Development and Performance Analysis of Optimal Multipoint Relaying Algorithm for Noisy Mobile Ad Hoc Networks

تطوير و تحليل الأداء لخوارزمية التوصيل المتبع المثالية للشبكات اللاسلكية العشوائية المتنقلة المشوَّشة

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التفويـــض

أنا رامي عيسى عبد اللطيف الرداد ، أفوض جامعة عمان العربية للدراسات العليا بتزويد نسخ من أطروحتي للمكتبات أو المؤسسات أو الهيئات أو الأشخاص عند طلبها.

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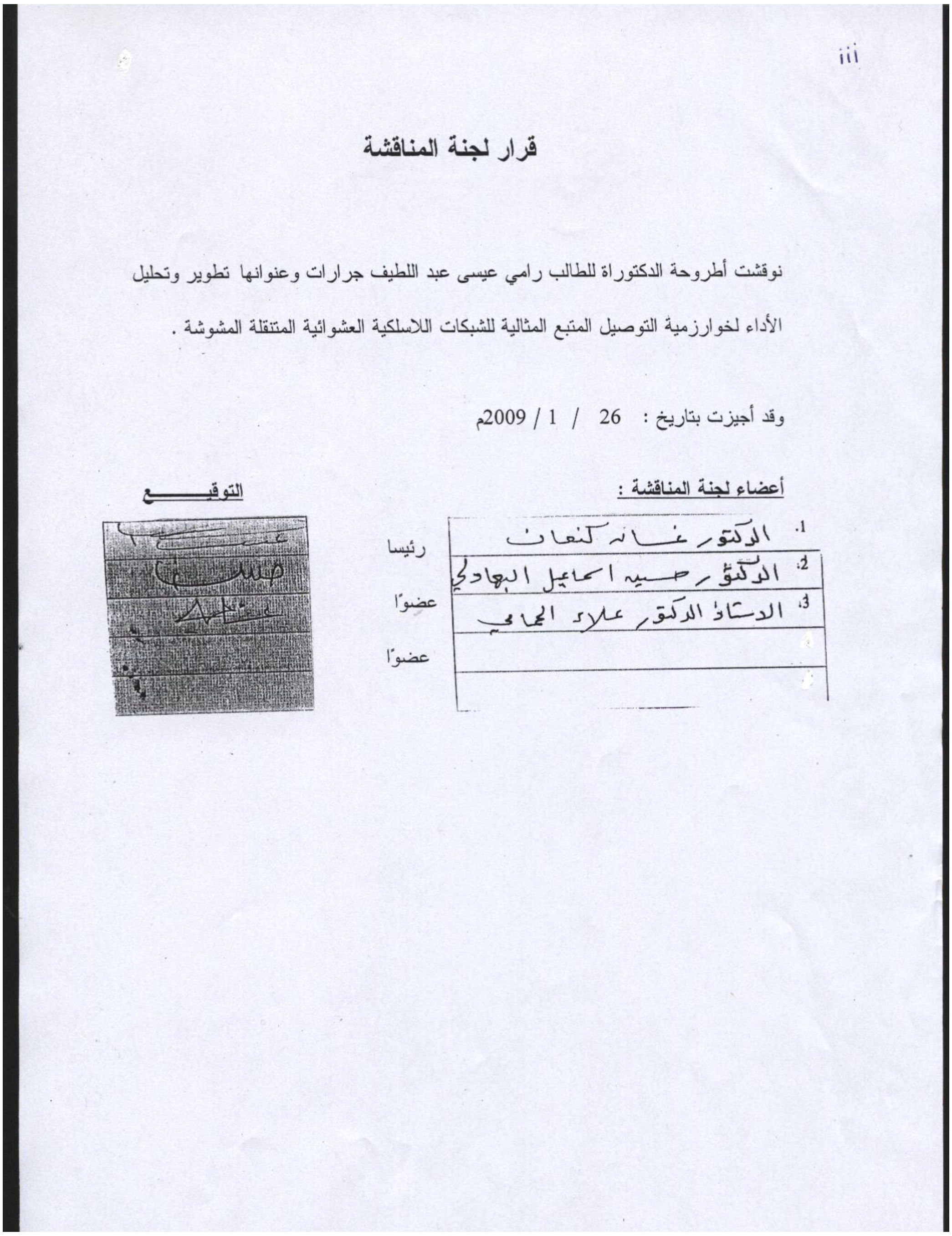

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قرار لجنة المناقشة

نوقشت أطروحة الدكتوراة للطالب رامي عيسى عبد اللطيف جرارات وعنوانها تطوير وتحليل الأداء لخوارزمية التوصيل المتبع المثالية للشبكات اللاسلكية العشوائية المتنقلة المشوشة .

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List of Abbreviations

ABR : Associated-Based Protocol

ACK : Acknowledgment

ADR : Average Duplicate Reception

AHBP : Ad Hoc Broadcast Protocol

AODV : Ad-Hoc On Demand Distance Vector

AP : Access Point

BER : Bit Error Rate

BRG : Broadcast Relay Gateway

BS : Base Station

CBRP : Cluster-Based Routing Protocol

CDS : Connected Dominating Set

CSMA : Carrier Sense Multiple Access

DS : Dominant Set

DSR : Dynamic Source Routing

IEEE : Institute of Electrical and Electronics Engineers.

IETF : Internet Engineering Task Force

LAR : Location Aided Routing

LENWB : Lightweight and Efficient Network-Wide Broadcast

MANET : Mobile Ad-hoc Network

MPR : Multipoint Relay

MPRDV : Multipoint Relay Distance Vector

OLSR : Optimized Link State Routing

OMPR : Optimal Multipoint Relaying

OPF : Optimized Flooding Protocol

PAN	:	Personal Area Network
PDA	:	Personal Digital Assistant
PDF	:	Probability Distribution Function
QoS	:	Quality of Service
RCH	:	Reachability
RERR	:	Route Error
RET	:	Number of Retransmission
RREP	:	Route Reply
RREQ	:	Route Request
RTS/CTS	:	Request To Send/Clear To Send
SBA	:	Scalable Broadcast Algorithm
SNR	:	Signal to Noise
SSR	:	Signal Stability Routing
TORA	:	Temporally Ordered Routing Algorithm
WAP	:	Wireless Access Point
WLAN	:	Wireless Local Area Network

Abstract

Multipoint Relaying (MPR) is a mechanism that can be used to reduce the number of retransmissions and maintain the reachability to all nodes while broadcasting a route discovery packet (i.e., route request (RREQ) packet) in wireless networks. The mechanism uses different heuristics to select the subset of the first-hop nodes set to forward the RREQ packet, so that the packet will be propagated to the whole network to maintain the highest possible reachability with less number of retransmissions. According to the heuristic that is used, three main types of MPR algorithms have developed, these are: (i) Connected Dominating Set (CDS)-based MPR (CDS-MPR), QoS-based MPR (QoS-MPR), and Optimized MPR algorithms.

It has been revealed in the literature that MPR algorithms, in general, demonstrate both simplicity and outstanding performance, as compared to other flooding optimization algorithms that are commonly used in wireless ad hoc networks. However, little efforts have been carried-out to investigate the performance of such algorithms in mobile ad hoc networks (MANETs) that suffer from wide range of packet-loss rate and node mobility.

The main objective of this work is to propose a new heuristic, which can be performed locally, for selecting an optimal set of first-hop neighbors to develop a cost-effective OMPR algorithm that efficiently diffuses RREQ packets in a MANET suffering from high packet-loss rate, due to the presence of noise and node mobility. The packet-loss rate is expressed in terms of reception probability (p_c), which is defined as the probability of a packet being successfully received by a node.

In order to compare and evaluate the performance of the new OMPR algorithm in a realistic MANET environment, four scenarios were simulated using the MANET simulator (MANSim). The first scenario compares the performance of the OMPR algorithm with other widely-used flooding optimization algorithms, such as: pure flooding, probabilistic flooding with fixed and dynamic

retransmission probabilities, location-aided routing scheme 1 (LAR-1), and hybrid LAR-1 and probabilistic (LAR-1P) algorithms.

The other three scenarios were aimed to investigate the effect of a number of parameters (e.g., node density (n_d), node mobility (u), and node radio transmission range (R), reception probability (p_c)) on the performance of the OMPR algorithm. In particular, the variation of number of retransmissions, average duplicate reception, and network reachability, with p_c for various n_d, u, and R were investigated in these scenarios.

The new OMPR algorithm demonstrates an excellent performance in dense, noisy, and high mobility networks when compared with other flooding optimization algorithms, as it achieves the highest cost-effective reachability. The main drawback of the OMPR algorithm is that it is very sensitive to noise-level; in fact it has the highest sensitivity to noise between all investigated algorithms. In addition, in this work, the limits of p_c up to which OMPR is able to ensure the diffusion of RREQ packets and still can guarantee satisfactory results under different realistic MANET environment, was studied.

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رامي جرادات

اشراف

الدكتور حسين البهادلي

Arabic Summary

الملخّص

الية التوصيل متعدد النقطة يمكن أن تُستَعملَ لتَخفيض عددِ الارسالات وتَبقي التوصيل إلى كُلّ العُقَد عند اذاعة حزمة إكتشافِ طريقِ في الشبكاتِ اللاسلكية. تَستعملُ الآليةُ طرق مختلفة لإخْتيارَ جزء من مجموعة العُقَدِ الجارة الأولى و التي تكون مسؤولة عن إرْسال حزمةِ إكتشافِ الطريقِ ، وبهذا فان الحزمة ستصل إلى كامل الشبكةِ باقل عدد من الارسالات. يمكن تصنيف الية التوصيل المتبع بناء على النهج المستخدم الى ثلاثة أنواعِ رئيسيةِ هي: المجموعة المهيمنة الموصولة، نوعية الخدمة، و المثالية.

الدراسات العلمية توضح ان خوارزمياتَ (MPR) عُموماً، تتميز بالبساطة والأداء البارز، بالمقارنة مع الخوارزمياتِ الأخرى التي تَستعملُ عموماً في الشبكاتِ اللاسلكيةِ. على أية حال، جُهود قليلة نُفّذتْ لتَحرّي أداءِ مثل هذه الخوارزمياتِ في الشبكاتِ المتنقلة العشوائية النقّالةِ التي تَعاني مِنْ تشكيلة واسعة من نسبةِ خسارةِ الحزمةِ وقابليةِ حركة العقدةِ.

إنّ الهدفَ الرئيسيَ من هذا العملِ هو أَنْ يَقترحَ طريقة جديدة، يُمْكِنُ أَنْ تنفذ محلياً، لإخْتيارَ مجموعة مثاليةَ مِنْ مجموعة العقد الجارة الاولى لتَطوير خوارزمية توصيل متبع مثالية (OMPR) تقوم بنشر حزم اكتشاف الطريق بشكل كفوء في الشبكات التي تَعاني مِنْ نسبةِ خسارةِ الحزمةِ العاليةِ، بسبب حضورِ قابليةِ حركة العقدةَ والضوضاءَ. إنّ نسبةَ خسارةِ الحزمةَ تم اعتبارها من ناحية إحتمالِ الإستقبالِ (pc)،التي يمكن تعريفها بإحتمال استلام الحزمة بنجاح.

لمقارنة و تقييم أداءَ الخوارزميةِ المقترحة الجديدة (OMPR) في بيئة واقعية، أربعة سيناريوهات تمت محاكاتها بإستعمال المحاكي (MANSIM). يُقارنُ السيناريو الأولُ أداءُ الخوارزميةِ بخوارزمياتِ اخرى ، مثل: الفيضان الصافي، فيضان إحتمالي بإحتمالاتِ إعادة الإرسالِ الثابتةِ والديناميةِ، مخطط توجيه بمساعدة الموقعِ هجين و مخطط توجيه بمساعدة الموقعِ إحتمالي.

السيناريوهات الأخرى الثلاثة هُدّفتْ لتَحرّي تأثيرِ عدد مِنْ البارامتراتِ مثل: كثافة العقد ، سرعة حركة العقد، ومدى إرسالِ العقد، إحتمال الإستقبالِ على أداءِ الخوارزميةِ (OMPR). بشكل خاص، إختلاف عددِ الارسالات، متوسط الإستقبال المضاعف و التوصيل على احتماليةالاستقبال (pc)

خوارزميةُ (OMPR) الجديدة بينت أداءاً ممتازاً في الشبكات ذات قابليةِ الحركة العاليةِ والصاخبةِ والكثيفةِ عند مقَارنتْها بالخوارزمياتِ الأخرى، بينما يُنجزُ التوصيل المربح الأعلى. إنّ العائقَ الرئيسيَ للخوارزميةِ بأنّها حسّاسُة جداً لمستوى التشويش، لذلك تمت دراسة حدود التشويش في الشبكات لتحديد قدرة الخوارزمية على ضمان إنتشارِ حزم اكتشاف الطريق في شبكات واقعية الظروف

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Chapter1

Introduction

1.1. Wireless Networks

Wireless networks usually consist of a number of wireless devices (e.g., computers, microprocessor-based devices, personal digital assistants (PDAs), mobile phones, or any digital devices with compatible communication capabilities) that are connected together without using wires [Bas 04, Tan 03, IEE 99]. Instead, they utilize radio waves to enable communication between devices in a limited coverage area. This allows communicated devices (also called nodes) to move around within the broad radio coverage area and still be connected to the network [Moh 05, Sun 01].

Wireless networks can be configured to operate in two modes [Mir 06, Tan 03]:

i. Infrastructure or Access Point (AP) mode: In this mode, nodes communicate with each other through a base station (BS) that works as a centralized controller.

ii. Infrastructureless or ad hoc mode: In this mode, nodes communicate with each other directly without relying on any infrastructure or centralized controller.

In the first configuration, a Wireless Access Point (WAP) is used as a centralized controller as shown in Figure (1.1). A WAP is a device that connects wireless devices together to form a wireless network, and it is usually connected to other wired networks to relay data between wired and wireless networks. Due to the nature of the radio links, nodes are allowed to be mobile within the WAP coverage area.

Furthermore, several WAPs can be linked together to form a larger network, similar to cellular mobile phone networks [Mir 06, Ily 03], that allows the exchange of data between devices connected to different BSs. As the node of one WAP travels into the range of another, a "hand off" occurs from the old WAP to the new one and the node is able to continue communication seamlessly throughout the network. Typical applications of this type of network include office and campus Wireless Local Area Networks (WLANs) [Moh 05, Ily 03].

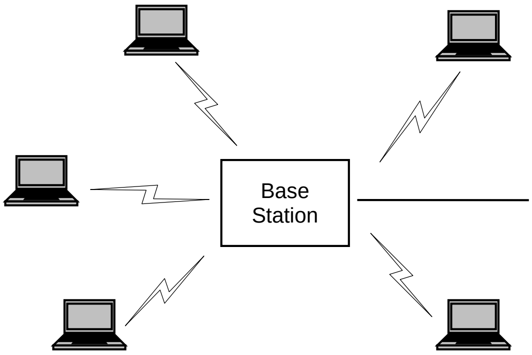


Figure (1.1) – Infrastructure (AP) network.

In contrast to the centralized control WAP networks, in ad hoc wireless networks, nodes manage themselves without the need for any WAP or centralized controller as shown in Figure (1.2). Once again, due to the nature of the radio links that connect nodes, nodes are allowed to move around, and therefore, such networks are also called mobile ad hoc networks (MANETs) [Par 03, Wu 03b].

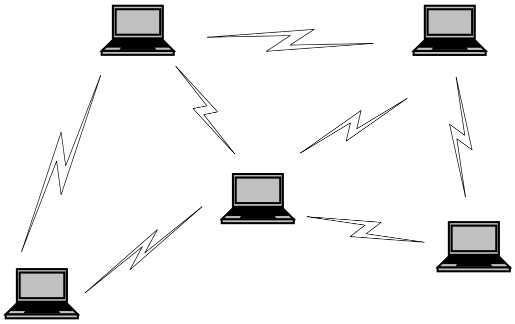


Figure (1.2) – Infrastructureless (ad hoc) network.

1.2 Mobile Ad Hoc Networks (MANETs)

A MANET is defined as a set of wireless mobile nodes that communicate with one another without relying on any pre-existing infrastructure or centralized control as shown in Figure (1.2) [Wu 06, Wu 03b, Tse 02]. The ad hoc network must autonomously determine its own configuration parameters including: addressing, routing, clustering, position identification, power control, etc [Moh 05]. In such configuration, due to the limited radio transmission range of each mobile node, it may be necessary for one mobile node to enlist the aid of other nodes in forwarding data packets to their destination.

A multi-hop network is a network in which the path from source to destination traverses several other nodes. Ad hoc networks often favor a sequence of short hops for obstacle negotiation, spectrum reuse, and energy conservation [Moh 05]. Figure (1.3) shows a multi-hop MANET consisting of three nodes A, B and C. Node B is in the transmission range of node A and node C, so it can communicate directly with them, however, nodes A and C cannot communicate and exchange information directly but via node B, in this scenario node B will function as a router.

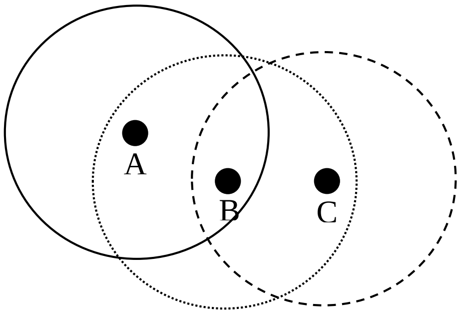


Figure (1.3): multi-hop MANET consists of three nodes A, B and C.

Thus, each mobile node operates not only as a host but also as a router using a specific routing mechanism (routing protocol) to efficiently and reliably forward data packets for other mobile nodes within the network, which may not be within the transmission range of the source node [Lou 02, Obr 01].

A routing protocol is defined as the algorithm by which a route is created to enable source and destination nodes to exchange data efficiently and reliably [Bas 04]. The efficiency of the routing protocol can dramatically affect the performance of the entire network in terms of bandwidth utilization, delay, and battery power consumption. Therefore, the process of route establishment should be done with a minimum complexity, overhead, and power consumption [Bas 04, Ily 03].

In MANET, nodes mobility results in a continuous change in network topology, and thereafter routes connecting nodes within the network continuously change, as shown in Figure (1.4). This requires more efficient routing algorithms for determining and maintaining new routes [Man 04, Roy 99].

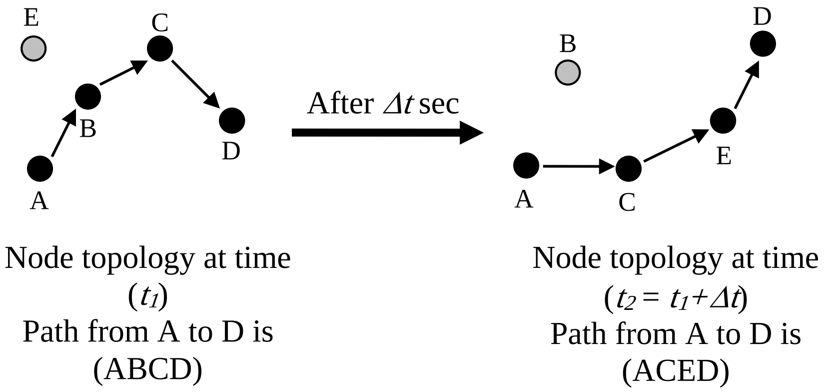


Figure (1.4): Change in network topology.

1.3 MANETs Applications, Challenges, and Limitations

During the last two decades, there has been a tremendous growth in the use of MANETs, not only due the development in the technology but also due to their high flexibility. MANETs can be used wherever there is a prompt need for establishing a networking environment for a limited duration of time. These networks provide cost-effective tremendous opportunities and can be used in numerous situations, particularly, where a communication infrastructure is non-existent or difficult to establish within timing constraints. They also provide an

alternative infrastructure in case of failure of the conventional one. Typical applications of MANETs include: industrial, commercial, academic, healthcare, military, search and rescue operations, and Personal Area Network (PAN) applications [Sar 07].

In general, the main challenges and limitations to the use of MANETs that need to be carefully considered may include [Sar 07, Moh 05]:

- Limited communication bandwidth and capacity.
- Limited battery power and lifetime.
- Size of the mobile devices.
- Information security.
- Communication overhead.
- Transmission errors.

1.4. Routing Protocols

A routing protocol is a part of the network layer software that is responsible for deciding which output path a packet should be transmitted on. Many routing protocols have been proposed for MANETs. These algorithms differ in the approach they use for searching a new route and/or modifying a known route, and each of them has its own unique characteristics, strengths and weaknesses [Mar 00, Pei 00, Jia 98, Ko 98, Par 98, Per 98, Dub 97, Joh 96, Mur 96, Ram 96, Per 94]. This section presents a comprehensive introduction to the MANETs routing protocols requirements, challenges, and classifications.

1.4.1 Requirements of MANETs Routing Protocols

The design of network protocols for MANETs is a complex issue. These networks need efficient algorithms to determine network organization (connectivity), link scheduling, and routing. The major requirements of routing protocols in MANETs can be summarized as follows [Bas 04]:

1. Minimum route acquisition delay
2. Quick route reconfiguration
3. Loop-free routing
4. Distributed routing approach
5. Minimum control overhead
6. Scalability
7. Provisioning of Quality-of-Service (QoS)
8. Support for time-sensitive traffic
9. Minimum energy consumption
10. Security and privacy

1.4.2 Challenges of MANETs Routing Protocols

The major challenges that a routing protocol for MANETs faces are mobility of nodes, bandwidth constraint, error-prone and shared channel, location dependent contention, and other resource constrains. In what follows a brief description is given for each of the challenges that are facing the developments of optimum routing protocols [Bas 04, Roy 99].

- Mobility: One of the most important properties of MANET is the mobility associated with the nodes. Nodes mobility results in many types of problems. A good routing protocol should be able to efficiently solve those problems.

- Bandwidth constraint: Since the channel is shared by all nodes in the broadcast region (any region in which all nodes can hear all other nodes), the bandwidth available per wireless link depends on the number of nodes and the traffic they handle. Thus, a fraction of the total bandwidth is available for every node.

- Error-prone and shared channel: The bit-error rate (BER) in a wireless channel is very high (of the order of 10^{-5} to 10^{-3}) compared to that in its wired counterparts (of the order of 10^{-12} to 10^{-9}). Routing protocols designed for MANETs should take this into account. Consideration of the state of the wireless link, signal-to-noise (SNR) ratio and path loss for routing MANETs can improve the efficiency of the routing protocol.

- Location-dependent contention: The load on the wireless channel varies with the number of nodes present in a given geographical region. This makes the contention for the channel higher when the number of nodes increases. The high contention for the channel results in a high number of collisions and a subsequent wastage of bandwidth. A routing protocol should have built-in mechanisms for distributing the network load uniformly across the network so that the formation of regions where channel contention is high can be avoided.

- Other resource constraints: The constraints on resources such as computing power, battery power, and buffer storage also limit the capability of a routing protocol.

1.4.3 Classification of Routing Protocols

Routing protocols can be classified into different categories according to their properties and applications. Classification of routing protocols into different categories is an important issue that needs to be carefully considered, since it helps researchers to understand distinctive characteristics of a routing protocol and find its fundamental relationship with each other.

There are different approaches that can be used in classifying MANET routing protocols, which are based on diverse criteria and from specific perspectives. However, routing protocols can be broadly classified into four categories based on [Roy 99]:

i. Routing information update mechanism.

ii. Temporal information.

iii. Topology information.

iv. Specific resources utilization.

The most widely used mechanism is that based on routing information update mechanism**.** Based on this mechanism, MANETs routing protocols can be classified into three major categories, these are [Ily 03]:

i. Proactive or static or table-driven routing protocols.

ii. Reactive or dynamic or on-demand routing protocols.

iii. Hybrid routing protocols.

In this thesis we are concerned with the route discovery process in reactive routing protocols; in the next section we review reactive routing protocols only. However, comprehensive reviews on the other routing protocols can be found in [Sar07, Tan 03, Roy 99].

1.4.4 Reactive routing protocols

Reactive routing protocols also called dynamic or on-demand routing protocols. Protocols that fall under this category do not maintain the network topology information. They obtain the necessary path when it is required, by using a connection establishment process. Hence these protocols do not exchange routing information periodically [Roy 99]. In fact, when a source wants to communicate with a particular destination, it invokes the route discovery mechanisms to find the path to the destination. The route remains valid till the destination is reachable or until the route is no longer needed.

Some of the popular reactive routing protocols are:

- Ad Hoc On-Demand Distance Vector (AODV) Routing [Per 98].
- Dynamic Source Routing (DSR) [Joh 96].

- Associated-Based Routing (ABR) [Lin 05].
- Signal Stability Routing (SSR) [Dub 97].
- Cluster-Based Routing Protocol (CBRP) [Jia 98]
- Temporally Ordered Routing Algorithm (TORA) [Par 98].
- Location-Aided Routing (LAR) [Ko 98].

Reactive routing protocols normally consist of two main phases, these are:

1. **Route discovery**. It is the mechanism by which a source node S obtains a route to a destination node D. Route discovery is used only when S attempts to send a data packet to D and does not already know a route to D.

2. **Route maintenance**. Route maintenance is the process of maintaining the existing route from initiating source node to the target destination node, against link failure due to dynamic network topology, or noise factors or both. The process is done using the route error (RERR) packets to inform the source node about link failure. When route maintenance indicates a source route is broken, S can attempt to use any other route it happens to know to D, or can reinitiate a new route discovery to find a new route. Route maintenance is used only when S is actually sending data packets to D.

1.5.Wireless Network Environments

The wireless network environment can be categorized, according to the presence of noise or packet-loss, into two types of environments; these are [Bah 07, Jar 07]:

- Noiseless (error-free) environment
- Noisy (error-prone) environment

1.5.1 Noiseless (Error-Free) Environment

Noiseless (error-free) environment represents an ideal network environment, in which it is assumed that all data transmitted by a source node is successfully and correctly received by a destination node. It can be characterized by the following axioms or assumptions [Jar 07, Kot 04]:

- The world is flat
- All radios have equal range, and their transmission range is circular
- Communication link symmetry
- Perfect link
- Signal strength is a simple function of distance.

1.5.2 Noisy (Error-Prune) Environment

Noisy (error-prone) environment represents a realistic network environment, in which the received signal will differ from the transmitted signal, due to various transmission impairments, such [Jar 07]:

i. Wireless signal attenuation (p_{att})

ii. Free space loss (p_{free})

iii. Thermal noise (p_{therm})

iv. Atmospheric absorption (p_{atm})

v. Multipath effect (p_{mult})

vi. Refraction (p_{ref})

All of these impairments are represented by a generic name, noise. The environment is called noisy environment. For modeling and simulation purposes, the noisy environment can be described by introducing a probability function, which is referred to as the probability of reception (p_c). It is defined as the probability that a wireless transmitted data survive being lost and successfully delivered to a destination node despite the presence of all or any of the above impairments. Thus, p_c can be calculated as:

$$p_c = p_{att} \cdot p_{free} \cdot p_{therm} \cdot p_{atm} \cdot p_{mult} \cdot p_{ref} \ldots\ldots \quad (1.1)$$

1.6.Route Discovery Algorithms in MANETs

Concept

This section introduces the concept of route discovery. To initiate a route discovery phase, the source node transmits a route request (RREQ) packet as a single local broadcast packet, which is received by (approximately) all nodes currently within wireless radio transmission range of the source node. Each RREQ packet identifies the source (initiator) and the destination (target) of the route discovery, and also contains a unique request sequence number or identification number (ID), determined by the source of the request. Each RREQ also contains a record listing the addresses of intermediate nodes through which this particular copy of the RREQ packet has been forwarded. This route record is initialized to an empty list by the source of the route discovery. In addition, the header of the RREQ packet contains information on the lifetime of the request. This is expressed in terms of the maximum number of intermediate nodes (hops count) that are allowed to forward the data packet from the source node to the destination node.

During the route discovery phase, each intermediate node reduces the hop count by 1. If at a particular intermediate node, the hops count approaches 0 before the RREQ reaches its destination, an error is detected and this is considered as an unsuccessful route discovery process. Then, this last node sends back a unicast route error (RERR) packet to the source. Upon receiving it, the source node initiates a new RREQ with different sequence number.

If the destination node is located and successfully receives the RREQ, the destination node sends back a unicast route reply (RREP) packet to the source node; otherwise, if the destination node is not located, then this is considered as an unsuccessful route discovery process and the source node should initiate a new RREQ with different sequence number. The RREP packet usually follows the same route followed by the first RREQ that has reached the destination, but in reverse order [Roy 99].

Figure 1.5 illustrates the route discovery process. Node S wants to find a route to node D; it broadcasts a RREQ packet by using flooding mechanism. RREQ is sent to all node S neighbors A, B, C and E. Each node forward the packet to its own neighbors until nodes D is reached. Node D sends the RREP packet (dashed arrow) only to node B and not to node F, since it received RREQ from B before F.

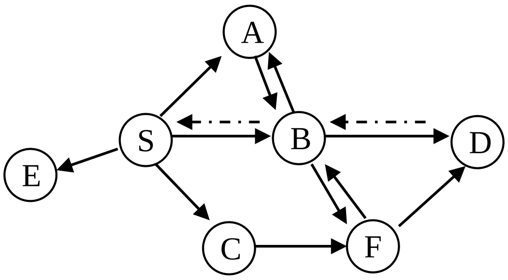


Figure (1.5): Route Discovery Process

Flooding is a fundamental communication primitive for exchanging topology information in proactive routing protocols and for route discovery in reactive routing protocols. Flooding algorithms can be classified into:

i. Pure flooding algorithm.

ii. Optimized flooding algorithms.

In what follows, we present an introduction to both pure and optimized flooding used in the route discovery process:

1.6.1 Pure Flooding Algorithm

One of the earliest flooding algorithms proposed in the literature is called “simple” or “blind” flooding, it is also known as “pure” flooding, in which each node retransmits the RREQ to its neighbors upon receiving it for the first time starting at the source node. In this protocol, nodes are allowed to retransmit the same packet only once (packets are identified through their sequence number). Figure (1.6) outlines this pure flooding broadcast algorithm [Ban 06, Sas 03].

Algorithm for pure flooding.

```
On receiving a RREQ packet at node i, do the following:
If  Ret(i)=0  Then
    Retransmit packet  // The node has not retransmitted the request before, Ret(i)=0
    Ret(i)=1  // Update the node retransmission index Ret(i) by equating it to 1
End if
```

Figure (1.6): Pure flooding algorithm.

Using pure flooding, it can be easily observed that the RREQ would reach every node that is reachable from a node S (potentially, all nodes in the network). It is obvious that pure flooding generates vast numbers of duplicate packets, some measures may be taken to damp the process. One such measure is to have a hop counter contained in the header of each packet, which is decremented at each hop, with the packet being discarded when the counter reaches zero. Ideally, the hop counter should be initialized to the length of the path from source to destination. If the sender does not know how long the path is, it can initialize the counter to the worst case, namely, the full diameter of the subnet.

It is obvious from the above discussion that the main advantages of pure flooding are its simplicity and reliability. But, despite the measures considered above, pure flooding still suffers from many drawbacks due to the large number of redundant rebroadcasts. This is because, in pure flooding, all nodes upon receiving the RREQ packet will be allowed to rebroadcast it only once, so that in a network of *n* reachable nodes, the number of rebroadcast is *n*-2. A straightforward flooding broadcast in wireless networks using the IEEE 802.11 protocols results in the following serious drawbacks [Tse 02]:

i. Duplicate reception: When a mobile node decides to rebroadcast a RREQ packet to its neighbors, all its neighbors may already have the same packet.

ii. Contentions: After a mobile node broadcasts a RREQ, if many of its neighbors decide to rebroadcast the packet, these transmissions (which are all from nearby nodes) may severely contend with each other.

iii. Collisions: Because of the deficiency of this mechanism, the lack of RTS/CTS dialogue, and the absence of collision detection, collisions are more likely to occur and cause more damage.

In 802.11 specifications, during route discovery, the only requirement made for broadcasting nodes is that they assess a clear channel before broadcasting, using the Carrier Sense Multiple Access (CSMA) protocol [Wil 02]. However, in congested networks, still a significant amount of collisions occur leading to many dropped packets due to the following reasons:

i. Clear channel assessment does not prevent collisions from hidden nodes.

ii. No resource is provided for collision avoidance when two neighbors assess a clear channel and transmit simultaneously.

iii. Lack of RTS/CTS dialogue, a node has no way of knowing whether a packet was successfully delivered to its neighbors, i.e., lack of acknowledgment (ACK).

Due to the nature of the flooding broadcast mechanism, the time required to find the optimum route connecting two nodes (i.e., route discovery between the source and the destination) is normally more than the time required for data packet transmission [Sas 03]. The main advantage of flooding is that it can always find the shortest path between sources and destinations, since topology packets have been through every possible path in parallel. However, the basic flooding mechanism can trigger a large number of packets forwarded in MANETs which will eventually overwhelm the network by redundant rebroadcasts, contention and collision. Thus, effective and efficient flooding algorithms always try to limit the probability of collisions and contention by limiting the number of retransmissions in the network.

1.6.2 Optimized Flooding Algorithms

There are several algorithms that have been proposed throughout the years to reduce the number of retransmission (redundant rebroadcasts); thereafter, duplicate reception, contentions, and collisions in MANETs. These include:

i. Probabilistic algorithms [Bah 07, Ban 05, Tse 02]
ii. Neighbor-knowledge algorithms
    a. Neighbor-designated algorithms
        - Multipoint relaying (MPR) algorithms [Wu 06, Adj 05, All 03, Qay 02]
    b. Self-pruning algorithms [Wu 03a, Lim 00]
iii. Area-based algorithms
    a. Location-based algorithms [Tse 02, Ko 98]
    b. Cluster-based algorithms [Tse 02, Kri 95]

In this work we will focus on MPR algorithms for flooding optimization during route discovery in dynamic routing protocols in noisy MANETs.

1.7. Neighbor-Knowledge Algorithms

Neighbor-knowledge algorithms can be classified as:

1. Neighbor-designated algorithms
2. Self-pruning algorithms

In neighbor-designated algorithms, a node that transmits a packet specifies which one of its one-hop neighbors should forward the packet, while in self-pruning algorithms, a node receiving a packet will decide whether or not to transmit the packet by itself. As an example of neighbor-designated algorithms are the MPR algorithms, which are the subject of this thesis. This section briefly introduces MPR algorithms and more details will be provided in Chapter 3 of this thesis.

1.7.1 MPR Algorithms

MPR algorithms are neighbor-designated algorithms that exhibit both efficiency and simplicity. Compared to other neighbor-knowledge broadcasting algorithms, MPR algorithms use a simple algorithm to calculate the forwarding nodes which makes it easy to implement. It can also significantly reduce the redundant broadcasting, thus efficiently delivering broadcast packets in both sparse and dense networks. MPR can be used in proactive protocols in order to optimize the flooding overhead of control traffic, and can also be used effectively for reactive MANET protocols in order to save overhead in route discovery [Lia 06a, All 03].

The idea behind MPR - as well as all flooding optimization techniques - is to achieve what pure flooding do with less number of duplicate message retransmissions. It defines a set of nodes called multipoint relays (MPRs) or relay nodes for each node in the network, these relay nodes are a subset of the one-hop neighbors of the node. They are responsible for forwarding the broadcast message upon receiving it for the first time, while non relay nodes will not forward the message.

With high transmission errors, some of the forwarding nodes may not receive the packet due to a transmission error; this may result in a failure of delivery of the broadcast packet to all nodes in the network. The optimized MPR algorithms usually reduce the number of redundant retransmissions at no cost of the network reachability.

Currently, many algorithms have been proposed to calculate the forwarding node set based on the MPR selection heuristic. These algorithms are put forward to improve different aspects of broadcasting performance in fixed-node wireless networks such as the number of forwarding nodes, collision avoidance, efficient power usage and quality of service (QoS). There are three main types of MPR algorithms, these are:

- Connected Dominating Set (CDS)-based MPR (CDS-MPR) algorithms.
- QoS-based MPR (QoS-MPR) algorithms.
- Optimized MPR algorithms

A detail explanation of these algorithms will be given in Chapter 3. However, this work is mainly concerned with the third class, namely, the optimized MPR algorithms.

1.8. Statement of Problem

It has been revealed in the literature that MPR algorithms demonstrate both simplicity and outstanding performance, as compared to other algorithms, in wireless ad hoc networks. However, little efforts have been carried-out to investigate the performance of such algorithms in MANETs that suffer from wide range of packet-loss rate and node mobility.

This work is aimed to develop, investigate, compare, and evaluate the performance of a new optimal MPR (OMPR) algorithm in noisy MANETs. The main objectives of this work can be summarized as follows: Develop a new optimal MPR algorithm that diffuses a broadcast packet in noisy MANETs such that the algorithm handles:

   a. Packet-loss rates (expressed in terms of p_c) due to radio transmission problems.

   b. Random node distribution.

   c. Node mobility

2. Evaluate and investigate the performance of the OMPR algorithm in a realistic and noisy MANET environment by running a number of simulations on the MANET simulator (MANSim) [Bah 08, Bah 07]. The simulations are aimed to estimate the variation of: (i) number of retransmissions (RET), (ii) average duplicate reception (ADR), and network reachability (RCH), with p_c for various (i) node densities (n_d), (ii) node mobility (u), and (iii) node radio transmission range (R).
3. Compare the performance of the OMPR algorithm with other flooding optimization algorithms, such as: pure flooding, probabilistic flooding, LAR-1, LAR-1P algorithms to demonstrate the efficiency and effectiveness of the OMPR algorithm.
4. Study the limits of p_c up to which the OMPR algorithm is able to ensure the diffusion of packets and can guarantee satisfactory results under different realistic and noisy MANET environment.

5.

1.9. Organization of the Thesis

This thesis is organized in five chapters. Chapter 1 provides an introduction to the general domain of this thesis. The rest of this thesis is organized as follows: Chapter 2 presents some of the previous work that is related to flooding optimization algorithms in MANETs, in particular, works that is related to the MPR algorithms.

Chapter 3 provides a description of the concept, cost, and classification of MPR algorithms. A detail description of the OMPR algorithm is given. Also, in chapter

3, an introduction is given for the MANET simulator (MANSim), which includes explanation of the network, mobility, computational, and algorithmic modules of MANSim. Finally, in Chapter 3, definitions of the network parameters, which are used to compare and evaluate the performance of the different flooding optimization algorithms, are given.

Chapter 4 presents a description and the simulation results obtained from MANSim for four different scenarios. The results obtained are discussed and presented in tables and graphs. Finally, in Chapter 5, based on the results obtained from the different simulations, conclusions are drawn and recommendations for future work are pointed-out

Chapter 2
Literature Reviews

2.1 Introduction

Flooding broadcast is a fundamental broadcast mechanism that is used in reactive and proactive mobile ad hoc networks (MANETs) routing protocols for route discovery and link state advertisement respectively [Avr 04]. Although flooding is extremely simple and easy to implement, it can be very costly and may lead to a serious problem known as “broadcast storm problem”. This problem is characterized by redundant packet retransmissions, network bandwidth contention, and collision [Tse 02].

A number of algorithms have been developed throughout the years to alleviate the flooding broadcast storm problem by inhibiting some nodes from rebroadcasting to reduce the number of retransmission, contention, and collision. These algorithms include: multipoint relaying (MPR) algorithms [Lia 06a, Wu 06, Adj 05, Har 05, All 03, Qay 02, Jac 02, Jac 01], probabilistic algorithms [Ban 05, Tse 02, Will 02], counter based algorithms [Tse 02], distance based algorithms [Tse 02, Wil 02], locations based algorithms [Tse 02, Ko 98], and cluster based algorithms [Bet 04, Jia 98].

In the next section, we review some of the research activities and development stages that are related to the MPR algorithms only. However, a comprehensive literature reviews on other flooding broadcast optimization algorithms can be found in [Tha 07, Jar 07, Tse 02, Wil 02].

2.2.A Review on Multipoint Relaying (MPR) Algorithms

A. Qayyum et. al. [Qay 02, Jac 01] developed an algorithm for flooding broadcast optimization in mobile wireless networks. It was developed to reduce the number of retransmissions while diffusing a broadcast message in the network. The technique restricts the forwarding of a message to a subset of the neighbor nodes instead of the whole set of neighbors. The problem is to find a subset of the neighboring nodes such that it covers the two-hop neighbors, each member in this set is called a multipoint relay (MPR). Therefore, they referred to this algorithm as MPR algorithm.

In MPR, each node uses the proposed algorithm to calculate its own set of relays, which is completely independent of the other nodes calculations. If the neighborhood of any node changes, it will update its MPR set to continue covering its two-hop neighbors. In MPR, each node must know about its one-hop and two-hop neighbors; periodic *HELLO* messages are used to maintain this knowledge. The authors proposed a greedy algorithm to select the MPRs:

1. Find all two-hop neighbors that can only be reached by one-hop neighbors. Assign those one-hop neighbors as MPRs.
2. Determine the resultant cover set (i.e., the set of two-hop neighbors that will receive the packet from the current MPR set).
3. From the remaining one-hop neighbors not yet in the MPR set, find the one that would cover the most two-hop neighbors not in the cover set.
4. Repeat from step 2 until all two-hop neighbors are covered.

In conclusion of their work, they found that in the range of error rate which is most common in wireless networks, MPR may give quite satisfactory results, with a tremendous gain in performance due to quite less traffic. The simulation results showed that MPR technique is superior over pure flooding scheme.

H. Lim and C. Kim [Lim 00] proposed two flooding methods, self pruning and dominant pruning. In self pruning each node knows about its one-hop neighbors via periodic *HELLO* messages, each node attaches its one-hop neighbors list with all its broadcast messages. Upon receiving a broadcast message, a node compares its own one-hop neighbors list with the node's it has heard from. A decision is made locally not to rebroadcast if no additional nodes is reached from its broadcast, in other words if its list of one-hop neighbors is the same as the node it has heard from. Dominant pruning extends the neighborhood knowledge to the two-hop neighbors and the decision of the forwarding nodes is made by the sender which will select a subset or all of its neighbors to be the forwarding nodes. Each one of the selected forwarding nodes will then decide its own forwarding nodes, given the knowledge of which neighbors have been already covered by the senders broadcast. Their performance analysis showed that both methods perform significantly better than blind flooding. Especially, dominant pruning performs close to the practically achievable best performance limit.

W. Peng and X. C. Lu [Pen 00] proposed a scalable broadcast algorithm (SBA) to enhance the performance of pure flooding in MANETs. All nodes must have knowledge of their one-hop and two-hop neighbors which is obtained via periodic *HELLO* messages. A node will use the neighbor knowledge to decide to forward or not. Upon receiving a broadcast message, a node will compare its list of neighbors with the sender's to determine if additional nodes are reached if it forwarded the message. The message is either not forwarded if no addition coverage is reached beyond the sender's coverage, or is scheduled for broadcasting after a random time. During this time, if the message is received from other sources, the node will again determine if additional nodes are reached by its rebroadcast given all the sources it has heard from. The process continues until the time expires and then the message will be sent.

J. Sucec and I. Marsic [Suc 00] proposed an approach to optimize the performance of flooding broadcast in multi-hop ad hoc networks, namely, The Lightweight and Efficient Network-Wide Broadcast (LENWB) protocol. The protocol requires one-hop and two-hop neighbor knowledge obtained via *HELLO* packets. However, instead of a node explicitly choosing nodes to rebroadcast, the decision is left to the receiving nodes. Each node must know which of its one-hop and two-hop neighbors have received the broadcast message from the source node and which neighbors have a higher priority to rebroadcast. The knowledge of this information lets a node determine which of its one-hop and two-hop neighbors are expected to rebroadcast. The priority is proportional to a node’s number of neighbors; the higher the node’s degree the higher the priority.

Since a node relies on its higher priority neighbors to rebroadcast, it can proactively compute if all of its lower priority neighbors will receive those rebroadcasts; if not, the node rebroadcasts.

They assessed the reliability of the LENWB algorithm under unreliable packet transmission conditions. Although, route discovery in on-demand routing protocols can tolerate a certain amount of unreliability in the RREQ packet propagation, the lack of reliability should not become so great that an excessive number of route discovery attempts need to be made in order for the source to learn a route to destination. Additionally, the impact of node mobility while NWB packets are propagating should be considered.

P. Jacquet et. al. [Jac 01] developed a proactive routing protocol for MANETs, namely, the optimized link state routing (OLSR) protocol that employs periodic exchange of messages to maintain topology information of the network at each node. OLSR uses the MPR technique to efficiently and economically flood its control messages and it provides optimal routes in terms of number of hops, which are immediately available when needed. The protocol is best suitable for large and dense MANETs. They showed that OLSR is an optimization over a pure link state protocol as it compacts the size of information sent in the messages, and furthermore, reduces the number of retransmissions to flood these messages in an entire network.

P. Jacquet et. al. [Jac 02] evaluated the performance of ad hoc proactive routing protocols and in particular the multipoint relay concept introduced in OLSR protocol [Jac 01] and basic link state protocols using full flooding. They considered two radio network models: the random graph model in which the main cause of link failure is the existence of random obstacles and the unit graph model in which the main cause of link failure is the attenuation of signals by distance.

W. Peng and X. C. Lu [Pen 02] proposed an efficient ad hoc broadcast protocol (AHBP). It is similar to MPR; it requires that all nodes have knowledge of their one and two-hop neighbors. In AHBP, only nodes that are selected as a broadcast relay gateway (BRG) within a broadcast packet header are allowed to rebroadcast the packet. BRGs are proactively chosen by the sender, which is a BRG itself. A BRG selects set of one-hop neighbors that most efficiently reach all nodes within the two-hop neighborhood as subsequent BRGs and for that it uses the MPR algorithm. AHBP differs from MPR in three ways:

1. In AHBP, the information about the selected set of BRGs from the one-hop neighbors set is delivered via the header of each broadcast packet. This allows a node to calculate the most effective BRG set at the time a broadcast packet is transmitted. In contrast, MPR informs one-hop neighbors of the MPR selection via *HELLO* packets.

2. In AHBP, when a node receives a broadcast packet and is listed as a BRG, the node uses two-hop neighbor knowledge to determine which neighbors also received the broadcast packet in the same transmission. These neighbors are considered already “covered” and are removed from the neighbor graph used to choose next hop BRGs. In contrast, MPRs are not chosen considering the source route of the broadcast packet.

3. AHBP is extended to account for high mobility networks. Suppose Node A receives a broadcast packet from Node B, and Node A does not list Node B as a neighbor (i.e., Node A and Node B have not yet exchanged *HELLO* packets). In AHBP-EX (extended AHBP), Node A will assume BRG status and rebroadcast the node. MPR could be similarly extended.

B. Williams and T. Camp [Wil 02] classified the existing broadcasting schemes into four categories: simple flooding, probability-based methods, area-based methods, and neighbor knowledge methods. Simple flooding requires each node to rebroadcast all packets. Probability-based methods use some basic understanding of the network topology to assign a probability to a node to rebroadcast. Area-based methods assume nodes have common transmission distances; a node will rebroadcast only if the rebroadcast will reach sufficient additional coverage area. Neighbor knowledge methods maintain state on their neighborhood, via *HELLO* packets, which is used in the decision to rebroadcast.

They discussed twelve algorithms for effective broadcasting, and compared four of them (one from each category) over a particular network conditions by varying network density, network mobility and network congestion.

G. Allard et. al. [All 03] showed that MPR can be used as well in reactive protocols in order to save overhead in route discovery. They specified a simple reactive protocol called multipoint relay distance vector (MPRDV) protocol. In MPRDV RREQs and RREPs are all flooded via MPRs. They both opened routes to their originators. Route repairs are performed by new RREQ flooding. They showed with simulation that the use of MPR flooding does not lead to the control traffic explosion that is experienced with basic reactive protocol in presence of frequent route discovery and failure and that MPR provide also another optimization since it tends to offer optimal routes to data packets and so increases the protocol performances.

V. K. Paruchuri et. al. [Par 03] proposed an optimized flooding protocol (OFP), based on a variation of the covering problem to minimize the unnecessary transmissions drastically and still be able to cover the whole region. OFP finds the minimum number of circles of radius R that covers the whole geographical area of the network, the nodes that are the nearest to the centers of the circles are the ones that will retransmit the broadcast packet. OFP assumes that each mobile node knows its location and that each broadcast packet contains two location fields, L1 and L2 in its header. Whenever a node transmits a broadcast packet, it sets L1 to the location of the node from which it received the packet and sets L2 to its own location. OFP does not need *HELLO* messages and hence it saves a significant amount of wireless bandwidth and incurs lesser overhead. The authors have presented simulation results that showed the efficiency of OFP and its scalability with respect to node density; it requires lesser number of transmissions at higher densities.

Adjih C. et. al. [Adj 05] described two algorithms for computing MPRs, Greedy algorithm [Qay 02] and Mini-ID MPR algorithm. Mini-ID algorithm is far from optimal but it has the advantage that the node can detect by itself whether or not

it belongs to the MPR set of a neighbor. It consists of selecting the nodes in the increasing order of their ID's (or any arbitrary increasing order), it works as follows: Start with an empty MPR set, and then check the neighbor nodes in the increasing order of their identifiers. If the current node covers a two-hop neighbor which was not yet covered by the current MPR set, then add the current node to the MPR set.

Adjih C. et. [Adj 05] proposed a connected dominating set (CDS) election algorithm based on MPR called (MPR-CDS). Unlike MPR, MPR-CDS algorithm does not require the last hop knowledge. The proposed algorithm requires a total ordering of the nodes. In this algorithm, a node decides that it is in the CDS if and only if:

- The node is smaller than all its neighbors
- Or it is a multipoint relay of its smallest neighbor.

They compared MPR-CDS with MPR algorithm described in [Qay 02]; the percentage of forwarding nodes in MPR algorithm was fewer than that in MPR-CDS by a minor amount.

The CDS-based broadcast algorithm is different from AHBP algorithm [Pen 02] in that it also considers the set of higher priority BRGs selected by the previous sender when calculating the BRGs. While AHBP only considers the source of the broadcast packet to determine a receiving node's initial cover set. It uses the same algorithm used in AHBP and MPR for its BRG's calculations.

O. Liang et. al. [Lia 06a] classified MPR schemes into three categories based on their objectives, these are: pure MPR schemes which is based on the original MPR selection heuristic; MPR based CDS scheme with the objective to reduce the number of forwarding nodes by generating connected dominant set (CDS) and QoS based MPR scheme which considers quality of service (Qos) constraints in the network by selecting MPRs that meet some QoS requirements

. They evaluated their performances in light of their costs. They concluded that MPR based broadcasting schemes provide different features based on different MPR selection criteria that can be customized to obtain different broadcast performances as required.

O. Liang et. al. [Lia 06b] proposed the gateway multipoint relays (GMPR) algorithm. As the original MPR algorithm, the GMPR also requires *HELLO* messages to be exchanged periodically in the network. The contents of the *HELLO* message used in both algorithms are similar. The only difference is that extra information is added in the GMPR’s *HELLO* messages to indicate the dominating state of a node. A node can be in one of the four dominating states: dominator, dominatee, connector and white node. A node is referred to as dominator if it is in the dominator state. Only nodes in the dominator and connector state relay broadcast packets and they form a CDS in the network. The GMPR constructs a CDS in two phases. In the first phase, a Maximal independent set (MIS) is generated in the network where nodes in the MIS are dominators and the nodes covered by dominators are dominatees. Initially, each node in the network is set to the white node state, and it becomes either a dominator or a dominatee subsequently based on the following steps:

- A white node *w* announces itself as a dominator if it has the largest node degree (number of one-hop neighbors) among all its white node neighbors (neighbors in the white node state) or it has no white node neighbors and dominators around.

- A white node *w* becomes a dominatee if a *HELLO* message has been received from a dominator *v*, and *v* has a larger node degree than *w*.

- A dominator *w* becomes a dominatee if a *HELLO* message has been received from another dominator *v*, and *v* has a larger node degree than *w*.

- A dominatee or a connector changes back to a white node if it has lost all dominators around.

The simulation results show that GMPR algorithm produces a smaller size CDS than the source-independent MPR in both sparse and dense networks.

O. Liang et. al. [Lia 06c] proposed an enhanced approach to the gateway multipoint relays (GMPR) algorithm to further reduce the CDS size. First, the extended *HELLO* messages to indicate node ID such that a dominator can have extra information about which dominators its one-hop dominatees or connectors belong to, and thus, a dominator knows whether all its one-hop neighbors have already been covered by another dominator and its connectors. Second, the self-pruning procedure used in the GMPR algorithm is enhanced such that a dominator *v* is eliminated from a CDS if all its one-hop neighbors can be covered by a two-hop away dominator *w* and the connectors “belong” to *w*, where *w* has a larger node degree than *v*, and the connectors are in the one-hop neighborhood of *v*. The simulation results showed that the enhanced algorithm generate a smaller size CDS while it still keeps a low message overhead.

J. Wu et. al. [Wu 06] provided several extensions to generate smaller CDS using complete two-hop information to cover each node’s two-hop neighbor set. They extended the notion of coverage in the original MPR and proved that the extended MPR has a constant local approximation ratio compared with a logarithmic local ratio in the original MPR. In addition, they showed that the extended MPR has a constant global probabilistic approximation ratio, while no such ratio exists in the original MPR and its existing extensions.

S. Crisostomo et. al. [Cri 08] compared two flooding techniques: MPRs and network coding (NC). Random linear network coding [Fra 06] can be viewed as a distributed method for combining different data flows. The basic principle is that each node in the network selects independently and randomly a set of coefficients and uses them to form linear combinations of the messages it receives. These linear combinations are then sent over the outgoing links. The global encoding vector, i.e. the matrix of coefficients corresponding to the operations performed on the messages, is sent along in the packet header to ensure that the end receivers are capable of decoding the original data [Ho 04]. They evaluated the

number of transmissions per source message and the incurred delay, both under two relevant classes of random graph models. The results showed that the number of transmissions required to flood a message with the NC flooding algorithm is asymptotically independent of the number of nodes while, the number of transmissions per message is not independent of the number of nodes with MPRs. They concluded that the NC flooding algorithm does not bring any benefits in terms of number of transmissions per message, when compared to MPR flooding

Chapter 3
Optimal MPR (OMPR) Algorithm

Multipoint relaying (MPR) algorithms aim to reduce the number of redundant retransmissions, so that they reduce the number of collisions, congestions, delays, and improve the efficiency of power usage in mobile ad hoc networks (MANETs). Though, the MPR algorithms significantly reduce the number of retransmissions. However, the collision problem may not be solved if the size of the MPR set is too large. The collision problem can significantly reduce the ratio of successful information transmission thus degrading the overall network performance [Toh 02, Tse 02].

This chapter presents a description of an optimal MPR (OMPR) algorithm that aims to reduce the size of the MPR set. An optimal MPR set for a node is a subset of the one-hop neighbors of that node, which covers the two-hop neighbors of that node, and it has the minimum number of nodes among all other sets that cover the two-hop neighbors of that node. The OMPR algorithm enhances the overall networks performance by minimizing the number of retransmissions, and at the same time provides equivalent reachability within the network as pure flooding. This is especially in noiseless networks, however, in noisy network, the performance may be degraded as we shall discuss in this chapter.

Section 3.1 provides an extensive elucidation to MPR algorithms that includes: concept, cost, and classification of MPR algorithms. In Section 3.2, a detail description is given to the OMPR algorithm, which includes the description of the heuristic proposed for the selection of the MPRs, and the main features of the algorithm. The MANET simulator (MANSim) that is used as a simulation platform to compute and compare the performance of the OMPR is briefly described in Section 3.3. The parameters computed by MANSim, which are used in evaluating the performance of the proposed algorithm, and the parameters that affect this performance, are defined in Section 3.4

3.1. MPR Algorithms

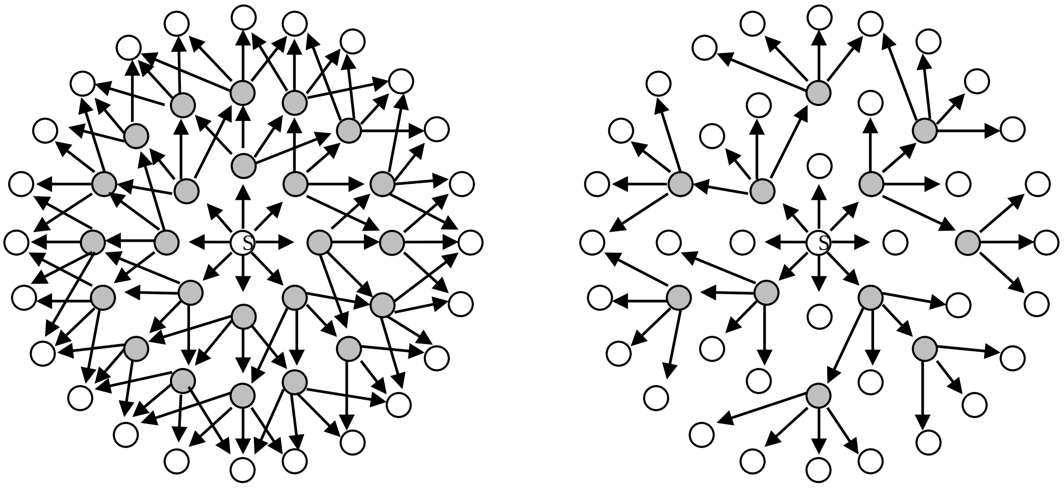
3.1.1 Concept of MPR Algorithms

MPR algorithms are neighbor-designated algorithms that exhibit both efficiency and simplicity. Compared to other neighbor-knowledge broadcasting algorithms (e.g., self-pruning algorithms), MPR algorithms use simple mechanisms to calculate the intermediate forwarding nodes which makes it easy to implement. Furthermore, they can significantly reduce the redundant broadcasting, thus efficiently delivering broadcast packets in both sparse and dense networks. MPR algorithms can be used in proactive protocols in order to optimize the flooding overhead of control traffic, and it can also be used effectively for reactive MANET protocols in order to save overhead in route discovery [All 03]. For these reasons, MPR has been successfully employed in many dynamic routing protocols in MANETs as the mechanism of RREQ packet distribution during route discovery [Lia 06a].

The idea behind MPR algorithms- as well as all flooding optimization algorithms - is to achieve what pure flooding do with less number of same message retransmissions. It defines a set of nodes called MPRs or relay nodes for each node in the network, these relay nodes are a subset of the one-hop neighbors of the node. They are responsible for forwarding the broadcast message upon receiving it for the first time, while non relay nodes will not forward the message [All 03, Qay 02].

Figure (3.1) illustrates how an optimized MPR algorithm works in a regular-geometry and noiseless (error-free) environment. It shows that to diffuse a packet to the three-hops neighbors, a source node uniformly surrounded by 8, 16, and 24 one-, two-, three- hops neighbors, respectively, an optimized MPR algorithm needs 11 retransmissions as compared to 24 for pure flooding [Qay 02].

It can be seen from Figure (3.1) that an optimized MPR algorithm reduces the number of redundant retransmissions at no cost of the network reachability in a noiseless environment. However, if the noise level is high, some of the forwarding nodes may not receive the packet due to a transmission error; this may result in a failure of delivery of the broadcast packet to all nodes in the network. In chapter 4 we will investigate the level of noise up to which our MPR algorithm can provide a satisfactory reachability.

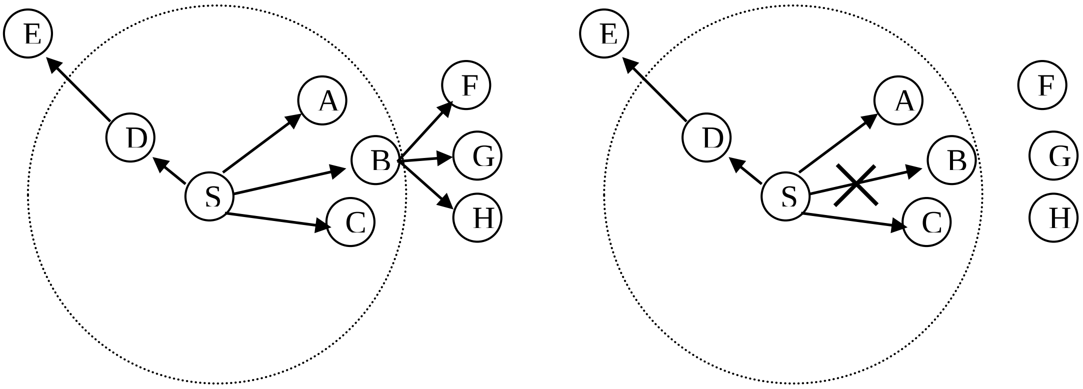


(A)

(B)

Figure (3.1): Diffusion of broadcast packet using: (A) Pure flooding. (B) Optimized MPR algorithm. Shaded circle represents a retransmitting node

Figure (3.2-A) shows the use of MPR algorithms for flooding of a broadcast packet in a network that is characterized by a non-uniform node distribution and noiseless environment (i.e, p_c=1), while Figure (3.2-B) shows the flooding of a broadcast packet using MPR in a noisy environment. If using pure flooding, nodes F, G and H will have a chance to receive the packet from nodes A, B, and C. While, using MPR nodes F, G, and H will have a chance to receive the packet from node B only. Therefore, in a noisy environment, if the link between the source S and B is broken, then nodes F, G, and H will fail to receive the packet.



(A) Noiseless environment (B) Noisy environment

Figure (3.2): Flooding of a broadcast packet using MPR algorithm in: (A) Noiseless environment. (B) Noisy environment.

3.1.2 Costs of MPR Algorithms

In order to implement the calculation of the forwarding node set, a certain number of procedures and information are required. These requirements form the cost of the MPR selection algorithm. Four costs of MPR algorithms described as follows [Lia 06a]:

- **Time complexity:** is the time required to complete the forwarding nodes calculations. A heuristic that requires much time to run the calculation may be too complex to be deployed. Furthermore, when the network topology changes rapidly, the frequency of a forwarding node calculation also increases, and thus the time consumption of the calculation is huge for a complex heuristic. Hence, an efficient heuristic that consumes less time is essential for the MPR set generation.

- **Message complexity:** is the number of *HELLO* messages required for the calculation of the MPR set. For any MPR scheme, a number of *HELLO* messages need to be exchanged between nodes in advance. These *HELLO* messages contain the necessary information for a heuristic to implement the forwarding node set calculation. Algorithms in different groups or even in the same group may require a different number of

- *HELLO* messages. However, frequent information exchange will consume the limited bandwidth in MANETs and also accelerate the energy consumption of mobile nodes. Therefore, the number of *HELLO* messages exchanged, which is regarded as the message complexity or communication complexity, can significantly affect the performance of an MPR algorithm.

- **Information range:** is the hop level of neighboring nodes information (i.e. two-hops, three-hops, etc.) needed for the calculation of MPRs. Generally, the larger information range an algorithm requires, the more time and message exchange it will need depending on the algorithm. For example, an information range up to four hops may not be efficient for an MPR algorithm because messages need a long time to be transmitted to the source node and the information they carry may be outdated by then.

- **Source dependant:** in which a forwarding node need to know from which node the packet was received in order to determine whether or not to retransmit this packet. If an algorithm is not source dependant, a forwarding node will broadcast all messages that are received for the first time. This requirement increases the complexity of both the message sending and receiving process in an algorithm.

3.1.3 Classes of MPR Algorithms

Currently, many algorithms have been proposed to calculate the forwarding node set based on the MPR selection heuristic. These algorithms are put forward to improve different aspects of broadcasting performance in MANETs such as minimizing the number of forwarding intermediate nodes, collision avoidance, efficient power usage, QoS, etc.

Different MPR algorithms can be classified into three main classes:

i. Connected Dominating Set (CDS)-based MPR (CDS-MPR) algorithms [Wu 06, Adj 05, Han 04].

ii. QoS-based MPR (QoS-MPR) algorithms [Bad 04, Ge 03, Mun 03].

iii. Optimized MPR algorithms [Lia 06a, Qay 02].

i. CDS-MPR Algorithms

CDS-MPR algorithms try to find a CDS where only the nodes in the connected set relay messages based on MPR algorithms. They aim to reduce the number of forwarding intermediate nodes in order to minimize retransmission overheads in the network [Wu 06, Adj 05, Che 04].

A Dominating Set (DS) is a subset of nodes in the network where every node is either in the subset or has at least one neighbor in the subset. The DS is called CDS if the subgraph it forms is connected. The connectedness of the DS insures that all nodes of the CDS will receive the packet (assuming no transmission error) and will thus be able to retransmit it. The MPR set plus the node forms a DS of the two-hop neighborhood of the node.

Upon receiving a broadcast message, only nodes inside the CDS broadcast it regardless where it comes from and eventually all nodes in the network will receive a copy of that message from their neighbors in the CDS. Because the CDS is source-independent, nodes inside a CDS do not require the source node information from broadcast messages, thus reducing the complexity of processing a broadcast packet. MPR algorithm needs source information in order to decide whether or not an MPR should broadcast messages. This source information may be difficult to obtain considering broadcasting in IP level.

CDS-MPR compute a CDS for a given network by electing a CDS based on the existing MPR set generated using the original MPR heuristic. It points out that the idea of the MPR technique is to compute a kind of local DS formed by a source node and its MPRs. By applying some strategies to this local CDS, a global CDS can be generated in the network.

The information required for a given node to implement the heuristic is the IDs of one-hop and two-hop neighbors of the node and the MPR selectors of the node. All the information can be piggybacked into *HELLO* messages and sent periodically by every node in the network. It is also worth noting that the source node information is not necessary for algorithms in this group, because nodes in a CDS will relay whatever messages they received for the first time. The strategy of the CDS-MPR is to apply two rules to the original MPR heuristic in order to generate a CDS in a network. A node *x* announces itself in the CDS if and only if it meets one of the following rules:

- Rule #1: It has the smallest node ID among its one-hop neighbors.
- Rule #2: It has been selected as an MPR and its selector has the smallest node ID among *x*'s one-hop neighbors.

Specifically, the first rule is applied to all nodes in the network while the second one is used only by nodes inside MPR sets.

In the CDS-MPR heuristic, the MPR scheme will be conducted first to generate MPR sets. All nodes then will inform their one-hop neighbors about the MPRs they selected. Upon receiving this message, nodes that have been selected as MPRs apply the second rule to decide whether or not they are the dominating nodes (nodes inside a CDS). Furthermore, all nodes in the network also apply the first rule to evaluate themselves. Finally, a CDS is formed by all the dominating nodes in the network.

It can be seen that the MPR heuristic is a special case of the CDS-MPR where the only node elected by the first rule is the source node. The merit of the MPR-CDS heuristic is that it does not need any distributed knowledge of the global topology to generate a CDS in a network. This makes the heuristic very attractive for MANETs since it needs only local updates at each detected topology change. Furthermore, because of the lack of the source node information in the *HELLO* messages, the implementation of the heuristic is eased.

However, the CDS-MPR heuristic may increase the number of MPRs in the network. This is due to the Rule #1 applied in the network, which elects extra nodes into the CDS. When the node ID is ordered arbitrarily, each node might be elected by Rule #1 with a probability of 1/*f*, where *f* is the maximum number of one-hop neighbors of a node. The average number of nodes elected by Rule #1 will be *n*/*f*, where *n* is the total number of nodes in the network. In such a case, the original MPR will perform better than the CDS-MPR in terms of the number of forwarding nodes generated.

ii. QoS-MPR Algorithms

QoS-MPR algorithms consider the QoS requirements in the network and attempt to find an MPR set that meets the QoS criteria. Because QoS metrics such as bandwidth and delay are essential for real-time applications, finding an MPR set that can guarantee these QoS conditions is the preliminary for better supporting QoS in MANETs [Zem 05, Ge 03].

QoS is an important issue in the traditional wired network and has been deployed more that ten years. Inevitably, it will also be a key feature in MANETs to provide multimedia service. To support QoS, the link state information, such as bandwidth and delay, should be available and manageable. This requires broadcast schemes in a wireless network to be able to efficiently disseminate the QoS information throughout the network. In the MPR scheme, MPRs are chosen based on non-QoS criteria and each MPR can only propagate information of links between it and its MPR selectors, good quality links may be hidden to other nodes in the network.

In figure (3.3), the number above each link represents the corresponding bandwidth. In non-QoS criteria, node S will select node B as the MPR because it covers more uncovered two-hop neighbors. Following the same heuristic, node B will choose node E as the MPR. Hence, node D knows that it can reach node S via the route {D, E, B, S} which has a low bandwidth. However, it is obvious that a better route should be {D, F, A, S} which has a higher bandwidth. This high bandwidth route is hidden from node D by using non QoS-MPR heuristic. Therefore, the MPR selection has to consider QoS information such as bandwidth and delay in order to provide suitable links for some specific applications.

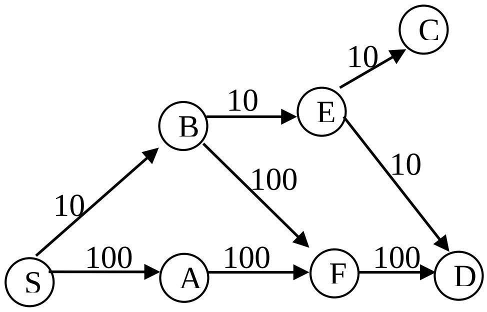


Figure (3.3): QoS-MPR

MPR-based broadcast schemes provide different features based on different MPR selection criteria. By using various kinds of node information, one can customize the MPR selection procedures and obtain different broadcast performances as required. QoS-MPR algorithms are such customized schemes which use QoS measurements to modify MPR heuristic to achieve QoS-awareness broadcast in the network. Based on this concept, it is possible to extend all MPR-based broadcast schemes by piggybacking extra node information into the *HELLO* messages and utilizing them to modify the MPR selection criterion.

MPR has relatively lower computation and communication complexity compared with most of the other schemes. This is due to the fact that MPR mainly focuses on reducing the number of forwarding nodes, while other schemes are interested in different features such as minimum overlapping, efficient energy usage, and QoS conditions which requires additional procedures and extra information, so that more time and message complexity are expected for them.

iii. Optimized MPR algorithms

Optimized MPR algorithms aim to reduce the size of the MPR set. They work in a distributed manner designed in view of the mobile and disperse nature of the Network nodes. Each node calculates its own set of MPRs, which is completely independent of other nodes' selection of their MPRs. Each node reacts when its neighborhood nodes change and accordingly modifies its MPR set to continue covering its two-hop neighbors.

An important aspect of the MPRs is the manner in which these MPRs are selected by each node. The goal is to achieve the maximum performance by selecting an optimal set of MPRs by each node. But this task is not a trivial one. If the mechanism of selecting the MPRs is too simple, it may not select efficiently the MPRs in a dynamic and complex situation, and the expected performance gain would not be achieved. If the algorithm of MPR selection is very complex and sophisticated to provide a near to optimal MPR set, it may become difficult to implement it. A highly sophisticated algorithm may generate its own control traffic, to gather information for its functioning, which becomes comparable to the saving in flooding of messages. Thus, there must be a compromise in designing such algorithms for the selection of MPRs: it should be easy to implement, and it should give near to optimal MPR set in "majority" of cases.

The information required to calculate the MPRs is the set of one-hop neighbors and the two-hop neighbors, i.e. the neighbors of the one-hop neighbors. To obtain the information about one-hop neighbors, most protocols use some form of *HELLO* messages, which are sent locally by each node to declare its presence. In a mobile environment, these messages are sent periodically as keep alive signals to refresh the information. To obtain the information of two-hop neighbors, one solution may be that each node attaches the list of its own neighbors, while sending its *HELLO* messages. With this information, each node can independently calculate its one-hop and two-hop neighbor set. Once a node has its one- and two-hop neighbor sets, it can select a minimum number of one-hop neighbors which covers all its two-hop neighbors.

3.2. Description of the OMPR Algorithm

3.2.1.The Proposed Heuristic for the Selection of MPRs

We describe here one heuristic for the selection of MPRs. To select the MPRs for the node *x*, let us call the set of one-hop neighbors of node *x* as $N_1(x)$, and the set of its two-hop neighbors as $N_2(x)$. Let the selected MPR set of node *x* be *MPR*(*x*).

The algorithm requires that each node knows the full list of its one-hop neighbors ($N_1(x)$) and its two-hop neighbors ($N_2(x)$) ($N_2(x)$ also called the neighbors of node *x* one-hop neighbors). This information is collected via the periodic *HELLO* messages. Mobile nodes perform neighbor sensing by periodically transmitting *HELLO* messages on all their interfaces. The *HELLO* messages contain the list of the neighbor nodes heard by the originator of the *HELLOs*. The heard neighbor nodes of a given node consist of the originators of the *HELLO*s received by this given node within a certain interval of time. If the number of heard neighbor nodes is too large to fit a single *HELLO* message, then several *HELLOs* will be used per period with the rule that all heard neighbor nodes must have been notified at least once per update period [All 03].

Definition: One-hop neighbor set

Node *y* is a one-hop neighbor of node *x*, if and only if *y* is located within the radio range of node *x*, this means that any transmission coming out of node *x* will reach node *y* directly. The one-hop neighbor set of node *x* ($N_1(x)$) is the set of all one-hop neighbors. In Figure (3.4), node (*S*) one-hop neighbor set = {B, C}.

Definition: Two-hop neighbor set

Node *y* is a two-hop neighbor of node *x*, if and only if *y* is a one-hop neighbor of some node *z* and *z* is a one-hop neighbor of node *x*, this means that the transmission of *x* can reach node *y* via node *z*. The two-hop neighbor set of node *x* ($N_2(x)$) is the set of all two-hop neighbors, in Figure (3.4), node (*S*) two-hop neighbors set = {A, F, G, H}.

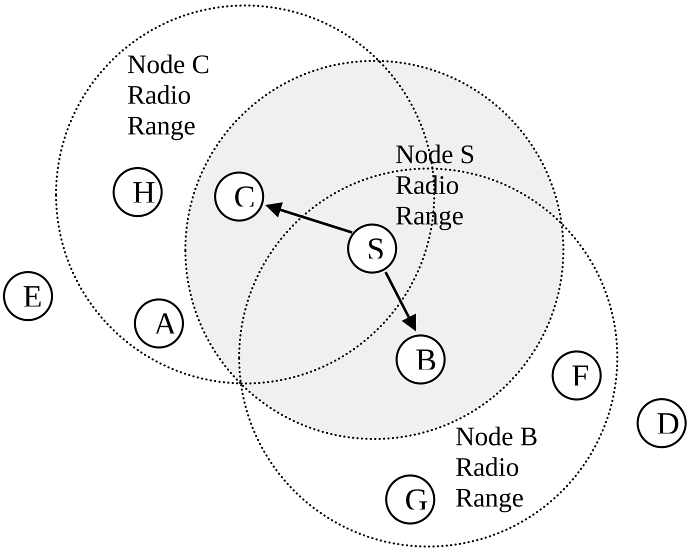


Figure (3.4): One hop and two hop neighbors of node *S*.

Definition: MPR set

The MPR set of node *x* (*MPR*(*x*)) is a subset of the one-hop neighbor set of *x* ($N_1(x)$), such that each two-hop neighbor of node *x* ($N_2(x)$) has a neighbor in the *MPR*(*x*) (multipoint relay set covers the two-hop neighbor set). The MPR set plus the node forms a dominant set (DS) of the two-hop neighborhood of the node [Adj 05].

Using the neighbor knowledge information obtained via periodic *HELLO* messages, each node calculates its own set of MPRs (using the algorithm shown in Figure (3.5)). Each node calculations are performed locally and totally independent of other nodes calculations of their MPRs. If the neighborhood of a node has changed, the node will modify its MPR set to continue covering its two-hop neighbors.

A node retransmits a broadcast packet, if and only if, it has not already received the packet and it is an MPR of the node it has received the packet from, which makes the process source dependant. So, the source node will inform its MPR nodes that they are selected to be MPRs when forwarding a broadcast packet, and each selected forwarding node will inform its MPRs when forwarding and so on until the packet is propagated to the entire network.

The number of relay nodes for each node will vary depending on the network topology, obviously it is less than or equal the number of one-hop neighbors. When the relay nodes are the same as the one-hop neighbors then this is pure flooding.

An optimal MPR set for a node is a subset of the one-hop neighbors of that node, which covers the two-hop neighbors of that node, and it has the minimum number of nodes among all other sets that cover the two-hop neighbors of that node. Since the goal of MPRs is to maximize the performance of the network, MPRs selection algorithm should not generate large control traffic to gather information for its functioning even though it will provide an optimal MPR set. Each node in the network will run the MPR algorithm in Figure (3.5) locally to generate the set of its MPRs:

The OMPR Algorithm

For each node do:

1. Start with an empty multipoint relay set $MPR(x)$
2. First select those one-hop neighbor nodes in $N_1(x)$ as MPRs which are the only neighbor of some node in $N_2(x)$, and add these one-hop neighbor nodes to the multipoint relay set $MPR(x)$
3. While there still exist some node in $N_2(x)$ which is not covered by the multipoint relay set $MPR(x)$:
    a. For each node in $N_1(x)$ which is not in $MPR(x)$, compute the number of nodes that it covers among the uncovered nodes in the set $N_2(x)$.
    b. Add the node of $N_1(x)$ to $MPR(x)$ for which this number is maximum. If i nodes cover a maximum, generate new sets $MPR(x)_1$, $MPR(x)_2$, …, $MPR(x)_i$ for each node and continue for each generated set.
4. For each set generated in step 3-b, exclude any node that is not the only covering node for at least one node in $N_2(x)$ among all other nodes in the set.
5. Select the MPR set with the least number of nodes as $MPR(x)$.

Figure (3.5): The OMPR algorithm.

In the OMPR algorithm, the second step permits to select some one-hop neighbor nodes as MPRs which must be in the *MPR*(*x*) set. Otherwise the *MPR*(*x*) will not cover all the two-hop neighbors. These nodes will be selected as MPRs in the process, sooner or later. Therefore, if the second step is omitted, the multipoint relays set can still be calculated with success, i.e. it will cover all the two-hop neighbors. The presence of step 2 is for optimizing the MPR set. Those nodes which are necessary to cover the two-hop set $N_2(x)$ are all selected in the beginning, which helps to reduce the number of uncovered nodes of $N_2(x)$ at the start of the normal recursive procedure of step 3. Step 3 is an important step as it eliminates all nodes in $N_1(x)$ that may cause redundant or duplicate retransmissions by choosing the highest covering neighbor to be in *MPR(x)*. Step 4 excludes any redundant node that maybe found in any generated MPR set from step 3-b. this is done by testing each set for any node that is not the only covering node to at least one node in $N_2(x)$ which can be excluded without affecting the coverage of the set. Step 5 ensures that the MPR set with the minimum number of nodes is selected. The selected set is the optimal MPR set among all the other generated MPR sets.

3.2.2 Features of the OMPR Algorithm

The main features of the optimal MPR algorithm can be summarized as follows:

- It is a neighbor-knowledge algorithm.
- Each node needs to know the full list of its one-hop neighbors, and should pass this information back to all of them.

- Each node calculates its MPR set locally. Therefore, it is a source-dependent process.
- It generates an optimal MPR set for each node which has the minimum number of nodes among all other sets that cover the two-hop neighbors for that node.
- The number of relay nodes for each node depends on the network topology and it is highly affected by the node mobility.

One of the serious drawbacks of this heuristic for the selection of the MPR set is that its performance (in terms of network reachability) may be extremely affected by the presence of noise, which in this work is expressed by the probability of reception (p_c). This is due to the fact that if the link between a source node (originator) and a relay node (a node in $N_1(x)$) is broken, then all nodes in $N_2(x)$ that are attained through this relay node are disconnected. Therefore, one of the main objectives of this research is to estimate the limits of p_c up to which the OMPR algorithm is able to ensure the diffusion of packets and can guarantee satisfactory results under different realistic and noisy MANET environment.

3.3. The MANET Simulator (MANSim)

MANSim is a MANET simulator especially developed to simulate and evaluate the performance of a number of flooding optimization algorithms for MANETs [Bah 08]. It is written in C++ language, and it consists of four major modules:

i. Network module

ii. Mobility module

iii. Computational module

iv. Algorithm module

In what follows a description is given for each of the above modules.

3.3.1 Network module (Geometrical configuration)

The network module is concerned with the geometrical configuration or nodes distribution within the network area. MANSim simulates two geometrical network configurations of different nodes distribution within the network area. These are:

i. Regular-grid node distribution

ii. Random node distribution.

For the two configurations, a geometrical area of size X×Y m is simulated.

i. Regular-grid node distribution configuration

In a regular-grid node distribution configuration, the network is considered as a regular-grid where nodes are placed at each intersection of the grid as illustrated in Figures (3.6) and (3.7). For this configuration, two node degrees are considered, namely 4-node degree and 8-node degree. In a 4-node degree (Figure (3.6)), each node is allowed to communicate directly with its vertical and horizontal neighbors, and the radio transmission range of the node covers one-hop neighbor in each direction. In an 8-node degree (Figure (3.7)), nodes are also allowed to communicate with the diagonal neighbors.

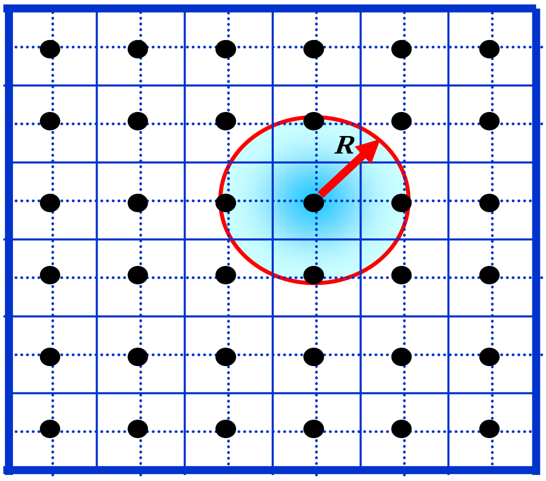


Figure (3.6): Regular-grid nodes distribution (4-node degree).

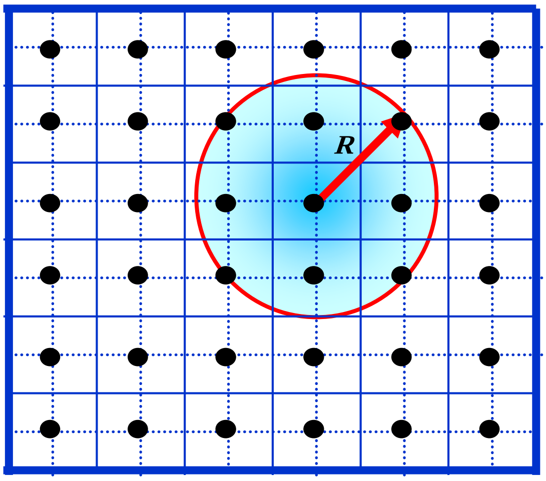


Figure (3.7): Regular-grid nodes distribution (8-node degree).

The regular-grid configuration is quite simplistic but it is useful for calculating benchmark analytical results for some computed network parameters for a specific network condition. These benchmark analytical results can be used to validate the simulation results. However, a more realistic configuration is required, that may consider random (non-regular) node distribution and produce variable node degrees.

ii. Random node distribution configuration

In a random node distribution configuration, the nodes are randomly placed on the X×Y network area as illustrated in Figure (3.8). They are placed according to a particular probability distribution function (PDF), such as linear distribution, Poisson’s distribution, etc. In our simulations, the *x* and *y* positions of the nodes are calculated according to a linear PDF, such that [Ko 98]:

$$x = X \bullet \square \qquad (3.1)$$

$$y = Y \bullet \square \qquad (3.2)$$

Where X and Y are the length and width of the network area, and $\square$ is a random number uniformly distributed between 0 and 1 ($0 \le \square < 1$). Two nodes i and j are considered to be connected or neighbors if the Euclidean distance between these two nodes (*r*) is less than or equal to radio transmission range of the node (*R*), where *r* is given by [Ko 98]:

$$r = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{3.3}$$

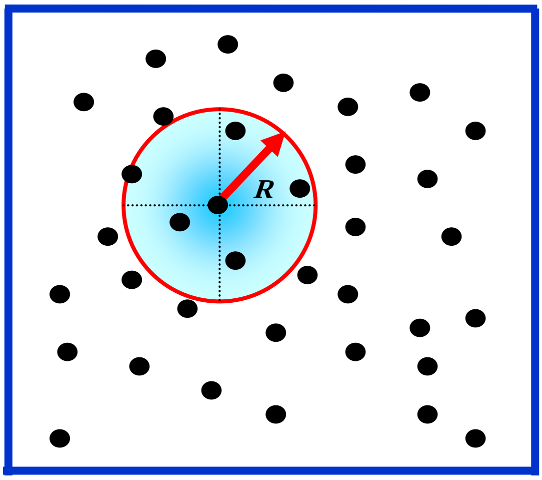


Figure (3.8): Random node distribution.

One important point that must be carefully considered using random node distribution is to make sure that initially each node within the network should have at least one neighboring node.

3.3.2 Mobility module

One of the main characteristics of MANETs is the mobility of their nodes. In the random walk mobility pattern, the direction of movement for a mobile node is randomly chosen from an appropriate PDF. In most applications, a node is allowed to move with equal probability in any direction within the geographical area of interest, i.e., the direction is sampled randomly from a uniform PDF.

In MANSim, the node mobility is simulated as follows: each node is allowed to move around randomly within the network area during the simulation. The movement pattern of a node is simulated by generating a direction (□), a speed (*u*), and a time interval (□), which is also referred to as a pause time. In MANSim, the pause time is calculated by [Bah 08]:

$$\tau = \frac{R}{u} \times q$$

(3.4)

Where □ is the pause time (sec), *R* is the radio transmission range of the node (m), *u* is the node speed (m/sec), and *q* is any value above zero. In this work it is taken to be 0.75, so that the location information of the node is updated before the node travels a distance of R m.

Nodes are either allowed to move with a pre-assigned average speed (u_{av}), i.e., $u=u_{av}$, a pre-assigned maximum speed (u_{max}), i.e., $u=u_{max}$, or a node speed is sampled randomly between 0 and u_{max} (i.e., $u=$□u_{max}). So that, the distance traveled by the node is calculated as [Ko 98]:

d = *u*□

(3.5)

The direction is sampled from a uniformly distributed function between 0 to *2*□□, which can be expressed as [Ko 98]:

□□= 2□□

(3.6)

Then, a new node location at time *t*+□ is calculated by:

$$x\,(t+\tau) = x\,(t) + d\,Cos\,(\theta)$$

(3.7)

$$y\,(t+\tau) = y\,(t) + d\,Sin\,(\theta)$$

(3.8)

Where *x*(*t*), *y*(*t*) and *x*(*t*+□), *y*(*t*+□) are the old and new locations of the node, respectively. This new node location must be checked to be within the network area, if it is not (i.e., the node leaves the network area), there are different ways to bring the node back to the network. In this model the researcher uses a reduced weight approach to ensure that the node remains within the network area.

In the reduced weight approach the node is kept moving in the same direction, but the distance traveled (*d*) is reduced by multiplying it by descending weight until the new location be within the network area (i.e., *d* =*d*•□). The weight □ is given by [Jar 07]:

$$\omega = \frac{(I_{\max} - k)}{I_{\max}}$$

(3.9)

An appropriate value for I_{max} is between 2 to 10, and *k* is set to zero and is incremented by 1 each time the node traveled outside the network area.

3.3.3 Computational module

Many computational models start a simulation from a single source node positioned at the center of the network area, or from a single source node randomly selected within the network area. The simulation is repeated for *S* times, i.e., the source node is assumed to transmit *S* request messages. The results obtained from these simulations are averaged to give average values for the computed parameters. The results obtained reflect the average behavior with regards to this particular source node, but they may not well reflect the average behavior of other nodes within the network.

But, a major feature of MANSim computational module is that it does not randomly pick a node and use it as a fixed source node. Instead, a loop is performed using all nodes within the network as source nodes, then the computations for the network parameters are performed over all nodes as destination nodes, except the source node. The computed parameters for each source node are averaged over (*n*-1), and then these averaged values are averaged again over (*n*). In other words, the computed parameters are averaged over (*n*(*n*-1)). In this case, the computed parameters may well represent the average behavior of any of the nodes within the network.

In order to enhance the accuracy of the solution, the computation is repeated, in an inner loop, for each source and destination nodes for a number of runs, i.e., each source is allowed to initiate S requested messages. Once again, the computed parameters are averaged over S. However, it has been found that with small number of runs the solution is converged to a more stable solution, and for networks having no probabilistic behavior, i.e., Retransmission Probability (p_t)=1, S has no effect on the computed parameters and can be set to 1, which is the case in our work.

As it has been mentioned earlier, in order to consider node mobility, a simulation time is set. It is divided into a number of time intervals ($nIntv$) that is calculated by:

$$nIntv = \frac{T_{sim}}{\tau} \tag{3.10}$$

Where, T_{sim} and τ are the simulation and pause times, respectively. The calculation is repeated, in an outer loop, for $nIntv$, and the results obtained for the computed parameters are averaged over $nIntv$. In general, it has been found that to obtain an adequate network performance, the pause time must be carefully chosen so that the distance traveled by the node, during location update interval, is less than the radio transmission range of the source node. For non-mobile nodes (fixed nodes) $nIntv$ has no effect on the computed parameters and can be set to 1.

3.3.4 Algorithm module

In this module, the flooding optimization algorithm is implemented. For example the flooding optimization algorithm discussed in Section 3.2 is implemented here.

This module consists of a number of procedures to calculate the computed network parameters. In particular, it has procedures to calculate

i. Nodes that receive the request message. This occurs if the receiving node is within the radio transmission range of the transmitting node, and no error occurs during data transmission due to noise interference. Each

ii. time a node (i) successfully receives a request, an index iRec(i) is incremented by 1, where i represents the node ID. This index is used to calculate the network parameters, e.g., ADR and RCH, which will be defined in Section 3.4.

iii. Nodes that succeed to retransmit the request message. A node index iRet(i) is set to 1 if the node i retransmits the received request. This index is used to calculate the number of retransmission (RET) within the network.

iv.

Figure (3.9) outlines the algorithm and the computational modules for the probabilistic flooding optimization algorithm.

Computational Module of the MANSim Simulator

```
Loop over the number of intervals (nIntv)
{
    Loop over the number of nodes as source nodes (i=1, n)
    {
        Loop over the number of nodes as destination nodes (j=1, n), except
        for i=j
        {
            Loop over the number of transmitted request message (k=1, S)
            {
                Compute IRec() and IRet()
            }
            Compute the average values of the computed parameters (over S)
            for source node i and destination node j.
        }
        Compute the average values of the computed parameters (over n-1)
        for source node i and n-1 destination nodes.
    }
    Compute the average values of the computed parameters (over n) for n
    source nodes and n-1 destination nodes.
}
Compute the average values of the computed network parameters (over
nIntv).
```

Figure (3.9) - Computational module of the MANSim simulator

3.4. Performance Measures

Using MANSim, a variety of network parameters is computed to evaluate, analyze, and compare the performance of the MPR algorithm. These parameters are recommended by the IETF to judge the performance of the flooding optimization algorithms. These parameters include: number of retransmission (RET), average duplicate reception (ADR), reachability (RCH), saved

rebroadcast (SRB), average hop counts (AHC), and disconnectivity (DIS). However, in this work we only consider the following computed network parameters:

i. Number of retransmission (RET). The average number of retransmissions or request messages, normalized to the total number of nodes within the network (*n*).

ii. Average Duplicate Receptions (ADR). The average number of request messages that is received by each node.

iii. Reachability (RCH). The average number of reachable nodes by any node normalized to the total number of nodes within the network (*n*).

In addition, MANSim can be used to investigate the effect of a number of input network parameters on the above computed parameters, such as: node density, node mobility, probability of error in reception (probability of reception), pause time, and simulation time.

In this work we are mainly concerned with studying the effect of the following input parameters on the computed results:

i. Node density (n_d). The number of nodes per unit area ($n_d = n/A$), where A is the network area ($A = X \times Y$).

ii. Node mobility or node speed (u). Nodes are assumed to move with either an average speed (u_{av}), maximum speed (u_{max}), or a random speed.

iii. Node transmission radius (R), which represents the area that can be covered by a certain node.

iv. Probability of reception (p_c). The probability of a request message being successfully received by a destination node located within the transmission range of the source node v.

Chapter 4
Simulations and Results

In order to compare and evaluate the performance of the proposed Optimal MPR (OMPR) algorithm in noisy MANETs, a number of scenarios are simulated using the MANET simulator (MANSim) [Bah 08, Bah 07, Jar 07], which was described in Chapter 3. In theses scenarios, we investigate the effects of a number of input network parameters, such as:

(1) Node density (n_d)

(2) Node mobility or node speed (u)

(3) Radio transmission range (R)

(4) Probability of reception (p_c)

The performance of the new algorithm is evaluated in terms of the following computed network parameters, which are defined in Chapter 3:

(1) Number of retransmission (RET)

(2) Average duplicate receptions (ADR)

(3) Reachability (RCH)

The main objectives of the four scenarios that are considered in this work can be summarized as follows:

(1) Scenario #1: Compare the performance of the proposed OMPR algorithm with a number of other flooding optimization algorithms, such as:

   a. Pure flooding algorithm.

   b. Probabilistic flooding algorithm.

c. Location-Aided Routing scheme 1 (LAR-1) algorithm.

d. Combined LAR-1 and probabilistic algorithms (LAR-1P) algorithm.

(2) Scenario #2: Investigate the effect of node density (n_d).

(3) Scenario #3: Investigate the effect of node mobility or node speed (u).

(4) Scenario #4: Investigate the effect of node transmission radius (R).

The results obtained for these scenarios are presented in tables and graphs. Also, for each scenario the results obtained are discussed. At this stage, it is important to know that in all simulations, certain assumptions are assumed, these are:

- If an error in reception occurred, there is no retransmission because the messages are considered to be broadcast messages which do not require acknowledgement to confirm the reception.
- Each link between a pair of nodes is a bidirectional link.
- The only traffic exists in the network is that of the diffusion of broadcast packet.
- A node will retransmit a packet - if it has to retransmit according to the protocol - only once.
- The channel is assumed to be time-slotted and each transmission takes one slot.
- Each time a node transmits a packet, its one hop neighbors receive this packet with probability a pre-defined reception probability (p_c).

4.1.Scenario #1. Comparison of Performance

This scenario compares the performance of the proposed OMPR algorithm against a number of flooding optimization algorithms such as: pure flooding, probabilistic flooding with fixed retransmission probabilities p_t=0.8, probabilistic flooding with dynamic retransmission probabilities, LAR-1, and LAR-1P with p_t=0.8. The performance is compared in terms of RET, ADR, and RCH for both fixed and mobile nodes. The input parameters for this scenario are listed in Table (4.1). The results obtained for this scenario are tabulated in Tables (4.2) to (4.4), and plotted in Figures (4.1) to (4.6).

Table (4.1)
Input parameters for Scenario #1.

Parameters	Values
Geometrical model	Random node distribution
Network area	1000x1000 m
Number of nodes (n)	100 nodes.
Transmission radius (R)	200 m
Average node speed (u)	0, 5 m/sec
Probability of reception (p_c)	From 0.5 to 1.0 in step of 0.1
Simulation time (T_{sim})	0 for fixed nodes, 300 sec for mobile nodes
Pause time (□)	0 for fixed nodes, 0.75*(R/u) for mobile nodes

The main points that are concluded from this scenario can be summarized as follows:

- The probabilistic approach always achieves the highest possible RCH, but at the same time it introduces the low reduction in RET and ADR, when it is compared with the other techniques.
- The LAR-1 and LAR-1P algorithms presents the highest reduction in RET and ADR but at the same time they provide the lowest RCH.
- The OMPR algorithm presents a moderate reduction in RET and ADR, when it is compared with probabilistic (fixed and dynamic p_t), LAR-1, and LAR-1P. It performs better than probabilistic and less than LAR-1 and LAR-1P for various network noise levels and nodes speeds. However, the RCH it achieves is higher than that of LAR-1 and LAR-1P algorithms.

- The RCH of the OMPR algorithm is highly affected and ruined in high mobility and noisy environment, see Figure (4.6).

Since the main objective of using flooding optimization during route discovery is to achieve a cost-effective reachability, which means a highest possible reachability at a reasonable cost, in this work, cost is measured in terms of RET and ADR. The results obtained demonstrate that the OMPR algorithm provides an excellent performance as it can achieve the most excellent cost-effective reachability, for various network noise levels and nodes speeds, as compared to probabilistic (fixed and dynamic p_t), LAR-1, and LAR-1P algorithms.

Table (4.4), Figure (4.5), and Figure (4.6) demonstrate that the OMPR algorithm provides an excellent network RCH in noisy environment when compared with LAR-1 and LAR-1P, at a significant reduction in RET and ADR. For example, for fixed nodes and p_c=0.5, it achieves a RCH of 47.1% compared with 33.9% and 23.8% for LAR-1 and LAR-1P (p_t=0.8), respectively. This is achieved at a cost of 11% RET compared with 6.6% and 4.2%, for LAR-1 and LAR-1P (p_t=0.8), respectively.

Table (4.4) shows that the probabilistic and OMPR algorithms provide almost a comparative performance in noiseless and low-noise environments (p_c>0.8). But, in terms of network reachability, the probabilistic approach overwhelmed the performance of the OMPR algorithm in noisy environment. For example, for mobile nodes with u=5 m/sec and p_c=0.5, the OMPR algorithm achieves a reachability of only 34.6%, while for the same environment, the probabilistic approach achieves over 85%. But, the probabilistic approach achieves this high network reachability at a very high cost of RET (≈68%) and ADR (≈3.5 duplicate reception per node) compared with RET=10.3% and ADR=0.587 for the OMPR algorithm.

In this work, we introduce a new parameter that illustrates the percentage change of the algorithm RCH with p_c (i.e., the network noise level). It is called the average rate of change of reachability. It is denoted by R_{RCH} and can be calculated by:

$$R_{\mathrm{RCH}} = \frac{\mathrm{RCH}_2 - \mathrm{RCH}_1}{p_{c,2} - p_{c,1}} \times 100 \qquad (4.1)$$

Where RCH_1 and RCH_2 are the algorithm reachabilities at $p_{c,1}$ and $p_{c,2}$, respectively. This parameter can be used to compare the performance of the different algorithms.

It is clear that all algorithms RCHs are negatively affected by presence of noise. However, the results obtained demonstrate that the OMPR algorithm is the more sensitive one to noise for both fixed and mobile nodes. Pure flooding is the least affected algorithm then probabilistic (fixed and dynamic p_t), followed by the LAR-1 and LAR-1P algorithms. Table (4.4) lists the values of R_{RCH} for the various algorithms. Finally, it is important to notice that the fluctuation in RCH achieved by the LAR-1 and LAR-1P algorithms are statistical.

Table (4.2) - Scenario #1
Comparing RET for various route discovery algorithms in a noisy MANET.

u (m/sec)	p_c	Pure (p_t=1.0)	Probabilistic		LAR-1P		OMPR
			p_t=0.8	p_t=D	p_t =1.0	p_t =0.8	
Fixed Nodes u=0 m/sec	1.0	99.0	79.0	80.1	9.4	6.8	30.8
	0.9	99.0	78.5	79.9	9.1	6.5	28.4
	0.8	98.9	77.8	79.5	8.7	6.1	25.2
	0.7	98.6	76.1	78.3	8.2	5.6	21.1
	0.6	97.5	73.4	75.6	7.6	5.0	16.2
	0.5	94.6	67.5	69.6	6.6	4.2	11.0
Mobile Nodes u=5 m/sec	1.0	99.0	77.9	81.3	15.9	10.4	36.1
	0.9	98.6	78.2	81.6	14.7	10.5	33.0
	0.8	97.8	76.9	79.8	13.8	8.9	28.8
	0.7	98.5	75.6	77.2	13.1	9.4	23.1
	0.6	97.0	72.3	73.3	12.8	8.6	16.5
	0.5	93.4	68.2	69.8	10.5	7.5	10.3

Pure: Pure flooding algorithm (p_t=1.0).

p_t=0.8: Probabilistic flooding with fixed retransmission probability (p_t=0.8) [Bah 08].

p_t=D: Probabilistic flooding with dynamic retransmission probability (p_t=D) [Bah 08].

LAR-1P (p_t=1.0): LAR-1 algorithm [Bah 08].

LAR-1P (p_t=0.8): LAR-1P algorithm with fixed retransmission probability (p_t=0.8) [Bah 08].

OMPR: Optimal MPR algorithm.

Table (4.3) - Scenario #1
Comparing ADR for various route discovery algorithms in a noisy MANET.

u (m/sec)	p_c	Pure (p_t=1.0)	Probabilistic		LAR-1P		OMPR
			p_t=0.8	p_t=D	p_t =1.0	p_t =0.8	
Fixed Nodes u=0 m/sec	1.0	10.04	8.02	7.63	0.757	0.561	4.262
	0.9	9.03	7.18	6.86	0.661	0.485	3.527
	0.8	8.02	6.34	6.08	0.566	0.408	2.797
	0.7	7.00	5.46	5.4	0.473	0.328	2.076
	0.6	5.96	4.55	4.37	0.380	0.255	1.4-8
	0.5	4.85	3.54	3.40	0.279	0.183	0.833
Mobile Nodes u=5 m/sec	1.0	9.91	7.59	7.34	1.379	0.887	3.700
	0.9	8.56	7.27	6.64	1.061	0.775	3.055
	0.8	7.65	6.03	5.83	0.938	0.567	2.386
	0.7	6.70	5.35	5.20	0.781	0.566	1.705
	0.6	6.32	4.17	4.23	0.657	0.477	1.075
	0.5	4.85	3.39	3.43	0.438	0.340	0.587

Pure: Pure flooding algorithm (p_t=1.0).

p_t=0.8: Probabilistic flooding with fixed retransmission probability (p_t=0.8) [Bah 08].

p_t=D: Probabilistic flooding with dynamic retransmission probability (p_t=D) [Bah 08].

LAR-1P (p_t=1.0): LAR-1 algorithm [Bah 08].

LAR-1P (p_t=0.8): LAR-1P algorithm with fixed retransmission probability (p_t=0.8) [Bah 08].

OMPR: Optimal MPR algorithm.

Table (4.4) - Scenario #1

Comparing RCH for various route discovery algorithms in a noisy MANET.

u (m/sec)	p_c	Pure (p_t=1.0)	Probabilistic		LAR-1P		OMPR
			p_t=0.8	p_t=D	p_t =1.0	p_t =0.8	
Fixed Nodes u=0 m/sec	1.0	100.0	99.5	99.9	67.1	56.2	100.0
	0.9	100.0	99.0	99.8	62.1	51.0	97.6
	0.8	99.9	98.0	99.4	56.9	44.8	92.2
	0.7	99.6	96.1	97.9	50.0	38.8	81.9
	0.6	98.3	93.0	94.8	42.3	31.5	66.6
	0.5	96.0	85.4	88.3	33.9	23.8	47.1
R_{RCH} (%)		8.0	28.2	23.2	66.4	64.8	105.8
Mobile Nodes u=5 m/sec	1.0	100.0	98.3	99.7	82.1	64.2	98.9
	0.9	99.7	98.6	99.5	77.6	66.2	95.0
	0.8	98.8	97.0	97.8	69.2	53.4	86.8
	0.7	99.6	95.4	96.7	66.4	56.6	72.7
	0.6	98.1	91.4	92.2	61.3	50.5	53.9
	0.5	94.5	86.3	88.3	49.5	42.1	34.6
R_{RCH} (%)		11.0	24.0	22.8	65.2	44.2	128.6

Pure: Pure flooding algorithm (p_t=1.0).

p_t=0.8: Probabilistic flooding with fixed retransmission probability (p_t=0.8) [Bah 08].

p_t=D: Probabilistic flooding with dynamic retransmission probability (p_t=D) [Bah 08].

LAR-1P (p_t=1.0): LAR-1 algorithm [Bah 08].

LAR-1P (p_t=0.8): LAR-1P algorithm with fixed retransmission probability (p_t=0.8) [Bah 08].

OMPR: Optimal MPR algorithm.

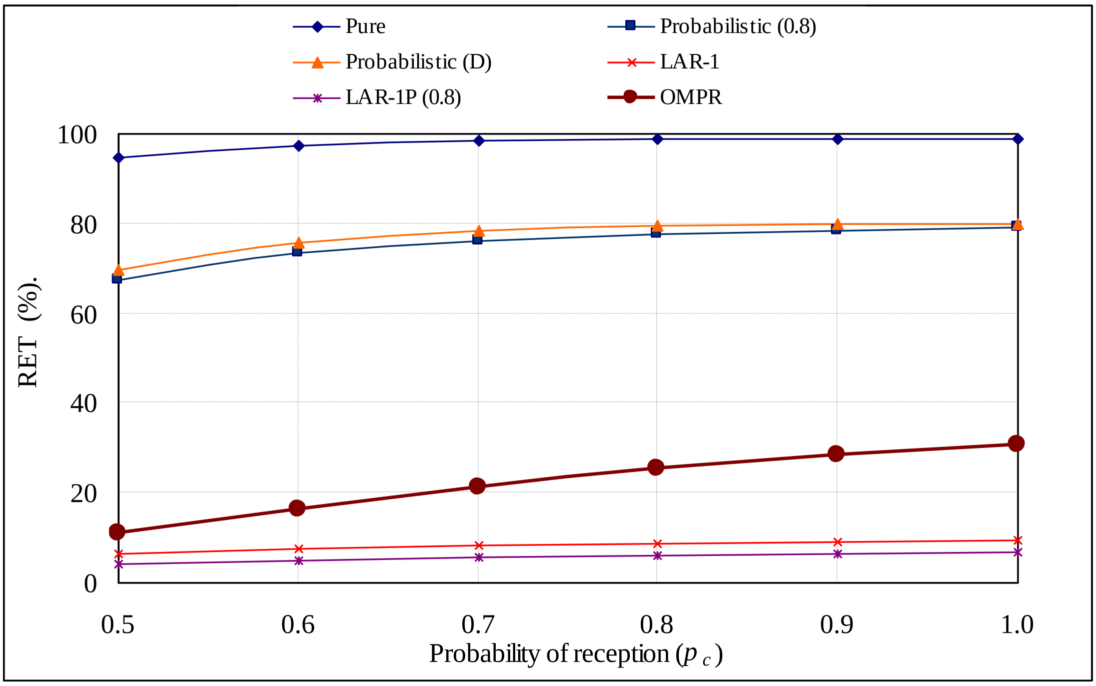


Figure (4.1). Variation of RET with p_c for various algorithms (fixed nodes).

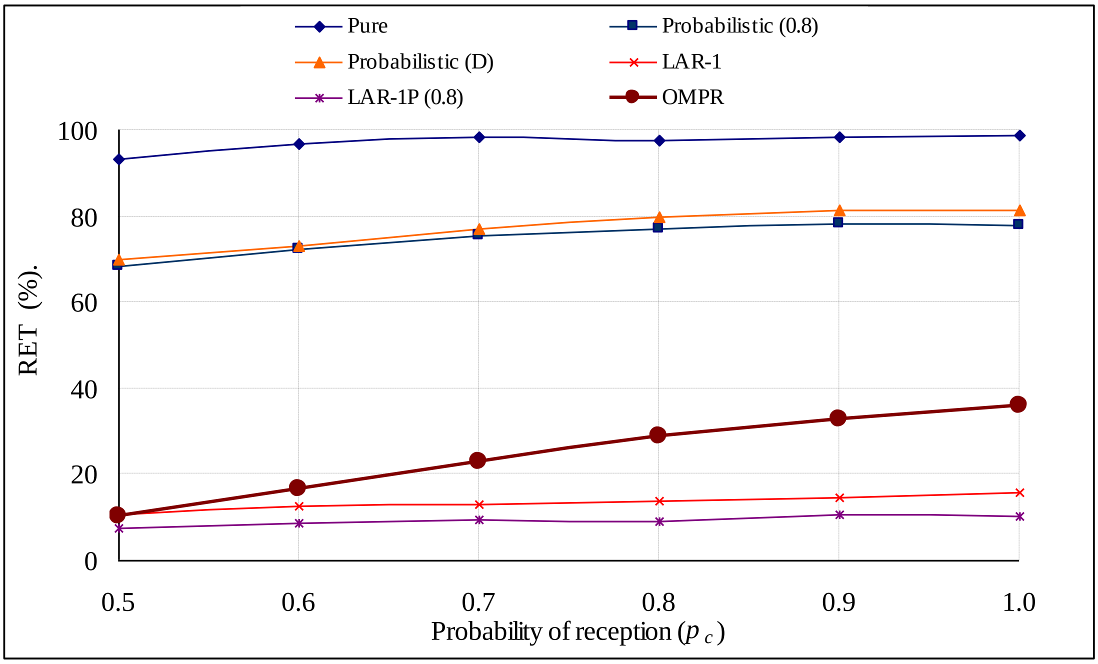


Figure (4.2). Variation of RET with p_c for various algorithms (mobile nodes).

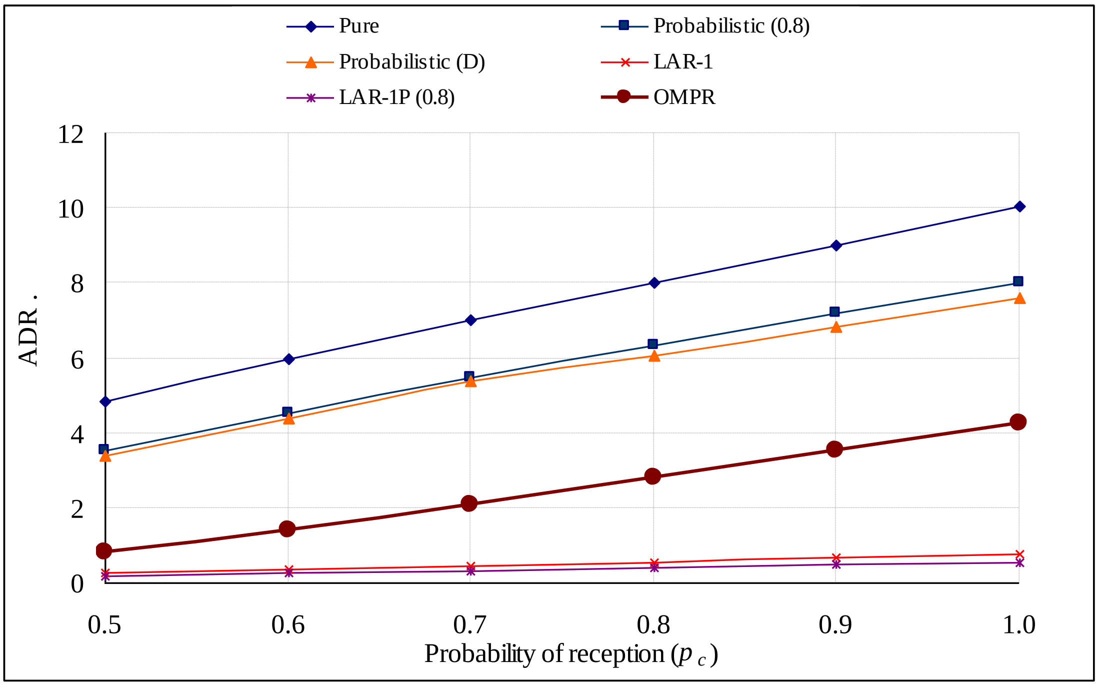


Figure (4.3). Variation of ADR with p_c for various algorithms (fixed nodes).

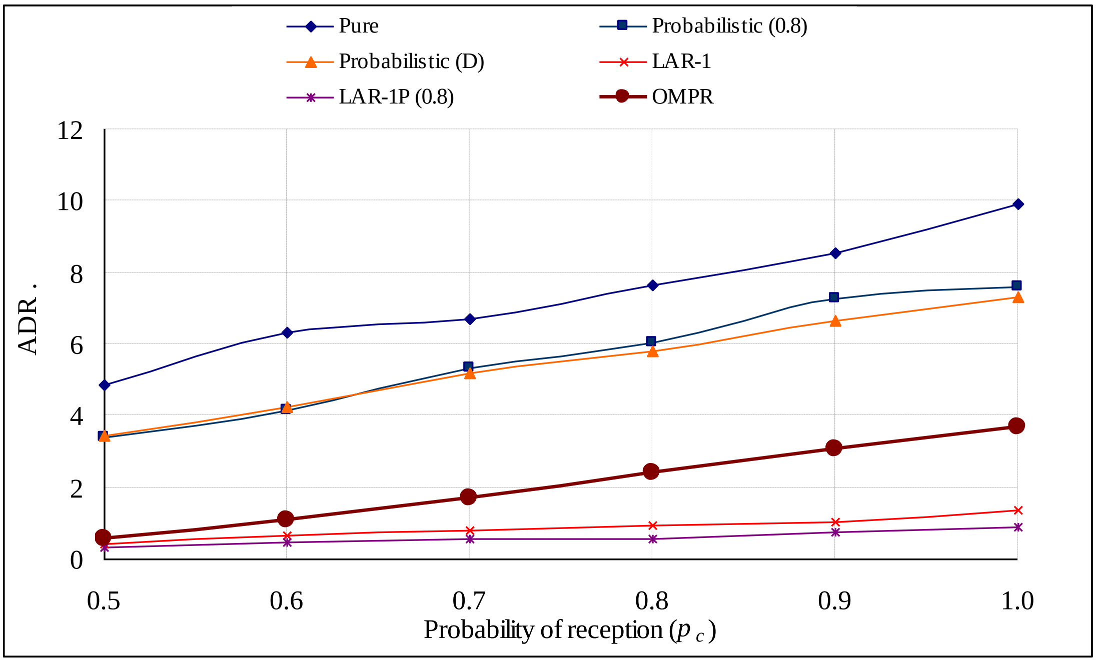


Figure (4.4). Variation of ADR with p_c for various algorithms (mobile nodes).

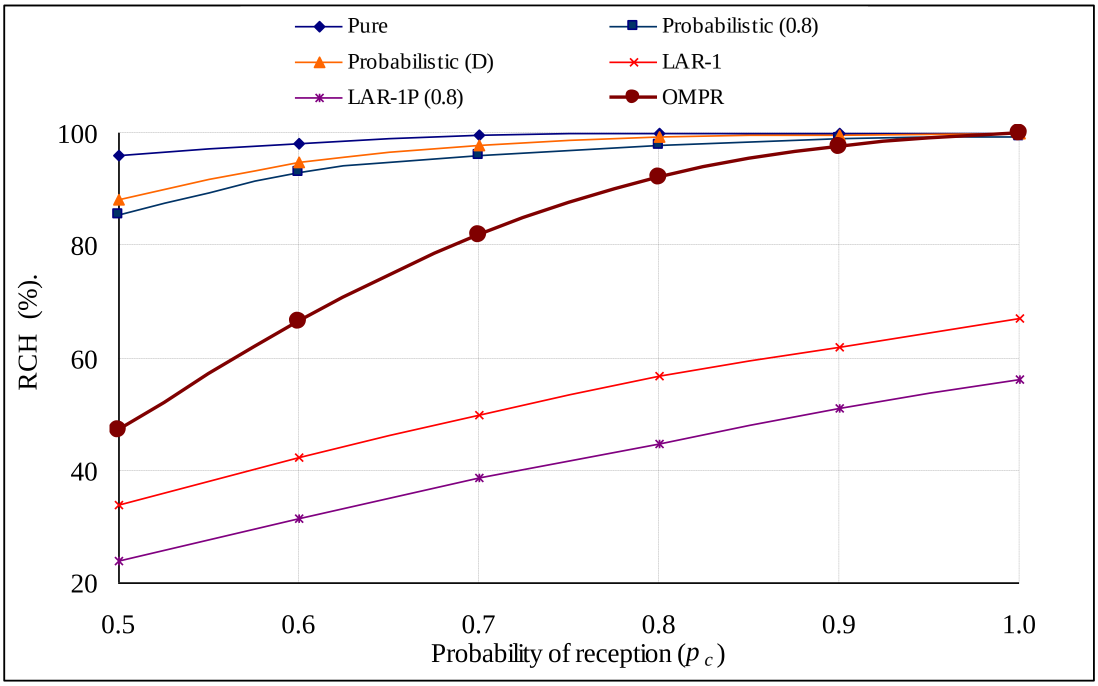


Figure (4.5). Variation of RCH with p_c for various algorithms (fixed nodes).

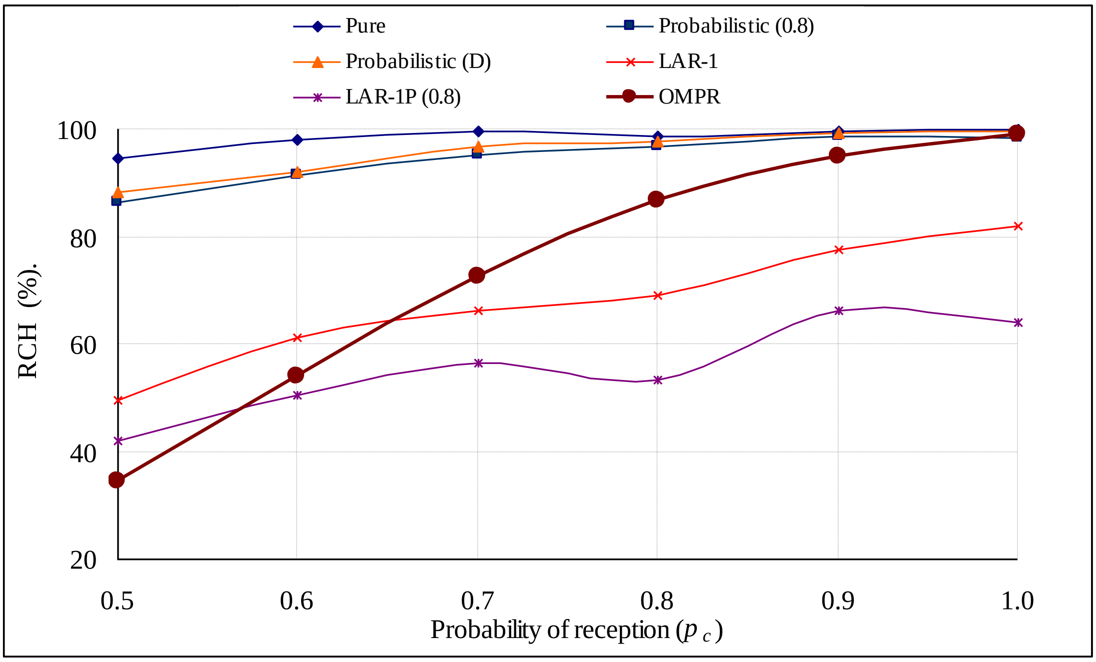


Figure (4.6). Variation of RCH with p_c for various algorithms (mobile nodes).

4.2.Scenario #2: Investigate the Effect of Node Density (nd)

This scenario investigates the variation of RET, ADR, and RCH with p_c for various number of node densities (n_d). The input parameters for this scenario are given in Table (4.5). The result obtained for RET, ADR, and RCH are tabulated in Table (4.6) and also plotted in Figures (4.7) to (4.9), respectively.

Table (4.5)
Input parameters for Scenario #2.

Parameters	Values
Geometrical model	Random node distribution
Network area	1000x1000 m
Number of nodes (n)	100, 200, 400 nodes
Transmission radius (R)	200 m
Average node speed (u)	5 m/sec
Probability of reception (p_c)	0.5 to 1.0 in step of 0.1
Simulation time (T_{sim})	900 sec
Pause time (□)	0.75*(R/u) sec

Table (4.6)
Values of RET, ADR, and RCH for Scenario# 2.

p_c	RET (%)			ADR			RCH (%)		
	n			n			n		
	100	200	400	100	200	400	100	200	400
1.0	36.1	26.2	19.8	3.7	6.0	8.158	98.9	100.0	100.0
0.9	33.0	23.6	17.5	3.1	4.8	6.516	95.0	99.2	99.5
0.8	28.8	20.8	15.1	2.4	3.8	5.024	86.8	96.9	98.0
0.7	23.1	17.7	12.7	1.7	2.9	3.711	72.7	91.6	94.6
0.6	16.5	14.3	10.3	1.1	2.0	2.579	53.9	80.5	87.4
0.5	10.3	10.2	7.7	0.6	1.2	1.623	34.6	61.1	73.0
R_{RCH} (%)							128.6	77.8	54.0

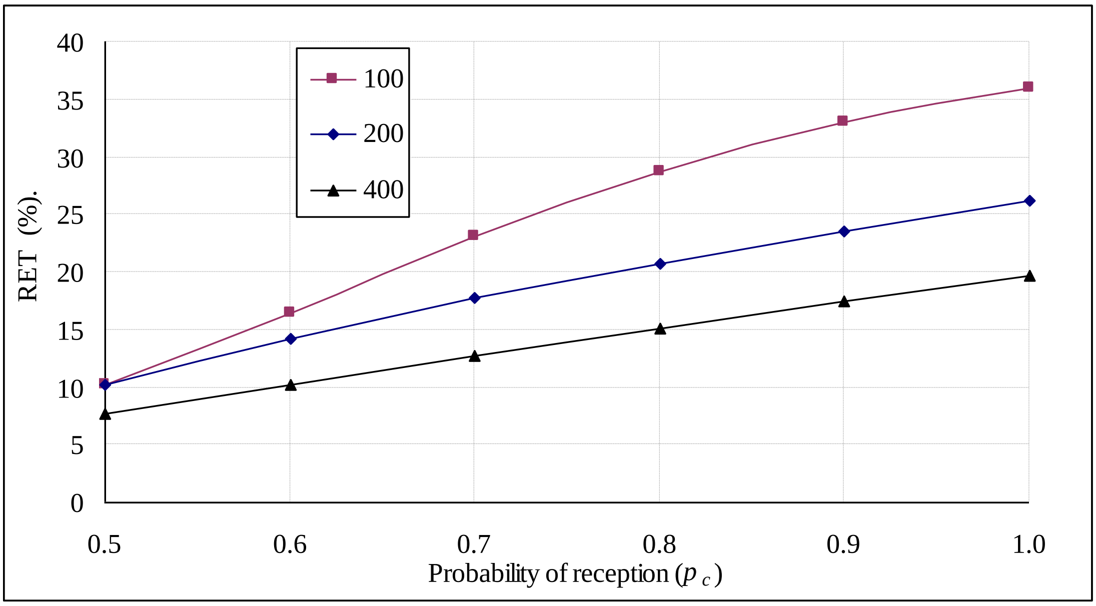


Figure (4.7). Scenario #2: Variation of RET with p_c for various values of n_d.

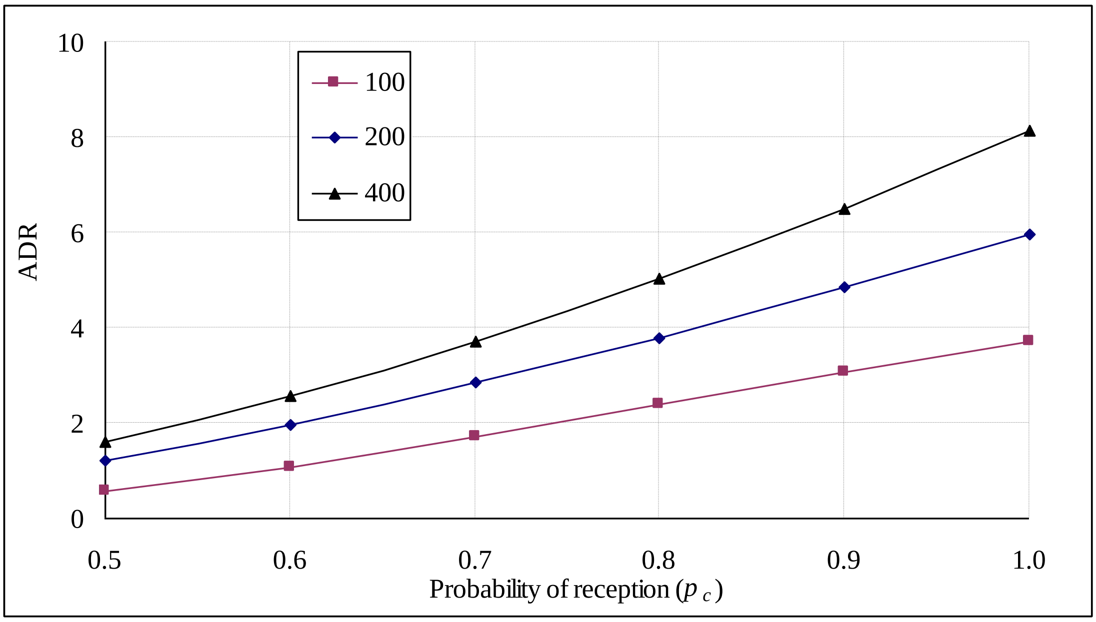


Figure (4.8). Scenario #2: Variation of ADR with p_c for various values of n_d.

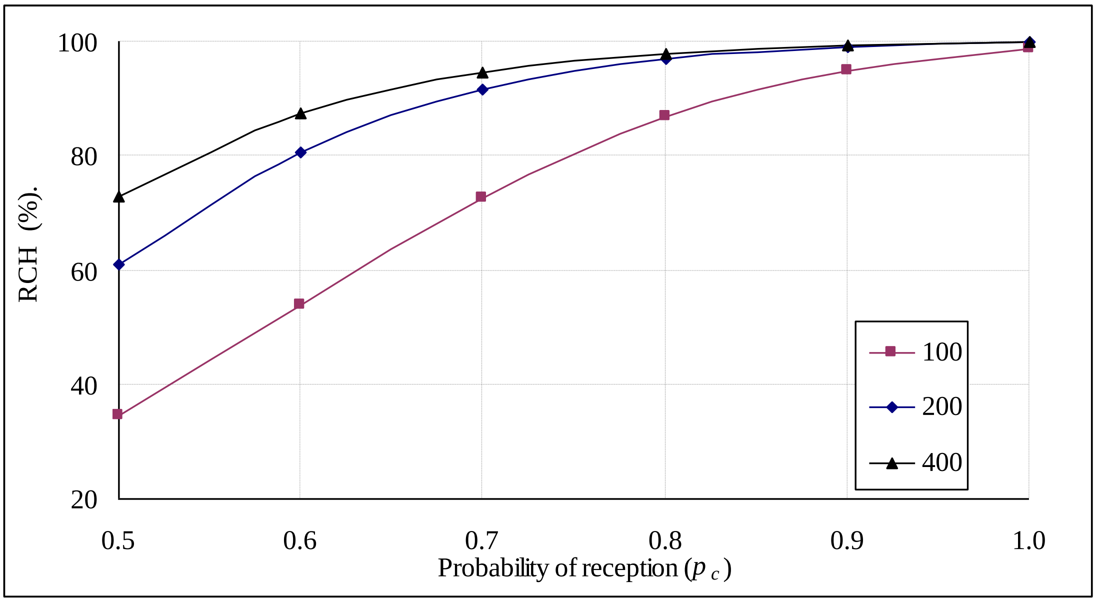


Figure (4.9). Scenario #2: Variation of RCH with p_c for various values of n_d.

The results obtained for Scenario #2 show that when p_c decreases, the computed parameters RET, ADRE, and RCH are decreased. The reduction in RET and ADR is an advantage while the reduction of RCH is a drawback. It can be seen from Figures (4.7) to (4.9) that it is very encouraging to use the OMPR algorithm, since the reduction in RCH is insignificant and acceptable for MANETs when the reception probability is relatively high (> 80%). RCH decrease because some of the relay nodes that are selected to forward the RREQ message will not receive the message because of error in reception. For large p_c, a message can reach the whole network.

It can be clearly seen that the variation of the node density significantly affects the performance of the OMPR algorithm, and for the same value of p_c (noise level), when the node density increases, RET decreases, ADR increases, and RCH increases. For example, using the OMPR algorithm with p_c=0.8; RCH is 86.8% for a 100 nodes network while it increases to 98.0% for a 400 nodes network. It indicates that OMPR is more suitable and efficient in dense networks.

Table (4.6) shows that the sensitivity of the OMPR algorithm also improves as n_d increases, where it becomes less sensitive to variation in p_c as n_d increases. For example R_{RCH}=128.6%, 77.8%, and 54.0% for n_d=100, 200, and 400 nodes, respectively.

4.3. Scenario #3: Investigate the Effect of Nodes Velocity (*u*)

This scenario investigates the effect of nodes velocities (u) on the performance of the OMPR algorithm. A number of simulations were carried out to estimate the variation of RET, ADR, and RCH with p_c for various average node velocities (u). It considers both fixed nodes (i.e., u=0 m/sec), and mobiles nodes with different average velocities, namely, u=2 and u=5 m/sec. The input parameters for this scenario are given in Table (4.7). The results obtained for RET, ADR, and RCH are listed in Table (4.8), and they are also plotted in Figures (4.10) to (4.12).

Table (4.7)
Input parameters for Scenario #3.

Parameters	Values
Geometrical model	Random node distribution
Network area (A)	1000x1000 m
Number of nodes (n)	100 nodes.
Transmission radius (R)	200 m
Average node speed (u)	0, 2, 5 m/sec
Probability of reception (p_c)	0.5 to 1.0 in step of 0.1
Simulation time (T_{sim})	0 for fixed nodes, 300 sec for mobile nodes
Pause time (□)	0 for fixed nodes, 0.75*(R/u) for mobile nodes

Table (4.8)
Values of RET, ADR, and RCH for Scenario# 3.

p_c	RET (%)			ADR			RCH (%)		
	u (m/sec)			u (m/sec)			u (m/sec)		
	0	2	5	0	2	5	0	2	5
1.0	30.8	35.3	36.1	4.262	3.831	3.700	100.0	98.5	98.9
0.9	28.4	32.3	33.0	3.527	3.163	3.055	97.6	94.9	95.0
0.8	25.2	28.3	28.8	2.797	2.484	2.386	92.2	87.6	86.8
0.7	21.1	23.1	23.1	2.076	1.803	1.705	81.9	74.9	72.7
0.6	16.2	16.8	16.5	1.408	1.160	1.075	66.6	57.0	53.9
0.5	11.0	10.7	10.3	0.833	0.647	0.587	47.1	37.6	34.6
R_{RCH} (%)							105.8	121.8	128.6

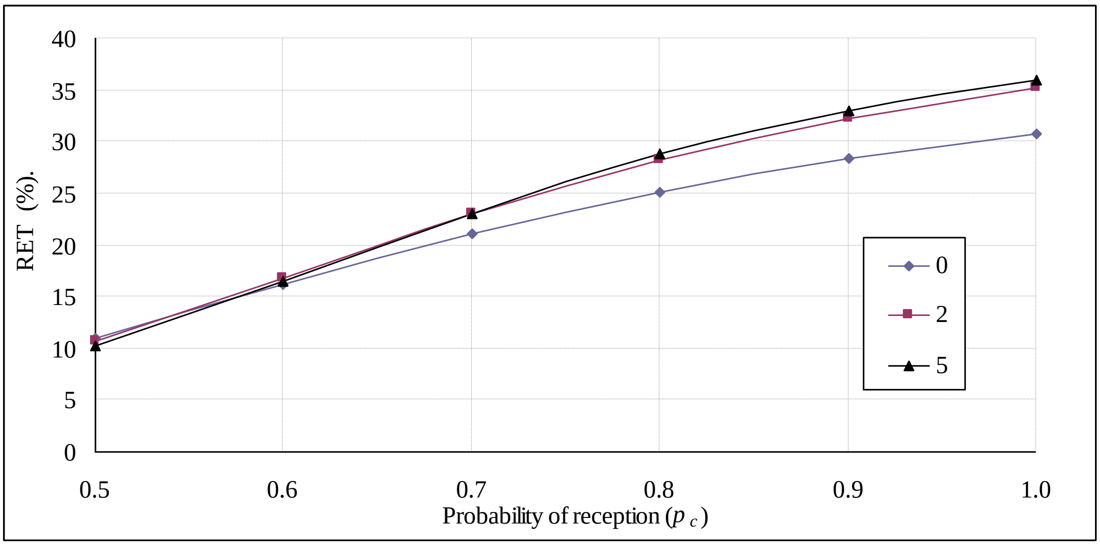


Figure (4.10). Scenario #3: Variation of RET with p_c for various values of u.

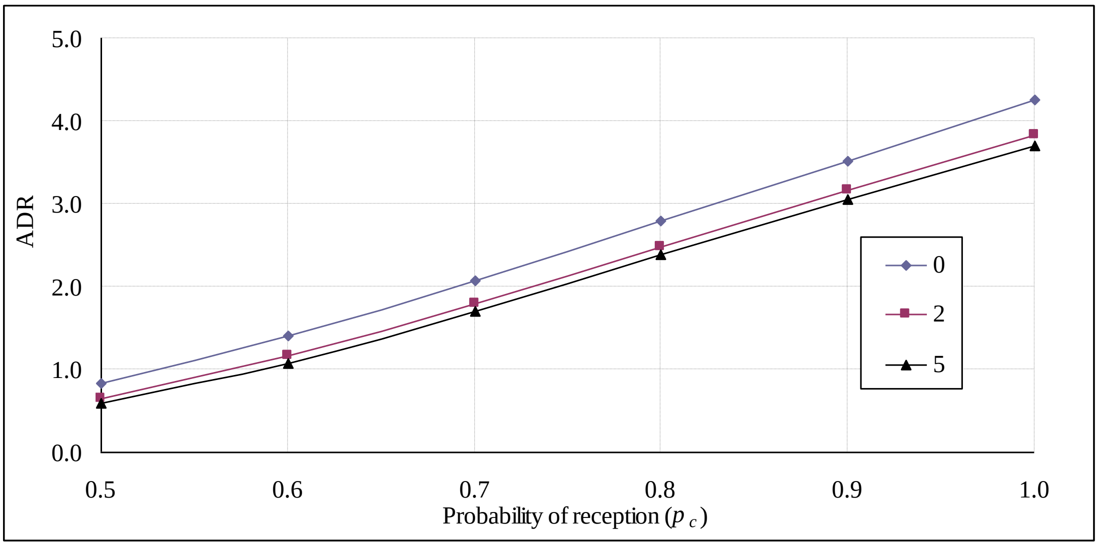


Figure (4.11). Scenario #3: Variation of ADR with p_c for various values of u.

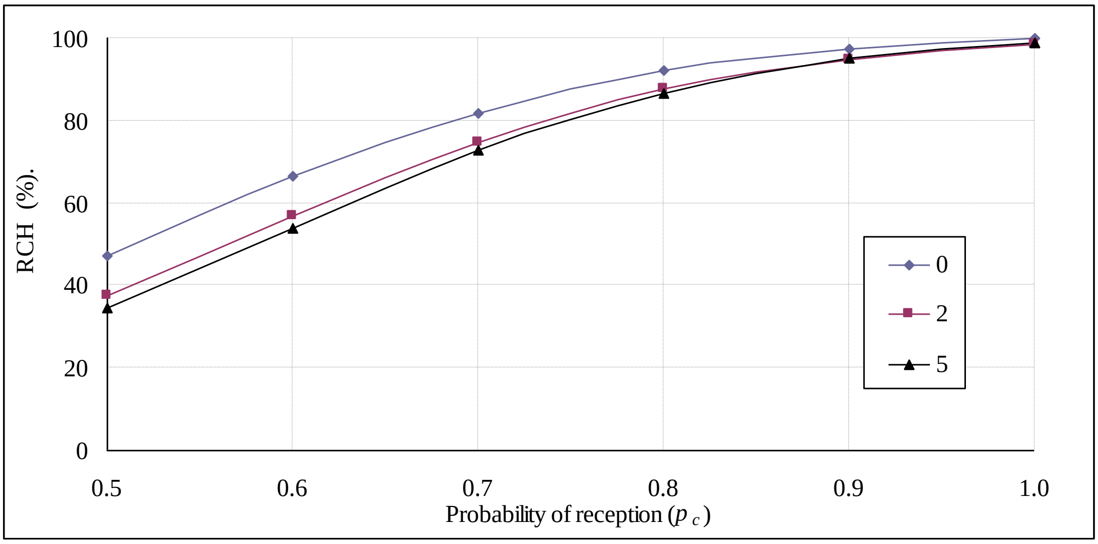


Figure (4.12). Scenario #3: Variation of RCH with p_c for various values of u.

Before we proceed with the discussion of the effect of node mobility on the performance of the OMPR algorithm, it is important to remember a number of facts that are assumed and used in the simulation, these are:

- All nodes are moving with the same average speed.
- Nodes can move in all direction with equal probability
- The reduced weight mobility model is used to bring a node leaving the network back.

- The mobility loop size is calculated as the ratio between the simulation time and the average pause time ($nIntv=T_{sim}/\square$).
- The average pause time (□) is calculated as $\square =0.75*R/u$.

The results obtained show that for all nodes velocities, the estimated parameters (RET, ADR, and RCH) are decreasing, when p_c decreases, i.e., increasing noise level. This is because as the noise level increases, the link failure is increasing and more RREQ packets fail to complete the journey to the destination. Furthermore, it can be easily recongnized that for the same noise level, the network RCH is decreasing when u increases. This is a typical behaviour, because increasing nodes speeds cause a frequent change in network topology, and the MPR set must be continuously updated, which significantly ruin the network resources.

The results in Figures (4.10) to (4.12) show that node mobility has a slight effect on the performance of OMPR, this is because the neighborhood information update frequency is chosen such that the information is updated every less than □□seconds. This insures that a source node has valid neighborhood information. On the other hand, if the update time is too high, a node may select another node as a relay node even though it is not in its neighborhood.

On the other hand, the algorithm sensitivity expressed in terms of R_{RCH} is increasing as u increases, as given in Table (4.8). For example, in this scenario, the R_{RCH} is calculated as 105.8%, 121.8%, and 128.6%, for u=0, 2, and 5 m/sec, respectively. Finally, it can be seen from Figure (4.12) that the node speed has a slight effect on RCH in low-noise environment p_c>=0.8.

4.4.Scenario #4: Investigate the Effect of Transmission Radius (*R*)

This scenario investigates the effects of the node radio transmission range R on the performance of the OMPR algorithm to provide a cost-effective route discovery mechanism for dynamic routing algorithms. A number of simulations are carried-out using our network simulator MANSim to predict the variation of

RET, ADR, and RCH with p_c for various values of R in a network of 100 nodes moving with an average speed u=5 m/sec. The input parameters for this scenario are given in Table (4.9). The results obtained for this scenario for RET, ADR, and RCH are tabulated in Table (4.10) and plotted in Figures (4.13) to (4.15).

Table (4.9)
Input parameters for Scenario #4.

Parameters	Values
Geometrical model	Random node distribution
Network area	1000x1000 m
Number of nodes (n)	100 nodes.
Transmission radius (R)	150, 200, 250 m
Average node speed (u)	5 m/sec
Probability of reception (p_c)	0.5 to 1.0 in step of 0.1
Simulation time (T_{sim})	900 sec
Pause time (□)	□ = 0.75*(R/u)

Table (4.10)
Values of RET, ADR, and RCH for Scenario# 4.

p_c	RET (%)			ADR			RCH (%)		
	R (m)			R (m)			R (m)		
	150	200	250	150	200	250	150	200	250
1.0	36.5	36.1	28.2	2.7	3.7	4.2	85.6	98.9	99.9
0.9	31.2	33.0	25.8	2.1	3.1	3.5	75.3	95.0	98.0
0.8	24.6	28.8	23.0	1.5	2.4	2.8	61.6	86.8	93.2
0.7	17.6	23.1	19.5	1.0	1.7	2.1	46.0	72.7	83.5
0.6	11.5	16.5	15.1	0.6	1.1	1.4	31.2	53.9	68.0
0.5	6.8	10.3	10.5	0.3	0.6	0.8	19.2	34.6	48.3
R_{RCH} (%)							132.8	128.6	103.2

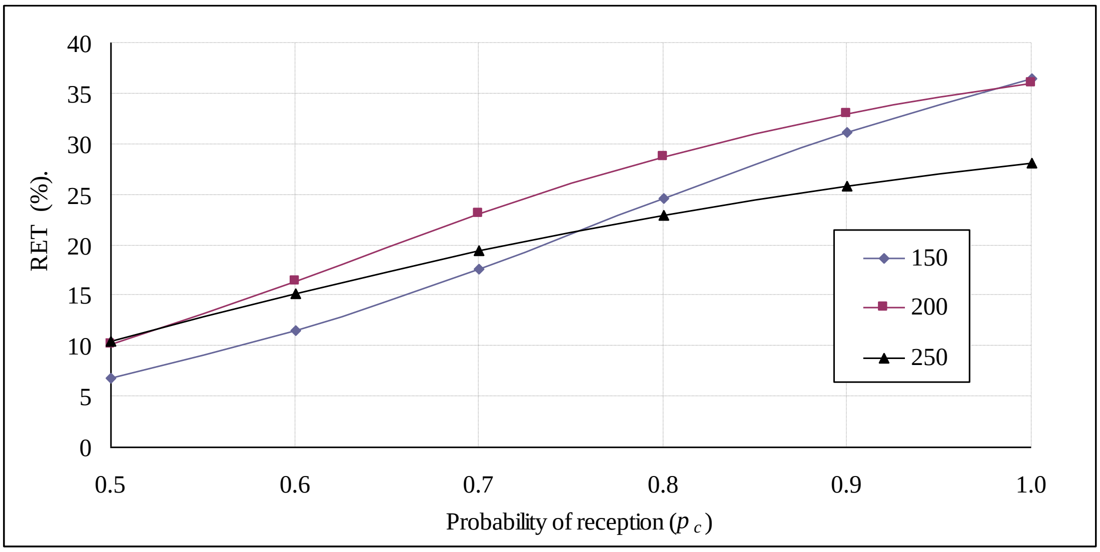


Figure (4.13). Scenario #4: Variation of RET with p_c for various values of R.

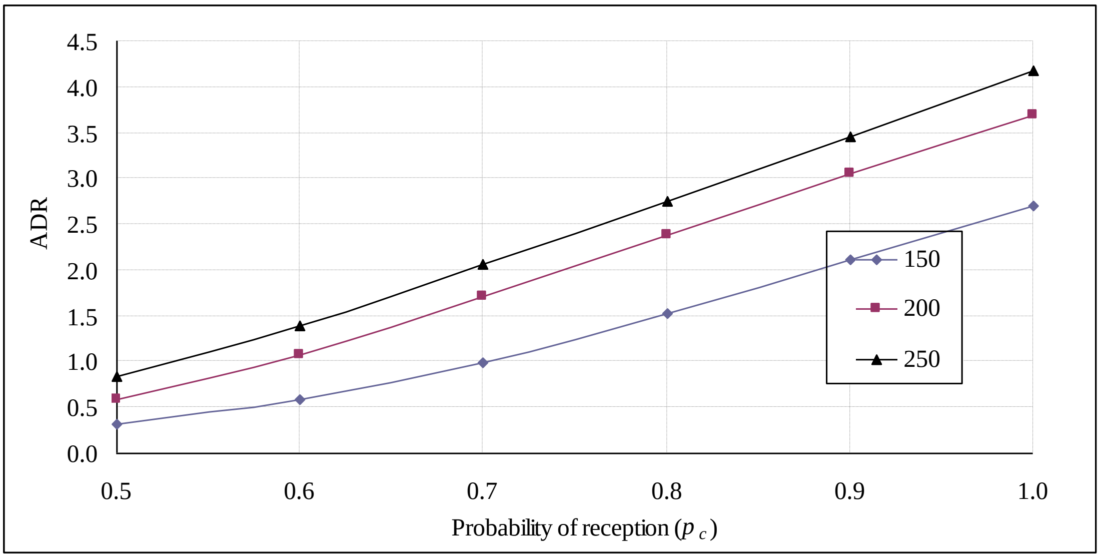


Figure (4.14). Scenario #4: Variation of ADR with p_c for various values of R.

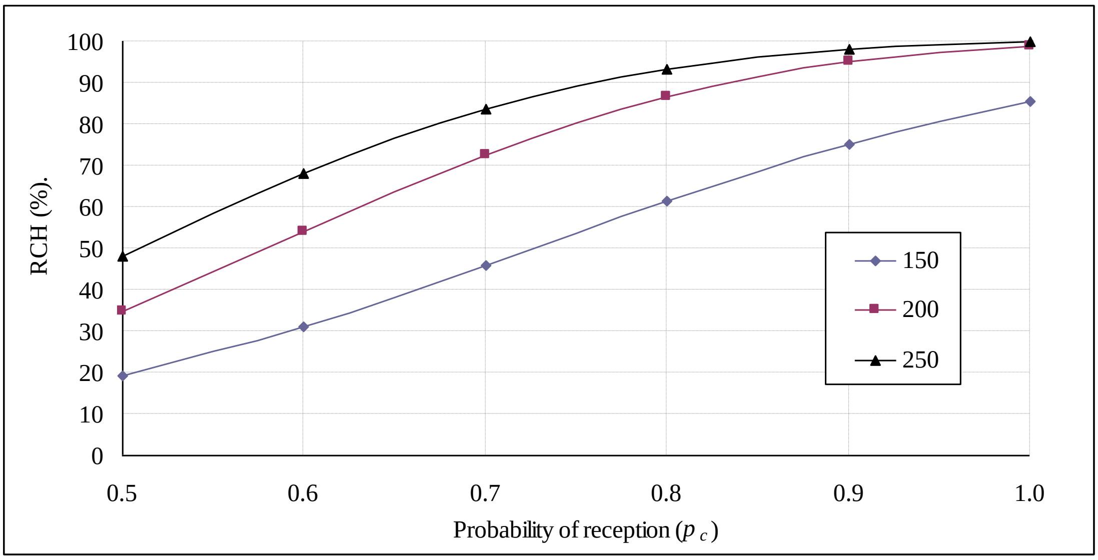


Figure (4.15). Scenario #4: Variation of RCH with p_c for various values of *R.*

Figure (4.13) shows that as *R* increases, the number of retransmissions required to diffuse a message to the entire network decreases. This is because as *R* increases the number of neighboring nodes for any transmitting node increases, and according to the OMPR approach, most of them will be prevented from retransmitting the RREQ packet. Therefore, the number of retransmission is significantly reduced as compared to shorter *R*. It is clear that if the radio range is big enough to cover the whole network area, a message sent by any source node can reach all other nodes in the network with only one transmission using OMPR.

We can see also that when *R* decrease to 150 m, the noise has a greater effect on the network and many relay nodes will not receive the PREQ which can be clearly seen from RCH values causing the number of retransmissions to decrease. Among all flooding optimization algorithms, OMPR is the only algorithm that has such positive behavior, where RET is inversely proportional to *R*. This is considered as one of the most important features of this algorithm.

It is obvious from the above discussion that since more nodes will be covered by extending R, i.e., a single transmission approaches more nodes within the network, then the ADR will be elevated, regardless whether these covered

nodes will retransmit the received message or not, in other words be part of the MPR relays or not. The noise level almost has an equal effect on ADR values for all R. For example, for R 150, 200, 250 m, ADR values are reduced by average rates of 48.0%, 62.3%, and 66.8% for a reduction if 0.1 in p_c. Figure (4.14) illustrates how ADR is affected by increasing R, the figure shows that increasing R will increase ADR since as R increases the average one hop neighbors for each node is increased, and consequently increases the number of times the same message is received.

Finally, in this section, we discuss the variation of RCH with p_c for various values of R as shown in Figure (4.15). Although, OMPR shows an excellent performance with increasing R, where a connectivity of pure flooding can be achieved with minimum RET and ADR. However, the OMPR algorithm is very sensitive to noise level within the network, where RCH is notably decreasing as p_c decreases. As it can be seen in Figure (4.15), the rate by which RCH decreases is less for higher R. For example, while RCH is reduced by ≈10% when p_c changed from 1.0 to 0.8 for R=250 m, it is reduced by ≈25% for R=150 m.

The performance of the OMPR algorithm is significantly affected by increasing the noise level (i.e., decreasing p_c); OMPR algorithm will achieve an RCH that is less than that is achieved by pure flooding algorithm for the same p_c. This is because in pure flooding, each node that receives a message will rebroadcast it; hence, a transmission error from one source can be compensated from another. Figure (4.15) shows that RCH is increasing with increasing R, This is obvious, since as R increases more intermediate nodes can be reached in a single hop, and thus, the broadcast messages are likely to be successfully delivered to the entire network.

Chapter 5
Conclusions and Recommendations for Future Work

5.1. Conclusions

This thesis presented a new optimal multipoint relaying (OMPR) algorithm that utilizes a locally performed heuristic for selecting the optimal set of first-hop neighbors to efficiently diffuse RREQ packets in MANETs suffering from high packet-loss rate, due to presence of noise and node mobility. Furthermore, the performance of the new OMPR algorithm was analyzed in a realistic MANET network conditions, taking into account various nodes densities, velocities, radio transmission ranges, and network noise level expressed in reception probability (p_c).

The main conclusions of this work can be summarized as follows:

- The OMPR algorithm demonstrated an excellent cost-effective performance as compared to other route discovery algorithms, such as: pure flooding, probabilistic flooding (fixed and dynamic retransmission probability), location-aided routing Scheme (LAR-1) algorithm, hybrid LAR-1 and probabilistic (LAR-1P) algorithm, for both fixed and mobile nodes. In particular:
    - OMPR provides a satisfactory reachability (RCH) as compared to pure and probabilistic algorithms in high mobility noiseless and low-noise level MANETs environment ($p_c \geq 0.8$), and always higher than LAR-1 and LAR-1P algorithms.
    - OMPR significantly reduces the number of retransmissions (RET) and consequently the average duplicate reception (ADR) while maintaining an appropriate RCH in various MANETs environments, when it is compared with above mentioned algorithms.

- OMPR demonstrated a much better performance in high density MANETs rather than low density MANETs in terms of lower RET and higher RCH.

- The algorithm handled the node mobility very well, so that it showed a satisfactory RET and RCH in high mobility MANETs compared to fixed nods MANETs.

- The algorithm responds positively to a higher nodes radio transmission range providing a lower RET and a higher RCH.

- Scenarios #2 to #4 shows that the algorithm demonstrates a competitive performance that is equivalent to the performance of pure flooding with minimum cost, when p_c>0.8.

- The main drawback of the OMPR algorithm is its high sensitivity to noise-level as it yields the highest average rate of change in reachability (R_{RCH}) in comparison with the algorithms considered in this thesis as demonstrated in Table (4.4).

5.2.Recommendations for Future Work

The main recommendations for future work are summarized as follows:

1. Considering other factors during the selection of multipoint relays (MPRs), such as: nodes residue energy level, nodes traffic load, nodes reliability, nodes security measures, etc.

2. Investigating the performance of the algorithm under:

    a. Realistic mobility models.

   b.

   c. Variable nodes radio transmission range, which can be adjusted dynamically according to the networks conditions.

3. Comparing the performance of OMPR algorithm with other MPR algorithms and flooding optimization schemes.

4. In order to overcome the main drawback of the OMPR algorithm, the heuristic for selecting the multipoint relays (MPRs) should be modified by adding supporting nodes to the MPR set so that RCH is maintained in high noise MANETs environment.

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