broadcasting scheme with 3-beam directional antennas with equally azimuthal beamwidth of 120° per direction beam. The source node *O* broadcasts packets using these three beams of the directional antenna simultaneously. All nodes within the transmission range of the source node receive the packet. The neighboring nodes such as node Y_7, Y_5 and Y_6 that are far away from the source node(s) more than the neighboring node such as Y_2, Y_{16} and Y_8 and therefore, will act as relaying nodes. On the other hand, the inner neighboring nodes such as node Y_{14}, Y_{12} and Y_9 that are geographically close to the source node(s) will be prevented from relaying the packets. This novel defer-time scheme will greatly reduce the number of redundant rebroadcast and reduces both contention and collision.

In summary, the proposed approach has the following features:

First of all, the broadcasting relay is performed on demand basis, which does not require network topology discovery and maintenance as well as the relevant routing algorithm across the entire network. This feature is able to save the resources in terms of overhead, bandwidth and energy associated in the process of discovering and maintaining network topology and routing table. This feature has great value in practice comparing to conventional topology-based broadcasting relay scheme. It is extremely important to sensor network, which usually has limited energy, communication capacity and computing power.

Second, the proposed approach deploys angle based broadcasting in three directions $\vec{x}_{o,i_o}(t) = \vec{\theta}_o(t) + i_o \times \frac{2\pi}{3}, \quad (i_o = 1,2,3)$ with the transmission angle $\vec{x}_{o,i_o}(t) \pm \alpha_o(t), \; \left(0 \le \alpha_o(t) \le \frac{\pi}{3}\right)$. Note that both the broadcasting direction and transmission angle can be dynamically changed from packet to packet. Therefore, this feature is able to significantly reduce the probability that the broadcasting is detected by enemy's electronic warfare system comparing to that conventional geometry-based broadcasting relay schemes.

Third, the proposed scheme does not require node's location information that satisfies the critical environment conditions where GPS is not available or not reliable such as in the battlefield due to electronic warfare interference. By contrast, both topology-based and geometry-based broadcasting relay schemes are compulsory to have pre-known node's location information for discovering and maintaining the entire network topology and routing table.

The node density distribution function certainly has some effect on the performance of the proposed broadcasting relay scheme. Note that this proposed broadcasting relay scheme is also capable to be used in an environment where nodes are arbitrary distributed rather than uniformly distributed. In this case, it needs to adjust the broadcasting directions $\vec{\theta}_o(t)$ according to the nodes arbitrary distribution pattern with suitable parameters including both the forwarding angle $\alpha_o(t)$ and $r_o(t)$ in order to improve the efficiency. However, the key issue related to this problem is the nodes arbitrary distribution pattern. This is the research focus of the Chapter 4.

5.5 Controlling Redundant Receptions

A random delaying scheme (RDS) is used to assigns each potential relaying node a different defer time according to its distance from the source node [15][16][32][50]. The distance between a neighboring node and the source node can be estimated from the received signal strength [1][2][12][24][36]. Recall the distance based defer time mechanism as described in Chapter 2, the basic idea of RDS is that a node located inside the symmetric area waits a calculated amount of time before rebroadcasting the packet. This defer time is inversely proportional to the distance between the source node and the relaying node.

In the proposed RDBR scheme, each neighboring node first calculates how far it is from the source node and then determines whether it is located inside of a relaying area or not. If a neighboring node is not located inside of a relaying area, it will simply drop the packet. Otherwise, a neighboring node that is farther away from the source node will be assigned a shorter defer time. Generally, the larger the distance between the source node and a neighboring node, the shorter the defer time. The idea is to let a neighboring node covering more new area to rebroadcast the packet. Note that a neighboring node closer to source node will be abandoned from rebroadcasting. That is, the farthest neighboring node from the source node rebroadcasts earlier than other neighboring nodes. The formula for calculating the defer time is given below:

$$\text{waitTime} = \text{maxWait}.(R^2\text{-}|d|)/R^2$$

where maxWait is the maximum waiting time a potential relaying node waits before retransmitting the packet, R is the transmission range of the source node, d is the distance between the sender and receiver.

Figure 5.5 shows the defer time scheme of the proposed RDBR scheme. In Figure 5.5, the neighboring nodes such as node Y_5, Y_6 and Y_7 that are far away from the source node(s) more than the neighboring node such as Y_1,Y_2, Y_3, Y_4, Y_8, and Y_{16} and therefore, will act as relaying nodes and will be assigned shorter defer time than other neighboring nodes. On the other hand, the inner neighboring nodes such as node Y_9, Y_{10}, Y_{11} and Y_{13} that are geographically close to the source node(s) will be prevented from relaying the packets. This novel defer-time scheme will greatly reduce the number of redundant rebroadcast.

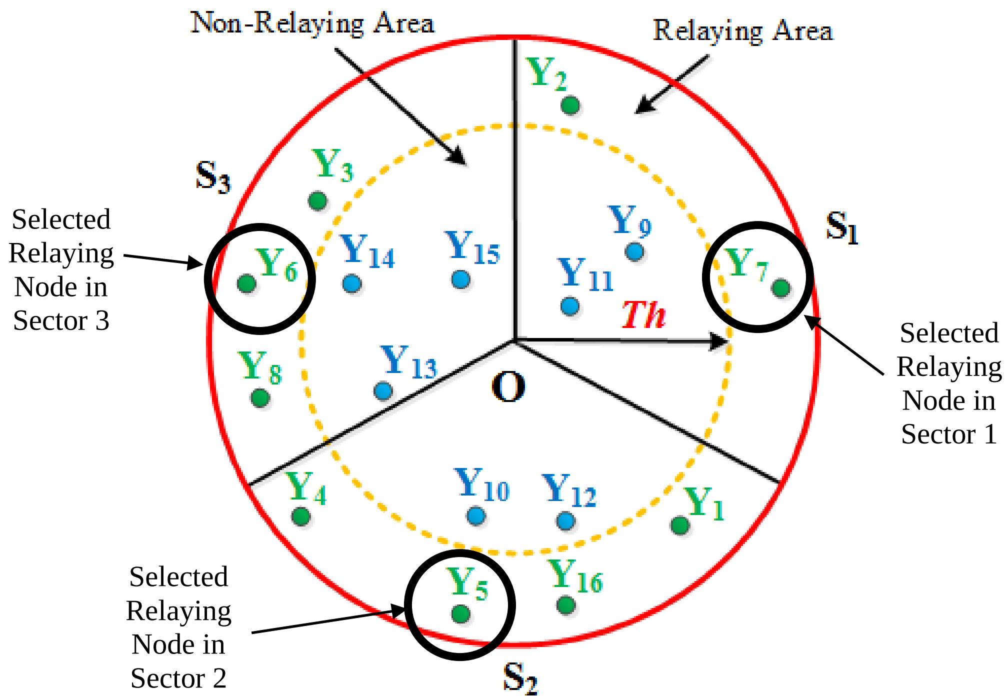


Figure 5.5: Defer time assignment

In order to prevent potential relaying nodes located at similar distance from the source node and belongs to the same beam, to retransmit concurrently, a small random jitter time is added to the waiting time. This jitter time is used to avoid collisions and redundant transmissions by potential relaying nodes located at the same distance from the source node. However, when compared to defer waiting time, jitter waiting time is much less than defer waiting time and hence its effect on the end-to-end delay could be neglected. The amended defer time formula is given below:

$$\text{waitTime} = \text{maxWait}.(R^2\text{-}|d|)/R^2 + \text{jitter}$$

5.6 Problem Formulation

The success or failure of each transmission is greatly dependent on the density of nodes in the network and the size of relaying area. More specifically, the beamforming angle and lower transmission boundary of relaying area, *Th*, have a great effect on the overall performance of the proposed RDBR scheme as these two parameters define the size of relaying area. In general, the relaying area size is a trade-off between transmission failure and communication overhead. It is clear that less relaying area reduces packet collision, bandwidth wastage and requires fewer number of hops to reach the destination but more prone to transmission failures due to small number of nodes. On the other hand, more relaying area is less prone to transmission failures due to large number of nodes involved. However, it requires higher number of nodes to reach the destination and the performance of the system in terms of collision and bandwidth consumption may shrink down.

As was described on in Section 5.2, the design of the proposed scheme depends on two key concepts: random selection of transmission directions and distance based defer waiting time. However, the proposed RDBR scheme has some limitations. The RDBR scheme suffers from the problem of nodes displacement from ideal locations as discussed in Chapter 4. Nodes displacement from ideal locations can result in the following two critical problems. First, the transmission range of some of the selected relaying nodes are overlapping such that each node is almost covering most of the other nodes transmission range. This can lead to severe contention and collision in the network especially in the high density network. The direct impact of contention and collision is both high redundant retransmissions and transmission failures.

The second problem is the uncovered area between neighboring sectors. This will greatly affect reachability as the nodes located in uncovered area will not receive the packet. Chapter 4 discusses some conditions to minimize the effect of nodes displacement from ideal locations. This is done by introducing a gap between each neighboring sectors such that nodes not located inside dedicated sectors are not act as relaying nodes. The gaps between neighboring sectors are able to reduce the relaying area sizes which will in turn reduce the overlap between relaying nodes. Furthermore, the gap will also greatly reduce the uncovered area between neighboring sectors. However, this scheme has some drawbacks. Increasing the gap will decrease the relaying area size and which in turn reduce the probability of finding a node in relaying areas. This means that as the gap increases the node density should also increase in order to ensure some nodes will be found in relaying area. Therefore, the gap should be selected such that it increases reachability while reducing contention and collision. This scheme will only work in high density networks to increase the probability of finding nodes in relaying areas after introducing gaps between sectors. In next section, the improved Random Directional Broadcasting Scheme (RDBR) which greatly reduces the contention and collision in high density networks and does not require any extra cost other than the increased number of directional antenna beams.

5.7 Improved RDBR Scheme

An improved broadcasting scheme has been designed to overcome the shortcomings of RDBR with respect to nodes displacement from ideal locations. The improved RDBR scheme is a directional antenna based broadcasting scheme that carefully selects relaying nodes instead of randomly selecting them. The proposed scheme relies on received signal strength to estimate the distance between the source nodes and the neighboring nodes without requiring any prior knowledge about network topology. Furthermore, the improved RDBR scheme chooses a smallest subset of neighboring nodes to rebroadcast the message and hence reduces the communication overhead and reduces transmission failures. Similar to RDBR, improved RDBR scheme attempts to increase packet delivery ratio while reducing the overhead. Conversely to the RDBR scheme, the improved RDBR scheme reduces the overlap between selected relaying nodes and therefore is able to resolve collisions and contentions between selected nodes.

The improved RDBR scheme is able to achieve higher reachability while reducing the number of rebroadcasts by selecting the relaying nodes that are farthest away from the source node. For convenience of presentation, the following description considers that all nodes are equipped with 6-beam directional antennas. Note that this scheme can be applied to other 3m-beam ($m = 1,2,3,\dots,M$) directional antennas. Each beam of the directional antenna represents a sector and each sector can only have one relaying node. Therefore, the proposed scheme requires only three relaying node i.e. one relaying node per beam. The reason behind selecting six beams directional antenna is that only three relaying nodes are required to achieve the upper bound of as was discussed in Lemma 3.1 and the remaining three sectors are used as gaps between neighboring sectors as was discussed in Lemma 4.2. The relaying nodes are selected using a distance based delaying mechanism. Each potential relaying node will be assigned a waiting time inversely proportional to the distance between the potential relaying node and the source node. A small random jitter is used to prevent potential relaying nodes located at similar distance from the source node and belongs to the same beam, to retransmit concurrently. The proposed random directional broadcasting scheme is described by the following flow-chart diagram as shown in Figure 5.6.

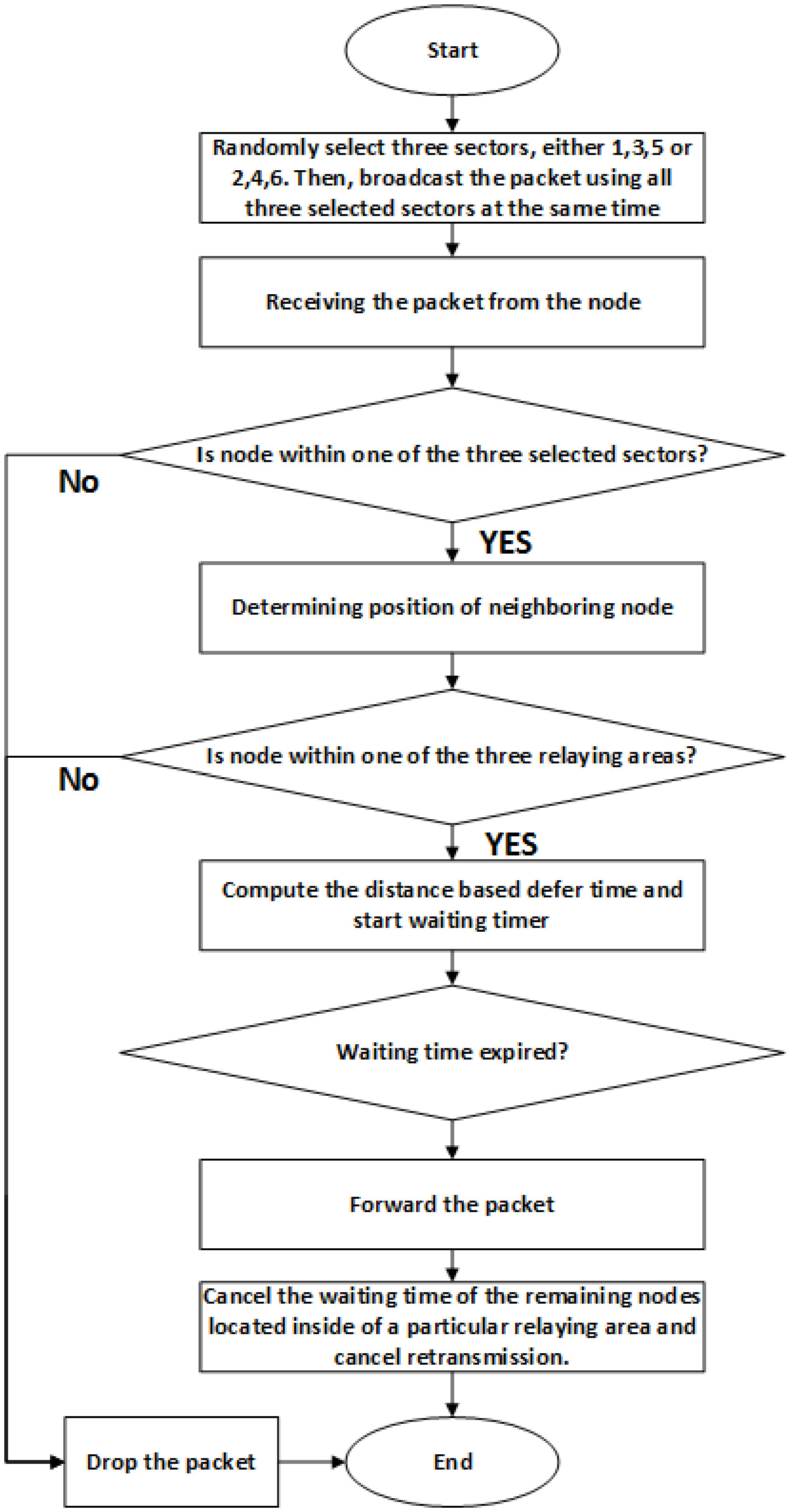


Figure 5.6: Flow-Chart of improved RDBR scheme

Step 1: Packet Broadcasting

Based on the steps described in Figure 5.6, a source node O randomly selects a direction as reference point $\vec{\theta}_o(t)$ broadcasts a packet at time t using three beams out of six beams simultaneously. All nodes within the transmission range of source node O will receive the packet. The source node randomly selects three beams such that the potential relaying nodes will be only selected from these beams. There are only two possible selections: the sectors 1, 3 and 5 or the sectors 2, 4 and 6. The unselected sectors will act as gaps to reduce the overlap between selected relying nodes. The neighboring nodes are denoted as Y. The header of the packet sent by the source node O consists of the following parameters as shown in Figure 5.7.

a. Packet ID is a unique identifier attached to each data packet which is created by the source node. Packet ID is used to detect and drop duplicate packets.

b. Timestamp specifies the time of packet creation by the source node, and it remains unchanged through broadcasting process. Timestamp is used to calculate the data dissemination delay.

c. Source ID is a unique ID that identifies the source node that created the message. A source ID can be represented by unique identifier such as the MAC address of the source node.

d. Sender ID; is a unique ID that identifies the selected relaying node. The value of this field changes every time a message is forwarded by a relaying node. As was the case with the source ID, the sender ID can also be represented by the MAC address of the relaying node.

e. *Th* is a distance threshold to indicate the distance from O beyond which the nodes are allowed to rebroadcast the packet where $Th \leq d \leq$ r.

f. k indicates the id of the beam from which the packet was sent where k = 1,2,3,…, 6. This parameter is used to eliminate redundant retransmissions received from other relaying areas.

g. Time-To-Live (TTL) indicates the maximum number of relaying hops a packet can travel. The value of TTL decreases as the number of hops increases.

Step 2: Packet Relaying

Upon receiving the packet, node Y inspects the received packet with the following procedures:

a) If the packet has been received more than one time, the packet is discarded. This is done by checking the id of the received packet.

b) If TTL of the received packet is equal to zero, the packet is discarded.

c) If the distance between Y and O, denoted as d is less than *Th*, then the packet is discarded. Note that d, can be obtained using received signal strength.

d) If and only if when d ³ *Th*, then the node Y is located inside of one of three relaying areas where S_k indicates the relaying areas.

e) Each potential relaying node will set a distance based waiting time using the formula described in Section 5.5.

f) When waiting time of a potential relaying node Y expires, the node Y broadcasts the packet in three directions using three beams simultaneously. All nodes within the transmission range of the node will receive the packet including the remaining potential relaying nodes.

g) Each potential relaying node will examine the received packet. Since the received packet is a duplicate packet, each potential relaying node checks the beam number k of the packet along with the packet id, if the beam number and packet id are the same, all potential relaying nodes within that particular beam will simply drop the packet and cancel the waiting process.

h) If the beam number is not the same then the potential relaying node will simply ignore the packet and continue waiting until the timer of one of the potential relaying nodes in that particular beam expires.

Step 3: Failure Recovery

After the source node O sends out a packet, it should receive the same packet from each relaying node within a time of T_Y $(0 \le T_Y \le 2t_{prop})$ to acknowledge the broadcasting was successful. Otherwise, the source node will rebroadcast the packet using the beam from which it didn't receive an acknowledgment.

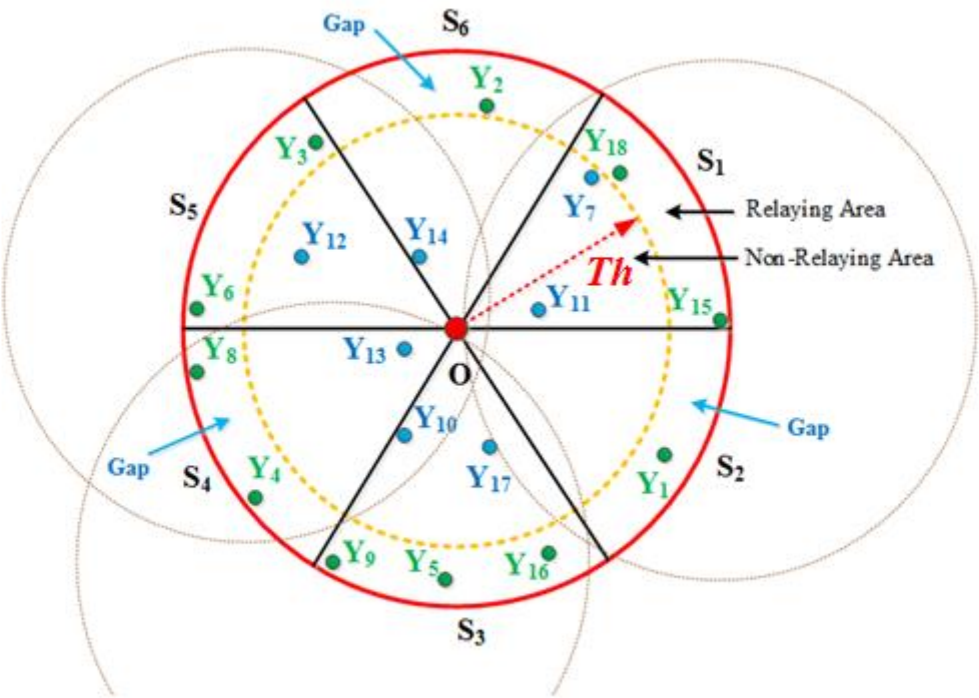


Figure 5.7: Improved Random Directional Broadcasting Relay Scheme

Figure 5.7 shows an example of the improved RDBR broadcasting scheme with 6-beam directional antennas. The source node *O* randomly choses three sectors out of six sectors in this example the selected sectors are 1, 3 and 5. The remaining sectors 2, 4 and 6 acts as gaps between neighboring sectors. The source node then broadcasts a packet using all beams of the directional antenna simultaneously. All nodes within the transmission range of the source node receive the packet. The nodes located in gaps (the idle sectors) will receive the broadcast but will not rebroadcast the packet. The neighboring nodes such as node Y_{15}, Y_9 and Y_6 that are far away from the source node(s) more than the neighboring node such as Y_{18}, Y_5 and Y_3 and therefore, will act as relaying nodes. On the other hand, the inner neighboring nodes such as node Y_7, Y_{10} and Y_{12} that are not located inside any relaying area will be prevented from relaying the packets. This novel defer-time-scheme will greatly reduce the number of redundant rebroadcast and reduces both contention and collision. The figure also shows that the overlap between neighboring sectors such as sector 3 and sector 5 greatly decreased and the uncovered area between neighboring sectors also decreased.

5.8 Summary

By introducing the concept of relying area and by the usage of directional antennas, the proposed RDBR scheme can significantly reduce the total number of hops required to transmit a packet. The proposed RDBR scheme greatly reduces the number of redundant retransmissions and achieving high delivery ratio using only three relaying nodes per hop. Furthermore, in order to reduce the effect of nodes displacement from ideal locations on the performance of RDBR scheme, an improved RDBR scheme was proposed. The improved RDBR scheme reduces the effect of nodes displacement by utilizing the concept of gaps that was proposed in Chapter 4.

The proposed scheme achieves better reachability than the RDBR scheme in high density environments. It is worth noting that both of the proposed RDBR schemes can achieve high reachability and reduce latency, without degrading the system performance in terms of delivery ratio and overhead compared to other existing schemes. The detailed simulation based performance evaluation of the proposed RDBR schemes with existing broadcasting schemes are presented in next Chapter.

Chapter 6: Performance Evaluation

This chapter presents a comprehensive performance evaluation of the proposed RDBR schemes using network simulations. The performance of these proposed schemes are compared with the Flooding and Distance-based scheme. The proposed schemes are implemented using NS-2 network simulator and the simulations are conducted by a number of different scenarios to investigate the performance under different network conditions. First of all, the performance evaluations focus on the efficiency in terms of capability for achieving high reachability while reducing both the number of retransmitting nodes and end-to-end delay. Second, the performance evaluations focus on the impact of the theorems of Lemma 3.1 and Lemma 4.2 on the different types of broadcasting relay schemes, especially in critical environments. The details of simulation environment, mobility model, performance measures and simulation results are presented in the following sections.

6.1 Simulation Model

The simulation used for the performance evaluations of the RDBR schemes is developed by the NS-2 network simulator version 3.5 [80][81]. The NS-2 is an open source discrete event simulation platform widely used for simulating both wired and wireless networks. Also, the NS-2 is a scalable simulation environment based on C++ and OTcl programming languages. Moreover, NS-2 is the most widely used network simulator for simulating mobile ad hoc networks [3][32][41][42][43][44][49][55][57]. The simulation platform developed for the evaluation of the proposed schemes considers a homogeneous mobile ad hoc network, in which all nodes are identical and have the same configuration. Two nodes can communicate with each other directly if and only if they are within the transmission range of each other. Therefore, the

Euclidean distance between these two nodes is at most the transmission range R. In the broadcasting process, a node is randomly selected to initiate a broadcasting message. The nodes are randomly deployed in a square area of 1000mx1000m. The transmission range of all nodes is equal to 250 meters, for both omni-directional and directional antenna models [56]. A Constant Bit Rate (CBR) traffic generator is used to generate traffic for data communication. CBR traffic is very well known and widely used traffic model for mobile Ad-hoc network. The MAC layer protocol used in the simulations is the IEEE standard 802.11 Distributed Coordination Function (DCF) [82] with no RTS/CTS/ACK mechanisms.

The popular two-ray ground reflection model is adopted as the radio propagation model. In the simulations, all packets have the same length of 1024 bytes and network bandwidth is 2 Mb/sec. However, the packet sequence generated by each individual node is independent random process. The maximum waiting time, denoted as maxWait, for a node to rebroadcast a packet is setup as 0.01s. This value of maximum waiting time has been used quite often in MANET literature [32][42][43][44][49]. The number of nodes in the network is varied from 20 to 200 nodes to evaluate the impact of node density (i.e. sparse and dense nodes distribution) on the performance. The average node degree (the number of neighbouring nodes within the transmission range of each node) varies approximately from 4 to 39 nodes[1], representing low density and high density respectively. The duration of each simulation run is 100 seconds plus 30 seconds as the warm up time period, which is not taken into account in the performance evaluation.

[1] $\lambda = (N-1)\frac{\pi r^2}{A}$, where A is network area (1000mx1000m)

Table 6.1: Simulation Parameters

Simulation Parameter	Value
Simulator	NS-2 (version 2.35)
Network Area	1000mx1000m
Transmission range	250m
Bandwidth	2 Mbps
Interface queue length	50
Packet size	1024byte
Traffic type	CBR
Packet rate	10 packets/sec
Number of nodes	20, 40, 60,…, 200
Number of trials	10
Mac Layer Protocol	IEEE 802.11
Simulation Time	100 sec
Confidence Interval	95%

Since each simulation run is driven by independent pseudorandom process, then the numerical results obtained from different simulation runs are different from each other. Therefore, each scenario has performed by 10 independent simulation runs and the actual mean is within the range of said interval. In most cases, the error bars have been found to be quite small. The confidence intervals are not included in the graphs to avoid clutter. In the simulation set up, all nodes are equipped with ideally sectorized multi-beam directional antennas of 3, 6, 9 or 12 beams. Note that the simulations ignore the effect of both side lobes and the overlap between sectors because their impact on overall performance is negligible [54][69][70][83]. The simulation experiments described in this chapter are performed on a machine with Intel Core i7 @2.90 GHz processor and 6 GB RAM running Linux Ubuntu 12.04. It is worth to mention that the simulation setup and the parameter values used for evaluation are quite common and widely used in the literature [42][44][52][55][56] [57][84]. Table 6.1 shows the detailed simulation environment and parameters values that have been used in the evaluation of the proposed RDBR schemes. The network parameters listed in Table 6.1 remain fixed for all simulations.

6.2 Broadcasting Scenarios and Their Measurements

Extensive simulations are performed to study the benefits of the proposed RDBR schemes and comparing them with other broadcasting schemes, including Flooding and Distance-based broadcasting schemes both of which use omni-directional antennas. To ensure fair comparison, these chosen ad hoc based broadcasting schemes can operate in the same critical environment. Furthermore, realistic simulation scenarios were generated which ensure equal conditions between the compared schemes. It makes no sense to compare the proposed RDBR schemes with location-based schemes, topology-based schemes and complex broadcasting schemes under the lack of both location and topology information, particularly when energy is a limited resource, as these broadcasting schemes would not operate properly in such a critical environment. The proposed RDBR schemes are the only integrated broadcasting schemes that use directional antennas to communicate omni-directionally and therefore can operate without any assumptions about location and topology information.

The performance of the proposed RDBR schemes is compared with Flooding and DB scheme [12][13] using the following performance metrics: 1) Reachability, 2) Number of retransmitting nodes, and 3) End-to-end delay. These metrics are the most popular and widely used performance metrics currently being used in evaluating ad hoc based broadcasting schemes [42] [44][52][49][55][56] [57].

1) *Reachability*, defined as *r/e*, where *r* is the number of nodes in the network that receives a broadcast packet and *e* is the number of nodes in the network that are reachable, directly or indirectly, from a source node.
2) *Number of Retransmitting Nodes*, the number of nodes in the network that received the broadcast packet and retransmitted it i.e. the average number of nodes in the network which take part in broadcasting the packet.
3) *End-to-End Delay*, the interval from the time the broadcast packet was sent by a source node to the time the last retransmitting node finished rebroadcasting the packet.

6.3 Mobility Model

In this section, an overview of the mobility model that is used in the performance evaluation of the proposed schemes is given. The mobility model used in this study is the Random Waypoint Mobility Model [76][77], which is one of the most widely used mobility models in simulating mobile ad hoc networks [32][42][43][44][49]. In this mobility model, nodes are randomly distributed over a given network area. Each node at the beginning of the simulation remains stationary for a certain period of time called pause time before starting a new movement. A node randomly selects a destination in the area and starts moving towards it with a constant speed. The speeds of the nodes were randomly selected from a uniform distribution in the range of [0, V_{max}], where V_{max} is the maximum allowable speed for every mobile node. After reaching the destination, the node waits for a certain pause time; it then selects a new random destination and speed. The mobile node then moves towards the newly selected destination with constant speed. This process continues until the simulation ends.

Node mobility is simulated using mobility scenes that are generated using the setdest utility of NS-2 simulator. The setdest utility is a popular mobility scene generator which generates node movement file according to the random waypoint mobility model. The continuous node mobility model has been used in the simulation, in which nodes are continuously moving until they reach their destination. As a result, the pause time of all mobility scenarios is set to zero. Many previous studies have shown that pause times of 20 seconds or above makes dynamic networks significantly stable [32][86][87]. Since this thesis considers broadcasting relay in a critical environment, the pause time is fixed to zero. This represents continuous node mobility without added stability.

All nodes in the network are mobile nodes, including the source nodes, the destination nodes, as well as the relaying nodes; however, mobile nodes may not always be on move. Nodes may move at any time in any direction with different speeds, and may even sometimes move continuously without stop. This may in some cases result in loss of communication between neighboring nodes due to high speed and different directions, but in this work it is assumed that the communication time is much less that the time it takes a node to change its positions. It is worth noting that the mobility model and mobility parameters mentioned in this section have been widely used in simulation studies of MANET broadcasting schemes [32][41][42][43][49].

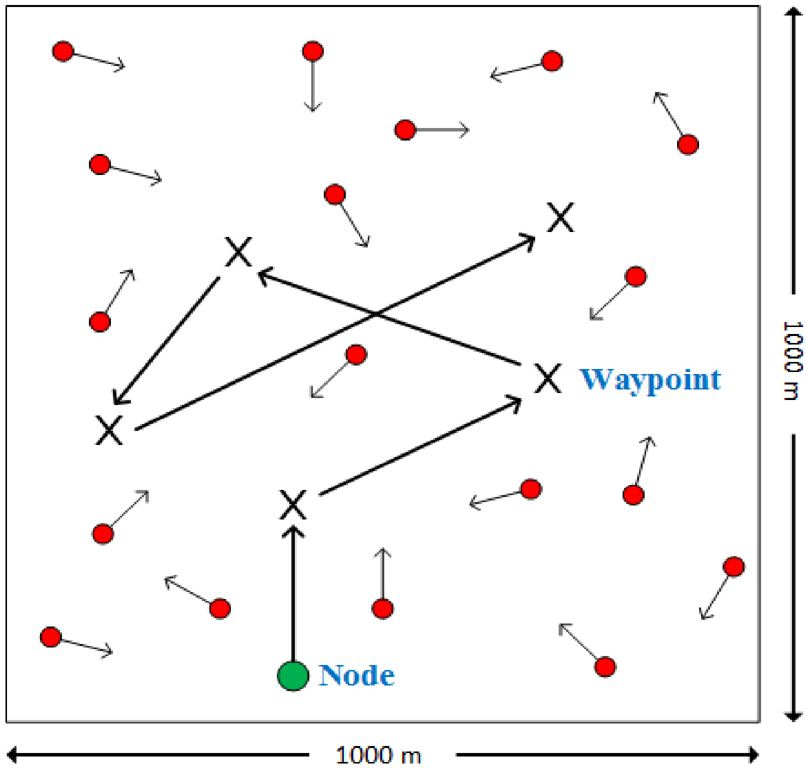


Figure 6.1: Example of node movement in the random waypoint model

Figure 6.1 shows an example of random waypoint model where circles represent nodes, arrows represent moving directions of nodes at specific time and "X" represent a waypoint. Each waypoint represents a destination at which the nodes stop and then resumes after a pause time towards a new randomly selected destination. It is worth noting that if the pause time is set to zero, the node will basically behave in the same way as described above except it will not stop at any destination. This represents a critical environment in which the communication time between nodes has to be fast otherwise they will lose the connection.

6.4 Performance Analysis

The study conducted in this section evaluates the performance of the proposed schemes under different network conditions. The simulations were carried out by varying the number of nodes, node mobility and traffic load. The impact of these factors on the performance of the proposed schemes is analyzed systematically. The network density, network traffic and node mobility parameters are not fixed for all experiments and therefore vary from one scenario to another. The simulations are performed in several static and mobile scenarios, with different performance metrics. Initially, the focus will be on the analysis and simulations on static networks. Later the impact of node mobility on performance of the proposed schemes is measured. The simulation is divided into four sets of experiments: the first set of experiments study the impact of node density on the performance of proposed schemes. The second set of experiments study the impact of node mobility on the performance of the proposed schemes. The third set of experiments study the impact of traffic load on the performance of proposed schemes. The fourth set of experiments study the impact of combined network conditions on the performance of the proposed schemes. In the first three sets of experiments, only one network condition is varied while the other network conditions are remained fixed in order to eliminate the effect of one network condition on the performance result of other network conditions. In the last set of experiments, a combined network condition is considered in which the performance of proposed schemes is evaluated under a wide range of varying network conditions. This allows us to study the impact of varying network conditions such as low network conditions, medium network conditions and high network conditions on the performance of the proposed schemes. The details of the three network conditions are given below:

1. *Network Density:* This refers to the total number of nodes in the network. This network condition is used to study the effect of varying node density on the performance of the proposed schemes. Network density in the range of 20 to 200 nodes was considered for this network condition representing low, medium and high density networks.

2. *Node Mobility*: This refers to the speed of nodes in the network. This network condition is used to study the impact of varying node mobility on the performance of the proposed schemes.
3. *Traffic Load:* This refers to the total number of packets generated per second. It is used to study the effect of varying traffic load on the performance of the proposed schemes. Traffic load of 10, 20, 30, and 50 packets per second were considered for this network condition.

In order to differentiate between the proposed RDBR scheme and the improved RDBR scheme, the proposed RDBR scheme will be referred as RDBR-3 and the improved RDBR scheme will be referred as RDBR-6, where 3 and 6 represent the number of directional antenna beams. In this Chapter, two more versions of the improved RDBR scheme will also be evaluated which will be referred as RDBR-9 and RDBR-12.

6.5 Network Density

The purpose of simulation based experiments in this section is to evaluate the performance of the proposed RDBR schemes with existing broadcasting schemes by comparing their performance in a static network. The proposed RDBR schemes are highly dependent on the network density. In sparse networks, the proposed RDBR-3 scheme is expected to achieve similar reachability as Flooding, whereas the proposed RDBR-6 scheme is expected to perform poorly due to large number of sectors and low nodes density. In the following subsections, the effect of node density on reachability, number of retransmitting nodes and end-to-end delay is considered. The node density is varied in the network by increasing number of nodes randomly distributed in a fixed square area of 1000mx1000m. The number of nodes in the network has been varied from 20 to 200 nodes. To reduce the effect of node mobility and traffic load on the performance of the network. The mobility is assumed to be constant and traffic load is fixed to 10 packets/sec. The distance threshold *Th* is set to 125. According to some studies [15][16][49][50][88], the suitable value of *Th* is equal to transmission range divided by two i.e. *Th* =R/2. The lower values will result in more contention and collision in the network whereas higher values will cause transmission failures and therefore result in low delivery ratio.

6.5.1 Impact of Density on Reachability

In this section, the effect of node density on the delivery ratio is investigated. Figure 6.2 shows the reachability achieved by all schemes over a varying node density and fixed distance threshold *Th*. The horizontal axis in Figure 6.2 shows the number of nodes in the network. The vertical axis in Figure 6.2 shows the delivery ratio.

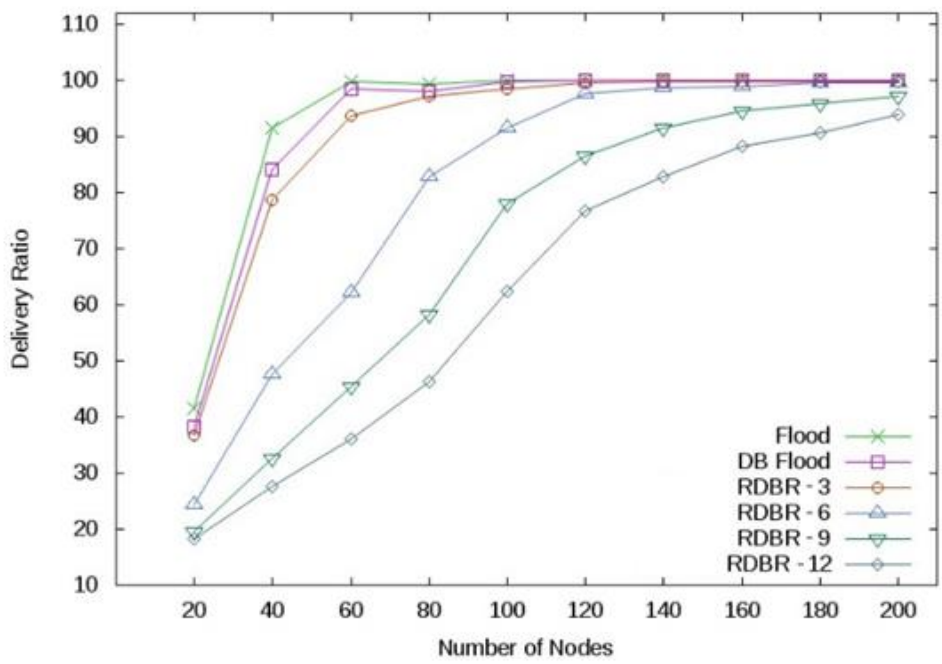


Figure 6.2: Impact of density on reachability

As shown, all schemes other than RDBR-9 and RDBR-12 are highly reliable in medium to dense networks; in sparse networks, Flooding, DB and RDBR-3 are the most reliable broadcasting schemes among all schemes. The delivery ratios achieved by all schemes increase with increasing node density. This is due to the fact that as node density increases, the network connectivity increases as well. This means that there is high possibility that more nodes are located within transmission range of each other. Figure 6.2 also shows that there is no significant difference between Flooding, DB and RDBR-3 in terms of reachability. For low densities, Flooding has slightly better reachability than DB which in turn has slightly better reachability than RDBR-3 scheme. The reason behind this is that both Flooding and DB schemes generate redundant transmissions to achieve better reachability, whereas the proposed RDBR-3 scheme reduces if not eliminates all redundant transmissions. For high nodes densities, all three schemes achieve high reachability. This indicates that the proposed RDBR-3 scheme is able to achieve the same level of reachability as Flooding while incurring little overhead as will be shown in next section.

On the other hand, the poor reachability achieved by all schemes at low density is due to poor connectivity suffered by sparse networks. Similarly, Figure 6.2 also shows that RDBR-6, RDBR-9 and RDBR-12 achieve the least reachability among all schemes specially in sparse to medium density networks (20 to 80 nodes). This is due to the fact that as the number of sector increases, the size of relaying area decreases which in turn decreases the possibility of finding nodes in relaying areas. But as the node density increases the reachability achieved by RDBR-6 increases until it reaches the same level of reachability of Flooding in very dense network (180 to 200 nodes). This is due to the fact that as the node density increases, the possibility of finding a node in a relaying area also increases. This indicates that RDBR-6 is also an effective broadcasting scheme which is able to achieve the same level of reachability as Flooding but in very dense networks.

6.5.2 Impact of Density on the Number of Retransmitting Nodes

In this section, the effect of node density on the number of retransmitting nodes is investigated. Figure 6.3 shows the number of retransmitting nodes required by each scheme over a varying node density. The horizontal axis in Figure 6.3 shows the number of nodes in the network. The vertical axis in Figure 6.3 shows the number of retransmitting nodes.

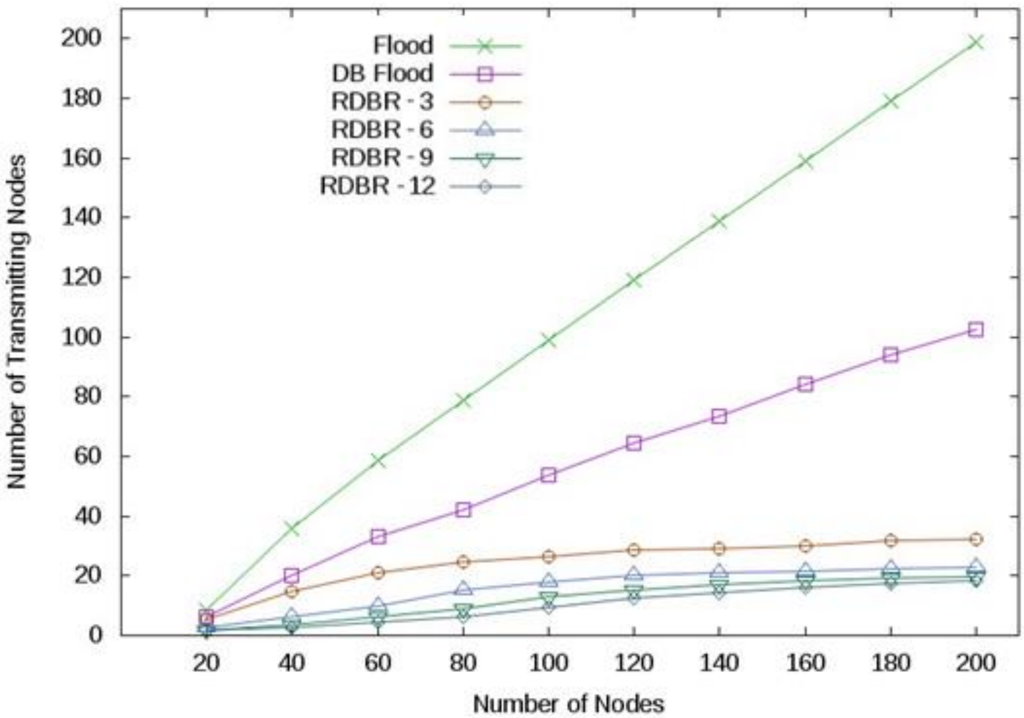


Figure 6.3: Impact of density on the number of retransmitting nodes

As can be seen from Figure 6.3, all schemes other than Flooding and DB are scalable in terms of number of retransmitting nodes in both sparse and dense networks. The number of retransmitting nodes required by both Flooding and DB schemes increase with increasing node density. This is due to the fact that as node density increases, the delivery ratio increases which comes at the cost of utilizing more retransmitting nodes. Figure 6.3 also shows that there is significant difference among Flooding, DB and RDBR-3 schemes in terms of number of retransmitting nodes. For all nodes densities, RDBR-3 outperforms Flooding and DB in terms of number of retransmitting nodes. RDBR-3 requires a significantly lower number of retransmitting nodes to achieve the same level of reachability as Flooding and DB schemes. As a result, it is more energy efficient and scalable than both Flooding and DB schemes. It is important to note that as the number of retransmitting nodes increase in the network with increasing density, the chances of collision and contention increases too. Therefore, in order to reduce both contention and collision, less number of retransmitting nodes should be used. However, this shouldn't come at the cost of lower reachability. The goal is to achieve high reachability while utilizing less number of transmitting nodes. The proposed RDBR-3 scheme was able to achieve the same level of reachability of Flooding while requiring less number of retransmitting nodes. This is due to the fact that RDBR schemes use fixed number of retransmitting nodes for all node densities. This indicates that the proposed RDBR-3 scheme is able to achieve the same level of reachability as Flooding while requiring much less number of retransmitting nodes.

Figure 6.3 also shows that the DB scheme requires less number of retransmitting nodes than Flooding scheme. The reason behind this is that Flooding scheme generates more redundant retransmission than DB scheme to achieve high reachability and therefore will obviously require more retransmitting nodes. On the other hand, the lower number of retransmitted nodes required by RDBR-6, RDBR-9 and RDBR-12 is due to low reachability as stated in Section 6.1. Similarly, Figure 6.3

also shows that RDBR-6 requires less number of retransmitting nodes than RDBR-3 scheme in dense networks given that both schemes achieve the same level of reachability as Flooding for very dense networks. This is due to the fact that in RDBR-6 scheme, the size of relaying areas are smaller than that of RDBR-3 scheme and therefore the probability of finding potential relaying nodes at ideal locations are much higher than that in case of RDBR-3 scheme. As stated earlier in Chapter 4, locating relaying nodes at ideal locations guarantee better network coverage which in turn guarantee better connectivity in the network. As a result, the RDBR-6 scheme is able to locate relaying nodes at ideal locations in dense networks, this proves the Lemma 4.2 and the concepts of gaps in which it stated that the best coverage can be achieved in dense networks when the size of relaying areas are small. This also indicates that RDBR-6 is more efficient than RDBR-3 scheme in terms of scalability and energy saving in very dense networks.

6.5.3 Impact of Density on End-to-end Delay

In this section, the effect of node density on the end-to-end delay is investigated. Figure 6.4 shows the end-to-end delay incurred by all schemes over a varying node density. The horizontal axis in Figure 6.4 shows the number of nodes in the network. The vertical axis in Figure 6.4 shows the end-to-end delay.

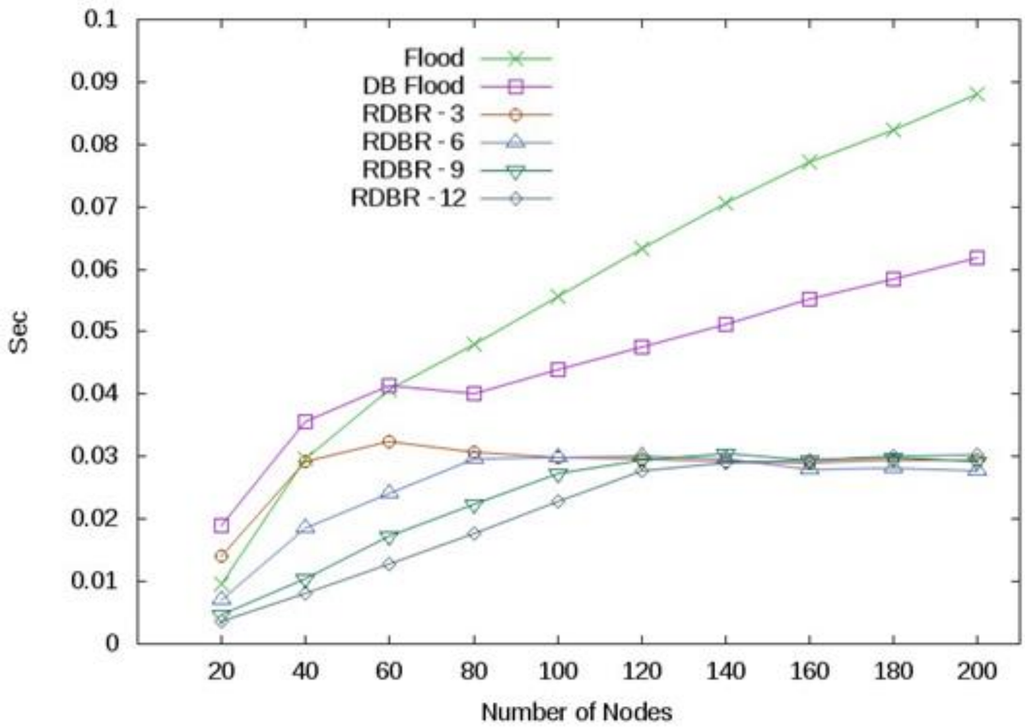


Figure 6.4: Impact of density of end-to-end delay

Looking at Figure 6.4, one can observe four important facts about the proposed RDBR schemes and the other schemes: (1) Flooding and DB schemes have the highest end-to-end delay, the delay increases with increasing node density; (2) the end-to-end delay of RDBR schemes are much lower than that of the Flooding and DB schemes especially in high density networks; (3) the end-to-end delay of RDBR schemes does not increase with increasing node density after reaching a certain node density; (4) the low reachability RDBR schemes i.e. RDBR-6, RDBR-9 and RDBR-12 and the high reachability RDBR scheme i.e. RDBR-3 have almost the same end-to-end delay in high density network. This means that the end-to-end delay does not increase with increasing node density. This also means that the proposed RDBR schemes are able to achieve high reachability while keeping the end-to-end delay as low as possible.

The reason why the proposed RDBR schemes have approximately equal end-to-end delays in high density networks (given that they have achieved different level of reachability) is because the RDBR schemes require only three relying nodes to rebroadcast the messages. This property of the proposed schemes guarantees that always three nodes are required for retransmission regardless of increasing node density. Therefore the end-to-end delay of RDBR schemes is much lower than that of the Flooding and DB schemes. The very low delay values for RDBR-9 and RDBR-12 are due to the low reachability and the low delay values for RDBR-6 in low density networks is also due to the low reachability. Whereas the low delay values for RDBR-6 in very high density network is not due to low reachability since RDBR-6 achieved the same level reachability of Flooding. The reason behind that is as discussed earlier is due to the use of fixed number of relaying nodes which does not change with changing node density. However, one can notice from Figure 6.4 that the RDBR-6 has the lowest delay among all schemes even lower than RDBR-3. This is due to the fact that RDBR-6 scheme has 6 sectors compared with 3 sectors for RDBR-3. The relaying area sizes of RDBR-6 schemes are therefore smaller than that of RDBR-3 and as a result the possibly of finding a node closer to the ideal locations in any of relaying area is high. As stated earlier, selecting a relaying node close to ideal locations will guarantee better coverage of the network and will ensure high reachability.

The end-to-end delay of both Flooding and DB schemes increase with increasing node density. On the other hand, the end-to-end delay of RDBR schemes remains fairly constant with increasing node density especially for high node density. This is due to the fact that the RDBR schemes use distance-based waiting time in which the waiting time assigned to each potential relaying node decreases as the distance from the source node increases. In other words, the farthest nodes from the source node will rebroadcast the message before the other nodes. The figure also shows that the end-to-end delay incurred by Flooding and DB schemes is worsened when node density in the network increased. It can also be observed that the end-to-end delay of DB scheme is lower compared to Flooding. This is due to the fact that DB scheme uses RAD timer which always the scheme to select farthest nodes and therefore reduces end-to-end delay.

In summary, the proposed RDBR-3 was able to achieve the same level of reachability as Flooding and DB scheme for medium to high density networks while using less number of retransmitting nodes and less end-to-end delay. On the other hand, the proposed improved RDBR-6 was able to achieve the same level of reachability as Flooding and DB scheme for very high density networks while using less number of retransmitting nodes and less end-to-end delay. Furthermore, the improved RDBR-6 scheme was also able to outperform RDBR scheme in terms of the number of retransmitting nodes and end-to-end delay in very high density networks.

6.6 Network Mobility

In the following subsections, the effect of node mobility on the performance of proposed RDBR schemes is investigated in terms of reachability, number of retransmitting nodes and end-to-end delay. The aim of this study is to focus on the ability of each broadcasting scheme to react effectively to mobility in MANET. A number of previous studies [15][16] [32] have shown that Flooding is relatively insensitive to node speeds; the proposed RDBR schemes should maintain this good property of Flooding. The maximum node speed in the network is varied over a range of 5, 10, 15, and 20 m/sec while the pause time was fixed to zero. To reduce the effect of node density and traffic load on the performance of the network. The total number of nodes in the network has been fixed to 100, which indicates the median value of node density from Section 6.5. The traffic load was fixed to 5 packets/sec. The distance threshold value *Th* is fixed to 125.

6.6.1 Impact of Mobility on Reachability

In this section, the effect of node mobility on the delivery ratio is investigated. Figure 6.5 shows the reachability achieved by all schemes over a varying node density. The horizontal axis in Figure 6.5 shows the speed of nodes. The vertical axis in Figure 6.5 shows the delivery ratio.

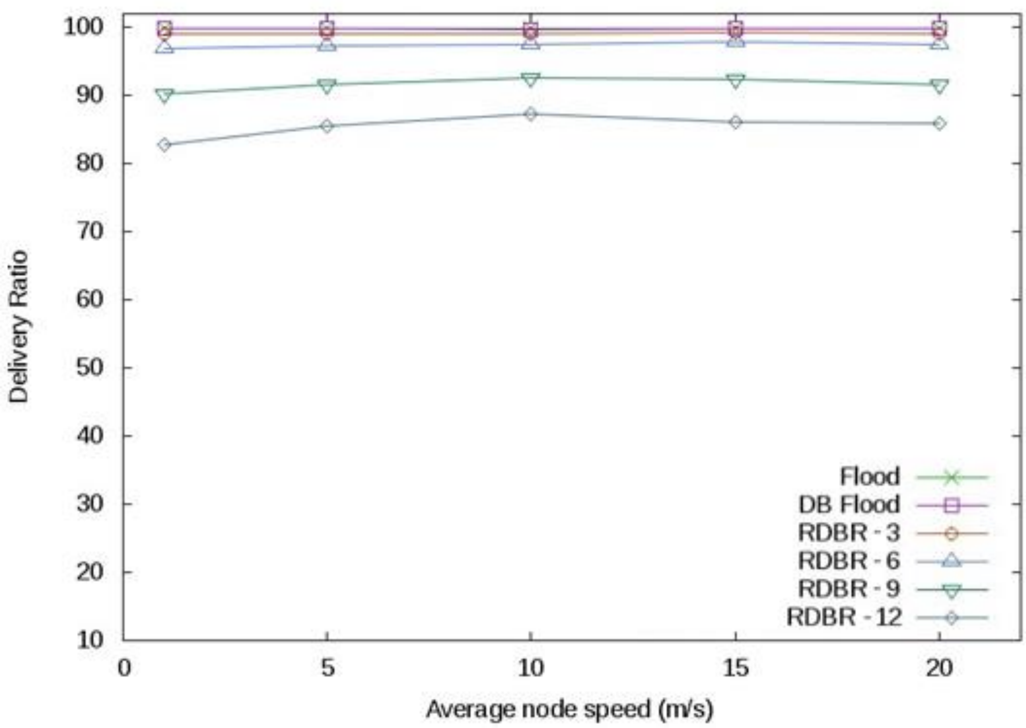


Figure 6.5: Impact of mobility of reachability

As can be seen from Figure 6.5, Flooding, DB, RDBR-3 and RDBR-6 schemes are not affected by increasing node mobility, whereas RDBR-9 and RDBR-12 schemes are slightly affected by increasing node mobility. Specifically, the delivery ratios achieved by all schemes almost remain constant with increasing node speed. There are three main reasons behind this behavior which are common among all schemes and some specific reasons related to the operation of each broadcasting scheme. The first common reason is that none of these schemes maintain network topology information which requires a lot of communication with neighboring nodes. The second common reason is that none of these schemes use complex AoA calculation in which multiple nodes communicate with each other to estimate the angle of arrival. The third common reason is that none of these schemes rely on location information which also requires communicating between neighboring nodes. The lack of topology, location and AoA communication implies that the communication time is much less than the time it takes the node to change its location. As a result, these schemes are not significantly affected by increasing node speed because the waiting time before retransmitting a packet is very short.

In Flooding scheme for example, beside the above mentioned common reasons, the delivery ratio is not affected by the increasing node mobility due to the large redundancy. This observation is consistent with the literature review in which the authors found that Flooding generate a lot of redundant retransmissions which helps this scheme overcome packets losses [32]. As a result, Flooding is less sensitive to increasing node speed. This is a good property of Flooding which should be one of the main design goals of any efficient broadcasting schemes. Besides Flooding, DB scheme also utilizes redundant retransmissions to overcome mobility effect but not in the same level of redundancy used in Flooding scheme. DB scheme uses distance threshold to reduce the number of redundant retransmissions while achieving high reachability. Unlike Flooding and DB schemes which rely on redundant retransmissions to overcome node mobility effect, RDBR schemes do not generate any redundant retransmission as stated earlier and relies on the proposed Lemma 3.1 and Lemma 4.2 to overcome the node mobility effect.

The reason why RDBR schemes are less sensitive to increasing node mobility is due to the use of the concept of sectors. In RDBR-3 for example, there are only three sectors and only one node is allowed to rebroadcast in each sector. Due to the large size of sectors in RDBR-3 schemes, the possibility of finding a node in any of these sectors is very high even with high mobility. But when the size of sectors are small as the case with RDBR-6, RDBR-9 and RDBR-12, the probability of finding a node in each sector decreases and hence these schemes get affected by high node mobility. In low to medium density networks, the increment in node speed might lead in better coverage due to the movement of nodes between different sectors. This increases the probability of finding nodes in specific sectors and thus guarantees better coverage of network and also ensures high connectivity. This explains the increment in delivery ratios for RDBR-9 and RDBR-12 schemes in low to medium density. However, the reason why the delivery ratio starts to decrease from medium to high density network is due to the high nodes mobility. Specifically, the delivery ratio for RDBR-9 and RDBR-12 increases with increasing node mobility until it reaches the node speed of 10 m/s and then it starts to slightly decrease. This is due to fact that as node speed increases the node moves very fast from one sector to another sector which causes this behavior.

6.6.2 Impact of Mobility on the Number of Retransmitting Nodes

In this section, the effect of node mobility on the number of retransmitting nodes is investigated. Figure 6.6 shows the number of retransmitting nodes required by each scheme over a varying node density. The horizontal axis in Figure 6.6 shows node speed. The vertical axis in Figure 6.6 shows the number of retransmitting nodes. As can be seen from Figure 6.6, all schemes have a constant number of retransmitting nodes despite increased node speed. Specifically, the number of retransmitting nodes required by each scheme remains constant with increasing node mobility. The reason why the number of transmitting nodes remains constant with increasing mobility is due to the use of fixed number of nodes in the network which is set to 100. Another reason is that the delivery ratio achieved by all scheme except RDBR-6, RDBR-9 and RDBR-12 remain constant with increasing node mobility.

Figure 6.6 also show that RDBR-3 outperforms Flooding and DB schemes in terms of number of retransmitting nodes. Recall from Section 6.5.2 that RDBR-3 requires a significantly lower number of retransmitting nodes than Flooding and DB schemes. This is due to the fact that the RDBR-3 scheme uses a fixed number of relaying nodes whereas Flooding and DB schemes generate redundant transmissions and thus requires more transmitting nodes to achieve high reachability. On the other hand, the lower number of retransmitted nodes required by RDBR-6, RDBR-9 and RDBR-12 is due to low reachability as stated in Section 6.5.1. Furthermore, the reason why RDBR-6, RDBR-9 and RDBR-12 schemes require constant number of retransmitting nodes despite the fact that these schemes achieved different delivery ratio for different node mobility is due to low connectivity.

More specifically, RDBR schemes use fixed number of relaying nodes regardless of number of sectors being used. Meaning that for a fixed number of nodes the number of relaying nodes remains fixed with increasing mobility as can be seen from Figure 6.6. However, increasing node mobility leads to a better connectivity and which in turn guarantees better reachability. This explains why each RDBR scheme achieved different level of reachability while the number of relaying node is constant.

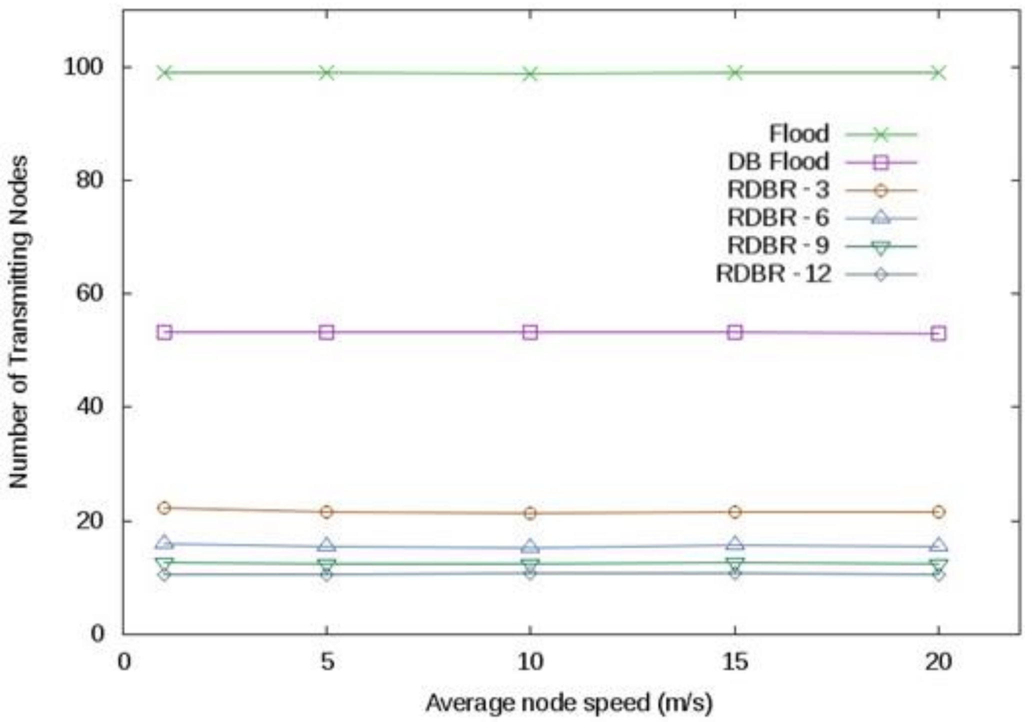


Figure 6.6: Impact of mobility of retransmitting nodes

6.6.3 Impact of Mobility on End-to-end Delay

In this section, the effect of increasing node mobility on the end-to-end delay is investigated. Figure 6.7 show the end-to-end delay incurred by all schemes over a varying node density. The horizontal axis in Figure 6.7 shows node speed. The vertical axis in Figure 6.8 shows the end-to-end delay. From Figure 6.7, one can observe the following important points: (1) Flooding and DB schemes have the highest end-to-end delay and the delay remains constant with increasing node mobility; (2) the end-to-end delay of RDBR schemes are much lower than other schemes; (3) the end-to-end delay of RDBR schemes also remains constant with increasing node mobility; (4) there is no significant difference between all RDBR schemes in terms of end-to-end delay. The low delay values for RDBR-6, RDBR-9 and RDBR-12 are due to the low reachability whereas the low delay values for RDBR-3 in due to the use of fixed number of relaying node and distance based waiting time scheme as stated in Section 6.6.2. On the other hand, the very high delay in Flooding is due to redundancy whereas the high delay in DB is due to both redundancy and waiting time scheme as stated in Section 6.6.2.

The reason why the delay is constant for all schemes with increasing node mobility is due to the use of fixed number of nodes which is equal to 100. Another reason is that all of the schemes except RDBR-9 and RDBR-12 achieved constant delivery ratios and constant relaying nodes. The main observation is that RDBR-9 and RDBR-12 schemes maintained a constant delay with increasing node speed given that the delivery ratio of these schemes was not constant with increasing node mobility as discussed in Section 6.6.2. There are two main factors which causes this behaviour. The first factor is the limited size of relaying area caused by increased number of sectors. The second factor is the fixed number of relaying nodes required by each source node. In more detail, the number of relaying nodes required by each node is fixed even in case of smaller relaying area.

Furthermore, node density plays an important role in this case because in high node density the network connectivity would be high and which will result in better reachability. However, in this experiment the node density was not high but due to node mobility the network connectivity was decreased while number of relaying nodes was fixed. This indicates that the delay is associated with the number of relaying node which is in turn affected by the distance based waiting method. Since the number of relaying nodes is constant with increasing node mobility, the delay is also constant. Meaning that, the delay is affected by the number of relaying nodes and not directly related to delivery ratio.

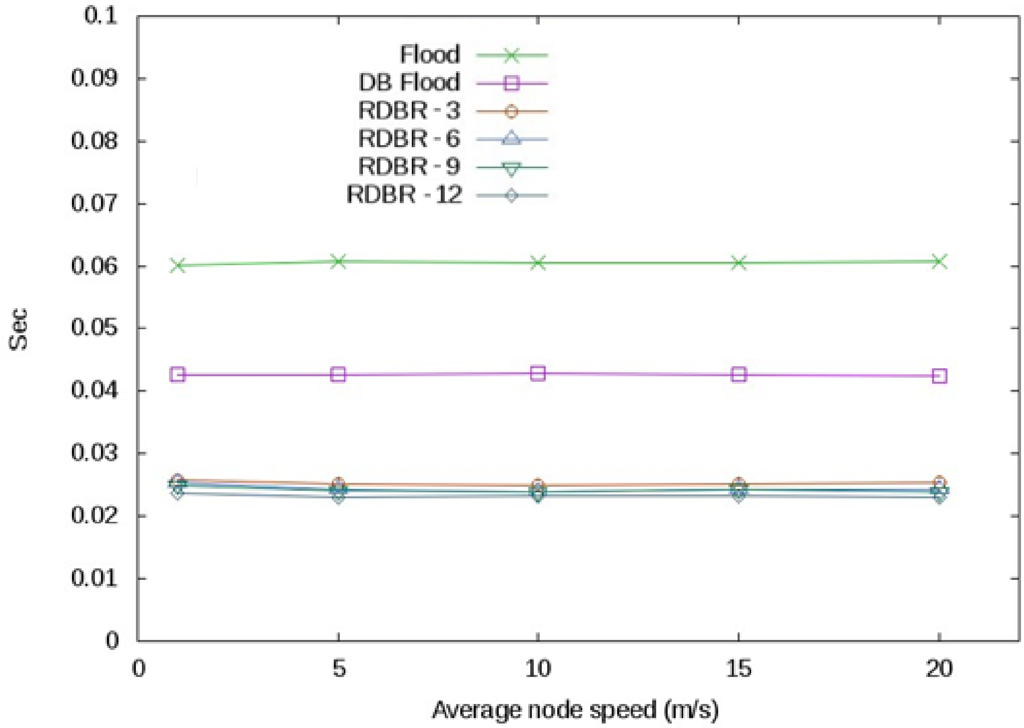


Figure 6.7: Impact of mobility of end-to-end delay

In summary, the performance of proposed RDBR-3 and improved RDBR-6 schemes was not degrading with increasing node mobility and it remained flat. This is a main property of Flooding which the proposed RDBR schemes were able to maintain. On the other hand, the proposed RDBR schemes outperformed both Flooding and DB scheme in terms of number of retransmitting nodes and end-to-end delay.

6.7 Network Traffic

This section investigates the effect of varying traffic load on the performance of proposed schemes in terms of reachability and number of retransmitting nodes. It should be expected that the delivery ratio of Flooding will decrease greatly. The reason is that heavily congested networks lead to packet collisions as well as data queue overflows. The proposed schemes, however, should be more efficient and less sensitive to network congestion. Traffic load rate of 10, 20, 40, 60 and 80 packets/sec were used to evaluate the effect of traffic load on the above performance metrics. In order to reduce the effect of both mobility and node density on the network performance, the number of nodes in the network is fixed at 100 nodes, which indicates the median value of node density from Section 6.5. The aim is to avoid sparse and dense scenarios and to get a general trend for the effect of traffic load on the performance. A static network was considered for this study where the maximum node speed is fixed to zero to avoid the effect of varying node mobility on the network performance. The distance threshold value *Th* is fixed to 125. The above simulation parameters are widely used in the literature.

6.7.1 Impact of Traffic Load on Reachability

In this section, the effect of increasing traffic load on the delivery ratio is investigated. Figure 6.8 shows the delivery ratio achieved by all schemes over a varying traffic load. The horizontal axis in Figure 6.8 shows traffic load. The vertical axis in Figure 6.8 shows the delivery ratio.

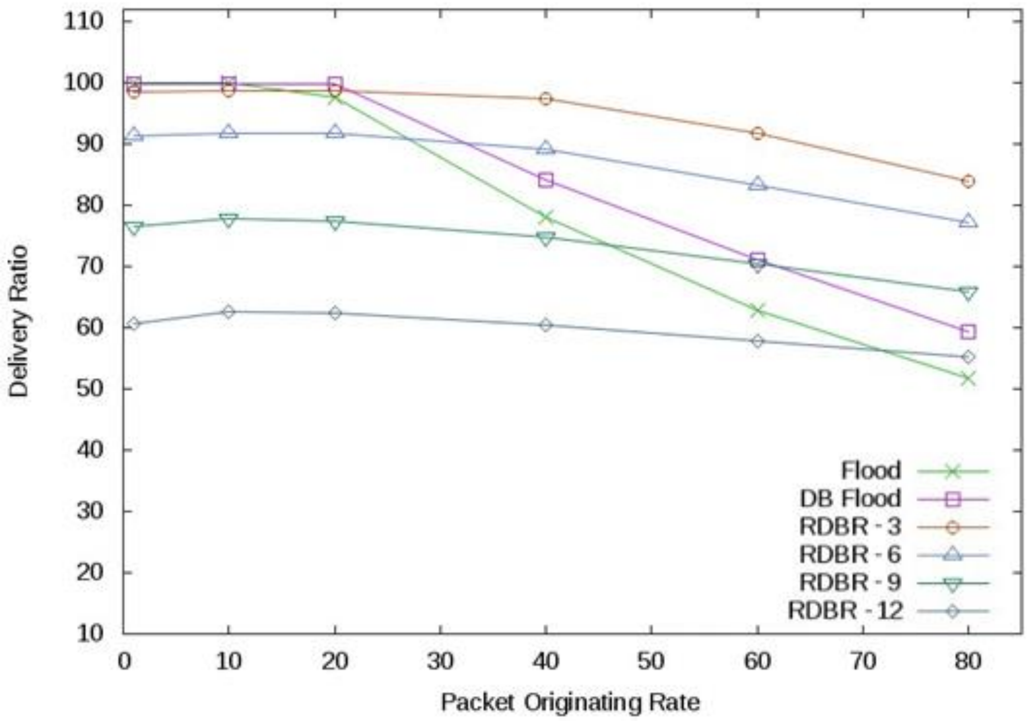


Figure 6.8: Impact of traffic load of reachability

From Figure 6.8, one can make the following observations: First, the delivery ratio of all schemes decrease as traffic load increases i.e. a higher traffic load will result in a lower reachability. Second, the delivery ratio of both Flooding and DB schemes decline quickly as traffic load increases. Third, although delivery ratio of RDBR schemes decline as traffic load increases, RDBR schemes are less sensitive to increasing traffic load when compared to both Flooding and DB schemes. Specifically, till a traffic rate of 20 packets/sec, all the schemes sustained a constant delivery ratio, with Flooding, DB and RDBR-3 schemes being the most efficient and RDBR-6, RDBR-9 and RDBR-12 being the least efficient. The delivery ratio of all the schemes start to decline under heavy traffic load (i.e. at traffic rate of 40 packets/sec or more) with RDBR schemes being the most efficient and Flooding and DB schemes being the least efficient. This is due to the fact that as traffic load increases, the number of broadcast packets retransmitted by each node also increases. Thus, the chances of two or more nodes transmitting a broadcast packet at the same time increases. This in turn leads to more contention, collision and delays in the network, as well as reduces channel access and energy wastage.

Collisions will prevent some broadcast packet from being rebroadcasted and thus affect the overall reachability. Furthermore, more collisions typically mean that more energy has been wasted in the collision resolutions. However, for very high traffic load (i.e. a traffic rate of 60 packets/sec and more), the delivery ratio of the RDBR-3 scheme is much higher than Flooding and DB schemes. For example, among the broadcasting schemes, Flooding is the most affected broadcasting scheme as delivery ratio falls to nearly 50% at a traffic rate of 80 packets/sec. The second most affected broadcasting scheme is DB scheme as the delivery ratio falls to nearly 60% at a traffic rate of 80 packets/sec. On the other hand, RDBR schemes are slightly affected by increasing traffic load, as they use fixed number of relaying nodes and distance based waiting time. Whereas, Flooding and DB schemes generates many redundant retransmissions which worsen the situation and eventually leads to packet drops. However, the most remarkable observation is that RDBR schemes such as RDBR-6, RDBR-9 and RDBR-12 outperformed Flooding scheme in very high traffic load (i.e. at a traffic rate of 80 packets/sec more). Furthermore, out of these three schemes, RDBR-6 and RDBR-9 schemes outperformed DB scheme with RDBR-12 slightly lower than DB scheme. This means that only RDBR schemes are able to operate under very heavy traffic load when compared with other two schemes and they are more energy efficient than Flooding and DB schemes.

6.7.2 Impact of Traffic Load on the Number of Retransmitting Nodes

In this section, the effect of increasing traffic load on the number of retransmitting nodes is examined. Figure 6.9 shows the number of retransmitting nodes required by each scheme over a varying traffic load. The horizontal axis in Figure 6.9 shows traffic load. The vertical axis in Figure 6.9 shows the number of retransmitting nodes.

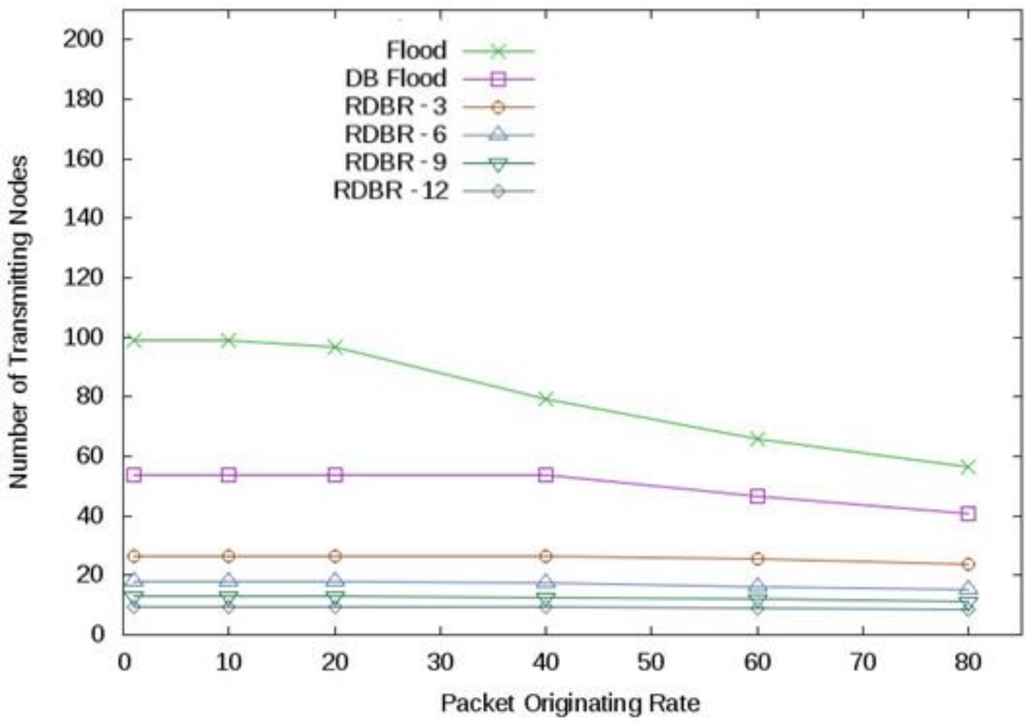


Figure 6.9: Impact of traffic load on the number of retransmitting nodes

Examining Figure 6.9, one can make the following two observations: First, the number of retransmitting nodes required by Flooding and DB schemes decrease as traffic load increases. Second, the number of retransmitting nodes required by RDBR schemes remains fairly constant for varying traffic load i.e. increasing traffic load does not affect the performance of RDBR schemes in terms of number of retransmitting nodes. Since the number of nodes in the network is fixed and nodes are static, one would expect the number of retransmitting nodes required by each scheme to remain fairly constant. However, only RDBR schemes seem to maintain the number of retransmitting nodes over varying traffic load.

The number of retransmitting nodes required by both Flooding and DB schemes, on the other hand, start to decrease as the traffic load increases. This can be caused by a number of factors such a contention, collision and mobility. Since the nodes in the network are static, the decrement in the number of retransmitting nodes may be caused by either contention or collision. It is worth mentioning that there is a difference between contention and collision. In case of a contention, a node backs off for a random time when the channel is occupied and then reattempts accessing the channel after the waiting time expires. This may cause IFQ buffer overflow and extra end-to-end delay. In case of a collision, multiple nodes transmit packets at the same time and some packets are lost due to interference.

Efficient broadcasting schemes such as the proposed RDBR schemes are less vulnerable to collision because they eliminate redundant retransmissions, while broadcasting schemes such as Flooding, and DB schemes, suffer mainly from contention because they generate a lot of redundant retransmissions. Reducing the number of redundant retransmissions can help reduce the effects of collision, but not for those of contention. Contention can be reduced by reducing the number of retransmitting nodes in the network whereas collision can be reduced by using efficient waiting time schemes. As shown in Figure 6.9, both Flooding and DB schemes suffer from the contention and that is the reason why the number of retransmitting nodes started to decreases with increasing traffic load. On the other hand, RDBR schemes uses a fixed number of retransmitting nodes and distance based defer time scheme both of which help to reduce the effect of contention. This explains why the number retransmitting nodes remains constant with increasing traffic load. As for the effect of collision, the delivery ratio of RDBR schemes starts to decrease with increasing traffic load as shown in previous section.

In summary, the proposed RDBR schemes are less sensitive to increasing traffic load when compared to both Flooding and DB schemes. This is due to the fact that the proposed RDBR schemes generate less or no redundant retransmissions which in turn reduce both contention and collision in the network. In the contrary, both Flooding and DB schemes suffer from increasing traffic load due to large number of redundant retransmissions generated by these schemes.

6.8 Combined Networks

In the previous three sections, the focus was on particular network conditions by varying node density, traffic load and node mobility. In order to eliminate the effect of one performance parameter on another, only one performance parameter was varied while the remaining parameters were fixed. The disadvantage of this approach is that different sets of constant performance parameters may have different behavior. Furthermore, focusing on a particular network condition without considering a combination of multiple performance parameters one misses the combined effects of node density, traffic load and node mobility on the performance of proposed schemes.

The aim of this group of experiments is to resolve those issues and concerns. To perform a comprehensive performance evaluation, a numerous combinations of node density, traffic load and node mobility were simulated. The trials technique which is widely used in the literature was used for evaluation [32][51][85]. Each trial is basically a combination of different network parameters. Five trials were used where trial 1 represents less severe network conditions while trial 5 represents most severe network conditions. The combination of different network parameters in form of trials demonstrates how the proposed broadcasting schemes react in real life scenarios. It allows us to measure the level of impact of each performance metric on the overall performance of each broadcasting scheme. It shows the limits of each broadcasting scheme for a specific network condition. In addition, it indicates which broadcasting scheme reacts best over a different range of network conditions.

6.8.1 Trials

This section investigates the effect of all three network parameters namely node density, node mobility and traffic load simultaneously on the performance of proposed schemes in terms of reachability, number of retransmitting nodes and end-to-end delay. The number of nodes in the network has been varied from 40 to 200 nodes. The maximum node speed in the network is varied over a range of 1, 5, 10, 15, and 20 m/sec while the pause time was fixed to zero. Traffic load rate of 10, 20, 40, 60 and 80 packets/sec were used to evaluate the effect of traffic load on the above performance metrics. The remaining simulation parameters are unchanged. Table 6.2 shows the combination of the all three network parameters in terms of trials.

Table 6.2: Trials Simulation Parameters

Trials	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
Number of nodes	40	80	120	160	200
Speed (m/s)	1	5	10	15	20
Traffic Rate (pkts/sec)	10	20	40	60	80

6.8.2 Delivery Ratio

Figure 6.10 shows delivery ratio for each broadcasting scheme in each trial. As the severity of the network increases, each broadcasting scheme has a “breaking point” in terms of its ability to deliver packets. As can be seen from Figure 6.10, Flooding achieves the highest delivery ratio among all broadcasting schemes for Trial 1 and achieves the third highest delivery ratio for Trial 2. However, the Flooding scheme collapses after Trial 2 and delivery ratio decreases until it reaches 40% for Trial 5. This is due to the fact that as the number of trial increases, the severity of the network increases in terms of number of nodes, traffic load and node mobility. Flooding schemes suffer from both contention and collision due to increased number of nodes, high mobility and redundant retransmissions. This indicates that the Flooding is not an efficient broadcasting scheme and it can’t operate under extreme condition due to broadcast storm problem.

The DB scheme achieves the second highest delivery ratio for Trial 1 and the highest delivery ratio for Trial 2. Likewise Flooding scheme, DB scheme also collapses after Trial 2. This is due to the fact that the DB scheme generates redundant retransmissions and therefore suffers from contention and collision. However, DB scheme achieves slightly better reachability than Flooding scheme. This is because DB scheme generates less redundant retransmission compared to Flooding. The RDBR-3 scheme achieves the third highest delivery ratio for Trial 1 and second highest delivery ratio for Trial 2. Unlike both Flooding and DB schemes, RDBR-3 scheme does not collapse after Trial 2. It achieves the highest delivery ratio for Trial 3. However, the delivery ratio of RDBR-3 scheme starts to slightly decrease after Trial 3. The RDBR-3 scheme achieves the second highest delivery ratio for Trial 4 and fourth highest delivery ratio for Trial 5. The delivery ratio of RDBR-3 scheme for Trial 5 is above 80% which is much more than both Flooding and DB schemes. The reason why RDBR-3 scheme achieves the third highest delivery ratio for Trial 1 is because of low connectivity in the network (low node density). Furthermore, the reason why the delivery ratio of RDBR-3 scheme starts to decreases after Trial 3 is due to increased collision and contention as result of increased node density, node mobility and traffic load. This indicates that the proposed RDBR-3 scheme is scalable and energy efficient broadcasting scheme which is able to achieve a delivery ratio of more than 80% in very severe network conditions.

The RDBR-6 scheme achieves the fourth highest delivery ratio for both Trial 1 and Trial 2. Furthermore, it achieves the second highest delivery ratio for Trial 3 with the delivery ratio slightly less than RDBR-3 scheme. As for Trial 4 and 5, RDBR-6 scheme outperform RDBR-3 scheme by achieving the highest delivery ratio among all broadcasting scheme. The reason why RDBR-6 scheme outperform RDBR-3 scheme in severe network conditions (for Trial 4 to 5) is due to the fact that RDBR-6 scheme has more sectors than RDBR-3 and therefore the relaying area size of RDBR-6 is smaller than that of RDBR-3 scheme. The benefit of this in severe network conditions is that density of nodes is high and therefore the probability of finding a node at ideal location is very high. As a result, the collision among the nodes is less because the overlap is decreased as stated in Lemma 3.1. This indicates that the RDBR-6 scheme is even more efficient than RDBR-3 scheme in very severe network conditions. Furthermore, this also proves the Lemma 4.2 in which it is that stated increasing the number of sectors and node density will ensure high delivery ratio even in severe network conditions.

As for RDBR-9 and RDBR-12 schemes, the most remarkable observation is that both schemes outperform Flooding and DB scheme for Trial 3 and above. The RDBR-9 and RDBR-12 schemes also outperformed RDBR-3 scheme for Trial 5. This indicates that RDBR-9 and RDBR-12 schemes are efficient broadcasting schemes. The reason why the delivery ratio of RDBR-9 and RDBR-12 scheme was low for Trial 1 and Trial 2 is due to low connectivity and large number of sectors. Furthermore, the reason why RDBR-9 and RDBR-12 schemes outperformed RDBR-3 for Trial 5 is the same justification for RDBR-6 when it outperformed RDBR-3 scheme. However, the delivery ratio of RDBR-12 is less than RDBR-9 which is in turn less than RDBR-6 scheme for all trials and specifically for Trial 4 and 5. The is due to the fact that the number of sectors of RDBR-9 and RDBR-12 schemes are more than that of RDBR-6 and therefore the probability of finding a node at ideal location for a given node density is higher in RDBR-6 than both RDBR-9 and RDBR-12. In order for RDBR-9 and RDBR-12 scheme to achieve the same level of reachability of RDBR-6 or even outperform it, the number of nodes in the network must be beyond 200 nodes. However, this is a special condition and whenever this condition is met both RDBR-9 and RDBR-12 scheme probably outperform RDBR-6 scheme.

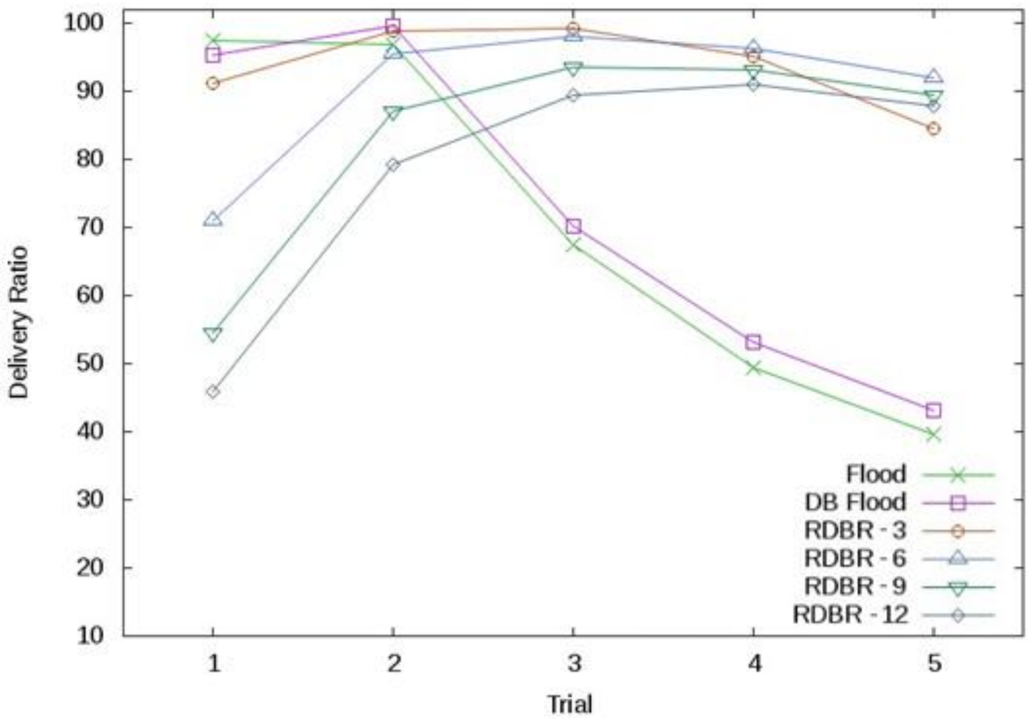


Figure 6.10: Delivery ratio as severity of network increases

6.8.3 Number of Retransmitting Nodes

Figure 6.11 shows the number of retransmitting nodes for each trial. The number of retransmitting nodes required by each broadcasting scheme increases as the severity of the network increases. This should be expected because as network severity increases the node density in the network increases and therefore the number of required retransmitting nodes by each broadcasting scheme also increases. The main observation about the number of retransmitting nodes for Flooding and DB is that as network severity increases the number of retransmitting nodes increases until it reaches Trial 3. After Trial 3, the level of increment in number of retransmitting node is less than the level of increment in Trials from 1 to 3. The reason is that the delivery ratio of both Flooding and DB scheme decreases as network severity increases (as shown in previous section) which in turn affect the number of retransmitting node.

Another reason is as stated earlier, the increased contention and collision due to increased node density, node mobility and traffic load.

As for RDBR schemes, the number of retransmitting nodes also increase with increasing network severity. RDBR-3 scheme required more retransmitting node followed by RDBR-6, RDBR-9 and RDBR-12, respectively. As stated earlier, RDBR schemes use fixed number of retransmitting node for each broadcast rely. However, the reason of increment in the number retransmitting node is due to increment in node density. This is already explained in Section 6.8.1.1. There are two main observations about RDBR schemes: First, the number of retransmitting node required by RDBR-3 scheme increases with increasing network severity until it reaches Trial 4 after which the number of retransmitting node decreases. Second, the number of retransmitting node required by RDBR-6, 9 and 12 are less than that of RDBR-3 given that these schemes outperformed RDBR-3 in terms of delivery ratio (see previous section). The reason why the number of retransmitting node required by RDBR-3 scheme decreases after Trial 4 is because the delivery ratio of RDBR-3 scheme was dropped after Trial 4 as shown in previous section.

Furthermore, one of the reasons why other RDBR schemes require less number of retransmitting node than RDBR-3 scheme despite the fact they achieve higher reachability than RDBR-3 scheme is due to the minimum overlapping between neighboring nodes. In fact, RDBR-6, RDBR-9 and RDBR-12 schemes didn't outperform RDBR-3 scheme by achieving higher reachability instead they managed to overcome the effect of contention and collision. All RDBR schemes other than RDBR-3 scheme are less susceptive to collision and contention because these schemes use less number of retransmitting nodes due to low density. This can be seen in Figure 6.11 in which all RDBR-6, RDBR-9 and RDBR-12 schemes achieved high reachability but not 100% reachability due to low node density whereas other nodes achieved almost 100% reachability due to absence of high traffic load. This indicates that RDBR-6, RDBR-9 and RDBR-12 schemes are more efficient than the remaining broadcasting schemes and even more efficient that RDBR-3 in severe networks conditions.

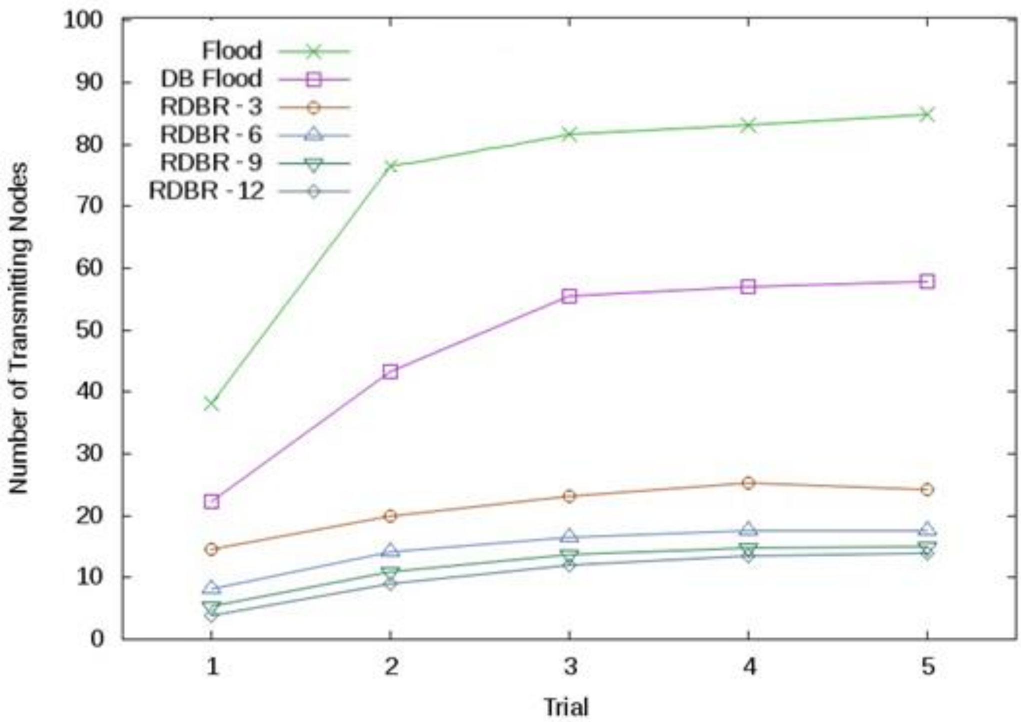


Figure 6.11: The number of retransmitting nodes as severity of network increases

6.8.4 End-to-end Delay

Figure 6.12 shows end to end delay as network severity increases. The end-to-end delay results follow the trends shown in Figure 6.12. The end-to-end delay by each broadcasting scheme increases as the severity of the network increases. This should be expected because as network severity increases, contention and collision in the network also increases and as a result the end-to-end delay of each broadcasting scheme also increases. However, the main observation from Figure 6.12 is that the end-to-end delay of both Flooding and DB schemes increase exponentially with increasing network severity whereas the end-to-end delay of RDBR scheme is much less than both the schemes. The end-to-end delay of both Flooding and DB schemes starts to exponentially increase after Trial 2. This is due to the fact that as trials increase the number of nodes, mobility and traffic load also increases in the network. As a result, contention and collision increases in the network which eventually results in increased delay.

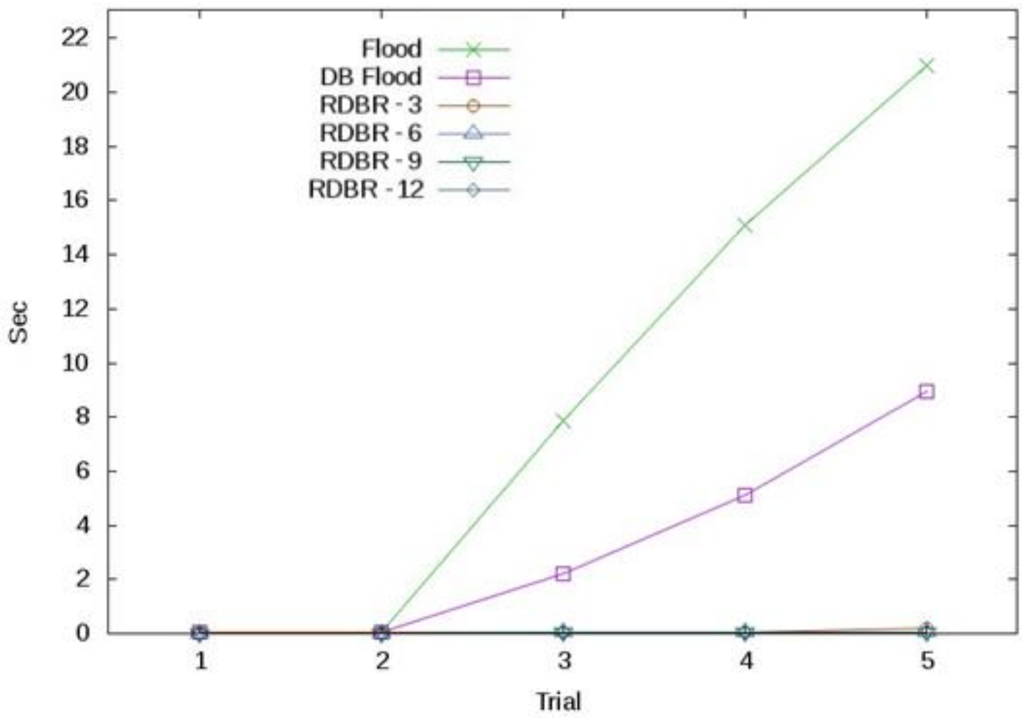


Figure 6.12: End-to-end delay as severity of network increases

As stated earlier, Flooding and DB schemes rely on redundant retransmissions to achieve high reachability and when network severity increases the situation gets worsen. More nodes try to rebroadcast at the same time which causes both contention and collision. On the other hand, RDBR schemes are less susceptive to contention and collision as shown in previous two sections and generate less delay. This indicates that RDBR schemes are more robust in severe network conditions than both Flooding and DB schemes. Among the RDBR schemes, RDBR-6 and RDBR-9 and RDBR-12 are the best performers as they achieved the highest reachability among all broadcasting node whiling requiring less retransmitting nodes and reduced delay. Furthermore, RDBR-6 scheme is the most robust among all broadcasting scheme due to high reachability and low end-to-end delay.

In summary, the proposed RDBR schemes were able to outperform both Flooding and DB scheme in extreme network conditions with high node density, high node mobility and high traffic load. However, the main observation was that the proposed improved RDBR-6 scheme was able to outperform RDBR-3 scheme in terms of delivery, number of retransmitting nodes and end-to-end delay in Trials 4-5. The reason behind this is that the proposed improved RDBR-6 scheme was originally designed to reduce contentions and collision in the system by reducing the overlap between neighboring nodes. This was possible by using the concept of gaps which was proposed in this research work.

Chapter 7: Conclusion and Future Work

In this dissertation, the broadcast storm problem and conventional ad hoc based broadcasting schemes were studied in details. New efficient ad hoc based broadcasting schemes have been proposed to overcome problems with existing broadcasting schemes such as higher redundant retransmissions, higher end-to-end delay, contention, collision, bandwidth consumption and energy consumption. The RDBR schemes have been proposed to provide efficient broadcasting in critical ad hoc environment without relying on topology, location and AoA information using directional antennas. Unlike RDBR scheme, the improved RDBR scheme was able to solve the contention and collision problems in high density, mobility and traffic environments. Some important findings and future work are also presented in this chapter.

7.1 Conclusion

Mobile ad hoc networks have gained increasing attention lately by both academia and industry to utilize MANET in critical environments such as military, sensor networks and disaster recover. This is not surprising, given the ability of ad hoc networks to construct efficient networks without requiring any pre-configurations or physical infrastructure. The performance of mobile ad hoc networks greatly depends on the message dissemination technique being used. Broadcasting forms the basis for many message dissemination techniques in MANET. Therefore, in order to increase the delivery ratio and decrease packet loss, it is crucial to design an efficient broadcasting scheme that can suppress the broadcast redundancy significantly while maintaining high reachability. However, achieving high reachability while reducing both redundant retransmission and end-to-end delay is a challenging problem. The problem gets even more sophisticated in absence of topology, location and AoA information.

The major focus of this research dissertation is to investigate an efficient ad hoc based broadcasting scheme for critical environments using directional antennas without relying on node location, network topology and AoA calculations. In this dissertation, an efficient ad hoc based broadcasting scheme, called Random Directional Broadcasting Relay (RDBR), is proposed. The RDBR scheme is able to reduce the number of rebroadcasting nodes and end-to-end delay while achieving high reachability. In order to further improve the performance of the proposed RDBR scheme in complex environments with high node density and high traffic load, an improved RDBR scheme is proposed. Both proposed schemes focus on the reduction of the number of redundant retransmissions, end-to-end delay, bandwidth consumption and energy consumption by selecting a subset of neighboring nodes to relay the packet using directional antennas without relying on node location, network topology and complex angle-of-arrival (AoA) calculations. The improved RDBR scheme uses a concept of “gaps” to minimize the overlap between selected relaying nodes in high density environments. The concept of “gaps” is able to reduce both contention and collision and at the same time achieve high reachability in high density environment.

The proposed RDBR schemes use the fixed beam directional antenna model to transmit messages among neighboring nodes. However, any other directional antenna model can be used such as single beam or adaptive beam directional antenna models. Directional antennas have shown their ability in better utilization of scare network resources such as bandwidth and energy consumption. Furthermore, directional antennas also showed their ability in minimizing wireless interferences between neighboring nodes when compared to omni-directional antennas. In this work, the directional antennas are only used to overcome the absence of GPS location, i.e. other features of directional antenna such as longer transmission range are not used.

Extensive simulation based performance evaluations have been conducted to investigate the performance of the proposed RDBR schemes using Random Walkway mobility model. The performance of the proposed RDBR schemes is compared with flooding and Distance-based schemes both of which utilize omni-directional antennas for transmission. Simulation results show that both proposed RDBR and improved RDBR schemes achieve high reachability while reducing end-to-end delay and the number of retransmitting nodes especially in high density environments. In addition to the performance improvements achieved by RDBR schemes over existing schemes, the main observation however is that the performance improvements of RDBR schemes do not come at the cost of extra overhead whether it is communication cost or computing power. This feature represents the key achievement of this research work and proves the efficiency of the proposed RDBR schemes. The main contributions of this research work can be summarized as follows:

(1) Investigation of the efficiency of broadcasting relay in critical ad hoc network environment using theoretical modeling and analysis basis. Note that the most research works in this field are evaluated by simulations. The theoretical model and analytical evaluations presented in this dissertation are able to provide an alternative approach for future research work in this field.

(2) This research work has investigated the impact of node location and broadcasting angle on the efficiency of broadcasting relay in critical ad hoc environment using theoretical analysis. Furthermore, the impact of nodes displacement from ideal locations on the total coverage area in terms of distance and angle has also been investigated theoretically.

(3) In this research work, two efficient ad hoc based broadcasting schemes are proposed i.e. RDBR and improved RDBR schemes. The proposed schemes are more suitable to be deployed in hostile environments such as disaster evacuation and military operations.

(4) In this work, different directional antennas models have been discussed and the widely multi-beam directional antenna model has been used in this study. The proposed RDBR schemes do not put any condition on the type of antenna to be used. Any directional antenna model can be used. The directional antennas model was implemented in NS-2 environment.

(5) The performance of the proposed schemes has been compared with flooding and distance-based schemes in terms of reachability, end-to-end delay and number of retransmitting nodes. Furthermore, simulation evaluations are associated with the theoretical analysis as the justification, especially the impact of host mobility, host location and broadcasting angle.

7.2 Future Work

The theoretical analysis and simulation results presented in this dissertation have demonstrated the efficiency of the proposed RDBR scheme and its improved version. However, several future works open up to improve the performance of the proposed RDBR schemes. This section briefly discusses some of the possible future works to improve the proposed RDBR schemes. This research work can be extended along the following research directions.

7.2.1 Considering disconnected network problem:

Even though this work uses directional antenna for transmitting packets among neighboring nodes, it does not consider the disconnected network problem. This problem can arise due to several factors such as battery drainage, high mobility and low node density. Directional antennas have the capability to reach out far nodes by concentrating the signal to specific direction. In the future, we are planning to extend this work to tackle the disconnected network problem by utilizing long range of directional antennas. This can be done by using sweeping feature of directional antennas. Instead of using all beams of directional antennas together which equally distribute the energy of the antennas, sweeping of beams can be used to reach out far away nodes by concentrating energy in each direction. Unlike existing schemes which may face sweeping delay due to large number of antennas beams being used, the proposed RDBR scheme may require the least delay due to the limited number of antennas beams.

To further improve the performance of the proposed RDBR schemes in terms of improving the bandwidth utilization and reducing the interference between neighboring nodes. We plan to enhance the proposed RDBR schemes by utilizing an adaptive directional antenna model in which the beamforming angle θ is dynamically adjusted to make it more suitable to the local node density environment. In fact, adaptive directional antennas have the capability of adjusting the width of beams as well as changing the direction of beams towards the intended destination.

7.2.2 Considering non-uniform distribution of nodes:

In this research work, the proposed RDBR schemes were tested in ad hoc network environment in which nodes were uniformly distributed. However, it would be an interesting future work to test the proposed RDBR scheme in more sophisticated ad hoc environments were nodes are distributed arbitrary i.e. nodes are not evenly distributed in the network. This represents a diverse network topology in which part or parts of the network significantly differ in mobile nodes density volumes. Several factors such as node mobility, battery drainage, and node destructions may lead to nodes to be non-uniformly distributed. The proposed original RDBR scheme might not face a big problem tackling this problem due to the large transmission range of each directional antenna beam. However, the main problem occurs in improved RDBR scheme in which the number of directional antennas is six or even more.

In improved RDBR scheme, the node randomly selects 3 sectors out of 6 sectors are potential relaying sector. The remaining sectors on the other hand just drop the packet and does not rebroadcast. The problem here is that the random selection of sectors may lead in selection of sectors with no nodes or sectors with few nodes which are located at close distance to the source node. This will greatly affect the performance of the proposed improved RDBR scheme in terms of delivery ratio. In future work, we are planning to further investigate this problem and come up with better solution to solve this problem. One possible solution would be selecting the gaps as relying sectors in case the source node does not hear back from a particular directional antenna beam. It would be interesting to investigate the effect of selecting a neighboring gap as relaying sector instead of the original sector which does not contain any node.

7.2.3 Considering different mobility models:

In this research work, only the widely used Random Walkway Mobility (RWM) model was used to measure the performance of the proposed schemes. The proposed schemes were able to remain stable under different mobility levels. It would be interesting to measure the performance of the RDBR schemes using different mobility models. This could be an important future work as different ad hoc environments may need different mobility model which suits that particular environment.

7.2.4 Considering different network settings:

In this research work, the proposed schemes were developed assuming a unit disk representation of the transmission range. It would be interesting to consider a non-disk representation of the transmission range where obstacle are present. Furthermore, in the proposed distance-based defer time, only the distance was considered as the criteria to select the relaying nodes. However, this might lead to a situation where the same node will be selected as relaying nodes several times which will greatly consume the limited battery power of that particular node. Therefore, it would be interesting to include the remaining battery power of the node as a criteria to select relaying nodes. Other important parameters that need to be considered in the future work include: Fault tolerance, QoS and opportunistic networks.

Bibliography

[1] Chen, X., Faloutsos, M., & Krishnamurthy, S. (2002). Distance adaptive (dad) broadcasting for ad hoc networks. In *MILCOM 2002. Proceedings* (Vol. 2, pp. 879-883). IEEE.

[2] Cao, Z., Ji, Z. Z., & Hu, M. Z. (2007). An energy-aware broadcast scheme for directed diffusion in wireless sensor network. *Journal of Communication and Computer*, *4*(5), 28-35.

[3] Kathiravan, K., Thamaral, S., & Reshm, R. (2007). Efficient Broadcasting in MANETs Using Directional Antennas. *Ubiquitous Computing and Communication Journal*, *2*(2), 1-7.

[4] Tilak, S., Murphy, A., & Heinzelman, W. (2003). Non-uniform information dissemination for sensor networks. *In Proceedings of the 11th IEEE International Conference on Network Protocols* (ICNP'03), (pp. 295-304).

[5] Reina, D. G., Toral, S. L., Barrero, F., Bessis, N., & Asimakopoulou, E. (2011). Evaluation of ad hoc networks in disaster scenarios. In *Third International Conference on Intelligent Networking and Collaborative Systems (INCoS),* (pp. 759-764).

[6] Frater, M., & Ryan, M. J. (2001). *Communications Electronic Warfare and the Digitised Battlefield*. Land Warfare Studies Centre.

[7] *Boukerche , A. (2008). Algorithms and Protocols for wireless and mobile ad hoc networks, Wiley&Sons, 2008.*

[8] Hoebeke, J., Moerman, I., Dhoedt, B., & Demeester, P. (2004). An overview of mobile ad hoc networks: applications and challenges. *Journal of the Communications Network*, *3*(3), 60-66.

[9] Basagni, S., Conti, M., Giordano, S., & Stojmenovic, I. (Eds.). (2004). *Mobile ad hoc networking*. John Wiley & Sons. IEEE Press, New York.

[10] John, H. (2012). NGL Advanced Tactical Jamming for Next-Generation Warfare. Journal of Electronic Defense, 35(6), p32-45.

[11] Schilling, D. L., Chang, S., Lomp, G. R., & Lundberg, L. A. (1990). High Data Rate Meteor-Burst Communications. *IETE Journal of Research*, *36*(5-6), 471-476.

[12] Ni, S., Tseng, Y., Chen, Y. & Sheu, J. (1999). The Broadcast Storm Problem in a Mobile Ad Hoc Networks. In: Proc. of the Annual ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM), pp. 151–162. IEEE Computer Society Press, Los Alamitos.

[13] Sun, M. T., Feng, W., & Lai, T. H. (2001). Location aided broadcast in wireless ad hoc networks. *In Proc. of Global Telecommunications Conference, GLOBECOM'01. IEEE* (Vol. 5, pp. 2842-2846).

[14] Lim, H., & Kim, C. (2001). Flooding in wireless ad hoc networks. *Journal of Computer Communications*, *24*(3), 353-363.

[15] Tseng, Y. C., Ni, S. Y., Chen, Y. S., & Sheu, J. P. (2002). The broadcast storm problem in a mobile ad hoc network. *Wireless networks*, *8*(2-3), 153-167.

[16] Tseng, Y.-C., Ni, S.-Y., & Shih, E.-Y. (2003). Adaptive Approaches to Relieving Broadcast Storms in a Wireless Multihop Ad Hoc Networks. IEEE Transactions on Computers. 52(5), 545–557.

[17] Peng, W., & Lu, X. C. (2000). On the reduction of broadcast redundancy in mobile ad hoc networks. In *Proceedings of the 1st ACM international symposium on Mobile ad hoc networking & computing* (pp. 129-130). IEEE Press.

[18] Lim, H., & Kim, C. (2000). Multicast tree construction and flooding in wireless ad hoc networks. In *Proceedings of the 3rd ACM international workshop on Modeling, analysis and simulation of wireless and mobile systems* (pp. 61-68). ACM.

[19] Wei, P., & Xicheng, L. (2001). Efficient broadcast in mobile ad hoc networks using connected dominating sets. *Journal of software*. 12, 4, 1265–1275.

[20] Lou, W. & Wu, J. (2002). On reducing broadcast redundancy in ad hoc wireless networks. *IEEE Transactions on Mobile Computing*, vol. 1, no. 2, pp. 111–123.

[21] Sun, M. T., & Lai, T. H. (2002). Location aided broadcast in wireless ad hoc network systems. In *IEEE Wireless Communications and Networking Conference, (WCNC2002).* (Vol. 2, pp. 597-602).

[22] Ko, Y. B., & Vaidya, N. H. (1997). Using location information to improve routing in ad hoc networks. *Technical Report 97-013, CS Dept, Texas AM Univeristy.*

[23] Dommety, G., & Jain, R. (1998). Potential networking applications of global positioning systems (GPS). *arXiv preprint cs/9809079*.

[24] Capkun, S., Hamdi, M., & Hubaux, J.P. (2001). GPS-free positioning in mobile ad-hoc networks, Proceedings of the Hawaii International Conference on System Sciences. pp. 3481-3490.

[25] Wisitpongphan, N., & Tonguz, O. K. (2006). Scalable broadcast strategies for ad hoc routing protocols. In *1st International Symposium on Wireless Pervasive Computing,* (pp. 6-pp).

[26] Perkins, C. E., & Bhagwat, P. (1994). Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers. In *Proc. of the ACM SIGCOMM computer communication review* (Vol. 24, No. 4, pp. 234-244).

[27] Ho, C., Obraczka, K., Tsudik, G., & Viswanath, K. (1999). Flooding for reliable multicast in multi-hop ad hoc networks. In *Proceedings of the 3rd international workshop on discrete algorithms and methods for mobile computing and communications* (pp. 64-71).

[28] Ko, Y. B., & Vaidya, N. H. (2000). Location-Aided Routing (LAR) in mobile ad hoc networks. *Wireless networks, 6*(4), 307-321.

[29] Qayyum, A., Viennot, L., & Laouiti, A. (2002). Multipoint relaying for flooding broadcast messages in mobile wireless networks. In *Proceedings of the 35th Annual Hawaii International Conference on System Sciences, HICSS.* (pp. 3866-3875).

[30] Perkins, C., Belding-Royer, E., & Das, S. (2003). *Ad hoc on-demand distance vector (AODV) routing* (No. RFC 3561). IETF, Internet Draft, draft-ietf-manet-aodv-00.txt.

[31] Reina, D. G., Toral, S. L., Jonhson, P., & Barrero, F. (2013). Hybrid flooding scheme for mobile ad hoc networks. *IEEE Communications Letters, 17*(3), 592-595.

[32] Williams, B., & Camp, T. (2002). Comparison of broadcasting techniques for mobile ad hoc networks. In *Proceedings of the 3rd ACM international symposium on Mobile ad hoc networking & computing* (pp. 194-205).

[33] Wu, J., & Lou, W. (2003). Forward-node-set-based broadcast in clustered mobile ad hoc networks. *Wireless Communications and Mobile Computing, 3*(2), 155-173.

[34] Yi, Y., Gerla, M., & Kwon, T. J. (2003). Efficient flooding in ad hoc networks: a comparative performance study. In *Proc. of IEEE International Conference on Communications. ICC'03.* (Vol. 2, pp. 1059-1063)..

[35] Stojmenovic, I., & Wu, J. (2004). Broadcasting and activity scheduling in ad hoc networks. In. *Mobile Ad Hoc Networking*, IEEE Press and John Wiley & Sons, New York. Chapter 7. 205-229.

[36] Dube, R., Rais, C. D., Wang, K. Y., & Tripathi, S. K. (1997). Signal stability-based adaptive routing (SSA) for ad hoc mobile networks. *IEEE Personal communications*, *4*(1), 36-45.

[37] Ruiz, P., & Bouvry, P. (2015). Survey on Broadcast Algorithms for Mobile Ad Hoc Networks. *ACM Computing Surveys (CSUR)*, *48*(1), 8.

[38] Keshavarz-Haddad, A., Ribeiro, V., & Riedi, R. (2006). Color-based broadcasting for ad hoc networks. In *4th International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks,* (pp. 1-10).

[39] Chen, C., Hsu, C. K., & Wang, H. K. (2005). A distance-aware counter-based broadcast scheme for wireless ad hoc networks. In *Military Communications Conference, MILCOM 2005.* (pp. 1052-1058).

[40] Al-Humoud, S. O., Mackenzie, L. M., & Abdulai, J. (2008). Neighbourhood-aware counter-based broadcast scheme for wireless ad hoc networks. In *GLOBECOM Workshops,* (pp. 1-6).

[41] Liarokapis, D., & Shahrabi, A. (2009). A probability-based adaptive scheme for broadcasting in manets. In *Proceedings of the 6th International Conference on Mobile Technology, Application & Systems* (p. 46).

[42] Mohammed, A., Ould-Khaoua, M., & Mackenzie, L. (2007). An efficient counter-based broadcast scheme for mobile ad hoc networks. In *Formal Methods and Stochastic Models for Performance Evaluation* (pp. 275-283). Springer Berlin Heidelberg.

[43] Mohammed, A., Ould-Khaoua, M., Mackenzie, L. M., & Abdulai, J. (2007). Improving the performance of counter-based broadcast scheme for mobile ad hoc networks. In *Proc. of International Conference on Signal Processing and Communications, ICSPC,* (pp. 1403-1406).

[44] Mohammed, A., Ould-Khaoua, M., & Mackenzie, L. M. (2008). Improvement to efficient counter-based broadcast scheme through random assessment delay adaptation for MANETs. In *Second UKSIM European Symposium on Computer Modeling and Simulation, EMS'08.* (pp. 536-541).

[45] Mohammed, A., Ould-Khaoua, M., Mackenzie, L. M., & Abdulai, J. (2008). An adjusted counter-based broadcast scheme for mobile ad hoc networks. In *Tenth International Conference on Computer Modeling and Simulation, UKSIM.* (pp. 441-446).

[46] Cartigny, J., & Simplot, D. (2003). Border node retransmission based probabilistic broadcast protocols in ad-hoc networks. In *Proceedings of the 36th Annual Hawaii International Conference on System Sciences* (pp. 10-pp).

[47] Kasamatsu, D., Shinomiya, N., & Ohta, T. (2009). A broadcasting method considering battery lifetime and distance between nodes in MANET. In *29th IEEE International Conference on Distributed Computing Systems Workshops, ICDCS Workshops' 09.* (pp. 406-411).

[48] Kokuti, A., & Simon, V. (2012). Adaptive multihop broadcast protocols for ad hoc networks. In *8th International Symposium on Communication Systems, Networks & Digital Signal Processing (CSNDSP),* (pp. 1-6).

[49] Liarokapis, D., Shahrabi, A., & Komninos, A. (2009). DibA: An adaptive broadcasting scheme in mobile ad hoc networks. In *Seventh Annual Communication Networks and Services Research Conference, CNSR'09.* (pp. 224-231).

[50] Leng, S., Zhang, L., Yu, L. W., & Tan, C. H. (2005). An efficient broadcast relay scheme for MANETs. *Computer Communications*, *28*(5), 467-476.

[51] Liarokapis, D., Shahrabi, A., & Raeburn, C. (2008). Constant-width zones broadcast algorithm in mobile Ad-hoc networks. In *Network-Based Information Systems* (pp. 159-168). Springer Berlin Heidelberg.

[52] Kim, J. S., Zhang, Q., & Agrawal, D. P. (2004). Probabilistic broadcasting based on coverage area and neighbor confirmation in mobile ad hoc networks. In *Global Telecommunications Conference Workshops, GlobeCom.* (pp. 96-101).

[53] Ramanathan, R. (2001). On the performance of ad hoc networks with beamforming antennas. In *Proceedings of the 2nd ACM international symposium on Mobile ad hoc networking & computing* (pp. 95-105).

[54] Shen, J., Zheng, W., Wang, J., Xia, Z., & Fu, Z. (2013). Routing Protocols using Directional Antennas in Ad Hoc Networks: A Comparative Review. *International Journal of Grid and Distributed Computing*, *6*(5), 39-50.

[55] Dai, F., & Wu, J. (2006). Efficient broadcasting in ad hoc wireless networks using directional antennas. *IEEE Transactions on Parallel and Distributed Systems*, *17*(4), 335-347.

[56] Hu, C., Hong, Y., & Hou, J. (2003). On mitigating the broadcast storm problem with directional antennas. In *International Conference on Communications, ICC'03.* (Vol. 1, pp. 104-110).

[57] Joshi, T., Cordeiro, C., Vogety, S., Yin, J., Gossain, H., & Agrawal, D. P. (2004). Broadcasting over switched single beam antennas. In *Proc. of the 12th IEEE International Conference on Networks. (ICON 2004).* (Vol. 2, pp. 671-675).

[58] Garg, A., & Garg, M. (2012). Node Selection Based Broadcast in Manets to Improve the Efficiency. *International Journal of Computer Technology and Applications*, *3*(1), pp. 87-89.

[59] Shen, C. C., Huang, Z., & Jaikaeo, C. (2006). Directional broadcast for mobile ad hoc networks with percolation theory. *IEEE Transactions on Mobile Computing, , 5*(4), 317-332.

[60] Cartigny, J., Simplot-Ryl, D., & Stojmenović, I. (2004). An adaptive localized scheme for energy-efficient broadcasting in ad hoc networks with directional antennas. In *Personal Wireless Communications* (pp. 399-413). Springer Berlin Heidelberg.

[61] An, X., & Hekmat, R. (2009). Probabilistic-based message dissemination in ad-hoc and sensor networks using directional antennas. In *6th International Conference on Mobile Adhoc and Sensor Systems, MASS'09.* (pp. 432-438).

[62] Nasipuri, A., Ye, S., You, J., & Hiromoto, R. E. (2000). A MAC protocol for mobile ad hoc networks using directional antennas. In *Wireless Communications and Networking Conference, WCNC.* (Vol. 3, pp. 1214-1219).

[63] Ko, Y. B., Shankarkumar, V., & Vaidya, N. H. (2000). Medium access control protocols using directional antennas in ad hoc networks. In *Proc. of Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies. INFOCOM.* (Vol. 1, pp. 13-21).

[64] Ueda, T., Masayama, K., Horisawa, S., Kosuga, M., & Hasuike, K. (2002). Evaluating the performance of wireless ad hoc network testbed with smart antenna. In *4th International Workshop on Mobile and Wireless Communications Network,* (pp. 135-139).

[65] Wang, Y., & Garcia-Luna-Aceves, J. J. (2003). Broadcast traffic in ad hoc networks with directional antennas. In *Global Telecommunications Conference, GLOBECOM'03.* (Vol. 1, pp. 210-215).

[66] Choudhury, R. R., & Vaidya, N. H. (2004). Deafness: A MAC problem in ad hoc networks when using directional antennas. In *Proceedings of the 12th IEEE International Conference on Network Protocols, ICNP 2004.* (pp. 283-292).

[67] Nasipuri, A., Mandava, J., Manchala, H., & Hiromoto, R. E. (2000). On-demand routing using directional antennas in mobile ad hoc networks. In *Proceedings. Ninth International Conference on Computer Communications and Networks,* (pp. 535-541).

[68] Choudhury, R. R., & Vaidya, N. H. (2002). Ad hoc routing using directional antennas. In *Illinois Computer Systems Symposium (ICSS) May 2002, UIUC*.

[69] Kang, I., Poovendran, R., & Ladner, R. (2003). Power-efficient broadcast routing in adhoc networks using directional antennas: technology dependence and convergence issues. *University of Washington, Washington, USA, Tech. Rep. UWEETR-2003-0015*.

[70] Qian, L., Zhang, H., Wu, D., & Wang, J. (2014). A Novel Approach for Efficient Route Request Flooding in MANETs with Directional Antennas. In *International Conference on Soft Computing in Information Communication Technology* (pp. 107-112).

[71] Kathiravan, K., Thamaral, S., & Reshm, R. (2007). Efficient Broadcasting in MANETs Using Directional Antennas. *Ubiquitous Computing and Communication Journal*, *2*(2). pp. 1-7.

[72] Li, M., Ding, L., Shao, Y., Zhang, Z., & Li, B. (2010). On reducing broadcast transmission cost and redundancy in ad hoc wireless networks using directional antennas. *IEEE Transactions on Vehicular Technology*, *59*(3), 1433-1442.

[73] Yang, S., Wu, J., & Cardei, M. (2008). Efficient broadcast in MANETs using network coding and directional antennas. The IEEE 27th Conference on Computer Communications, pp. 1499-1507.

[74] Yang, S., Wu, J., & Dai, F. (2007). Efficient backbone construction methods in manets using directional antennas. In *27th International Conference on Distributed Computing Systems, ICDCS'07.* (pp. 45-45).

[75] Clark, B. N., Colbourn, C. J., & Johnson, D. S. (1990). Unit disk graphs. *Discrete mathematics*, *86*(1-3), 165-177.

[76] Broch, J., Maltz, D. A., Johnson, D. B., Hu, Y. C., & Jetcheva, J. (1998). A performance comparison of multi-hop wireless ad hoc network routing protocols. In *Proceedings of the 4th annual ACM/IEEE international conference on Mobile computing and networking* (pp. 85-97).

[77] Navidi, W., Camp, T., & Bauer, N. (2004). Improving the accuracy of random waypoint simulations through steady-state initialization. In *Proceedings of the 15th International Conference on Modeling and Simulation (MS'04)* (pp. 319-326). Marina Del Rey, California, USA, 2004.

[78] Fisher, M. L. (1985). An applications oriented guide to Lagrangian relaxation. *Interfaces*, *15*(2), 10-21.

[79] Guignard, M. (2008). *Lagrangian relaxation: A tutorial*. Retrieved from *http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.155.1317&rep=rep1&type=pdf*.

[80] The Network Simulator NS-2: www.isi.edu/nsnam/ns/

[81] Breslau, L., Estrin, D., Yu, H., Fall, K., Floyd, S., Heidemann, J., Helmy, A., Huang, P., McCanne, S., Varadhan, K. & Xu, Y. (2000). Advances in network simulation. *IEEE Computer*, (5), 59-67.

[82] ANSI/IEEE Std 802.11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification, 1999.

[83] Wieselthier, J. E., Nguyen, G. D., & Ephremides, A. (2002). Energy-limited wireless networking with directional antennas: the case of session-based multicasting. In *Proc. of Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies.* (Vol. 1, pp. 190-199).

[84] Zhang, X. M., Wang, E. B., Xia, J. J., & Sung, D. K. (2011). An estimated distance-based routing protocol for mobile ad hoc networks. *IEEE Transactions on Vehicular Technology*, *60*(7), 3473-3484.

[85] Barritt, B. J., Malakooti, B., & Guo, Z. (2006). Intelligent multiple-criteria broadcasting in mobile ad-hoc networks. In *Proc. of 31st IEEE Conference on Local Computer Networks,* (pp. 761-768).

[86] Boleng, J. (2001). Normalizing mobility characteristics and enabling adaptive protocols for ad hoc networks. In *Proceedings of the local and metropolitan area networks workshop (LANMAN)* (pp. 9-12).

[87] Bani-Yassein, M., Ould-Khaoua, M., Mackenzie, L. M., & Papanastasiou, S. (2006). Performance analysis of adjusted probabilistic broadcasting in mobile ad hoc networks. *International Journal of Wireless Information Networks*, *13*(2), 127-140.

[88] Kim, K. W., Kim, K. K., Han, C. M., Lee, M. M. O., & Kim, Y. K. (2008). An enhanced broadcasting algorithm in wireless ad-hoc networks. In *International Conference on Information Science and Security, ICISS.* (pp. 159-163).

[89] Scott, D. and Yasinsac, A. (2004). Dynamic Probabilistic Retransmission in Ad Hoc Networks. *Proc. Int'l Conf. Wireless Networks (ICWN)*, pp. 158-164.

[90] Peng, W., & Lu, X. (2001). AHBP: An efficient broadcast protocol for mobile ad hoc networks. *Journal of computer science and technology*, *16*(2), 114-125.

[91] Lou, W., & Wu, J. (2004). Double-covered broadcast (dcb): A simple reliable broadcast algorithm in manets. In *Twenty-third Annual Joint Conference of the IEEE Computer and Communications Societies, INFOCOM.* (Vol. 3, pp. 2084-2095).

[92] Ruiz, P. and Bouvry, P. (2010). Enhanced distance based broadcasting protocol with reduced energy consumption. In *Workshop on Optimization Issues in Energy Efficient Distributed Systems (OPTIM), part of the 2010 International Conference on High Performance Computing and Simulation (HPCS)*, 2010, pp. 249–258.

[93] Ruiz, P., & Bouvry, P. (2010b). Distributed energy self-adaptation in ad hoc networks. In *GLOBECOM Workshops (GC Wkshps),* (pp. 524-528).

List of Publications

Journal Articles:

- Ahmed Karam and Liren Zhang. Topology Discovery in Multi-hop Clustering Vehicular Networks, Computer Applications: An International Journal (CAIJ), Vol.2, No.3/4, November 2015.

- Ahmed Karam and Liren Zhang. Novel Random Directional Broadcast Relay Approach in Support of Wireless Ad Hoc Sensor Network with Serious Interferences. [Forth Coming]

- Ahmed Karam and Liren Zhang. A Novel Directional Antenna Based Broadcasting Scheme for Critical Ad hoc Environments. [Under Preparation]

Conference Papers:

- Ahmed Karam and Nader Mohamed. Middleware for mobile social networks: A survey. In *System Science (HICSS), 2012 45th Hawaii International Conference on* (pp. 1482-1490). IEEE, 2012.

- Ahmed Karam, Liren Zhang and Abderrahmane Lakas. An efficient broadcasting scheme in support of military ad hoc communications in battlefield. in Innovations in Information Technology (IIT), 2013 9th International Conference on. IEEE, 2013, pp. 78–83.

- Ahmed Karam, Liren Zhang and Abderrahmane Lakas. An Efficient Broadcasting Scheme for Military Operations Using Directional Antennas. The 5th International Conference on Connected Vehicles & Expo (ICCVE 2015), Oct. 2015.

- Liren Zhang and Ahmed Karam. UAV tracking moving target scene using on-board ISAR sensor. *Innovations in Information Technology (INNOVATIONS), 2014 10th International Conference on,* Al Ain, 2014, pp. 88-92.

- Ahmed Karam and Liren Zhang. An Efficient Broadcasting Scheme for Critical Environments Using Directional Antennas. [Under Preparation]