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LIST OF ABBREVIATIONS AND ACRONYMS

ACK	ACKnowledgement
AHR	Adaptive Hello Rate
AODV	Ad hoc On Demand Distance Vector
AP	Access Point
ARS	Autonomous Reconfiguration System
BEST-MAC	Bitmap-Assisted Efficient and Scalable TDMA-Based WSN MAC
BSR	Backup Source Routing
BW	BandWidth
CB	Competing Backup
CHAMP	Caching and Multiple Paths
D	Destination node
DA	Destination Address
DSR	Dynamic Source Routing
FDM	Frequency Division Multiplexing
GBR	Greedy-based Backup Routing
GBR-CNR	GBR with Conservative Neighborhood Range
GPS	Global Position System
GPSR	Greedy Perimeter Stateless Routing
IACA	Interference Aware Channel Assignment
LLLA	Link Layer and Learning Automata
LRD	Least Remaining Distance
MAC	Media Access Control

MANET	Mobile Ad hoc NETwork
MDA	Mobility Detection Algorithm
MFR	Most Forward within R
MHD	Maximum Hop Distance
NFP	Nearest with Forward Progress
NIC	Network Interface Card
OLSR	Optimized Link State Routing
PDORP	PEGASIS-DSR Optimized Routing Protocol
pdr	packet delivery ratio
PET	Path Expiration Time
PREQ	Path REQuest
QoS	Quality of Service
RA	Receiver Address
RBD	Reliability Block Diagram
RM-AODV	Radio-Metric AODV
RREP	Route REPply
RV	Random Variables
RWP	Random WayPoint
S	Source node
SA	Source Address
SMORT	Scalable Multi-path On demand Routing
TA	Transmitter Address

TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TGs	Task Group “s”
TLF	Time to Link Failure
TWC	Time Without Change
WMN	Wireless Mesh Network
WSN	Wireless Sensor Network

LIST OF SYMBOLS

C	the area of the circular sector
F	the selected forwarding node
$\mathrm{f(T,R)}$	the distance traveled by the packets from the transmitter to the receiver
$\mathrm{gain}_{\mathrm{pdr1}}$	the achieved increase in pdr1
$\mathrm{gain}_{\mathrm{pdr2}}$	the achieved increase in pdr2
HC	the expected number of hops in MHD
$\bar{\mathrm{h}}$	the expected number of hops in LRD
K	the number of missing Hellos
k	the number of hops
$\mathrm{L}_{\mathrm{max}}$	the longest path from S to D during the flow
$\mathrm{M_t}$	the number of true failure detections over T
$\mathrm{\lvert M_m \rvert}$	the number of mis-detected failures over T
N	the number of nodes inside the area C
$\mathrm{N_r}$	successfully received packets
$\mathrm{N_s}$	the total number of packets sent during the entire flow
$\mathbf{N_l'}$	packets lost due to link failure detection delay
$\mathrm{N_l''}$	the average number of lost packets due to undetected failures
pdr1	the flow packet delivery ratio with two routes
pdr2	the flow packet delivery ratio with two route
$\mathrm{p_B}$	the probability of receiving a Hello beacon successfully when the link is up
$\mathrm{P_{down}}$	the probability that a link will be considered as a failed link

$P_{con\_oneroute}$	the probability of one-way connectivity in the general case
$P_{dcon\_oneroute}$	the probability of one-way connectivity in the default case
$P_{con\_tworoutes}$	the probability of two-ways connectivity in the general case
P_k	the probability that two k-hop routes exist between S and D
$P(n)$	the probability that a mobile node has n neighbors inside a specified area
R	the transmission range
r	the Euclidean distance between S and F where the nodes are uniformly distributed in the network area
rr	the expected value of Ω
R_{fd}	the reduction in the false link failure detection ratio
r_{FD}	the false detection rate
r_{LF}	link failure rate
r_{MD}	misdetection rate
T	the flow duration
T_B	the Hello interval
t_{fail}	the link failure duration
t_m^B	the failure detection delay at sub-duration 1 (phase B)
$t_m^{B'}$	the failure duration at sub-duration II (phase B')
z	the remaining distances to D.
$\overline{Z_{def}}$	the expected maximum progress in the default case
λ	the sending rate
ϵ	a negligible variance due to channel congestion
δ'	the average detection delay

τ	the per-hop delay
ρ	the node density
θ	the angle between the line connection S and D and the line connecting S and F
ϕ	a dummy variable between 0 and $\pi/2$
ψ	the probability that the source node has at least two neighbors
δ	the least remaining distance to D
ε	the forward progress per hop in LRD
$\bar{\varepsilon}$	the average progress per hop in LRD
Ω	the maximum Euclidean distance between S and its neighbor

INTRODUCTION

In this thesis, we study two kinds of multi-hop wireless networks, namely Wireless Mesh Network (WMN) and Mobile Ad hoc NETworks (MANET). Each client node in WMNs can operate as a host and a router at the same time. WMNs consist of mesh clients, mesh routers and gateways organized in a mesh typology in order to increase connectivity. These components have different functions and specifications. Usually, mesh clients have mobility, the ability to form a wireless mesh network among themselves (composing MANET), or with mesh routers, limited power, and relatively simple structure. On the other hand, mesh routers have minimal mobility, unlimited power, and advanced structure. Actually, mesh routers form the backbone of WMNs. Finally, the gateways connect WMNs with other kinds of networks, like Internet, cellular, and sensor networks.

In addition to routing operations, wireless mesh routers perform several other tasks, as shown below. Usually, they have specialized routing functions to support mesh networking. Wireless mesh routers achieve the same amount of network coverage with much less power compared to traditional wireless routers. In addition to that, they have the ability to use some enhanced Media Access Control (MAC) layer protocol to achieve more scalability.

The nodes in WMNs automatically establish and maintain mesh connectivity on their own, which makes WMN self-configured, self-organized and self-healed. WMN have many advantages like low setup cost, easy network maintenance, robustness, and reliable service coverage (Akyildiz, Wang & Wang, 2005). Mesh clients nodes like phones, laptops and desktops contain wireless Network Interface Cards (NICs) which connect them directly to wireless mesh routers. Clients without wireless NICs can access WMNs through an Ethernet card (Akyildiz et al., 2005). WMN has many applications such as broadband home networking, community and neighborhood networks and enterprise networking. In July 2004, industrial standards group IEEE established IEEE Task Group “s” (TGs) in order to propose a standardized framework for WMNs (Minh, Nguyen, & Yamada, 2013). This group proposed a new standard, namely the IEEE 802.11s, for flexible and extensible client mesh networks in September 2011 (Minh et al., 2013). Figure 0.1 taken from (Henry, 2011) shows the architecture of a 802.11s MANET/mesh network.

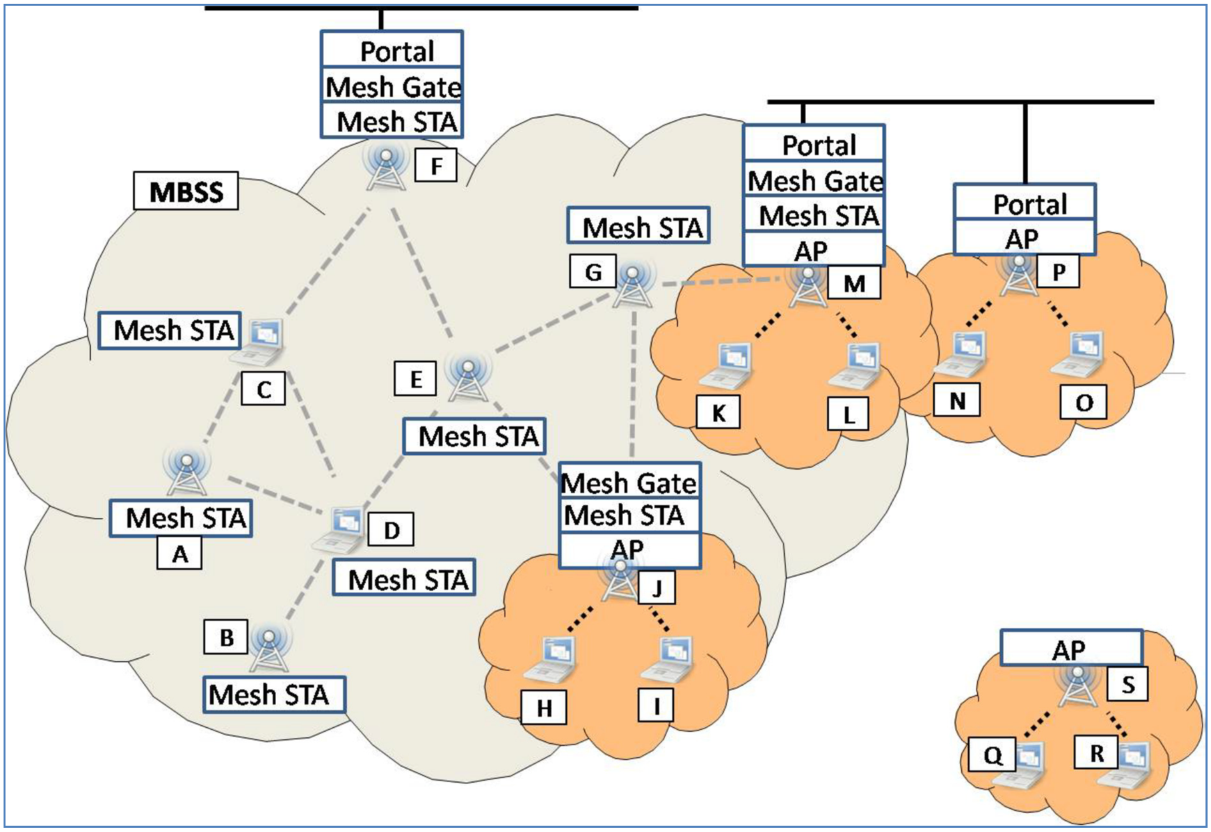

Figure 0.1 The IEEE 802.11s mesh network architecture
Taken from Henry (2011, p. 9)

As we can see from Figure 0.1, the 802.11s MANET/Mesh Network consists of three kinds of nodes (Henry, 2011):

- **Station:** station is a device that cannot route frames. It works just like a host that associate itself to one of the mesh Access Points (AP); in order to get services, such as nodes K and H in Figure 0.1;

- **Mesh station (Mesh STA):** an IEEE 802.11 station with mesh capabilities. Thus, it can work as a host or a router at the same time. Mesh stations can communicate with others mesh stations, but they cannot communicate directly with non-mesh stations.
- **AP:** a mesh station with additional functions over mesh stations. It works as proxy to connect non-mesh nodes with the mesh network. In order for a mesh AP to support both the traditional IEEE 802.11 stations and IEEE 802.11s stations, MAP should be able to transform four-address format into six-address format, and vice verse (Minh et al., 2013).
- **Mesh Gate:** a mesh station, which has the ability to connect mesh stations to IEEE 802.11 networks.
- **Portal:** a mesh station with bridging capability. It connects IEEE 802.11s mesh network to the non-802.11 networks.

IEEE 802.11s uses the Hybrid Wireless Mesh Protocol (HWMP) as a routing protocol. HWMP was firstly proposed by Michael Bahr in 2006 (Minh et al., 2013). This protocol is a mix of the reactive Ad hoc On Demand Distance Vector (AODV) and the proactive tree-based routing protocols, and it works on layer 2 instead of layer 3 with MAC addresses instead of the IP addresses. It is also called the Radio-Metric AODV (RM-AODV), because it uses a radio-aware metric as routing metrics.

IEEE 802.11s defines a new MAC frame format in order to support the MAC-based routing protocols. This format has six addresses, while the traditional IEEE 802.11 has four addresses (Minh et al., 2013). All the six addresses are needed in order to allow a non-mesh station sends packets to another non-mesh station. If non-mesh station wants to send packets to a mesh station or vice versa, five addresses are needed. On the other hand, if a mesh station wants to communicate with other mesh stations, the traditional four addresses are sufficient. The traditional four addresses in the conventional IEEE 802.11 are Source Address (SA), Destination Address (DA), Transmitter Address (TA) and Receiver Address (RA). IEEE 802.11s adds two other addresses to the above four addresses in order to support layer 2 routing protocols between non IEEE 802.11 stations and IEEE 802.11s stations or vice versa. These two additional addresses are mesh SA and mesh DA, representing the mesh start and mesh end points, respectively.

There are many reasons to choose WMNs and not other kinds of networks. The first reason is that WMNs have the ability to resolve the limitation of MANETs, and to improve the performance of ad hoc networks. WMNs also have higher flexibility over wired networks. They also provide wireless connection in places where wired connections is not possible, or it is very expensive, such as large indoor environments (warehouses), and far away rural areas.

MANETs can be considered as a subset of WMNs. Usually the WMNs are configured in a mesh topology; in order to increase the network connectivity, while MANETs can take any topology. MANET's nodes form a network on the fly, and that is why it is named ad hoc networks. All MANET nodes have the same functionalities, rules, and specification, and can move randomly without any restrictions. On the other hand, in WMNs some nodes have certain functions and specifications, and usually they are static nodes.

The big challenge in WMNs and MANETs is the link failures, which are frequent events in both kinds of networks. Channel interference, dynamic obstacles, mobility, and applications' bandwidth demands are the causes of link failures in WMNs and MANETs. Link failures interrupt the communication till the failure is detected and fixed; which causes severe performance degradation especially for multimedia communications. Based on that, studying link failure detection and network recovery are interesting and important research topics to conduct. By implementing a fast and an accurate mechanism to detect link failures, and a powerful reconfiguration scheme to recover from the link failures, and by proposing a fault tolerant routing protocols and metrics greatly enhance the WMNs' and MANETs' performance. The above mitigate the bad impacts of link failures, and increase the network reliability and availability.

In this thesis, we study the approaches used to detect link failures, the techniques used to recover from these failures, the reliable routing protocols and metrics, and the network reliability and connectivity. Link layer feedback and Hello based link failure detection approaches are the two main approaches that are used to detect link failures in WMNs and MANETs. Since Hello based link failure detection approach is the most used, as we show later, we give more attention to this approach. Specifically, we mathematically analyze Hello based link failure detection approach, adapt its parameters to the communications types and Quality of Service (QoS) requirements, and propose some modifications to it in order to enhance its performance. After that, we study the reliable routing protocols and metrics used in MANETs and WMNs, network reliability, and the network requirements to ensure network connectivity. In addition to that, we propose some techniques to increase the network reliability and availability. Finally, we propose a novel adaptive greedy forwarding strategy for MANETs in order to reduce the hop count, save energy and memory size, and reduce the nodes spatial distributions.

Problem Statement

MANETs and WMNs are two kinds of wireless communications which have properties and working conditions that are different from wired communications. In wired communications, all the required BandWidth (BW), to successfully complete a communication session, is reserved before the communications start. In wireless communications this is not the case, and nothing is reserved at all. Thus, all networks that are working in the same region, and using the same frequency band, and even the users at the same network are competing for the available BW. This sometimes causes wireless communications link failures. In addition to that, we have other factors that make the communications links frequently fail in MANETs and WMNs. These factors are nodes mobility, dynamic obstacles, fading, limited energy resources, and spectrum allocation regulations. Thus, MANETs and WMNs are vulnerable to frequent link failures that severely degrade the network performance and reduce the network reliability. Based on that, maintaining an acceptable performance, availability, and reliability of MANETs and WMNs in the face of link failures is a challenging, interesting and important problem. The above motivate us to investigate how we could handle the frequent link failures, how we could maintain an acceptable performance and reliability in the face of link failures, how we could support multimedia communications over MANETs and WMNs, and the network requirements that ensure the networks are connected.

Research Objectives

Our research objectives can be summarized in the following points:

- Developing a mathematical model for Hello based link failure detection approach implemented in WMNs routing protocols that use two routes;
- Proposing a powerful technique to recover from link failures that can increase the packet delivery ratio and the network reliability the most, and can support multimedia communications;
- Finding the amount of improvement the use of two routes instead of one brings to the network ;
- Dynamically assigning the values of the Hello interval and the number of missing Hellos according to the application types and the QoS requirements, while taking into account the available bandwidth and resources;
- Proposing a novel protocol to enhance Hello based link failure detection scheme performance;
- Developing a novel reliable routing protocol that suits MANETs the most;
- Investigating the reliable routing protocols and metrics;
- Mathematically finding the node density which is required to ensure the existence of two routes between any source and destination pair;
- Proposing some techniques that can increase the network reliability and ensure the network is connected;
- Studying the effects of node mobility on the network connectivity.

Thesis Contribution and Innovation

Our contributions in this thesis can be summarized as follows:

- Mathematically analyzing the Hello based link failure detection approach that is implemented in a WMN routing protocol that catches two routes;
- Providing a closed form formula that finds the packet delivery ratio in the above approach;
- Finding how much gain we could achieve by using two routes instead of one;
- Comprehensively investigating the effects of the network parameters on the packet delivery ratio and the achieved gain;
- Providing a novel framework that dynamically assigns the values of Hello based link failure detection approach parameters, i.e. the Hello interval and the number of missing Hellos, based on the multimedia communications types and the QoS requirements;
- Proposing a novel protocol to enhance the performance of the traditional Hello based link failure detection approach;
- Proposing a novel adaptive greedy forwarding strategy that adapts the forwarding region size to the network node density;
- Providing a complete mathematical framework that determines the optimum forwarding region which ensures the one-way connectivity or the two-ways connectivity;
- Studying the relationships between the forwarding region size and both the node density and the transmission range;
- Providing a probabilistic model that finds the node density, in terms of number of neighbors, which ensures the existence of two routes between any randomly chosen source node and destination node pair in MANETs where the nodes are either static and uniformly distributed, or moving according to the random waypoint mobility model;
- Investigating the relationship between the node density and the probability of having two routes in the above two cases;
- Proposing some solutions to increase the network node density to the required density that ensures the existence of two routes;

- Comparing the optimization criterions in Maximum Hop Distance (MHD) and Least Remaining Distance (LRD) greedy forwarding strategies potentials to select the shortest path.

CHAPTER 1

LINK FAILURE DETECTION APPROACHES

1.1 Related work

The first logical step in any network recovery system is the detection of failures, and that is why the first chapter of this thesis is the link failure detection approaches used in WMNs and MANETs. The Link failure is a common event, and it is the main reason for network degradation, and network unreliability in WMNs. To mitigate these failures impacts, we should at first detect them accurately and fast. The fastest way to detect these failures is to use a cross layer model which combines the MAC and network layers. However, Hello based link failure detection scheme is the most used, as we explain later.

The node failure and the link quality degradation to unacceptable levels are the two reasons of link failures in wireless networks (Gomez, Catalan, Mantecon , Paradells & Calveras, 2005a). Severe and permanent interference and the nodesmobility can cause the quality of a link to decrease to unacceptably levels, which ultimately will make the link down. Link failure on a route that is currently in use, interrupts the communication until the link failure is detected and an alternate route is found. Thus, to increase the overall performance of the network, we should fast detect link failures.

We have two mechanisms to detect link failures, namely neighbor discovery using Hello beacons and cross-layer. To accelerate the detection of failed links, the cross-layer mechanism is used. In the following two subsections, we show how these two mechanisms work and the literature review for each mechanism.

1.1.1 Link layer feedback failure feedback approach

Link failure detection delay in Hello based approach is in the order of one second. Cross-layer approach has been proposed in order to decrease the above detection delay. To provide a frame transmission service in wireless networks as reliable as in wired Ethernet networks, a retransmission mechanism has been implemented in the IEEE 802.11 MAC layer (Lindhorst, Lukas & Nett, 2010). Each frame transmission must be acknowledged by the receiver to ensure successful frame transmissions. If a frame is not acknowledged, it is retransmitted several times until an Acknowledgment is received. After a certain number of retransmissions, the frame is considered as a lost frame. We can use the above mechanism as a link failure detection approach by making the MAC layer information regarding frame transmission available to the routing layer. Thus, the routing layer can decrease the failure detection delay by using the MAC layer information regarding the frame transmissions and retransmissions.

Physical data rate influences the transmission errors. As we increase the transmission rate, the transmission errors also increase. That is why low data rates are used for the last frame transmission in order to increase the chance that this frame is successfully received. The IEEE 802.11 standards use several modulation techniques, which results in different physical data rates. Thus, the transmission rates are not fixed in IEEE 802.11 standards. Transmission rate algorithm has to adapt with the link quality variations, especially in wireless communications. In (Lindhorst et al., 2010) two failure detection models based on the Cross-layer approach was proposed. The first model is independent of the data transmission rates, while the second model is dependent on data transmission rates. On the following paragraph, we explain these two models in detail.

The first model is FrmLoss. This model only considers complete frame losses and does not care about the transmission rates. A counter (n_p) is used to count the number of complete frame losses. This counter is incremented by one every time a frame loss occurs, and it is rested to the initial value when the frame is successfully transmitted. A link failure is assumed when $n_p \geq n_l^{thr}$, otherwise the frame losses are due to interference is assumed. The second model is TxError. This model considers the transmission rates, erroneous frame transmissions, in addition to complete frame losses. A counter (n_e) count the number of consecutive erroneous frame transmissions at the basic data rates only. n_e is rested to the initial value when a frame transmitted either successfully at basic data rate or any other rate. A link failure is assumed when $n_e \geq n_e^{thr}$, otherwise the frame losses are caused by interference is assumed. How fast the data rates adaptation algorithm switch to the basic data rate determines the detection delay in this model.

In summary, (Lindhorst et al., 2010) proposed two cross-layer models that emphasized the importance of distinguishing between transient and permanent transmission errors to ensure correct link failure detections. They took into account the impact of the physical data rate and the data rate adaptation algorithm. High data rates provide the highest throughput, but at the same time the highest transmission error probability (Lindhorst et al., 2010). The challenge in the above two approaches is how to choose the appropriate threshold values for n_l^{thr} and n_e^{thr}. Their results show that the delivery probability strongly depends on the used modulation modes, and hence the physical transmission rates. The detection delay decreased from the order of one second to some millisecond was experienced by a test-bed experiment (Lindhorst et al., 2010).

(Pandey, Pack, Wang, Duan & Zappala, 2007) proposed a Mobility Detection Algorithm (MDA). MDA is a cross-layer approach that helps MANET routing protocols determine the real cause of frame losses, whether they are due to link failures (mobility) or congestion. The main objectives in MDA are to reduce the routing overhead and to increase throughput. Another approach that can distinguish between the frame losses that are due to congestion or link failures is signal strength measurements (Goff, Abu-Ghazaleh, Phatak & Kahvecioglu, 2002); (Klemm, Ye, S. V. Krishnamurthy &Tripathi, 2005). As it is known, when a mobile node starts moving away from a neighbor, the signal strength measured at that neighbor starts decreasing till it reaches a certain threshold, and at that time that neighbor declares that the link has broken. The drawback of using signal strength measurements to determine broken links is the complications of fading, multipath effects, and power conservation mechanisms that affect the accuracy of signal strength measurements (Pandey et al., 2007).

1.1.2 Hello based link failure detection approach

Neighbor discovery detects link failures in the routing layer as a part of the routing protocols. Most proactive and reactive routing protocols detect link failures by means of Hello beacons. In proactive routing protocols, like Optimized Link State Routing (OLSR), to discover the nodes neighborhood and establish links to neighbor nodes, each node periodically sends Hello beacons to neighbor nodes. After that, information obtained through Hello beacons is propagated through the network. In this way, all nodes are aware of the whole network topology. When one node detects a failed link, this node declares this failed links to all neighbors. On the other hand, in reactive routing protocols like AODV, a route is determined on demand. However, when this route is established, link failures are also detected by means of Hello beacons during the rout connection period (Gomez et al., 2005a).

Hello based link failure detection approach is the most used approach to detect link failure, even though the cross-layer using link layer feedback is faster in detecting link failures. This is due to many reasons. On the one hand, link layer feedback frequently misinterprets transient transmission errors as permanent transmission errors. On the other hand, Hello based link failure detection scheme is easier to implement in MANET routing protocols and it is a link layer independent (Tschudin, Gunningberg, Lundgren & Nordstrom, 2005); (Gomez, Cuevas, & Paradells, 2006), and it requires less memory and power resources (Gomez et al., 2005a).

Link failure detection scheme with Hello beacons works by periodically sending Hello beacons to all neighbors. If a node receives a certain number of successive Hellos, it considers the link as active, while if a node does not receive a Hello beacon or any kind of frames for a certain period of time, a certain number of successive missing Hellos, it considers the link as inactive. Based on that, the failure detection delay is determined by the Hello interval (T_B), and the number of missing Hellos (K). Hello based link failure detection scheme is used in many WMNs and MANETs routing protocols to detect links failures and to maintain route connectivity (Perkins, Belding-Royer & Das, 2003) and (Bellur & Ogier, 1999). Traditionally, the routing protocols use fixed values of K and T_B. For example, in AODV T_B is chosen to be 1 second and K is chosen to be 2 (Gomez et al., 2006). Later in this thesis, we will see that the use of fixed values of K and T_B is not the best choice.

Some authors were aware that the classical behaviour of choosing fixed values for both T_B and K might not be the best choice, and that was why they proposed some approaches to adaptively choose the T_B. To the best of our knowledge, the proposals available in literature just adapted the T_B parameter and ignored the K parameter to enhance Hello based link failure detection approach performance. This was due to the fact that the researchers focus was on maintaining the routing table's accuracy and not in specific link failure detection. In this thesis, we will consider both T_B and K to enhance Hello based link failure detection approach performance. In the following, we introduce to some proposals that adapt the T_B parameter.

(Gome et al., 2006) proposed a two-state adaptive mechanism for link connectivity maintenance in AODV, namely Adaptive Hello Rate mechanism (AHR) algorithm to dynamically choose the Hello interval based on two parameters, Time to Link Failure (TLF) and Time Without Change (TWC). TLF and TWC parameters determine the link lifetime duration, and the dynamicity of the communication links, respectively. AHR algorithm has two states, the first one is a low dynamic state that uses low Hello rate, and the second one is a highly dynamic state that uses high Hello rate. This mechanism switches between these two states based on two thresholds. AHR enters the highly dynamic state when the estimated TLF become smaller than the first threshold; while it enters the low dynamic state, when TWC becomes greater than the second threshold. The difficulty in this mechanism is how to choose these two thresholds.

(Giruka & Singhal, 2005) proposed three protocols, namely, Adaptive Hello protocol, Reactive Hello protocols, and Event Based Hello protocol in order to achieve the best trade-off between Hello overhead and routing tables' accuracy, and to reduce the network congestion. In Adaptive Hello protocol, the Hello rate is chosen based on the node average speed, direction, and position. A Hello beacon is sent once the node moves a certain distance. This protocol assumes that each node knows its average speed, direction, and position. To deal with very high speeds and long pause times, (Giruka & Singhal, 2005) proposes two parameters to control the high rate beaconing and low rate beaconing. These parameters are MIN-BEACON-INTERVAL and MAX-BEACON-INTERVAL. When the Hello interval is less than MIN-BEACON-INTERVAL, then the Adaptive Hello protocol resets the Hello interval to MIN-BEACON-INTERVAL. On the other hand, when the Hello interval is greater than MAX-BEACON-INTERVAL, it resets the Hello interval to MAX-BEACON-INTERVAL. Reactive Hello protocol works like reactive routing protocols, where the nodes only send Hellos, when they need to build routes to send data. Finally, Event Based Hello protocol works as the classic periodic Hello protocol, with the exception that if a node does not receive any messages and does not need to send any packet, that node stops sending Hellos. Even though the last protocol reduces the overhead, it comes at the expense that some nodes may never be detected.

Hello beacon exchanges among neighbors are also used in order to maintain up-to-date neighbors' positions in the geographic routing, i.e. position based routing protocols. Choosing fixed value of the Hello interval does not optimize the network performance in terms of overhead, packet delivery ratio and the average end to end delay is proven in (Chen, Kanhere & Hassan, 2013). (Chen et al., 2013) recommend to adaptively choosing the Hello interval based on the node mobility and the traffic patterns, as it is shown below. They propose Adaptive Position Update (APU) beaconing strategy to adapt the Hello periodic beaconing scheme employed in position based routing protocols based on the node mobility and the traffic loads. The Hello interval in APU strategy is chosen based on two rules, which are Mobility Prediction (MP) rule and On-Demand Learning (ODL) rule. These two rules are explained in the following two paragraphs.

The Hello interval is adapted to the nodes' speeds and directions in the MP rule. The Hello beacon shall contain the nodes' speeds and directions in order to employ the MP rule track, as explained later. Each of node i's neighbors records its position and velocity upon receiving a Hello beacon from it in order to periodically track node i’s position using a simple prediction scheme (Chen et al., 2013). The neighbors check whether node i is still within their transmission range, and update their neighbor list accordingly based on the above estimation (Chen et al., 2013). Based on that, node i broadcasts a Hello beacon when the estimated error between its actual position and the predicted position in its neighbors is greater than a certain threshold.

On the other hand, the ODL rule improves the topology accuracy in the vicinity of the active routes, as shown below. The nodes must be in the promiscuous mode in order to implement the ODL rule. Node i broadcasts a Hello beacon when it overhears the transmission of a packet order to ensure that the nodes involved in the packets forwarding maintain a more up-to-date local network topology (Chen et al., 2013). Thus, the nodes that do not overhear ongoing data transmissions are not affected by the ODL rule. It is important to mention that the MP rule and ODL rule separately work and no rule affects the operation of the other rule. They are shown in (Chen et al., 2013) that the APU beaconing scheme reduces the Hello beaconing overhead, increases packet delivery ratio, and decreases the packets delay in comparison with the traditional Hello beaconing scheme and other updating beaconing schemes. Like other updating scheme, the drawback of APU is the choice of the optimal MP rule's threshold.

(Zadin & Fevens, 2014) and (Zadin, Fevens & Bdiri, 2016) studied the effects of the Hello interval and node velocity on different types of greedy forwarding strategies. It was shown via simulations that decreasing the Hello interval increase the total number of delivered packets and packet delivery ratio (Zadin et al., 2016).

Recently, new studies have been conducted to improve the network reliability and increase the packet delivery ratio. However, these studies were not ideal candidates for WMNs and

MANETS for many reasons. Firstly, some of these studies had their own constrains and assumptions. Secondly, some of the main objective was the energy consumption saving and not the improvement of WMNs' reliability and packet delivery ratio. This is due to the fact that some of them were specifically designed for Wireless Sensor Networks (WSNs). Finally, they were a little bit complex to implement them in WMNs or MANETs. In the following, we briefly introduce some of the above studies.

Link Layer and Learning Automata (LLLA) protocol for channel assignment in multi-radio WMNs was proposed in (Shojafar, Abolfazli, Mostafaei & Singhal, 2015) and (Shojafar, Pooranian, Shojafar & Abraham, 2014). As it is names imply, LLLA protocol depends on learning automata. However, the above protocol has many drawbacks as shown below. At first, a lot of constraints and assumptions on the networks topology, node structures and data traffic are put in LLLA. Some of them are not realistic. For example, LLLA assumes each network node has at least three radios, and uses a combination of Time Division Multiplexing (TDM) and Frequency Division Multiplexing (FDM) as the MAC layer protocol to transmit data (Shojafar et al., 2015). As it is known, usually mesh nodes are equipped with one radio and one channel, and use contention based MAC protocol, i.e. they neither use TDM nor FDM; therefore, the above assumptions are not realistic. In addition to that, LLLA is very complex to implement it in mesh nodes and has a lot of overhead in terms of bandwidth and processing time. Finally, LLLA technique considers an ideal network where there are no link failures at all. Indeed, this is not a realistic condition in MANETs and WMNs, where the node mobility causes a lot of link failures.

The first authors who mathematically analyzed Hello based link failure detection approach implemented in AODV routing protocols that caught just one route were Valera and Tan (Valera & Tan, 2012). This thesis modifies and extends the above analysis by incorporating two routes, a primary route and a backup route, instead of one route. To this end, a complete analytical framework that clarifies how Hello based link failure detection approach implemented in a routing protocol that uses two routes works is provided. With the aid of that framework, an equation that can be used to find the packet delivery ratio is formulated.

In addition, we find the gain we can achieve by implying a backup route. The obtained results show that this gain is 1.5, and it is insensitive to the number of loads. Later in this thesis, we will see that this gain plays a crucial rule to allow WMNs and MANETs support multimedia communications.

In the following, we analyzed the Hello based link failure detection approach that is implemented in a WMN routing protocol that catches two routes. After that, we provide a novel framework that can be used to select the proper Hello based link failure detection approach parameters to satisfy the QoS requirements for the different kinds of multimedia communications. Finally, we propose a novel algorithm to enhance the performance of the traditional Hello based link failure detection approach. The contributions of our studies are as follows:

(i) It is the first study that mathematically analyzes Hello based link failure detection approach that is implemented in a WMN routing protocol that catches two routes;

(ii) It calculates the improvement in the packet delivery ratio (pdr) by using two routes instead of one;

(iii) It provides a novel framework that dynamically assigns the values of Hello based link failure detection approach parameters based on the multimedia communication types and the QoS requirements. This framework can be used as a guideline to choose the proper Hello based link failure detection approach parameters to satisfy the QoS requirements;

(iv) It proposes a novel algorithm to enhance the performance of the traditional Hello based link failure detection approach.

1.2 Mathematical analysis of Hello based link failure detection approach

This section analyzes the Hello based link failure detection approach that is implemented in a WMN routing protocol that catches two routes to mathematically find the packet delivery ratio. This analysis is based on the analysis provided in (Valera & Tan, 2012). The major difference between our analysis and that analysis is that our analysis analyzes the Hello based link failure detection approach that is implemented in a WMN routing protocol that catches two routes, while the analysis in (Valera & Tan, 2012) analyzes the same link failure detection approach, but with just one route. In addition to that, our analysis is more comprehensive, where it studies the impacts of link failure rates on the packet delivery ratio, besides the other parameters that affect the packet delivery ratio. The main objective of our analysis is to mathematically prove that the two routes improve the packet delivery ratio, and how much improvement the two routes bring to the network.

1.2.1 Network model and assumptions

A WMN is modelled as an undirected graph G = (V, E) where V and E are the set of nodes and links, respectively. A link (i, j) is up if node i and node j can directly communicate. Our concern in this study is the QoS requirements based on routing; therefore, we are not considering physical layer, modulations or channels assignment. In this analysis, we assume the following:

(i) The Link Failure Rate (r_{LF}) is the same for all links in E;

(ii) A backup path is always available where it is immediately used in case of failures, and after that the routing protocol starts looking for another route to ensure that a backup route is always available. The WMN is arranged in a mesh topology that provides multi-route between any two nodes. Based on that, our assumption to have two routes available is a realistic assumption that can be easily satisfied in WMNs. For example, the Greedy-Based Backup Routing (GBR) protocol (Yang, Yang, Yang &Yang, 2011), which is introduced in chapter 2, can be used to satisfy this requirement.

(iii) The WMN nodes are equipped with just one channel and one radio.

1.2.2 Mathematical analysis

To smoothly start our analysis, we firstly explain how Hello based link failure detection approach works. It works as follows: mesh or ad hoc network nodes send periodic Hello beacons to all neighbors. The link is considered active (up) and used for routing, upon the reception of a certain number of successive Hello beacons. If a node does not receive a Hello beacon for a certain period of time (certain number of successive missing Hellos), it considers the link as inactive (down) and no more uses it for routing. Thus, the Hello interval (T_B), and the number of missing Hellos (K) determine the maximum delay (δ) to detect link failures. The following equation taken from Lindhorst et al. (2010, p. 45) determines how we can find the maximum delay δ mathematically:

$$\delta = KT_B + \epsilon \tag{1.1}$$

Taken from Lindhorst et al. (2010, p. 45)

Where :
K : the numbers of Hellos.
T_B : Hello interval.
ϵ : a negligible variance due to channel congestion.

δ has a uniform distribution on $[(K-1)T_B, KT_B]$ (Valera & Tan, 2012). According to that, δ average (δ') is:

$$\delta' = \frac{(2K-1)T_B}{2} \tag{1.2}$$

Where K is an integer ≥ 1, and $T_B > 0$.

Transient and permanent transmission errors are the two kinds of transmission errors. Transient transmission errors are caused by interference and congestion, while permanent transmission errors are caused by link failures. To ensure correct link failure detections, we should distinguish between these two kinds of errors. Retransmissions in the MAC layer compensate transient transmission errors while finding and using a new path in the routing layer compensate permanent transmission errors. If a transient error is misinterpreted as a permanent error, a new route must be found, and this will cause network topology destabilization and additional incurred overhead, while further retransmissions in the MAC layer will be sufficient to deliver a frame. Thus, to ensure correct link failure detections, the misinterpretation of transient transmission errors as permanent transmission errors must be avoided or at least minimized. The false interpretations of transient transmission errors as permanent transmission errors are called false positives alert. The false positive alert probability is $(1 - p_B)^K$, where p_B is the probability of receiving a Hello beacon successfully when the link is up. To have a meaningful parameter, a false detection rate (r_{FD}) is provided, which is equal to false positive alert probability divided by T_B (Valera &Tan, 2012). Equation 1.3 taken from Valera & Tan (2012, p. 670) finds r_{FD}.

$$r_{FD} = \frac{(1 - p_B)^K}{T_B} \tag{1.3}$$

Taken from Valera & Tan (2012, p. 670)

Where p_B is the probability of receiving a Hello beacon successfully.

Failures can be missed by Hello based link failure detection approach, when the failure time is less than minimum detection delay $(K - 1)T_B$. Equation 1.4 taken from Valera & Tan (2012, p. 670) calculates the misdirection rate (r_{MD}) that gives us the number of undetected failures per second. Note that when K equals to 1, the minimum detection delay is equal to zero. Based on equation 1.4, r_{MD} in the above case is equal to zero. In other words, the probability of missed failures is equal to zero.

$$r_{MD} = r_{LF}\, P\, [t_{fail} < (K-1)T_B] \tag{1.4}$$

Taken from Valera & Tan (2012, p. 670)

Where:
t_{fail} : the link failure duration.
r_{LF} : link failure rate.

1.2.3 Analytical framework

Figure 1.1 shows the events and phases that affect the packet delivery ratio for a single multi-hop flow from the Source node (S) to the Destination node (D),and it applies to both proactive and reactive routing protocols that catch two paths. Assume that S sends packets to D at a rate of λ packets per seconds. Figure 1.1 has two sub-duration (events), sub-duration I and sub-duration II, and three phases, phases A, B, and B'. A true link failure happens in sub-duration I, while mis-detected failure (the duration of the failure is less than the minimum detection delay) happens at sub-duration II. Phase A starts when the path is established, and ends when the link fails, while phase B starts when the link truly fails till that failure is detected. When the link failures last for a duration that is smaller than the minimum detection delay, phase B' occurs. The false detection link failure phase has been omitted in Figure 1.1, because this phase will not influence our analysis, since the routing protocol will switch the operating path to the backup path without any losses.

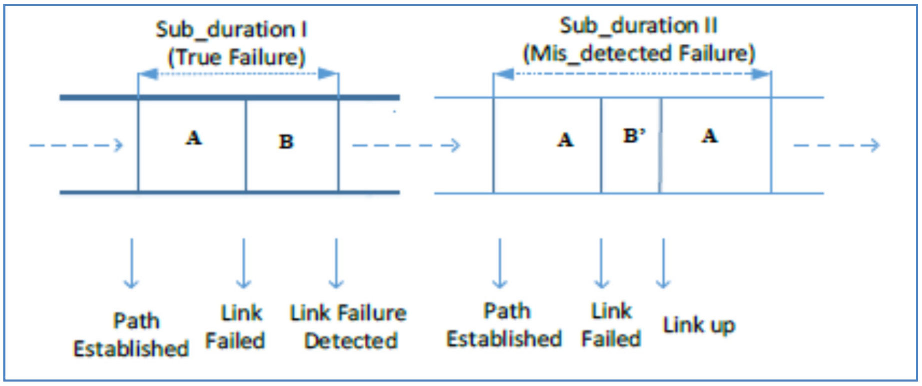

Figure 1.1 An analytical framework for a single multi-hop flow

1.2.4 Multi-path packet delivery ratio

The packet delivery ratio (pdr) for a multipath routing protocol that implements Hello based failure detection as the failure detection scheme will be calculated in this subsection. The pdr is the ratio between the total number of successfully received packets (N_r) to the total number of transmitted packets (N_s), as shown in the following equation.

$$\mathrm{pdr} = \frac{\mathrm{N_r}}{\mathrm{N_s}} = \frac{(\mathrm{N_s} - \text{ lost packets})}{\mathrm{Ns}} \tag{1.5}$$

The lost packets in our model occur at phase B and B'. In the following, we find these losses.

1) Packets lost due to link failure detection delay (N_l')

The packets are lost here, because the link goes down, while the routing protocol is still not aware of this failure, as shown in phase B in Figure 1.1. Thus, the losses depend on the average detection delay δ'. The following equation, taken from Valera & Tan (2012, p. 671), can be used to find these losses:

$$N_l' = E\left[\lambda \sum_{m \in M_t} t_m^B\right] = \lambda |M_t|\, \delta' \qquad (1.6)$$

Taken from Valera & Tan (2012, p. 671)

Where:
t_m^B : the failure detection delay at sub-duration 1 (phase B).
$|M_t|$: the number of true failure detections over the flow duration (T).
λ : the packets sending rate.

$|M_t|$ depends on r_{LF} , r_{MD}, T, and the route length from S to D (the number of hops between S and D). Suppose that L_{max} is the longest path from S to D during the flow, then

$$N_l' \leq \lambda L_{max} T (r_{LF} - r_{MD}) \frac{(2K-1)T_B}{2} \qquad (1.7)$$

Taken from Valera & Tan (2012, p. 671)

If we assume that $L_{max} = L$ (all the used paths during the flow are of the same length) , then the total number of packets lost due to link failure detection delay (N_l') is

$$N_l' = \lambda L T (r_{LF} - r_{MD}) \frac{(2K-1)T_B}{2} \qquad (1.8)$$

Taken from Valera & Tan (2012, p. 671)

2) Packets lost due to undetected link failures (N_l'')

The loss occurs here, because the path is temporarily down, while the sending node keeps sending packets, since it is unaware of this failure. The failure duration in this case is less than the minimum detection delay (K-1)T_B, then

$$E\left[\sum_{m \in M_m} t_m^{B'}\right] < |M_m|\,\delta' = |M_m|\,\frac{(2K-1)T_B}{2} \tag{1.9}$$

Taken from Valera & Tan (2012, p. 671)

Where:
$t_m^{B'}$: the failure duration at sub-duration II (phase B').
$|M_m|$: the number of mis-detected failures over T.

$|M_m|$ depends on r_{MD}, T, and the route length from S to D. Then the average number of lost packets due to undetected failures ($N_l^{''}$) is upper bounded by

$$N_l'' < \lambda L_{max} T\, r_{MD}\, \frac{(2K-1)T_B}{2} \tag{1.10}$$

Taken from Valera & Tan (2012, p. 671)

3) The flow packet delivery ratio with two routes (pdr1)

The total number of packets sent during the entire flow (N_s) is equal to λT packets, because the sending rate is λ and the flow duration is T. Then based on equation 1.5, the pdr can be easily calculated as:

$$\mathrm{pdr} = \frac{N_r}{N_s} = 1 - \frac{\text{lost packets}}{\lambda T} \tag{1.11}$$

The lost packets are the total number of lost packets that happen at phase B and phase B', as we said before. Based on that, the lost packets is equal to $N_l' + N_l''$. Substitute the values of N_l' and N_l'' from equations 1.8 and 1.0, respectively, into equation 1.11. Then the pdr in our model (pdr1) is lower bounded by

$$\mathrm{pdr1} > 1 - \left((2K-1)T_B\right)\left[\frac{L\, r_{LF}}{2}\right] \tag{1.12}$$

1.3 Evaluation

In this section, we comprehensively investigate the effects of the various network parameters on the packet delivery ratio and the achieved gain. In addition to that, we find how much gain we could achieve by using two routes instead of one.

1.3.1 The effect of T_B and K on the packet delivery ratio

The objective of this subsection is to show how T_B and K affect pdr1. To see the effect of T_B and K on pdr1, fixed values of L and r_{LF} are taken. Assume as in (Valera &Tan, 2012) L = 3 hops and r_{LF} = .0167 failures per second. Similar values of L and r_{LF} are assumed as in (Valera &Tan, 2012) in order to later compare the pdr in our model to the model provided there that just uses one route. By assuming fixed values of L and r_{LF} , and changing the values of K from 1 to 4 and T_B from 0.25 to 1.75 seconds in equation 1.12, Table 1.1 is obtained that shows the pdr1 values for different values of K and T_B. The reason behind choosing the above values of K is that in reality K cannot be above 4 or less than 1. In a practical network operation, T_B shall not be below 0.25 second, because otherwise it will consume a relatively huge bandwidth and power. On the other hand, if T_B is larger than 1.75 seconds the pdr will be very small. That is why the values of T_B in Table 1.1 are from 0.25 to 1.75 seconds.

Table 1.1 The values of pdr1 for different values of K and T_B

T_B **K**	**0.25**	**0.50**	**0.75**	**1.00**	**1.25**	**1.50**	**1.75**
1	0.994	0.988	0.981	0.975	0.969	0.962	0.956
2	0.981	0.962	0.944	0.925	0.906	0.887	0.869
3	0.969	0.937	0.906	0.875	0.843	0.812	0.781
4	0.956	0.912	0.869	0.825	0.781	0.737	0.693

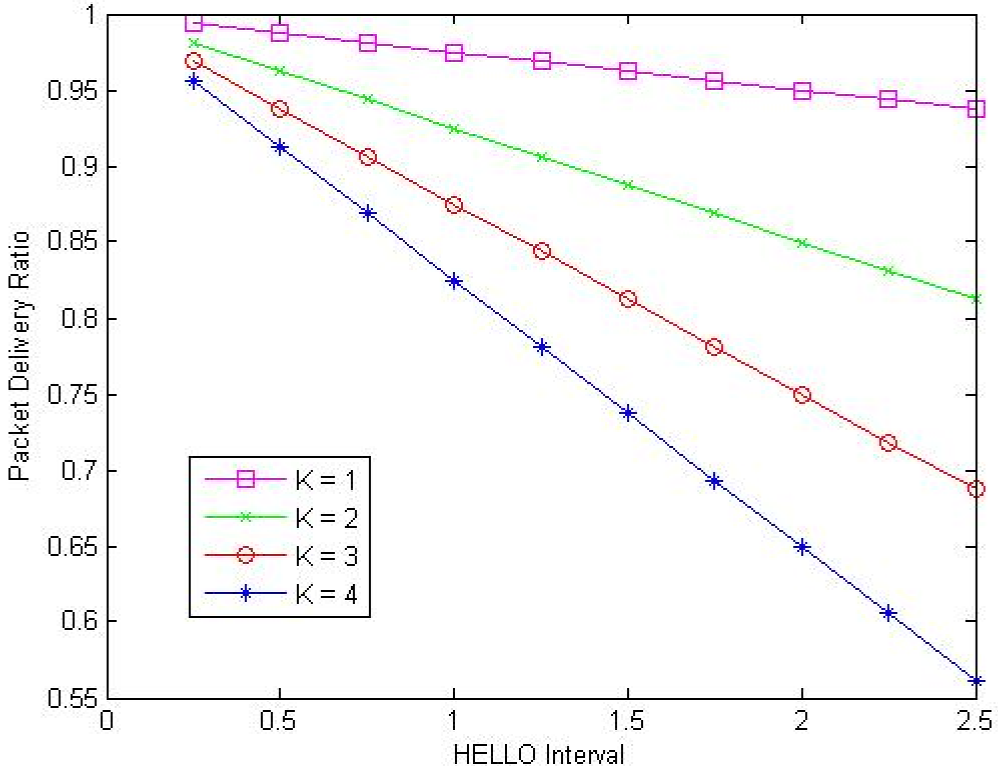

Figure 1.2 Packet delivery ratio versus T_B for K=1, 2, 3 and 4

The relationship between the pdr1 values and the T_B values for K=1, 2, 3, and 4 is shown in Figure 1.2. As it is expected, we have an inverse relationship between the packet delivery ratio and the Hello interval (see Figure 1.2). To get the highest delivery ratio we should choose K=1 and T_B as small as possible. We can use Figure 1.2 to choose the best values of K and T_B that satisfy the QoS requirements, type of application, or according to the required data reliability at the expense of more overhead and more bandwidth. For example, for applications that are sensitive to pdr, like speech communications, we can choose K = 2 and T_B = .25 seconds; while in applications that are insensitive to pdr, we can choose higher values of K and T_B, such as K = 3 and T_B = 1.5 seconds. For heavy loaded wireless networks with limited bandwidth, we should choose higher values of T_B in order to save bandwidth. In the next section, we will further study how to assign the values of K and T_B according to the applications types and the QoS requirements.

1.3.2 The effect of the sending rate on the pdr and the achieved gain

To demonstrate the usefulness and effectiveness in implementing two routes instead of one, we compare the flow packet delivery ratio in two flows, one flow that uses two routes and the second flow that uses one route. The failure detection scheme in the two flows is Hello based link failure detection scheme. The pdr for the first flow (pdr1) is achieved by using equation 1.12 in this thesis; while the pdr for the second flow (pdr2) is achieved by using the following equation:

$$\mathrm{pdr2} = 1 - \frac{L}{2}\left\{ \begin{matrix} r_{LF}\,[(2K-1)T_B + (L-1)\tau] + \dfrac{(1-p_{B})^{K}}{T_B} \\ [(L-1)\tau] \end{matrix} \right\} \tag{1.13}$$

Taken from Valera & Tan (2012, p. 672)

Where:

L : the route length in terms of number of hops between S to D.

r_{LF} : the link failure rate.

K : the number of missing Hellos.

T_B : the Hello interval.

τ : the per-hop delay.

p_B : the probability of receiving a Hello successfully.

The Misdetection Rate (r_{MD}) is ignored in equation 1.13, because most losses are due to link failure rate and false link failure detection rate (Valera &Tan, 2012). The achieved gain is obtained by dividing pdr1 over pdr2.

$$\mathrm{Gain} = \mathrm{pdr1}/\mathrm{pdr2} \tag{1.14}$$

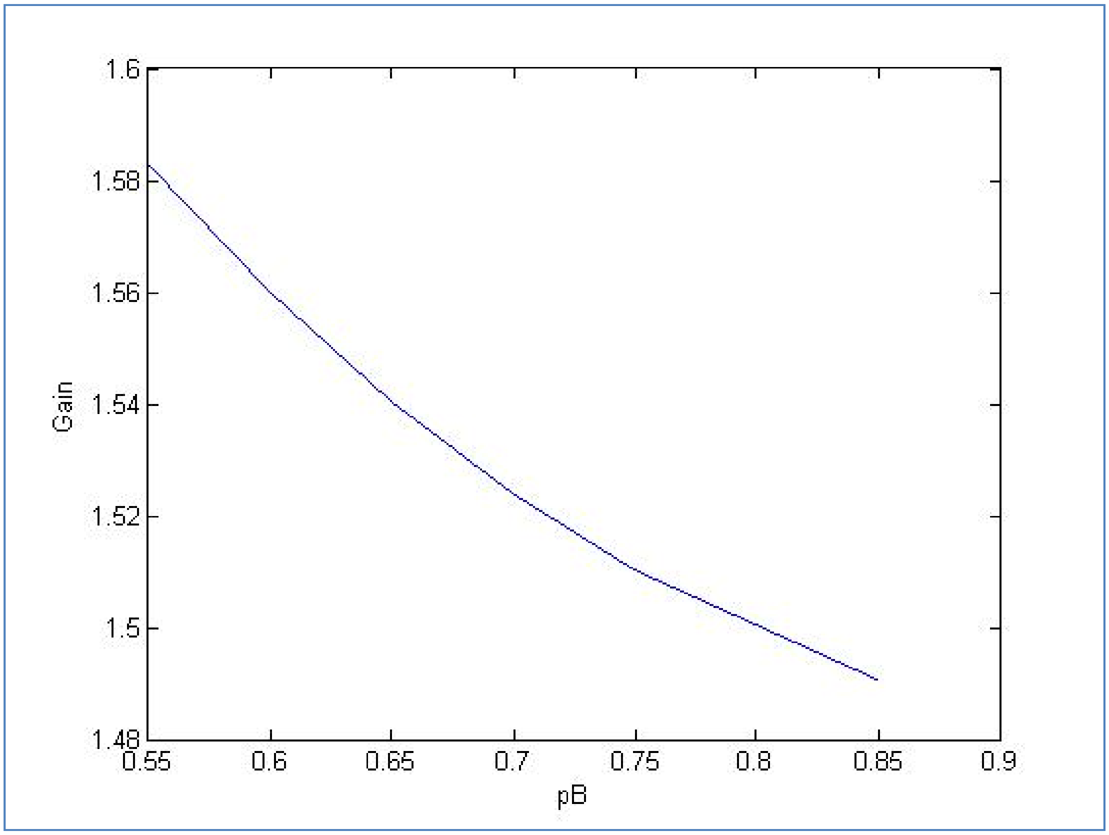

Figure 1.3 The relationship between the Gain and p_B

Assume L = 3 hops, r_{LF} = 0.0167 failures per second, τ = 0.1 second, K = 2, and T_B = 1 second. These values were taken from (Valera &Tan, 2012), because they were realistic values experimentally determined. To study the effect of the sending rate λ on the achieved gain, different sending rates are considered. In equation 1.13, pdr2 does not have an explicit relationship with λ; however, it has an implicit relationship via the probability of receiving the Hello beacon successfully (p_B). When λ increases, p_B decreases. For λ equal to 0.0, 25, 50 and 100 packets per second, p_B will be equal to 0.85, 0.7, 0.65 and 0.55 (Valera &Tan, 2012), and the achieved gain, produced by using equation 1.14, will be equal to1.4909, 1.5240, 1.5405 and 1.5827, respectively. These results show that the pdr1 increased roughly by 1.5 for all sending rates, which means that the p_B has a negligible impact on the achieved gain. In summary, by using two routes instead of one route, pdr is roughly increased by a factor of one and a half for all p_B values as shown in Figure 1.3.

To have a better understanding of the effect of p_B on the packet delivery ratio, we investigate how p_B separately influences pdr1 and pdr2. Equation 1.12 shows that pdr1 does not depend on p_B. This is due to the fact that, p_B depends on the sending rate, and when it increases, the probability that the Hello beacons lost due to collision increases. Thus, p_B affects the false detection rate (r_{FD}) as shown in equation 1.3. In the case of false link failure detections, the routing protocol will use the backup path without any packets loss. This explains why p_B has no effect in pdr1. On the other hand, pdr2 has an implicit relationship with p_B via λ parameter. In the case of routing protocols that use just one route, when a node erroneously declares that a link has failed, it drops all the packets that are using this route and sends an error message all the way back to the source. All the intermediate nodes that are using this route and the source node drop all packets that are using this route upon the receiving of this error message. Figure 1.4, shows the relationship between pdr2 and p_B, for $L = 3$ hops, $r_{LF} = 0.0167$ failures per second, $\tau = 0.1$ second, $K = 2$ and $T_B = 1$ second.

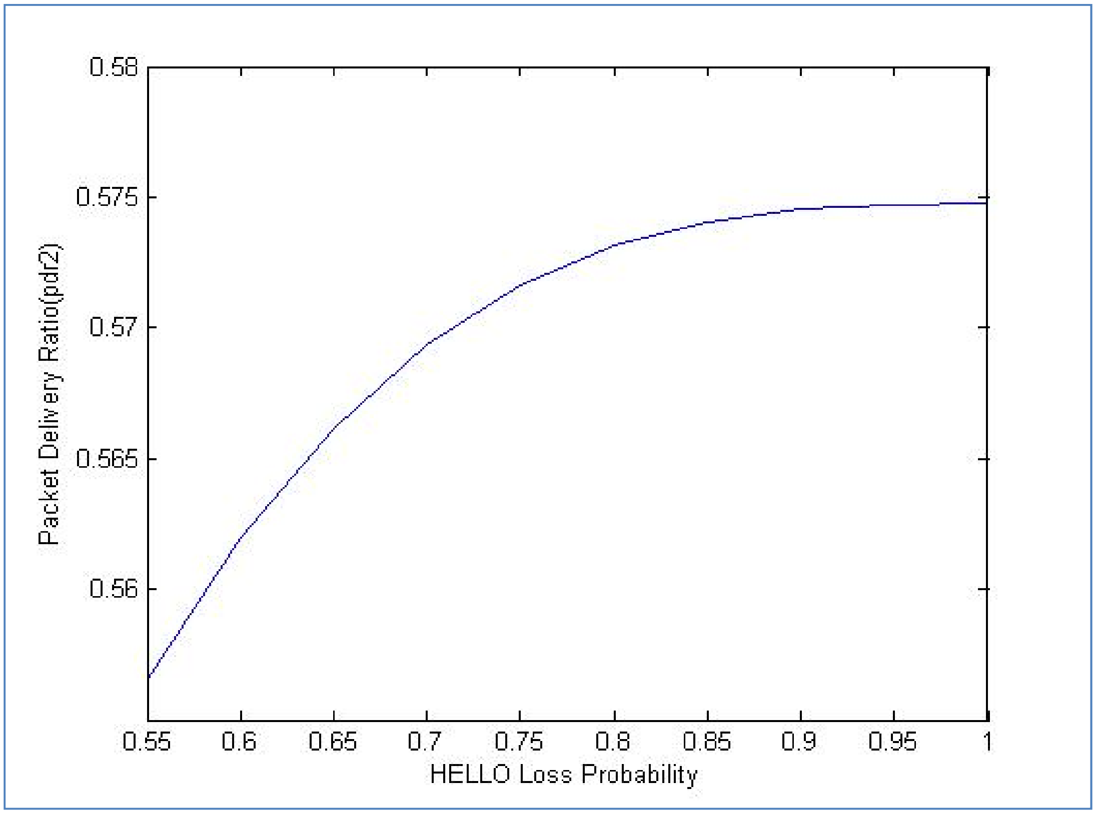

Figure 1.4 The relationship between pdr2 and the Hello loss probability (p_B)

As shown in Figure 1.4, when p_B increases, pdr2 also increases till it saturates, i.e. pdr2 keep approximately at the same value. Actually, when p_B increases, this means that the chance to receive the Hello beacons successfully increases and the false detection rate decrease, which will lead pdr2 to increase. For higher values of p_B, pdr2 cannot increase beyond a certain point. This is due to the fact that we are using just one route, most losses are due to the real failure detections that need the corresponding nodes to drop all the packets that are using the failed route, in addition to the losses that are due to failure detection delay.

1.3.3 The effects of the link failure rate on the pdr and the achieved gain

Both K and T_B parameters have an inverse relationship with pdr as shown before. Another parameter that affects pdr is the link failure ratio (r_{LF}). Here we change the values of r_{LF} parameter, while keeping the other parameters fixed ($p_B = .7$, $K = 2$, $T_B = 1$ second, $\tau = 0.1$ second, and $L = 3$ hops) in order to see how r_{LF} affects prd1, pdr2 and the achieved gain. Figure 1.5 shows the relationship between pdr1 and pdr2 with r_{LF}. As shown in Figure 1.5, both pdr1 and pdr2 have a linear inverse relationship with r_{LF}, which means that when the link failure rate increases, the packet delivery ratio for both one route and two routes decrease. As it is expected, pdr1 has higher delivery ratio than pdr2 for all r_{LF} values. The difference between prd1 and pdr2 gets bigger when r_{LF} increases more. This means that it is more urgent to use two routes instead of one with networks with higher r_{LF} values, i.e less reliable networks.

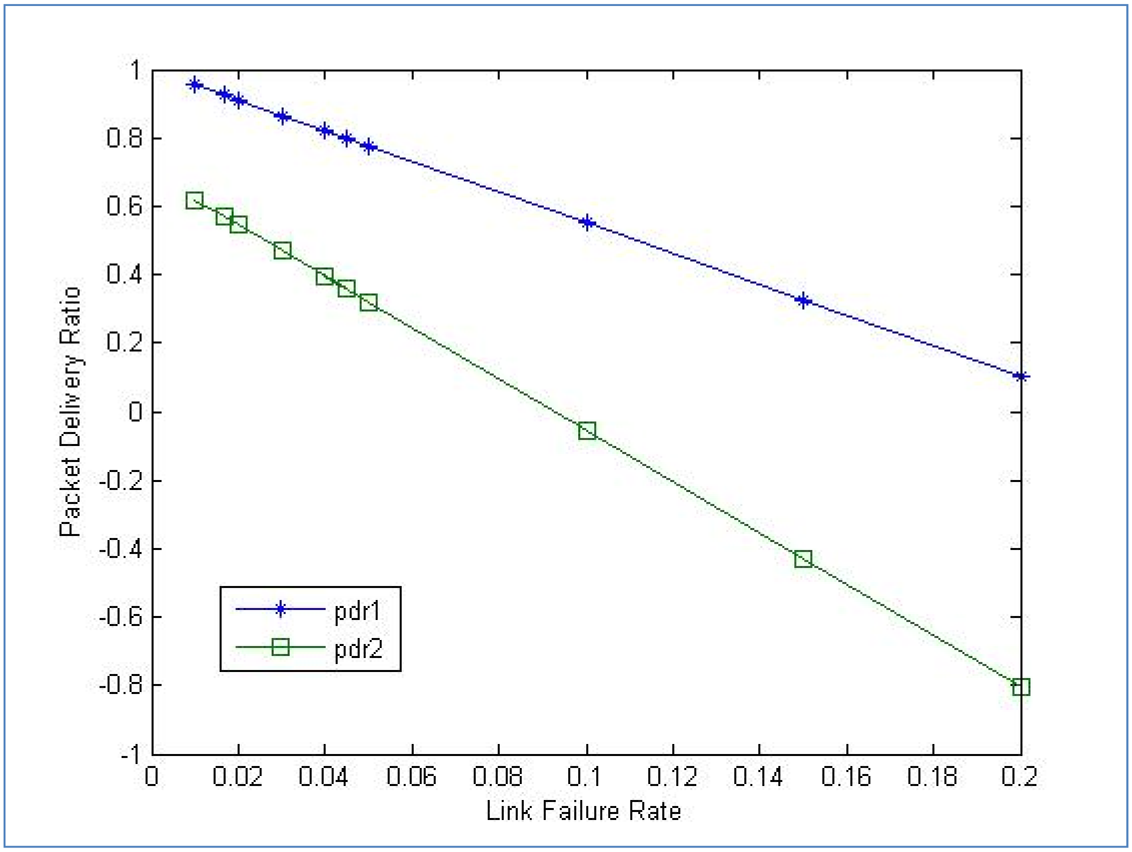

Figure 1.5 The relationship between the packet delivery ratio for two routes and one route cases and the link failure rate

The values of pdr1, pdr2 and the achieved gain for different values of r_{LF} are shown in Table 1.2. We can notice from Table 1.2 that when the link failure rate becomes very high, the pdr for both flows goes negative, which means that the Hello based link failure detection scheme is no more applicable at these link failure rates. At $r_{LF} = 0.2$ failures per second, pdr2 goes negative, while pdr1 goes negative at $r_{LF} = 0.3$ failures per second. These results make sense, because in pdr1 we have two paths. Based on that Hello based link failure scheme can stand up in networks that use two routes with higher failure rates. For the above reasons, this thesis studies the effect of r_{LF} on the achieved gain for networks with r_{LF} less than 0.1 failures per second.

Table 1.2 The effect of r_{LF} on pdr1, pdr2 and gain

r_{LF}	**pdr1**	**pdr2**	**Gain**
0.01	0.955	0.637	1.499
0.0167	0.925	0.607	1.524
0.02	0.910	0.592	1.537
0.03	0.865	0.547	1.581
0.04	0.820	0.502	1.633
0.05	0.775	0.457	1.696
0.1	**0.550**	**0.232**	**2.371**
0.2	**0.100**	**0.000**	**0.000**
0.3	0.000	0.000	0.000
0.4	0.000	0.000	0.000
0.5	0.000	0.000	0.000

As shown in Table 1.2 both prd1 and pdr2 increase, when r_{LF} decreases. The highest prd2 we can achieve is 0.637, while the highest prd1 we can achieve is much bigger, 0.995. The relationship between the gain and r_{LF} is shown in Figure 1.6. This Figure shows two linear regions. The first linear region is from r_{LF} 0.01 till 0.05 failures per second, lower r_{LF} region; while the second linear region is from r_{LF} 0.05 till 0.1 failures per second, higher r_{LF} region. The slope in the lower r_{LF} region is low, while the slope in the higher r_{LF} region is high. This means that the achieved gain is higher in networks with higher r_{LF} values (less reliable networks), and the gain get bigger faster for higher r_{LF} values. From the above results, we can conclude that the need to use two routes instead of one route is more urgent for less reliable networks, where the link failure rate is higher.

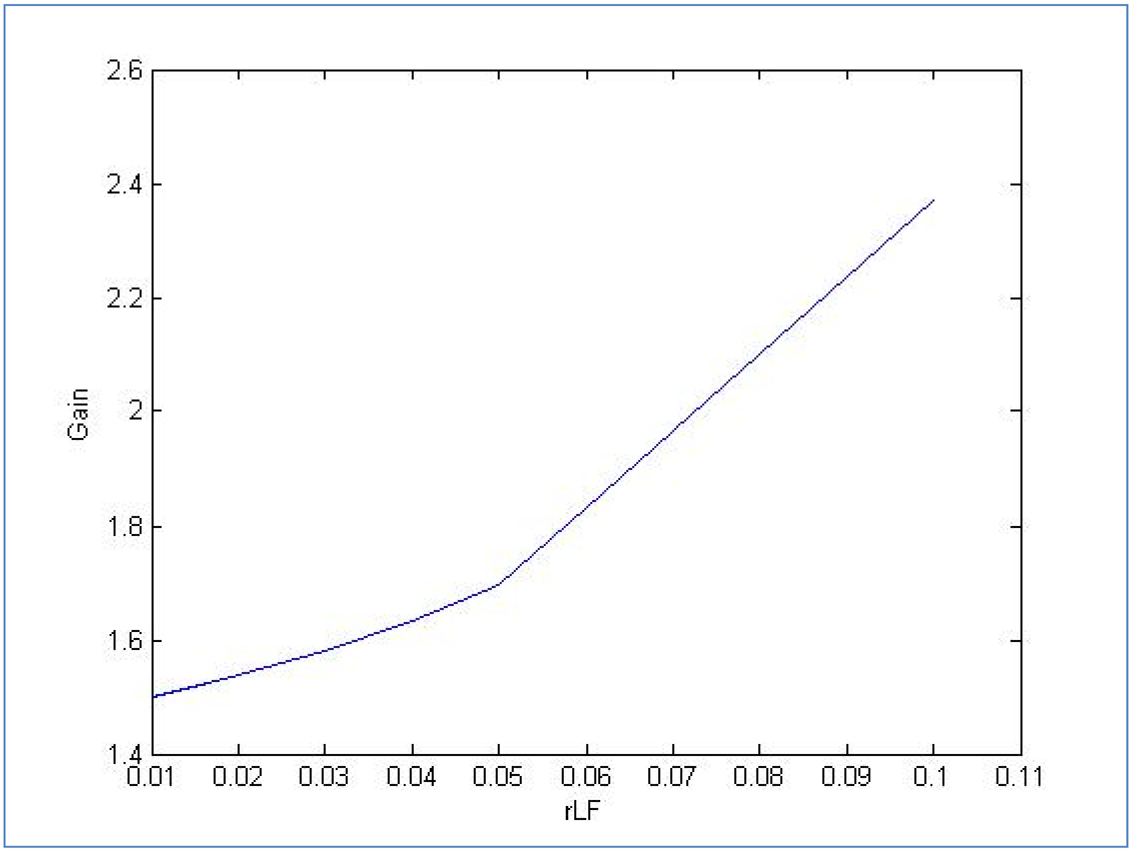

Figure 1.6 The relationship between the Gain and r_{LF}

1.4 Assigning the values of K and T_B based on the communications types

This section provides a complete and a novel framework that dynamically assigns the values of Hello based link failure detection approach parameters based on the multimedia communication types and the QoS requirements. It investigates the two cases, namely, the one route case, where the routing protocols just catch one routes, and the two routes case, where the routing protocols catch two routes.

1.4.1 Introduction

Wireless Mesh Networks and Mobile Ad-hoc Networks should have the ability to support speech and video communications, because ordinary customers are more concerned in these types of communications. Supporting speech and video communications over wireless media is more challenging than supporting them in wired media, due to the erroneous nature of wireless communications. The wireless MAC layer stander IEEE 802.11 ensures reliable data communications by using retransmission techniques at the MAC layer, transport layer or both. To increase frame transmission reliability, the current IEEE 802.11 standards retransmit the frames up to 7 times for smaller frames, and up to 4 for bigger frames (Pandey et al., 2007). After the retransmission counter reaches its maximum values without receiving an Acknowledgement (ACK), IEEE 802.11 standard declares that the frame cannot be correctly transmitted (Pandey et al., 2007), and in case of routing protocols that relay on the MAC layer to maintain the communication link, like Dynamic Source Routing (DSR) protocol, these routing protocols declare that the link has failed.

Multimedia communications have two main types, speech communications and video communications. For speech communications, we have three types, which are toll, business and low quality, while video communications have two types, which are interactive video, like video conferencing, and streaming video, like YouTube or Netflix (Chakeres, Dong, Belding-Royer, Gersho & Gibson, 2004). The speech and video quality mainly depend on the percentage of the packet loss. Toll speech and interactive video can tolerate up to 1 percent of the packet loss, business speech 3 percent, while streaming video 5 percent, and finally low can tolerate up to 10 percent (Chakeres et al., 2004) and (Szigeti & Hattingh, 2004). Voice encoders and decoders have a great impact on the acceptable packet loss percentage by hiding some losses (Chakeres et al., 2004). However, they are beyond the scope of this thesis. To be consistent with our previous work, the loss percentages shall be converted to the equivalent pdr. This conversion can be easily done based on equation 1.5. Table 1.3 shows the different multimedia communications types, packet loss percentage and the equivalent pdr.

Table 1.3 Acceptable pdr for different multimedia communications types

Multimedia Communications Quality	Acceptable Loss	Equivalent pdr
Speech (Toll), Interactive Video	1 %	0.99
Speech (Business)	3%	0.97
Streaming Video	5%	0.95
Speech (Low)	10 %	0.90

In the following, we provide a complete and a novel framework which dynamically assigns the proper values of K and T_B parameters based on the multimedia QoS requirements, instead of the traditional approach that assigns fix values of K and T_B. For example, for speech communications with Toll or Business quality that needs higher QoS requirements, we shall assign smaller values for K and T_B values; while we assign higher K and T_B values for speech communication with Low quality in order to save bandwidth and power. This framework can be summarized as follows: the pdr values for different combinations of K and T_B are calculated based on equations 1.13 and 1.12 for the one route case and the two routes case, respectively. The above pdr values along with the K and T_B values are put in a table. Based on that table, we pick up the pdr value which is not less than the required pdr, as shown in Table 1.3, to ensure that the QoS requirement is satisfied. Finally, we assign the corresponding K and T_B values to the selected pdr as the Hello based link failure detection scheme parameters. The following two subsections explain in detail how this framework works, and what are the suitable values of K and T_B parameters for the one route case and the two routes case to satisfy the different multimedia communication types' requirements?

1.4.2 The one route case

The minimum required pdr2 value in order to support the lowest multimedia communication quality over WMNs is equal to 0.9, as shown in Table 1.3. On the other hand, the highest pdr for the one route case, i.e. pdr2, at $P_B = 0.7$, $K = 2$, $T_B = 1$ second, and $r_{LF} = 0.01$ failures per second is equal to 0.637, as shown in Table 1.2. Based on that, the highest pdr2 value in

Table 1.2 is lower than the lowest required pdr to support any type of multimedia communications. This means that the one route case cannot support any type of multimedia communications. We can increase pdr2 by choosing lower values of r_{LF}, K and T_B, and higher P_B values. When K equals to 1, T_B is almost 0, r_{LF} equals to 0, and P_B equals 1, the maximum pdr2 is obtained, which is equal to 0.7. This maximum value is still lower than the minimum required pdr for any type of multimedia communications.

LLLA channel assignment protocol proposed in (Shojafar et al., 2015), which uses one route, multi-channel and multi-radio, increases pdr2 in the traditional AODV routing protocol that uses just one route. In the ideal case, where the link failure rate, r_{LF}, is equal to 0, the maximum achieved pdr in LLLA is equal to 0.77, which is still far away from the minimum required pdr value to support multimedia communication types over WMNs. Thus, LLLA channel assignment protocol cannot support any type of multimedia communications.

The maximum achieved pdr in the routing algorithm proposed in (Ahmadi et al., 2014) is equal to 0.93. Therefore, it cannot support the superior multimedia communications types; rather it can just support the lowest multimedia communications type that is speech with low quality. However, the above routing protocol is not suitable for WMNs, because it assumes constraints that are difficult to satisfy in WMNs. On the one hand, it assumes the existence of k neighbor nodes around each node, i.e. very high node density is assumed. On the other hand, it assumes the nodes are fixed, and there are no link failures, i.e. the ideal case is assumed. Based on the above analysis, we can argue that we cannot support multimedia communications over WMNs or MANETs by using just one route. The next subsection investigates the two routes case.

1.4.3 The two routes case

The three main factors that affect the packet delivery ratio in the two routes case, i.e. pdr1, are K, $T_{B,}$ and r_{LF}, as shown in equation 1.12. Thus, to demonstrate how our framework works, and how the values of K and T_B change according to the QoS requirements and r_{LF}

values, we take different values of r_{LF} and find the corresponding K and T_B that satisfy the multimedia QoS requirements while keeping the overhead minimum. Actually, the link failure rate, i.e. r_{LF}, depends on many factors like node mobility and interference. The network designer can analyze the network and estimate the value of r_{LF}. This thesis assumes that the value of r_{LF} is known.

We arbitrary start with $r_{LF} = 0.01$ failures/second. Table 1.4a shows pdr1 values for different combinations of K and T_B. Based on this Table, Table 1.4b is built to find the proper K and T_B values for the different multimedia communications types. Table 1.4b is built by taking a look at its corresponding Table, Table 1.4a, and pick up the corresponding K and T_B that satisfy the required pdr1 for the different multimedia communication types. For example, for the speech communications with toll quality or interactive video communications, the minimum prd1 is equal to 0.99. Thus, we take this value and scan Table 1.4a for the corresponding K and T_B for pdr equals to 0.99. It is hard to find an exact pdr1 value in that Table, so we pick up the entry with the closest higher pdr1. The closet higher pdr1 and not closet smaller pdr1 is picked up in order to ensure that QoS requirement is satisfied while the overhead is minimized. In the above example, the highest closest pdr1 is equal to 0.992, and the corresponding K and T_B values are K = 1 and T_B = 0.5 seconds. The same procedure is repeated for different values of r_{LF} to find the proper K and T_B values. Tables 1.5b, 1.6b, 1.7b, and 1.8b, show the proper K and T_B values for r_{LF} equal to 0.03, 0.09, 0.14, and 0.27 failures per seconds, respectively.

Table 1.4a pdr1 for different combinations
of K and T_B at $r_{LF} = 0.01$

T_B \ K	**0.25**	**0.50**	**0.75**	**1.00**	**1.25**	**1.50**	**1.75**	**2.00**
1	0.996	0.992	0.989	0.985	0.981	0.977	0.974	0.970
2	0.989	0.978	0.966	0.955	0.944	0.932	0.921	0.910
3	0.981	0.962	0.944	0.925	0.906	0.888	0.869	0.850
4	0.974	0.948	0.921	0.895	0.869	0.842	0.816	0.790

Table 1.4b The required K and T_B values at $r_{LF} = 0.01$

Multimedia Communications Quality	**pdr**	**K**	**T_B**
Speech (Toll) & Interactive Video	0.99	1	0.50
Speech (Business)	0.97	2	0.50
Streaming Video	0.95	2 or 3	1.00 (K=2) or 0.50 (k=3)
Speech (Low)	0.90	2 or 3	2.00 (K=2) or 1.25 (k=3)

Table 1.5a pdr1 for different combinations
of K and T_B at $r_{LF} = 0.03$

T_B / **K**	**0.25**	**0.50**	**0.75**	**1.00**	**1.25**	**1.50**	**1.75**	**2.00**
1	0.989	0.978	0.966	0.955	0.944	0.932	0.921	0.910
2	0.966	0.932	0.899	0.865	0.831	0.798	0.764	0.730
3	0.944	0.888	0.831	0.775	0.719	0.663	0.606	0.550
4	0.921	0.843	0.764	0.685	0.606	0.528	0.449	0.370

Table 1.5b The required K and T_B values at $r_{LF} = 0.03$

Multimedia Communications Quality	**pdr**	**K**	**T_B**
Speech (Toll) & Interactive Video	0.99	n/a	n/a
Speech (Business)	0.97	1	0.50
Streaming Video	0.95	1 or 2	1.00 (K=1) or 0.25 (k=2)
Speech (Low)	0.90	2 or 3	0.50 (K=2) or 0.25 (k=3)

Table 1.6a pdr1 for different combinations
of K and T_B at $r_{LF} = 0.09$

T_B / **K**	**0.25**	**0.50**	**0.75**	**1.00**	**1.25**	**1.50**	**1.75**	**2.00**
1	0.966	0.932	0.898	0.940	0.831	0.798	0.764	0.730
2	0.898	0.798	0.696	0.595	0.494	0.392	0.291	0.190
3	0.831	0.662	0.494	0.325	0.156	0.000	0.000	0.000
4	0.764	0.528	0.291	0.055	0.000	0.000	0.000	0.000

Table 1.6b The required K and T_B values at $r_{LF} = 0.09$

Multimedia Communications Quality	**pdr**	**K**	**T_B**
Speech (Toll) & Interactive Video	0.99	n/a	n/a
Speech (Business)	0.97	n/a	n/a
Streaming Video	0.95	1	0.25
Speech (Low)	0.90	1	0.50

As shown in Table 1.5b, the speech communications with toll quality and interactive video communications, the multimedia communications types with the highest QoS requirement, cannot be supported when the $r_{LF} = 0.03$ failures per seconds. This is because at this link failure rate, the links often fail, which cause more packets to be lost before the routing protocol detects these failures. Even at K =1, and very small T_B value, the routing protocol cannot handle all these failures to support the superior multimedia quality. However, the lower three multimedia communication types, namely, speech communications with business quality, streaming video, and speech communications with low quality, can be supported due to the backup path, which is used upon recognizing link failures. If the link failure rate keeps increasing, at some point we cannot support the lower multimedia communication types. At r_{LF} = 0.09 failures per second, the two upper communication types cannot be supported, as shown in Table 1.6b. On the other hand, at r_{LF} = 0.14 failures per second the upper 3 communication types cannot be supported as shown in Table 1.7b. This is because at very high link failure rate, the two routes still cannot support the three highest communication types, because even when the routing protocol recognizes a link failure and switch to the backup route, after a while it will recognize another one and will keep on switching the route. Base on that many packets are lost before the routing protocol recognizes the link failures due to the link failure detection delay. For the same reason at r_{LF} = 0.27 failures per second, all multimedia communication types cannot be supported, as shown in Table 1.8b. The good news is that these link failure rates are very high and rarely occurring in reality even in MANETs with high mobility rate.

From the above analysis, we can conclude that WMNs and MANETs can support all multimedia communication types in case the routing protocol catches two routes, and cannot support any multimedia communication type if the routing protocol uses just one route. This is an important and a novel conclusion that the network designers shall put in mind when they design their networks that are intended to provide customers with multimedia communication services.

Table 1.7a pdr1 for different combinations
of K and T_B at r_{LF} = 0.14

T_B / K	**0.25**	**0.50**	**0.75**	**1.00**	**1.25**	**1.50**	**1.75**	**2.00**
1	0.947	0.895	0.843	0.790	0.737	0.685	0.633	0.580
2	0.843	0.685	0.527	0.370	0.213	0.055	0.000	0.000
3	0.737	0.475	0.213	0.000	0.000	0.000	0.000	0.000
4	0.633	0.265	0.000	0.000	0.000	0.000	0.000	0.000

Table 1.7b The required K and T_B values at $r_{LF} = 0.14$

Multimedia Communications Quality	**pdr**	**K**	**T_B**
Speech (Toll) & Interactive Video	0.99	n/a	n/a
Speech (Business)	0.97	n/a	n/a
Streaming Video	0.95	1	0.25
Speech (Low)	0.90	1	0.50

Table 1.8a pdr1 for different combinations
of K and T_B at $r_{LF} = 0.27$

T_B / K	**0.25**	**0.50**	**0.75**	**1.00**	**1.25**	**1.50**	**1.75**	**2.00**
1	0.899	0.797	0.696	0.595	0.494	0.393	0.291	0.190
2	0.696	0.393	0.089	0.000	0.000	0.000	0.000	0.000
3	0.494	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	0.291	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 1.8b The required K and T_B values at $r_{LF} = 0.27$

Multimedia Communications Quality	**pdr**	**K**	**T_B**
Speech (Toll) & Interactive Video	0.99	n/a	n/a
Speech (Business)	0.97	n/a	n/a
Streaming Video	0.95	n/a	n/a
Speech (Low)	0.90	n/a	n/a

1.5 A novel enhanced Hello based link failure detection approach

To enhance the performance of the traditional Hello based link failure detection approach, we propose a novel link failure detection approach. This approach has two modes. The first mode has the potential to stabilize the routing protocols by decreasing unnecessary route changes, while the second mode has the potential to decrease the link failure detection delay and in turn increase the packet delivery ratio.

1.5.1 The proposed algorithm

As we said before, contention, congestion and link failures cause packet losses in MANETs and WMNs. Thus, not all packets losses are due to link failures, and that is why a link failure is declared after several missing Hellos and not after the first missing one, as in the wired networks. Unstable links, which cause fluctuating in the network topology, are the result of decreasing the value of K and T_B, due to an unnecessary route change, because of the misinterpretation of the frames losses as link failures. Decreasing the period of Hello beacons decreases the detection delay and in turn increases the packet delivery ratio on one hand, and increases the communication overhead on the other hand, because in this case more bandwidth is used for the Hello beaconing. Thus, we should carefully choose the K and T_B values in order to balance between overhead and performance. In the following paragraphs, we propose a novel protocol that that enhances the Hello based link failure detection approach performance with negligible overhead.

Our protocol has two modes of operations. The first mode works as follows: When a node does not receive the last Hello beacon, that node sends a probe packet to the corresponding node, and waits for an ACK, before it declares that the link is down. If no ACK is received, after waiting for a certain period of time, that is greater than round trip time, and less than the Hello interval, it declares that the link has failed. On the other hand, if the ACK is received, the node considers the link up. In order to overcome the congestion, buffering in the incoming queue, we mark this prop packet with the highest priority. In this way, we virtually increase the K value by 1 with negligible overhead, which in turn leads to reduce the false detected failures, and increase the packet delivery ratio. Increasing the K parameter stabilizes the routing protocols by decreasing unnecessary route changes. As it is known, finding a new route in MANETs and WMNs consumes a huge bandwidth, and requires a considerable time to find that route. Thus, increasing the K value by 1 greatly enhances the performance of data communications by decreasing the packet delay and by saving bandwidth. This mode can also improve the transport layer performance. When the routing protocol finds another route instead of the failed route, the two routes do not necessarily have the same lengths, and this can affect the transport layer protocol by receiving unordered packets.

For networks, where their main concern is higher packet delivery ratio, like speech communications, we propose the second mode. In this mode, the probe packet is sent in case we do not receive two successive Hello beacons in case K = 3. In this way, we virtually decrease the K value by 1, while the failure detection scheme still works with the same K value. As we explain earlier, when the K value is decreased, the failure detection delay is reduced, and in turn the packet delivery ratio is increased. We recommend the use of the this mode for communication types that need higher QoS requirements, like speech communications with toll quality; while we recommend the use of the first mode with communication types that need lower values of packet delivery ratio, like streaming video and speech communications with low quality. The following algorithm shows in details how our proposed protocol works.

Algorithm 1.1 Enhanced Hello Based Link Failure Detection Approach

Enhanced Hello Based Link Failure Detection Approach

Input: T_B, K & Ni : the neighborhood of node i
Output: The link up or down

```
Initialize k = 0;
 For every node i do:
        {
        For c =1 * $T_B$ : 10000 * $T_B$
                Broadcast a Hello beacon.
                For every node j ϵ Ni
                        If (A Hello beacon is not received) then
                            If k <= 0
                                k = 0;
                            else
                                k = k - 1;
                        end If
                        If (Hello beacon is received) then
                            If k < K
                                k = k + 1;
                            If k = K
                                k = K;
                        end if

      % Link Failure Detection
      For jj = K * $T_B$ : K * $T_B$ : 10000 * $T_B$
            If (k == K) then
                The link is up;
            end If
            If (k<1) then
                Send a probe packet to node j;
                Wait for ACK;
                If (ACK is received by node i) then
                    The link is up;
                    else
                        The link is down;
                end If
            end If
      end for
            }
```

1.5.2 Evaluation

The Hello loss probability shall initially be found in order to quantify the reduced false link failure detection in the first mode. p_B can be estimated by numbering the Hellos with sequence numbers (Chen, Toueg & Aguilera, 2002). Thus, during a period of time, we can estimate p_B by dividing the number of the received Hellos over the highest Hellos' sequence number (Chen et al., 2002). The probability that the link is considered as a failed link is equal to the probability that we do not receive any Hello during the failure detection period, i.e. $K * T_B$. Assume the Hello losses are independent events, then the probability that a link will be considered as a failed link (P_{down}) is equal $(1 - p_B)^K$. If we virtually increase K by 1, P_{down} will be equal to $(1 - p_B)^{(K+1)}$. In this case, the false link failure detection ratio is reduced by $(1 - P_B)$, as shown in the following equation:

$$R_{fd} = 1 - p_B \tag{1.15}$$

Where:

R_{fd} : the reduction in the false link failure detection ratio.

p_B : the probability of receiving a Hello beacon successfully.

The objective in the second mode is to increase the packet delivery ratio by virtually decreasing the K value by 1. For the two routes case, the achieved increase in pdr1 ($gain_{pdr1}$) is equal to pdr1 with K = K - 1 over pdr1 with K = K. Equation 1.16 determines $gain_{pdr1}$.

$$\mathrm{Gain}_{pdr1} = \frac{1 - \left((2K-3)T_B\right)\left[\frac{L\, r_{LF}}{2}\right]}{1 - \left((2K-1)T_B\right)\left[\frac{L\, r_{LF}}{2}\right]} \tag{1.16}$$

Figure 1.7 shows that there is an approximately linear relationship between Gain_{pdr1} and the link failure rate. In other words, the improvement in pdr1 (Gain_{pdr1}) is better with higher link failure rates.

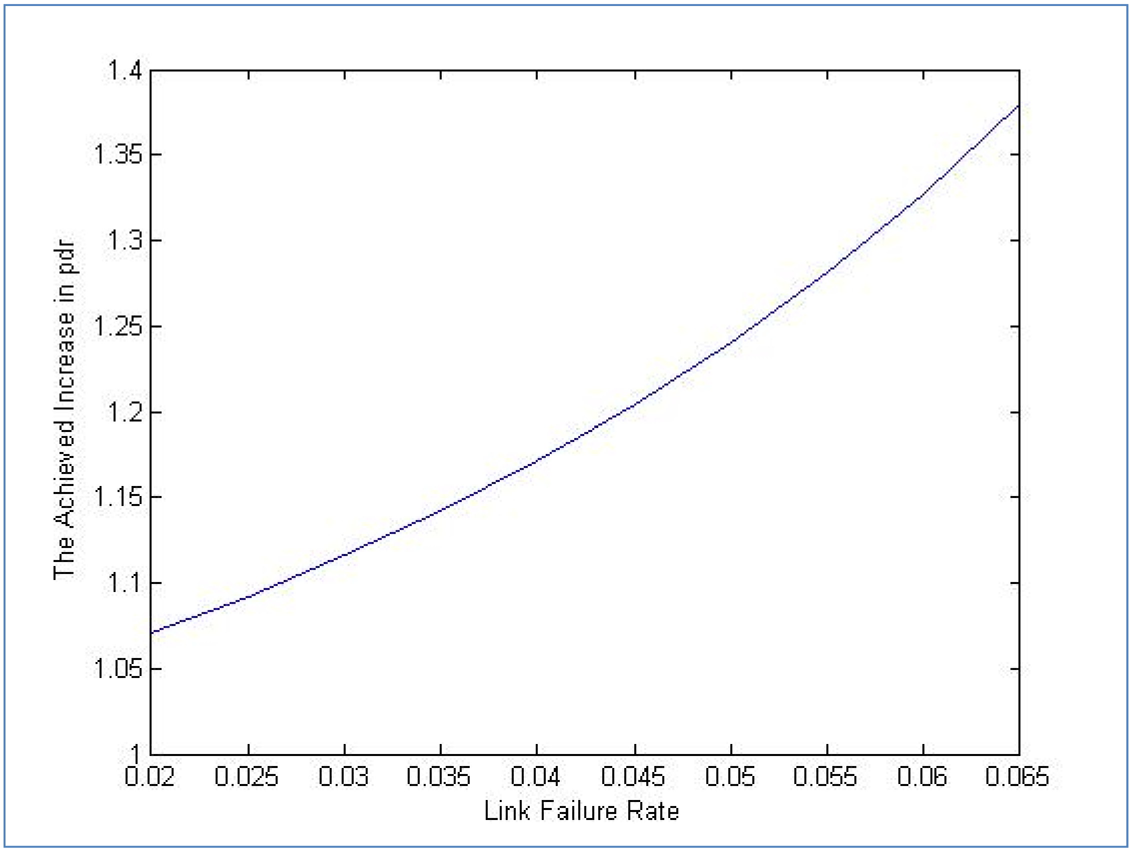

Figure 1.7 The relationship between the achieved increase in pdr and the link failure rate in the two routes case

The same analysis can be applied to the case with just one route. In this case, the achieved increase in pdr2 ($gain_{pdr2}$) is equal to pdr2 with K = K - 1 over pdr2 with K = K as shown in equation 1.17. If we plot the relationship between $gain_{pdr2}$ and the link failure rate, we obtain Figure 1.8.

$$\mathrm{Gain}_{\mathrm{pdr2}} = \frac{\mathrm{pdr}_2 \text{ with } \mathrm{K} = \mathrm{K} - 1}{\mathrm{pdr}_2 \text{ with } \mathrm{K} = \mathrm{K}} \tag{1.17}$$

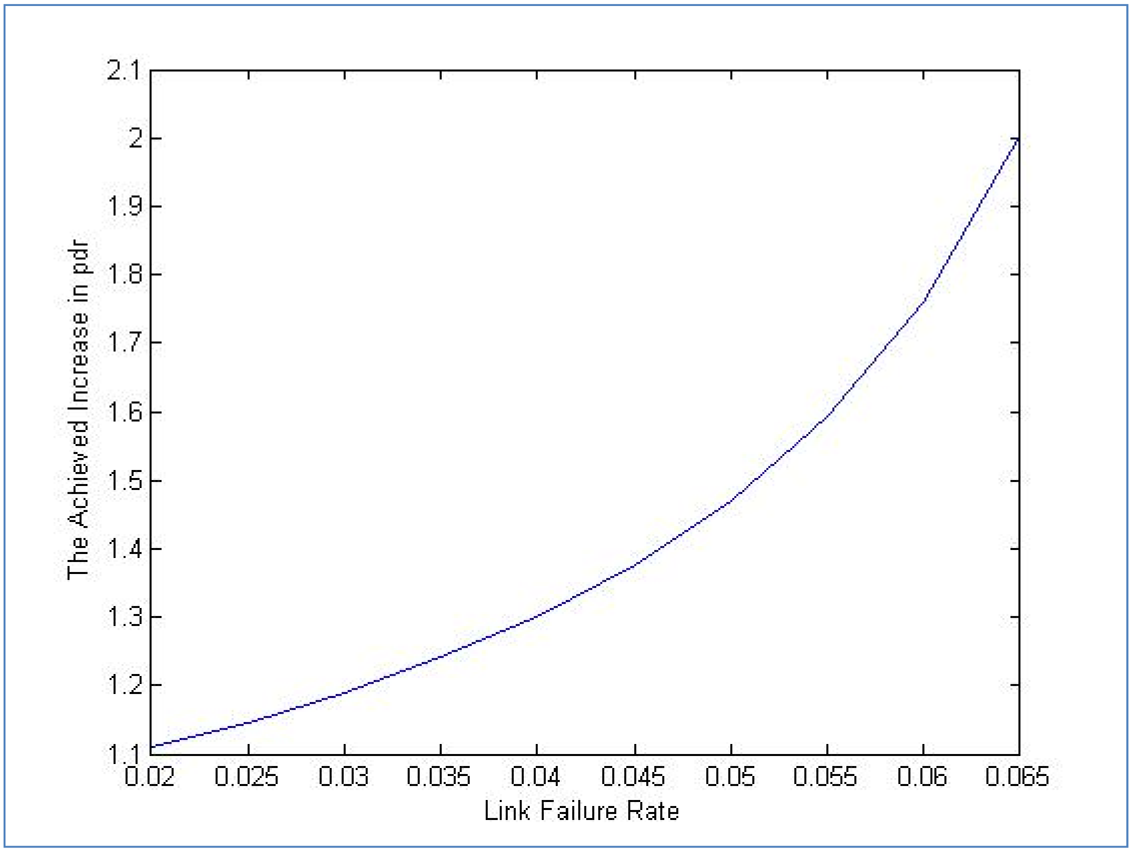

Figure 1.8 The relationship between the achieved increases in pdr and the link failure rate in the one route case

From Figure 1.8, we can clearly see the same relationship between the achieved increases in the packet delivery ratio versus the link failure rate in the one route case as in the two routes case. However, in the one route case, we can achieve more gain when the link failure rate increases compared to the two routes case. For example, in the one route case (see Figure 1.8), when the link failure rate is at 0.06, the achieved increase in pdr is 1.8, whereas in the two routes case (see Figure 1.7) it is at 1.3.

1.6 Proposed solutions to network recovery

The network recovers from link failures at the MAC layer, routing layer or both. Initial resource allocation, greedy channel assignments, fault-tolerant routing protocol, Interference Aware Channel Assignment (IACA), and Autonomous Reconfiguration System (ARS) are the techniques used for link recovery in MANETs and WMNs.

1.6.1 Initial resource allocation method

Initial resource allocation method provides theoretical guidelines for initial network resource planning. It is a comprehensive and optimal network configuration plan. This plan often requires global configuration changes, which are undesired in case of frequent local link failures as it is the case in MANETs and WMNs. (Alicherry, Bhati & Li, 2005) propose joint channel assignment method for link recovery, which is a hybrid approach of channel assignment and routing based in some concepts in mathematics. It considers interference, channel availability, and based in them, they find an optimal network configuration. Experimental results demonstrated the effectiveness of this approach.

The drawback of this approach is that the global configuration requires the recovery from the link failures. Based on this approach, every time a link fails, the network needs to find an optimal reconfiguration based overall network setting. This consumes a lot of time and resources, and interrupts the communications until the network finds an optimal solution. Thus, we do not need to do a global configuration, every time a failure occurs.

1.6.2 Greedy channel assignment method

(Raniwala & Chiueh, 2005) proposed greedy channel assignment method to eliminate the global configuration drawback in the initial resource allocation method. Greedy channel assignment method changes only the setting of faulty links to recover them. Since this method changes only the setting of faulty links, it may not be able to achieve full improvement, which can be only achieved by considering the configurations of neighbor nodes as well as the faulty links (Kim & Shin, 2011). Another drawback of this method is the ripple effect associated with it, where one local change triggers the changes of additional network setting at neighboring nodes (Kim & Shin, 2011). One solution to the ripple effect drawback is the transforming the mesh typology into a tree topology at the expense of reducing network connectivity and path diversity (Kim & Shin, 2011).

1.6.3 Interference aware channel assignments

Interference Aware Channel Assignments protocol (IACA) tries to solve the problem of interference in multi-radio mesh networks. IACA minimizes the interference between a mesh network and other wireless networks in a specific region by wisely assigning the channels to radios (Ramakrishnan, Sankar Ram & Alheyasat, 2012). It implements in all mesh nodes an interference estimation scheme which estimates the nodes interference. IACA can only improve the overall capacity by using additional channels, and it does not consider other aspects besides channel assignments like link associations and local traffic information (Ramakrishnan et al., 2012).

1.6.4 Autonomous reconfiguration system

(Kim & Shin, 2011) propose a new recovery system for wireless mesh networks that is Autonomous Reconfiguration System (ARS). ARS is a powerful cross-layer technique which benefits from channel and radio diversities in WMNs. This system overcomes the major drawbacks in greedy channel assignment and resource–allocation algorithms. While recourse–allocation algorithms reconfigure the whole network setting to overcome a link failure, greedy channel assignment just changes the faulty link setting. ARS comes in the middle between these two approaches by changing the faulty link setting, and the setting of the neighborhood to achieve better improvement without changing the whole network setting. Based on changes in radios, paths and channels, ARS generates a set of plans to overcome link failures. Among this set, ARS chooses one plan which maximizes network throughput and satisfy some of the QoS constrains. Compared to other types of recovery systems, ARS greatly improves the performance of WMNs (Kim & Shin, 2011).

ARS preserves network performance by enabling a multi-radio WMN to autonomously recover from local link failures (Kim & Shin, 2011). Based on channel, radio and route diversities in WMNs, ARS generates the necessary changes to recover link failures (Kim & Shin, 2011). After that, the system cooperatively reconfigures network settings among local mesh routers according to the generated changes. Even though ARS is a powerful network recovery scheme, it still has some drawbacks. The first drawback is that ARS is not a cost-aware scheme, which means it gives the channel switch, radio switch and detour path the same weight. The second drawback is that ARS considers only the channel related failures, and does not deal with other types of failures. (Ramakrishnan et al., 2012) propose Enhanced Reconfiguration System (ERS), based on ARS, to make ARS a cost aware scheme.

ARS is a distributed system that runs in every mesh node. It is easily implemented in IEEE 802.11 based multi-radio WMNs. ARS has the following features:

- **Localized reconfiguration**: in contrast to initial resource allocation method which recovers a link failure by changing the whole network setting, and greedy channel method which just changes the faulty link setting, ARS recovers from links failures by changing the setting of mesh nodes in the vicinity, where the link failures occurred, while keeping the setting in remote areas without touch. ARS makes these changes based on multiple channels and radios available;
- **QoS-aware planning**: the main objective of ARS is the faulty link recovery, but at the same time, it tries to satisfy the QoS requirements as much as possible;
- **Autonomous reconfiguration via link-quality monitoring**: ARS measures the quality of links of each node to detect link failures. After that, it generates feasible plans that recover from the detected failures;
- **Cross-layer approach:** ARS use both the network and MAC layer information for network recovery and planning.

ARS works as follows: each node continuously monitors the link quality, and sends the results to a gateway. In case a node detects a link failure, this node triggers the formation of a group among local mesh routers that use the faulty channel. Among the group members, one member is elected as a leader, and this leader sends a planning request message to the gateway. Upon the receipt of a planning request, the gateway generates a reconfiguration plan, and sends it to all group members. Finally, once the members receive the plan, they execute the configuration changes in that plan.

ARS consists of three steps as shown in Figure 1.9. The first step generates feasible plans. Subsequently, the other steps initiate QoS test and optimal plan selection. A feasible plan is a set of configuration changes for a network to recover from link failures on a channel. These changes include channel switch, link association and detour path. As we said before, ARS generates these plans based on the configuration around the vicinity of the faulty link.

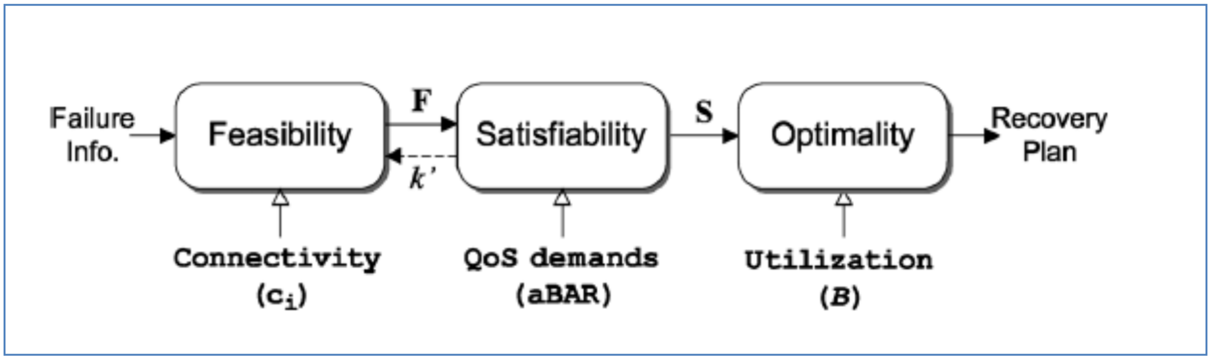

Figure 1.9 ARS steps
Taken from Kim & Shin (2011, p. 396)

At first, ARS finds reconfiguration plans that recover the failed links by applying the connectivity and link-failure constraints. These plans may include changes in channels, links, and routes around the faulty link. After that, it applies QoS constrains and network utilization constrains within the reconfiguration plans to identify the one that satisfies the QoS requirements. To see if a feasible plan passes the QoS test, ARS has to estimate per-link bandwidth by measuring each link’s capacity and its available channel airtime. ARS passively monitors the transmissions of data or sends probing packets in order to measure packet delivery ratio and data transmission rate to estimate links capacities (Kim & Shin, 2011). Finally, it chooses the best plan that best satisfies the QoS requirements, and maximizes the channel utilization.

To avoid the ripple effect occurs in the greedy channel assignment technique, ARS generates feasible changes, and then combines some of these changes in order to preserve the network connectivity. After ARS ensures the network is connected, it maximizes the network utilization by avoiding the use of the same channel among radios in the same node, and making each radio associates itself with at least one link (Kim & Shin, 2011). ARS tries to limit the network changes as much as possible. On the other hand, it needs to find a locally optimal solution by considering more network changes. ARS controls the scope of reconfiguration changes by using a k-hop reconfiguration parameter, which is the number of hops from the faulty link, in order to trade off between locality and optimality. Thus, ARS starts from the faulty link (i.e. k=1) and generates feasible plans, then it increases the k value by 1 in case it cannot find a local optimal solution, and generates another feasible plans. The same steps are repeated until a local optimal solution is found.

ARS has been implemented and evaluated extensively on an IEEE 802.11-based WMN test-bed in a Linux OS, as well as through ns2-based simulation (Kim & Shin, 2011). Throughout the simulation, a grid topology with 25 nodes in an area of 1 km^2 was used. Adjacent nodes were separated by 180 m, each node was equipped with a number of radios depending on its proximity to the gateway, and the gateway was located at the centre. The gateway was equipped with four radios, one-hop away nodes from a gateway with three radios, and other nodes with two radios. The above experiment and simulation results showed that compared to local rerouting scheme, ARS improved network throughput and channel efficiency (the ratio of the number of successfully delivered data packets to the number of total MAC frame transmissions) by more than 26% and 92%, respectively. They also showed that the chance to meet the varying QoS demands was increased in ARS by

200% on average and up to three times compared to static-assignment algorithms, and for re-routing it depended on the path the data followed. Note that the ability of ARS to satisfy the QoS requirements came from discovering and using the idle channels.

ARS takes 15 seconds to recover from link failures (Kim & Shin, 2011). Within this delay, actual channel switch delay is less than 3 msec, which causes negligible flow disruption, while the radio switch and detour path take a lot more time (Ramakrishnan et al., 2012). This fact highlights one of the ARS weaknesses that it is not a cost-aware reconfiguration scheme. To overcome the above weaknesses, we shall give channel switch less weight compared to radio switch and detour path. (Ramakrishnan et al., 2012) notices this weakness, and proposes Enhanced Reconfiguration System (ERS) that is cost aware. The following subsection introduces ERS.

1.6.5 Enhanced reconfiguration system

Enhanced Reconfiguration System (ERS) is a cost aware reconfiguration technique for network recovery based on ARS. As in ARS, ERS considers local channels, radio and routes switch to recover from local link failures. While ARS chooses the best plan that maximizes channel utilization, ERS chooses the best plan that minimizes the cost associated with the reconfiguration plan. ERS is used in multi radio wireless mesh networks, and it is running in every mesh node within the network. By traversing all possible channels, links and route changes around the faulty link, and by considering the given connectivity and link failure constraints, ERS generates a set of feasible plans. After that, the QoS and network utilization constraints are applied to identify a reconfiguration plan that satisfies the QoS requirements and improves overall network utilization (Ramakrishnan et al., 2012). Finally, the total reconfiguration cost incurred with each plan generated is computed and the best plan is chosen based on the minimum cost and the highest utilization.

As in ARS, the first step in ERS algorithm is the feasible plan generation. Figure 1.10 shows how the feasible plan generation step works. In summary, this step works as follows: ERS finds feasible changes (radio, link and detour path) around the faulty link that remove the link failure, and maintain the existing network connectivity.

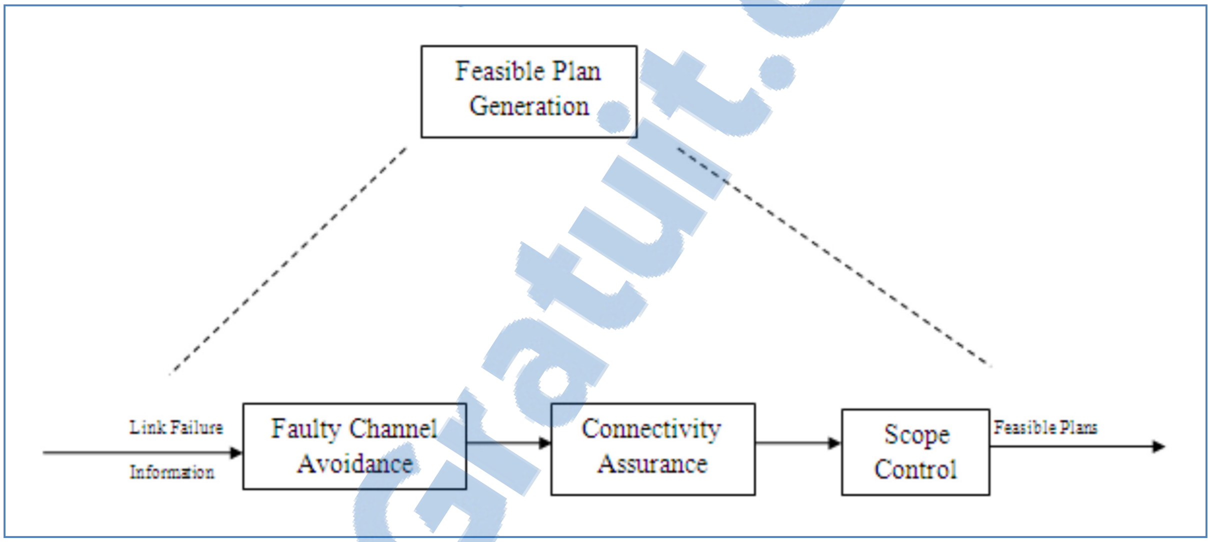

Figure 1.10 Feasible plan generation in ERS
Taken from Ramakrishnan et al. (2012, p. 304)

After the feasible plans set were generated, ERS applies QoS test to generate subset that satisfies the QoS requirement as much as possible. In addition to that, it checks whether the neighboring links are affected. We can identify if the neighboring links are affected by evaluating the QoS satisfaction of links one hop away from affected nodes (Ramakrishnan et al., 2012). If the QoS requirements in the nodes one hop away from the faulty links are not violated, the effects will not propagate. Otherwise, the effects will propagate, and this will cause cascaded QoS failures. The QoS test step is shown in Figure 1.11.

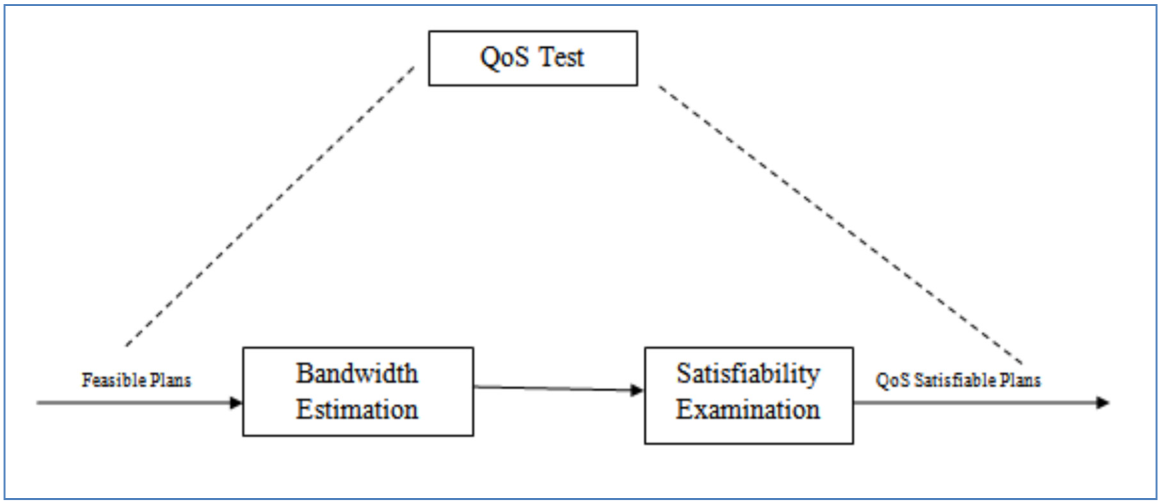

Figure 1.11 ERS QoS test
Taken from Ramakrishnan et al. (2012, p. 305)

At this stage, we have a subset of feasible plans that satisfy the QoS requirements. The next step is the computation of the cost of every plan within that subset. As we know, a feasible plan is a combination of three operations, which are channel switch, radio switch and route switch. Every operation from the above operations has different costs, because their implementation complexities are not the same, and also the delays to implement them are not the same. The channel switch operation has the least cost, because it is the easiest operation to implement, and has the least implementation delay. That is why we should give channel switch the least cost. The formula for computing the total reconfiguration cost (CRi) is given by the following equation:

$$CRi = p\alpha + q\beta + r\gamma \tag{1.18}$$

Taken from Ramakrishnan et al. (2012, p. 305)

Where p, q, and r represent the number of channel switch operations, the number of radio switches and the number of route detour operations, respectively. Ri is the reconfiguration plan. And the values of α, β, and γ are the cost of the channel switch, radio switch and detour operation, respectively.

Finally, the plan that maximizes the utilization and at the same time minimizes the reconfiguration cost is chosen as the best plan. That is why a new parameter η, where η is the ratio of the utilization and the cost, is introduced. The best plan in ERS is the one that has the maximum η. It is important to mention that both ARS and ERS consider link bandwidth as the sole QoS parameter. Thus, one way to enhance these systems is to consider other QoS parameters like delay and jitter. Another direction for future research is the joint optimization with flow assignment and routing (Kim & Shin, 2011).

1.6.6 Fault tolerant routing protocols

Routing protocols are very important protocols for network recovery. In case of link failures, the routing protocol shall find an alternate path instead of the faulty path. Multi-path routing, local rerouting and redundant transmissions are the main techniques used at the routing layer level to make the routing protocols fault tolerant. This thesis relies on the fault tolerant routing technique. It specifically relies on the backup route recovery technique. The reason behind the above selection is that the above technique is the most reliable network recovery technique and it can support multimedia communications, as proved earlier. Another reason is that the other network recover techniques usually rely on the redundant channels or radios, which is not the case in MANETs where the nodes are mostly equipped with one channel and one radio.

CHAPTER 2

RELIABLE ROUTING

2.1 Introduction

One of the MANETs big challenges is the frequent link failures, which reduces the network connectivity and reliability, and complicates the routing process. One solution to handle these failures is to use multi-route instead of the traditional use of one route. The use of multi-route can virtually decrease the packet loss to zero, and can support multimedia communications over MANETs and WMNs. Thus, one issue that shall be considered when designing MANETS is the ensuring of the existence of at least two routes between any randomly chosen pair of nodes. This depends on the network node density. As such, node density must be above a certain threshold in order to ensure the existence of two routes.

Ensuring a completely stable route in MANETs is an unachievable task (Moussaoui & Boukeream, 2015). In addition to that, a MANET routing protocol which catches just one route cannot support multimedia communications, as it was shown in the first chapter. Thus, the implementation of routing protocols that catch multi-route is required for reliable and stable communications, and supporting multimedia communications. Another technique that can be used to increase the network reliability is the selection of the most stable paths among the available paths (Moussaoui, Semchedine & Boukerrama, 2014) and (Moussaoui, Semchedine & Boukerrama, 2014). Based on the above analysis, the only ways to provide reliable and stable communications, and to support multimedia communications in MANETs are to use multi-route instead of one, and to let the routing protocol select the most stable routes among the available routes.

Routing protocols is a complex task in MANETs and WMNs due to the unpredictable nodes' movements that cause the frequent link failures. Thus, the routing protocols shall be fault tolerant in order to deal with the frequent link failures. To virtually decrease the packet loss to zero, and support multimedia communications over MANETs, two routes must be used, one as the main route, and the other one as a backup route, which is used once the main route fails (Hayajna & Kadoch, 2016) and (Hayajna & Kadoch, 2017b). In case a route failure happens, the routing protocol must immediately switch to the backup route, and start searching for another route, in order to ensure it has always two routes available (Hayajna & Kadoch, 2016) and (Hayajna & Kadoch, 2017b).

2.2 Related work

In general, MANETs routing protocols can be classified into two categories, namely, topology-based and position-based routing protocols (Mauve, Widmer & Hartenstein, 2001). Topology-based routing protocols include proactive, reactive and hybrid routing protocols. The information regarding the links between nodes is used to build routes between the source and the destination nodes in the topology-based routing protocols. On the other hand, additional information is required in position-based routing protocols to build the routes. This information is geographical position of a packet's destination, its own position, and the position of its neighbors. Usually, Global Position System (GPS) is used by the nodes to determine their positions; while one hop broadcasts, like Hello beacons, are used to determine the neighbors' positions. The destination position must be known by the source node, which includes it in the packets headers. One of the location services techniques is used by the source node to obtain the destination position. However, location service techniques are beyond the scope of this thesis. One advantage of position-based routing protocols over topology-based routing protocols is that position-based routing protocols have the ability to transmit the packets to all nodes in a specified geographic region, i.e. Geocasting (Mauve et al., 2001).

Greedy packet forwarding, restricted directional flooding and hierarchical routing are the three kinds of position-based routing protocols. Greedy packet forwarding strategy is the most used protocol due to its simplicity. Packets in greedy forwarding are forwarded to only one neighbor in the direction of the destination, whereas in restricted directional flooding, the packets are flooded to all neighbors in the direction of the destination (Mauve et al., 2001). In case a position-based routing protocol fails to find a neighbor node in the direction of the destination, a recovery technique is used to complete the routing process. Recovery techniques are usually more complex than both greedy forwarding and restricted directional flooding protocols. Some form of hierarchy is used in hierarchical routing protocols in order to reduce the routing complexity and make the network more scalable.

One may ask this question, is it better to use position-based routing protocols or topology-based routing protocols in MANETs and WMNs? The answer to this question is that it is better to use position-based routing protocols in MANETs and WMNs due to many reasons, as illustrated below. Some of the limitations of topology-based routing protocols are eliminated by using the locations of the neighbors and the destination (Mauve et al., 2001). Position-based routing protocols eliminate the need of expensive route request beacons to build routes, broadcasting beacons to keep routing tables fresh, and the worry about routes failures. In position-based routing, there are no static routes, and the nodes route the packets by hop basis (Cadger, Curran, Santos & Moffett, 2013). This means that the need to construct routes from the source node to destination node is eliminated. At the beginning of the routing process in position-based routing protocols, the source node obtains the destination location by using one of the locations services techniques, and includes this information in the packets' headers. After that, the source node and the forwarding nodes route the packets based on the locations of the neighbors and the destination, in other words, based on a specified geographic criterion. Thus, the route establishment and maintenance are not necessary. Based on that, the nodes' storage space and power are minimized. Another advantage of position-based routing protocols over topology-based routing protocols is that the packets can be simultaneously transmitted to all nodes in a certain region in position based routing protocols. Because of all of the above advantages of position-based routing protocols over topology-based routing protocols, dynamic behaviour of MANET can be handled better in position-based routing protocols (Cadger et al., 2013).

Different strategies have been proposed to greedy forward the packets, which are Most Forward within R (MFR), Nearest with Forward Progress (NFP), compass routing, random forwarding, Least Remaining Distance (LRD), and Maximum Hop Distance (MHD). The following paragraphs explain all these strategies.

MFR was originally proposed in (Takagi & Kleinrock, 1984) as a tool to find the optimal transmission range, which maximizes the probability of the expected progress and the probability of successful packet transmissions in the random wireless networks, where the nodes are uniformly distributed in the network area. According to MFR, the Source node (S) or the forwarding node chooses a neighbor node that lies inside a half circle with a radius equal the transmission range, centred at the source node that has the maximum progress towards the Destination node (D). Maximum progress means here the maximum distance between S and the projection of the forwarding node into a line connecting S and D, i.e. maximum X, see Figure 2.1. In case the source node itself has the maximum progress towards D, MFR will choose a node from all nodes within its transmission range, which has the least backward progress. The objective of MFR is to reduce the hop count between S and D (Mauve et al., 2001). The drawbacks of MFR are twofold, the transmission to a node that has the least backward progress may create loops, and the remaining distance towards D may not be minimized in MFR (De, 2005) and (Younes & Thomas, 2011). Interestingly, later MFR used as a potential greedy forwarding strategy, especially for randomly distributed networks where the nodes cannot adjust their transmission power according to the distance to the receiver (Mauve et al., 2001). Like other greedy forwarding strategies, MFR should convert to face routing in order to accomplish the routing process, in case there is no neighbor in a half-circular area in the direction of D.

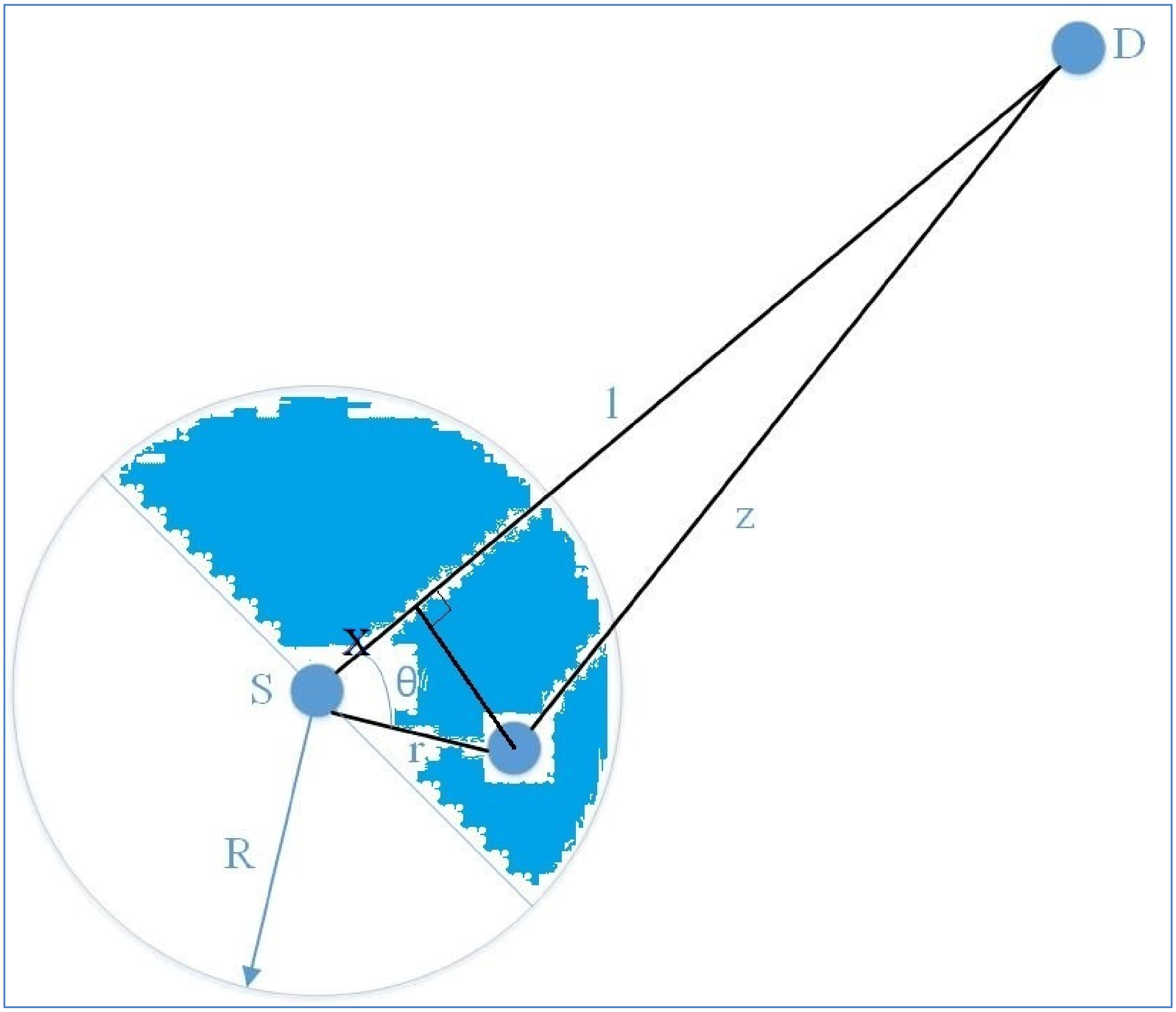

Figure 2.1 MFR greedy forwarding strategy

The source node or the forwarding node in NFP forwards the packets to a neighbor node which is closest to itself in the direction of the destination. NFP outperform MFR, in case the nodes can adapt their transmissions power to the distance to the receiver, and have high loads (Mauve et al., 2001) and (Hou & Li, 1986). This is due to the fact that, when the sender node just uses enough power to reach the receiver, the interference is reduced, and in turn, the collisions are reduced. Even though the packet travels longer distance per hop towards the destination in MFR, NFP has higher average progress, when the collision probability is considered. The average progress is equal to $p * f(T, R)$, where p is the probability of successful transmission, and $f(T, R)$ is the distance travelled by the packets from the transmitter to the receiver (Mauve et al., 2001).

In compass routing, the neighbor, which is closest to the straight line between the sender and the destination, is selected as the relay node to forward the packets. The goal behind this selection criterion is to reduce the packets spatial distribution. Another greedy forwarding strategy is random forwarding which is used to minimize the required accuracy about the neighbors' positions, and to reduce the complexity of the forwarding strategy (Mauve et al., 2001). The source node or the forwarding node in random forwarding strategy forwards the packets to any neighbor in the direction of destination, which is closer to the destination than the node itself.

Least Remaining Distance (LRD) forwarding strategy was proposed in (De, 2005) and (De, Caruso, Chaira & Chessa, 2006) to estimate the hop count for MANETs where the nodes are uniformly distributed in the network area. The packets in LRD are forwarded to a neighbor node which has the least remaining Euclidean distance to the destination. By using the above selection criterion, LRD forwarding strategy overcomes one of MFR forwarding strategy drawbacks by ensuring the chosen forwarding node has the minimum distance to the destination. The last forwarding strategy is Maximum Hop Distance (MHD), which is proposed in (Younes & Thomas, 2011) as a tool to estimate the hop count for a MANET where the nodes are non-uniformly distributed in the network area. The source node in MHD selects a neighbor node located in the direction of the destination which has the maximum per hop progress. Even though it makes sense to choose a neighbor which has the maximum per hop progress, this does not guarantee that such a neighbor node has the minimum distance to the destination, or it will reduce the hop count. Later in this thesis, we show that that the chosen path from the source node and the destination node in LRD forwarding strategy is shorter than the chosen path in MHD forwarding strategy. This means the selection criterion in LRD forwarding strategy is better than the selection criterion in LRD forwarding strategy is terms of reducing the hop count.

Usually, the expected forwarding region in all greedy forwarding strategies is a half-circular area, centred at the forwarding nodes with radius equals to the transmission range, in the direction of the destination. In this thesis, we propose a novel Adaptive Greedy Forwarding Strategy. Unlike other kinds of greedy forwarding strategies, our strategy adapts the expected forwarding region to the node density to find the optimum area in order to reduce the hop count, reduce network nodes spatial distribution, and minimize the switching from the simple greedy forwarding strategy to the complex and costly face routing. To the best of our knowledge, this is the first work that provides a complete mathematical framework to determine the optimum angle based on node density which specifies the circular sector area in order to ensure the existence of one route or multi-route between any randomly chosen pair of nodes.

(Ahmadi, Shojafar, Hajeforosh, Dehghan & Singhal, 2014) proposed a novel routing protocol for WSNs to preserve k-coverage and data reliability with the least energy consumption. k-coverage refers to the number of nodes that cover an area. In the above routing protocol, all sensor nodes are assumed fixed and are aware of their locations, residual energies, and neighbors' positions and residual energies. It consists of three phases that are phase 1: collection and processing of the required information, phase 2: creation of coverage clusters for the selected targets and the selection of the cluster heads, and phase 3: the selection of active transmitting nodes. To preserve the k-coverage and minimize energy consumption, k nodes are set as active nodes, and the remaining nodes as idle nodes in each cluster.

The above routing protocol forwards the packets based on hop by hop basis, and it works as follows: Each forwarding node checks its neighbor distances to the sink node. If it finds a neighbor node whose distance to the sink node is less than the forwarding node itself distance to the sink node, it selects this node as the next hop node. In case the forwarding node cannot find such node, it uses a communicative fitness function as the selection criterion to select the next hop node. The neighbors' distances to the sink node, their residual energies and distances to the forwarding node determine the next hop in the above fitness function.

The neighbor node which has the maximum residual energy, closest to the sink node and farthest from the forwarding node is selected as the next hop.

An energy-efficient direction based (PDORP) routing protocol for WSNs was proposed in (Brar et al., 2016). PDORP stands for PEGASIS-DSR Optimized Routing Protocol. The above routing protocol makes the Dynamic Source Routing (DSR) protocol an energy aware and a reliable routing protocol by using hybridization of genetic algorithms and bacterial foraging optimization techniques. PDORP enhances the network reliability by using the proactive routing and reactive routing methodologies, and by composing a trust list of forwarding nodes (Brar et al., 2016). However, PDORP has two main drawbacks that make it not a suitable routing protocol for WMNs and MANETs. On the one hand, it is specifically designed for WSNs, where the nodes are fixed, and the main objective is power saving. On the other hand, it is a little bit complex to implement it in WMNs and MANETs nodes.

To support multimedia communications over MANETs and WMNs, stable routes that have long route lifetimes, low control overheads and high packet delivery ratio are required (Hayajna & Kadoch, 2016) and (Yang et al., 2011). However, the high dynamic topologies in MANETs due to the nodes' random movements cause poor route availability. Stable routing has three main categories that are topology stability routing, communication stability routing and energy stability routing (Yang et al., 2011). The route instability caused by link dynamics, wireless interference and energy consumption are addressed by topology stability routing, communication stability routing and energy stability routing, respectively (Yang et al., 2011). This thesis concentrates on topology stability routing, which is primarily classified into single-path stable routing and backup routing.

Al-Akaidi & Alchaita (Al-Akaidi & Alchaita, 2007) recommended using the single-path stable routing protocol by selecting the path that has the longest link lifetime. It was analytically shown in (Al-Akaidi & Alchaita, 2007) that the expected path lifetime was approximately the reciprocal of the sum of the reciprocal of the expected lifetimes of all links in the path (Yang et al., 2011). This means that the selected stable route should simultaneously satisfy two conditions that are the path length should be the shortest and the link lifetime should be the largest. Based on that, the routing metric proposed in (Al-Akaidi & Alchaita, 2007) fails to select the truly stable route, because it does not consider the route length. On the other hand, different kinds of greedy forwarding strategies, like Greedy Perimeter Stateless Routing (GPSR) strategy (Karp & Kung, 2000), fails to select the truly stable route, because they choose the shortest routes, but they do not consider the route link lifetimes. In addition, longer link distances in the above greedy forwarding strategies, compared to shorter link distances, may easily cause link failures due to node mobility. Note that the source node and the forwarding nodes in GPSR strategy choose a neighbor node which has the minimum distance to the destination. Actually, what we need is a routing protocol that considers both the route length and the route's link lifetimes.

Backup routing increases the network stability and packet delivery ratio by incorporating a backup route that is used in case of link failures. The main drawback of some of the existing backup routing protocols, like Backup Source Routing (BSR) (Guo, Yang & Shu, 2005), Caching and Multiple Paths (CHAMP) routing (Valera, Seah & Rao, 2005), and Scalable Multi-path On demand Routing (SMORT) (Reddy & Raghavan, 2007) is that they ignore the fact that when the primary route fails, the backup path may also fail (Yang et al., 2011). (Lai, Hsiao & Lin, 2007) tries to solve the above drawback by using the data overhearing mechanism for the backup routing updating at the expense of more energy used while the nodes are in the promiscuous mode instead of the sleeping mode.

(Yang et al., 2011) proposed a Greedy-based Backup Routing (GBR) protocol in order to improve the network stability by considering the route length and the lifetime of each path's link. GBR protocol builds the primary route based on an ordinary greedy forwarding strategy; therefore, the primary path usually has the shortest route length. On the other hand, it builds the local backup routes for each link during the primary path discovery procedure based on the link lifetime. To explain how GBR works, let us take the example taken from (Yang et al., 2011).

Assume that node S wants to send packets to node D as shown in Figure 2.2. At first, S checks if it has a route to D. If so, it uses that route, otherwise it starts the route discovery procedure as illustrated below. Based on a greedy forwarding strategy, the nearest S's neighbor to D, i.e. node a, is selected by S as the next hop. After that, S unicasts a PREQ packet to node a to build the first link (S,a) of the primary path. Then, node b is selected by node a as the next hop, and after that node a unicasts a PREQ message to node b to build the second link (a,b) of the primary path . Upon the reception of the above two RREQ messages by nodes e and j, they calculate the Path Expiration Time (PET) for both the routes (S, e, a) and (S, j, a), respectively. If both PET(S, e, a) and PET (S, j, a) are greater than the Link Expiration Time (LET) between node S and a, both nodes e and j broadcast a Competing Backup (CB) packet after a predefined delay. Note that if node e broadcast a CB packet before node j to build the local backup path (S, e, a) for the link (S,a), it blocks node j from broadcasting a CB packet, and vise versa. All intermediate nodes repeat the same steps. The reception of the Route REPly (RREP) message from node D completes the establishment of the primary path, while when the PREQ message reaches D, the establishment of the local back links are completed.

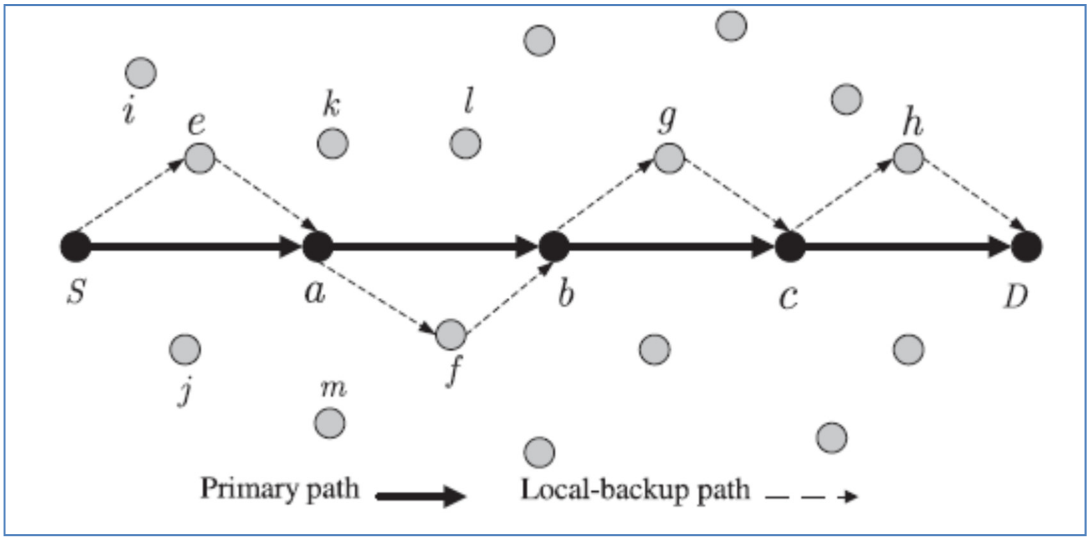

Figure 2.2 The establishment of the primary path and the local-backup path in GBR
Taken from Yang et al. (2011, p. 664)

(Zadin & Fevens, 2013) tried to improve the performance of GBR routing protocol by proposing GBR with Conservative Neighborhood Range (GBR-CNR) routing protocol. It implements some ideas in the GBR routing protocol in order to improve its performance. The first idea is the construction of the backup route from nodes farther than two hops from the two nodes constructing the link in case GBR routing protocol cannot find a backup route within two hops neighbors. The other idea is the rediscovering of the primary route from the last reachable node instead of the source node in case of the primary route fails. The last idea is the restriction of the selections of next hop nodes to neighbors within a Conservative Neighborhood Range (CNR), which is lower than the actual selection range, i.e. the transmission range. The Hello interval and the nodes' maximum speed determine the CNR's size.

Even though GBR-CNR routing protocol has promising ideas, it has two main drawbacks as shown below. The first one is that it is very hard to know the nodes' maximum speed; therefore, it is almost impossible to determine CNR. In addition to that, the knowledge of the nodes' maximum speed only cannot determine the likelihood of link failures. Actually, CNR depends on the nodes movement directions in addition to their speed, because in some cases the nodes are moving closer to each other and the link's lifetime is increased. The second drawback is that GBR-CNR implicitly assumes high node density. In case of lower nodes density, the probability that GBR-CNR routing protocol fails is high, because the probability to find a neighbor within CNR is very low.

2.3 Adaptive greedy forwarding strategy in MANETs based on node density

As we illustrated earlier in this thesis, routing protocols play a crucial role in MANETs recovery systems. Greedy forwarding strategy is a potential forwarding strategies for routing protocols in MANETs, because it is simple, scalable, and can be easily implemented in this type of network. In this thesis, we propose a novel adaptive greedy forwarding strategy. Unlike other greedy forwarding strategies, the forwarding region is not fixed and the size of this region depends on the nodes density. As such, the minimum area that ensures the network connectivity has to be found. This strategy can be described as follows: For high node density, the expected forwarding region is relatively small. When the node density starts decreasing, the expected forwarding region starts increasing to compensate the lower density until it reaches an area which ensures the existence of a forwarding node in that region, i.e. keep the network connected. In this way, the hop count and network nodes' spatial distribution are reduced, the switching from the greedy forwarding strategy to the complex and costly face routing is minimized, and the size of memory is reduced due to the fewer neighbors that a node needs to keep their locations. To this end, a complete probabilistic model will be provided.

2.3.1 Mathematical model analysis

This study considers a MANET, where the nodes are uniformly distributed in the network area and using MFR greedy forwarding strategy as the greedy forwarding strategy. The node density (ρ) is the same everywhere in the network area. The nodes are either static or mobile according to random walk mobility model (Roy, 2011), i.e. the nodes are always uniformly distributed in the network area. The node transmission range is the same for all nodes, and it is equal to R. Two nodes are considers neighbors if the distance between them is less than R.

The pdfs of the distance (r) and the angle (θ) between the source node (S) and the selected forwarding node (F) for uniformly distributed nodes, see Figure 2.1, are given in equation 2.1 and 2.2, respectively, as

$$\mathrm{f_r(r)} = \begin{cases} \dfrac{2\mathrm{r}}{\mathrm{R}^2}, & 0 \le r \le R \\ 0, & otherwise \end{cases} \tag{2.1}$$

$$\mathrm{f_\theta(\theta)} = \begin{cases} \dfrac{1}{2\phi}, & -\phi \le \theta \le \phi \\ 0, & otherwise \end{cases} \tag{2.2}$$

Where:

r : the Euclidean distance between S and F.

θ : the angle between the line connection S and D and the line connecting S and F.

ϕ : the angle of the circular sector with respect to x (a dummy variable between 0 and $\pi/2$).

The expected forwarding region is determined by the angle ϕ, see Figure 2.3. Usually in literature, the expected forwarding region is taken as a half circle with radius R, i.e. $\phi = \pi/2$. In contrast, in our adaptive greedy forwarding strategy, ϕ does not take a fixed value, rather it is determined based on node density. For example, if the node density is high, the range of ϕ will be small. This is because when the node density is high, the probability to find a neighbor node in smaller area is higher and it is not necessary to consider the whole half circle, and smaller region will be sufficient to find a neighbor node to forward the packets to it. On the other hand, if the node density is low, the range of ϕ will be higher.

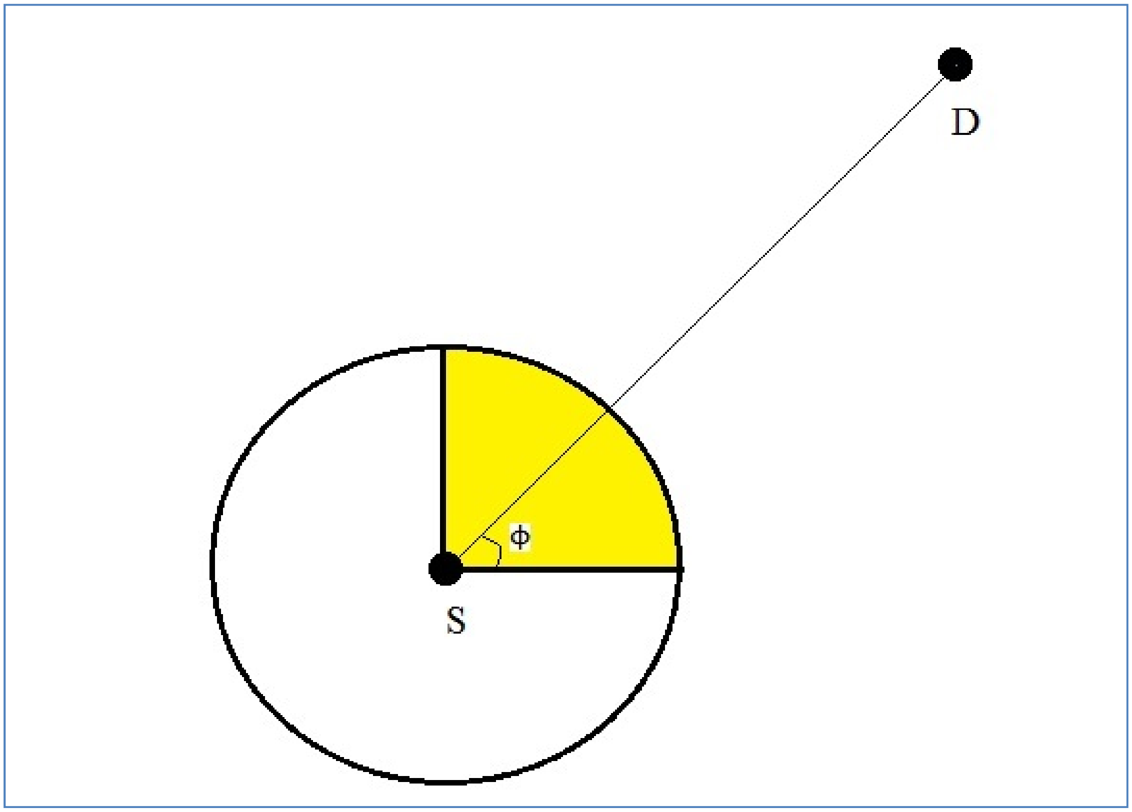

Figure 2.3 The angle ϕ in our adaptive greedy forwarding strategy

To continue our analysis, the joint pdf of r and θ ($f_{r\theta}(r,\theta)$) is required. The joint pdf of r and θ is equal to the multiplication of their pdf, because they are mutually independent events. Thus,

$$f_{r\theta}(r,\theta)=\begin{cases}\dfrac{r}{\phi R^2}, & 0\le r\le R \text{ and } -\phi\le\theta\le\phi\\ 0, & otherwise\end{cases} \tag{2.3}$$

Since our analysis deals with the Cartesian coordinates, $f_{r\theta}(r,\theta)$ shall be transformed from the polar coordinates to Cartesian coordinates with x and y axes. As we said before, MFR is the used greedy forwarding strategy. Thus, x here represents the distance between the source node and the projection of the forwarding node into the line connecting the source node and the destination node. The above transformation can be obtained by using random variables transformation, that is

$$f_{xy}(x,y)=\begin{cases}\dfrac{1}{\phi R^2}, & 0\le x\le R, -R.sin(\phi)\le y\le R.sin(\phi) \text{ and } x^2+y^2\le R^2\\ 0, & otherwise\end{cases} \tag{2.4}$$

Here ϕ takes any value between 0 and π/2. Note that $y^2\le R^2-x^2$, then $-\sqrt{R^2-x^2}\le y\le\sqrt{R^2-x^2}$. Rewrite the above equation with this condition, then

$$f_{xy}(x,y)=\begin{cases}\dfrac{1}{\phi R^2}, & 0\le x\le R, -\sqrt{R^2-x^2}\le y\le\sqrt{R^2-x^2}\\ 0, & otherwise\end{cases} \tag{2.5}$$

As it is known, the marginal pdf of x ($f_x(x)$) is found by integrating the joint pdf $f_{xy}(x,y)$ over the range of y. Thus,

$$f_x(x) = \begin{cases} \frac{2\sqrt{R^2 - x^2}}{\phi R^2}, & 0 \le x \le R \\ 0, & otherwise \end{cases} \tag{2.6}$$

Integrating the above equation over x, gives us the cdf $F_x(x)$. Then,

$$F_x(x) = \begin{cases} \frac{1}{\phi R^2}\left(x\sqrt{R^2 - x^2} + R^2 \arctan\frac{x}{\sqrt{R^2 - x^2}}\right), & 0 \le x \le R, R \ne x \\ 0, & otherwise \end{cases} \tag{2.7}$$

Assume Z is the maximum distance x among all neighbor nodes inside the circular sector, i.e. Z = max (x_1, x_2 ... x_n). Thus, $F_Z(Z) = F_x(z)^n$

$$F_z(z) = \begin{cases} \left(\frac{1}{\phi R^2}\right)^n \left(z\sqrt{R^2 - z^2} + R^2 \arctan\frac{z}{\sqrt{R^2 - z^2}}\right)^n, & 0 \le z \le R \\ 0, & otherwise \end{cases} \tag{2.8}$$

The pdf $f_z(z)$ can be obtained by taking the derivative of the cdf in equaion 2.8 with respect to z, as shown in equation 2.9. Note that, the default value of ϕ, which is used in literature, is equal to π/2. Substitute this value in equation 2.9, we get the default pdf of Z ($f_{z\_def}(z)$), as shown in equation 2.10.

$$f_z(z) = \begin{cases} n\left(\frac{1}{\phi R^2}\right)^n \left(z\sqrt{R^2 - z^2} + R^2 \arctan\frac{z}{\sqrt{R^2 - z^2}}\right)^{(n-1)} \left[\frac{R^2 - 2z^2}{\sqrt{R^2 - z^2}} + \frac{R^4 - R^2 z^2}{(R^2 - z^2)^{1.5}}\right], & 0 \le z < R \\ 0, & otherwise \end{cases} \tag{2.9}$$

$$f_{z\_def}(z) = \begin{cases} n\left(\frac{2}{\pi R^2}\right)^n \left(z\sqrt{R^2 - z^2} + R^2 \arctan\frac{z}{\sqrt{R^2 - z^2}}\right)^{(n-1)} \left[\frac{R^2 - 2z^2}{\sqrt{R^2 - z^2}} + \frac{R^4 - R^2 z^2}{(R^2 - z^2)^{1.5}}\right], & 0 \le z < R \\ 0, & otherwise \end{cases} \tag{2.10}$$

The average progress per one hop in the default case is given by the expected maximum progress ($\overline{Z_{def}}$). Thus,

$$\overline{Z_{def}} = \int_0^R t f_z(t) dt \tag{2.11}$$

The probability that a mobile node has n neighbors inside a specific area can by approximated by using Poisson distribution, since the mobile nodes are uniformly distributed in the network area (Dung & An, 2013). Then,

$$P(n) = \frac{(\rho C)^n}{n!} e^{-\rho C} \tag{2.12}$$

Where:

$P(n)$: the probability that a mobile node has n neighbors inside a specific area (C).

ρ : node density.

C : the circular sector area (ϕR^2).

Since the uniform distribution is considered in this analysis, the number of potential forwarding nodes inside a circular sector with angle ϕ (N) is equal to the multiplication of ρ and C ($N = \rho * C = \rho\phi R^2$). Thus, equation 2.12 can be rewritten in terms of N as

$$P(n) = \frac{(N)^n}{n!} e^{-N} \tag{2.13}$$

2.3.2 One-way connectivity

The average number of neighbors which ensures one-way connectivity for a single hop equals to 8 was proven by Takagi and Kleinrock in (Takagi & Kleinrock, 1984). One of the main drawbacks of the above approach is its complexity, since it involved the MAC layer and routing layer point of view. In this thesis, we provide another approach to prove that the average number of neighbors equals to 8 indeed ensures one-way connectivity. Our approach is efficient, simple, and from the routing layer point of view only. This also can provide a hint that the analysis used in this study that ignores the consideration of the MAC layer has negligible impacts in terms of network connectivity.

A. The default case

The pdf of the per one hop progress (Z) for the default case ($f_{z\_def}(z)$), where ϕ is equal to $\pi/2$, is shown in equation 2.10, and is plotted in Figure 2.4 for N = 4 and R = 100m. Figure 2.4 shows that the probability to find small values of z is very small, and it is more likely to be greater than 0.6*R. Note that the same result was obtained in (Takagi & Kleinrock, 1984).

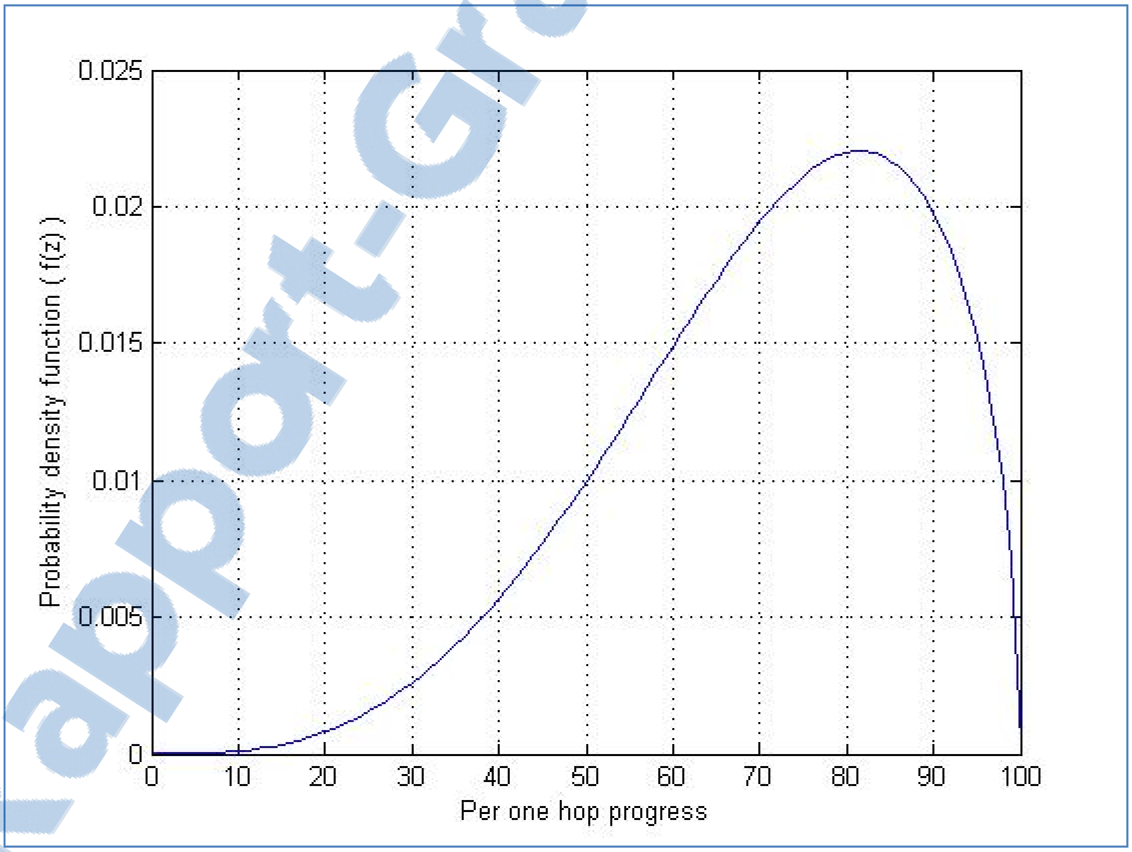

Figure 2.4 Probability density function $f_z(z)$ for the default case at N = 4 and R = 100m

One important thing we should study is the effect of the node density, i.e. n, on the average per one hop progress ($\overline{Z_{def}}$). The relationship between $\overline{Z_{def}}$ and n is found by using equation 2.11, and it is shown in Figure 2.5 for R = 100m.

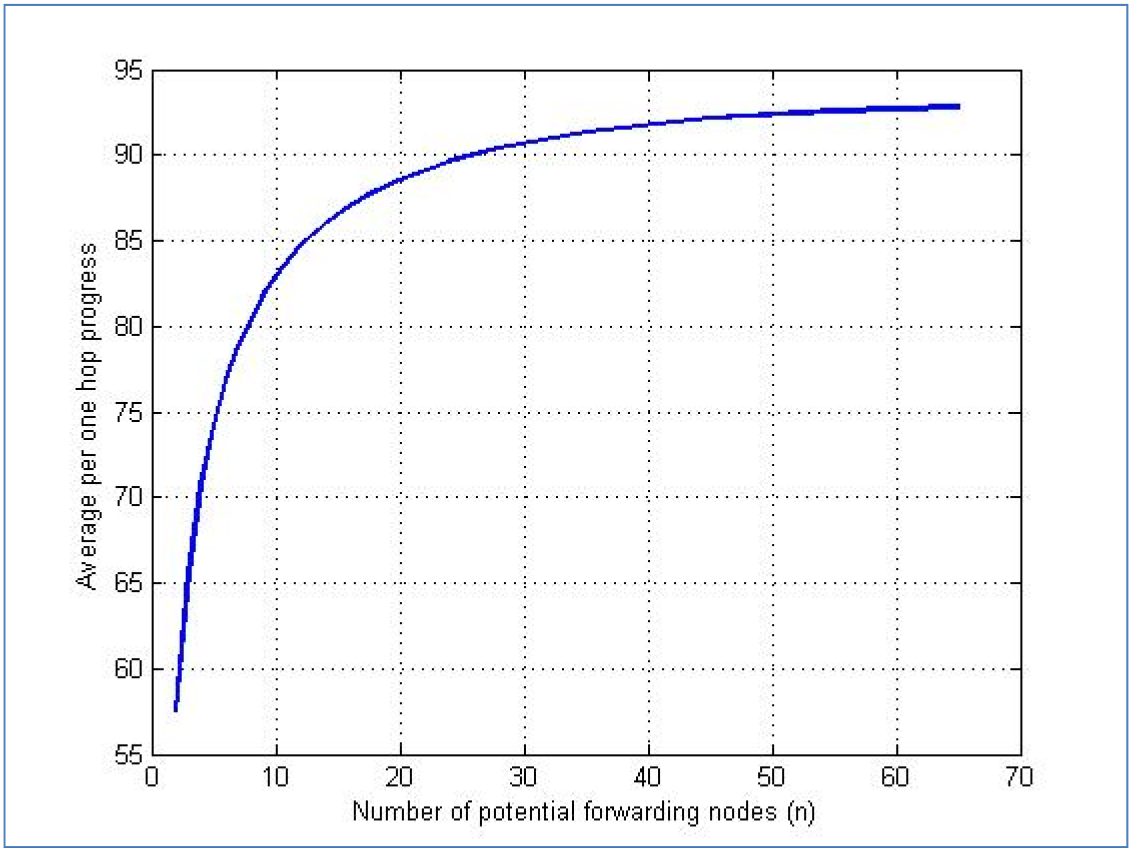

Figure 2.5 The relationship between the average value of Z ($\overline{Z_{def}}$) and the number of potential forwarding nodes (n) at R = 100m

Figure 2.5 clearly shows that the average per one hop progress has two regions. In the first region, from n = 2 to n = 15, $\overline{Z_{def}}$ exponentially increases with n. In the second region, where n > 15, $\overline{Z_{def}}$ increases slowly with n till it reaches the saturation region, where the increase in n negligibly increases $\overline{Z_{def}}$ and it is almost constant.

Our main objective in this subsection is to find the value of N that ensures the one-way connectivity. To ensure the one-way connectivity, the source node must have at least one neighbor node in the expected forwarding region. Thus, we shall put $n \geq 1$ in equation 2.13 in order to obtain the probability of one-way connectivity ($P_{dcon\_oneroute}$). Based on that,

$$P_{dcon\_oneroute} = p(n \geq 1) = 1 - p(0) = 1 - e^{-N} \qquad (2.14)$$

Figure 2.6 shows the relationship between $P_{dcon\_oneroute}$ and N as indicated in the above equation. This figure shows that the network is almost surely one-way connected, i.e. $P_{con\_oneroute}$ is greater than 0.95, at N = 4. This proves that the number of neighbors a node must have in order to ensure one-way connectivity is 8, i.e. N = 4, which is the same value obtained in (Takagi & Kleinrock, 1984).

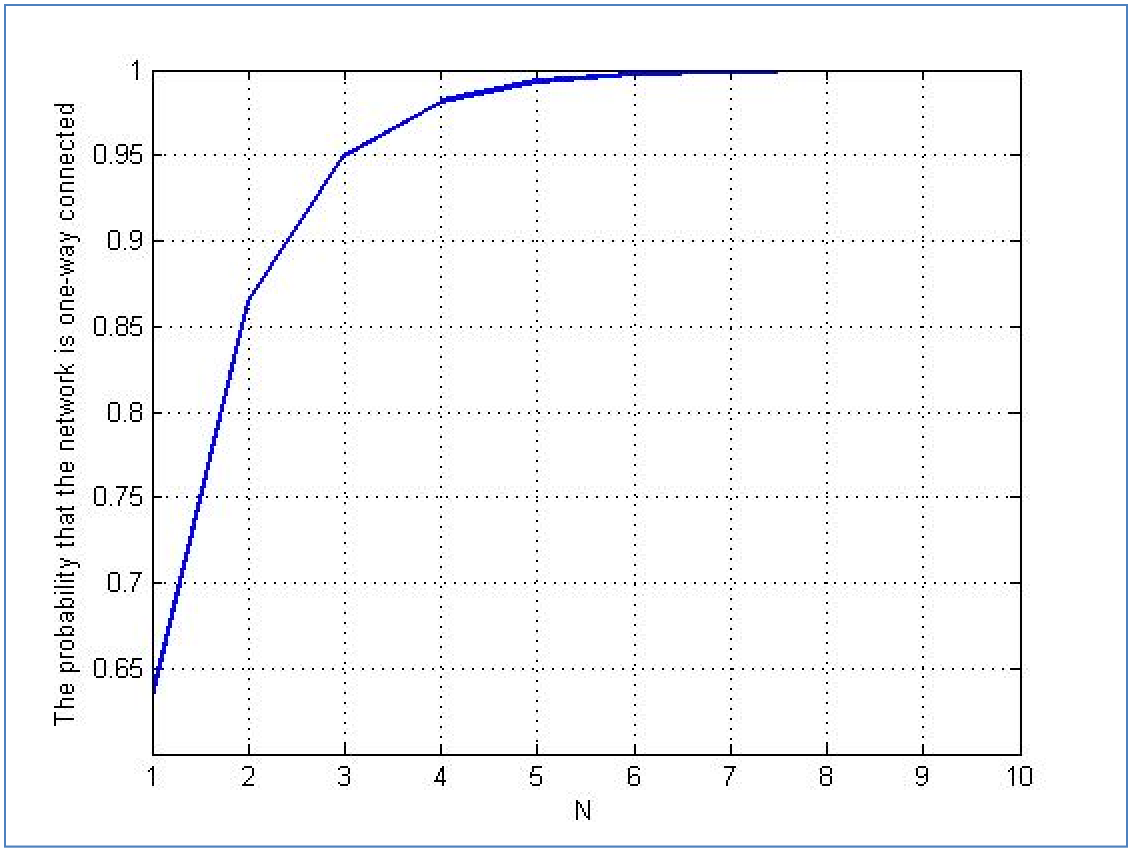

Figure 2.6 The probability that the network is one-way connected vs. N

B. The general case

The number of neighbors that ensures that the network is one-way connected is obtained by using equation 2.12, and putting $n \geq 1$. Thus, $P_{con\_oneroute}$ can be expressed as

$$P_{con\_oneroute} = p(n \geq 1) = 1 - e^{-\rho C} \tag{2.15}$$

Now, consider a MANET with square area of 1 km^2 and the number of nodes in this area is 1000 nodes. All nodes have the same transmission range (R) equals to 100m. As it is well known, the node density (ρ) equals the total number of nodes in the network over the network area. Thus, ρ equals 0.001 m^{-2}. Figure 2.7 shows the relationship between the probability that the network is one-way connected and the angle ϕ at $\rho = 0.001 m^{-2}$ and $R = 100m$. As shown in this Figure, ϕ equals to 0.3rad is sufficient in order to achieve almost surely one-way connected network instead of 1.571rad, the default angle used in literature.

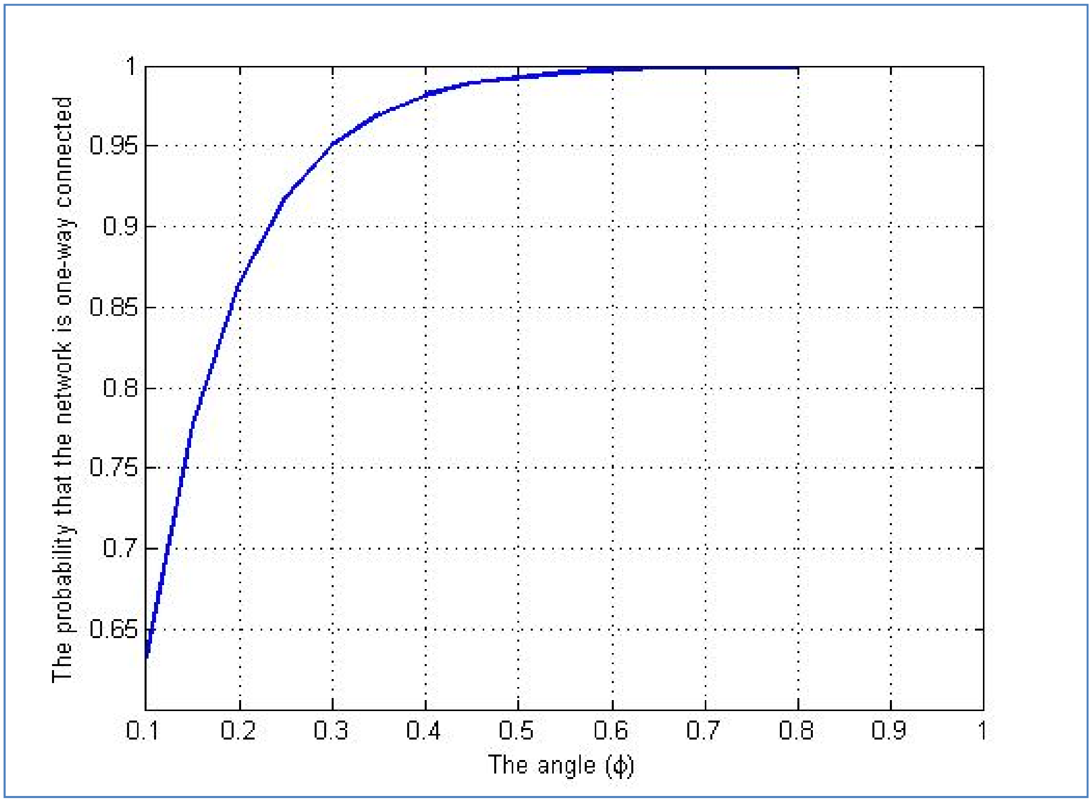

Figure 2.7 The relationship between the probability that the network is one-way connected and the angle ϕ at $\rho = 0.001 m^{-2}$ and $R = 100m$

Now consider the network is almost surely one-way connected when $P_{\text{con\_oneroute}}$ is greater than 0.95. The angle ϕ which ensures the network is almost surely one-way connected is obtained by substituting the above value into equation 2.15, that is

$$\phi \geq \frac{2.996}{\rho R^2} \tag{2.16}$$

The above equation shows that if the network node density (ρ) and the network transmission range (R) are known, the required angle ϕ to almost ensure the network is one-way connected can be found. It also shows that there is an inverse relationship between the angle ϕ and both ρ and R. The relationship between the angle ϕ and R, when the network is almost surely one-way connected, while ρ is fixed at 0.001 m^{-2} is shown in Figure 2.8.

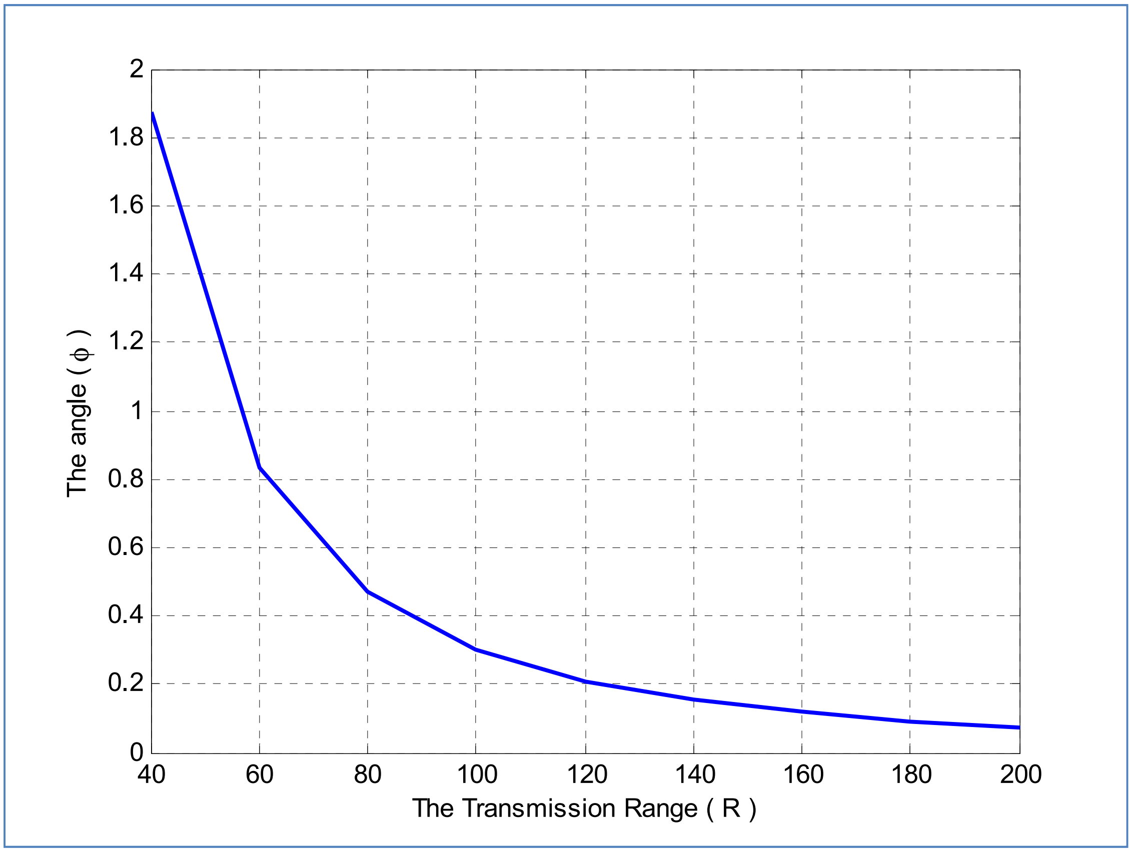

Figure 2.8 The relationship between the angle ϕ and R when the network is almost surely one-way connected at $\rho = 0.001 m^{-2}$

For relatively high transmission range, it is sufficient to choose a small angle to forward the packets, as it is shown in Figure 2.8. For example, at $\rho = .001\text{m}^{-2}$ and R greater than 160 m it is sufficient to choose the angle equals to 0.1rad instead of 1.571rad. There are many advantages of reducing the angle ϕ as mentioned below:

- Reducing the hop count;
- Reducing the network nodes' spatial distribution;
- Minimizing the conversion from the simple greedy forwarding strategy to the complex and costly face routing;
- Reducing the nodes' memory sizes due to the fewer neighbors that they need to maintain their locations.

2.3.3 Two-ways connectivity

To ensure that the network is two-ways connected, n must be greater than or equal to 2 ($n \geq 2$). Putting this value into equation 2.12 gives us the probability that the network is two-ways connected $P_{\text{con\_tworoutes}}$. Thus,

$$P_{\text{con\_tworoutes}} = p(n \geq 2) = 1 - e^{-\rho C} - (\rho C)e^{-\rho C} \tag{2.17}$$

Equation 2.17 can be rewritten in terms of ρ, ϕ and R by butting the value of C, which is equal to ϕR^2, in this equation. Thus,

$$P_{\text{con\_tworoutes}} = 1 - e^{-\rho\phi R^2} - (\rho\phi R^2)e^{-\rho\phi R^2} \tag{2.18}$$

Equation 2.18 shows that the probability to have two routes depends only on ρ, R and ϕ. As in the one route case, the required angle ϕ to almost ensure the network is two-ways connected can be found if ρ and R are known. Now, we study the relationship between the probability that the network is two-ways connected and the angle ϕ. In addition, we study the relationship between the angle ϕ and R.

Assume the same values of ρ and R as in the one route case, i.e. $\rho = 0.001\ m^{-2}$ and R = 100m. By putting these values in equation 2.18 and changing the angle ϕ, we obtain the relationship between the probability that the network is two-ways connected and the angle ϕ as shown in Figure 2.9. As in the one-way connectivity, the probability that the network is two-ways connected exponentially increases when the angle ϕ increases until it reaches the saturation region, where the probability that the network is two-ways connected is almost constant. However, the two routes case requires higher angle compare to the single route case to achieve the same probability that the network is connected as shown in Figure 2.9. This is because the two route case requires at least two neighbor nodes inside the circular sector; while in the one route case just one neighbor node is enough. Thus, in the two routes case a higher area, i.e. higher angle, is required to have at least two nodes; while in the one route case smaller area is sufficient to find a single node.

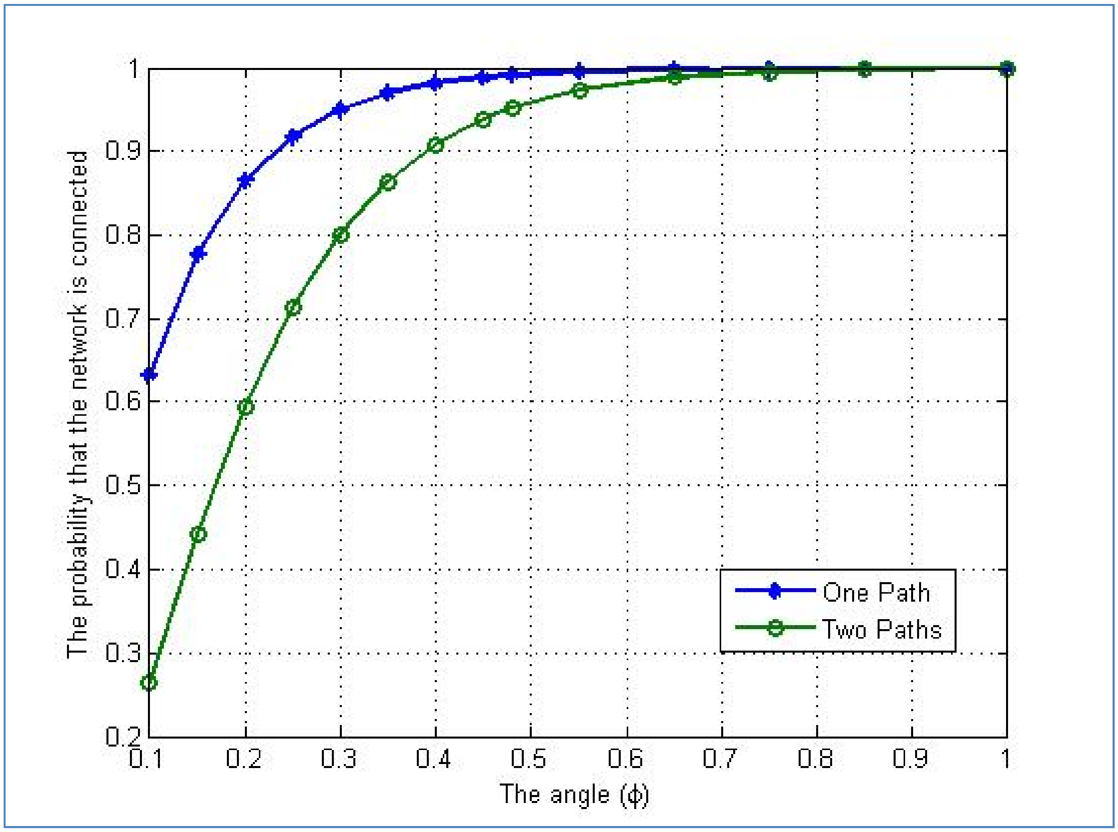

Figure 2.9 The probability of one-way and two-ways connectivity vs. ϕ at $\rho = 0.001\ m^{-2}$ and R = 100m

One interesting relationship to study is the relationship between ϕ and R when the network is almost surely two-ways connected. This relationship can be found based on equation 2.19, where $P_{con\_tworoutes} = 0.95$. Based on that, the relationship between ϕ and R when the network is almost surely two-ways connected is shown in the following equation, and it is plotted in Figure 2.10.

$$\rho\phi R^2 = \ln\left(\frac{1 + \rho\phi R^2}{0.05}\right) \tag{2.19}$$

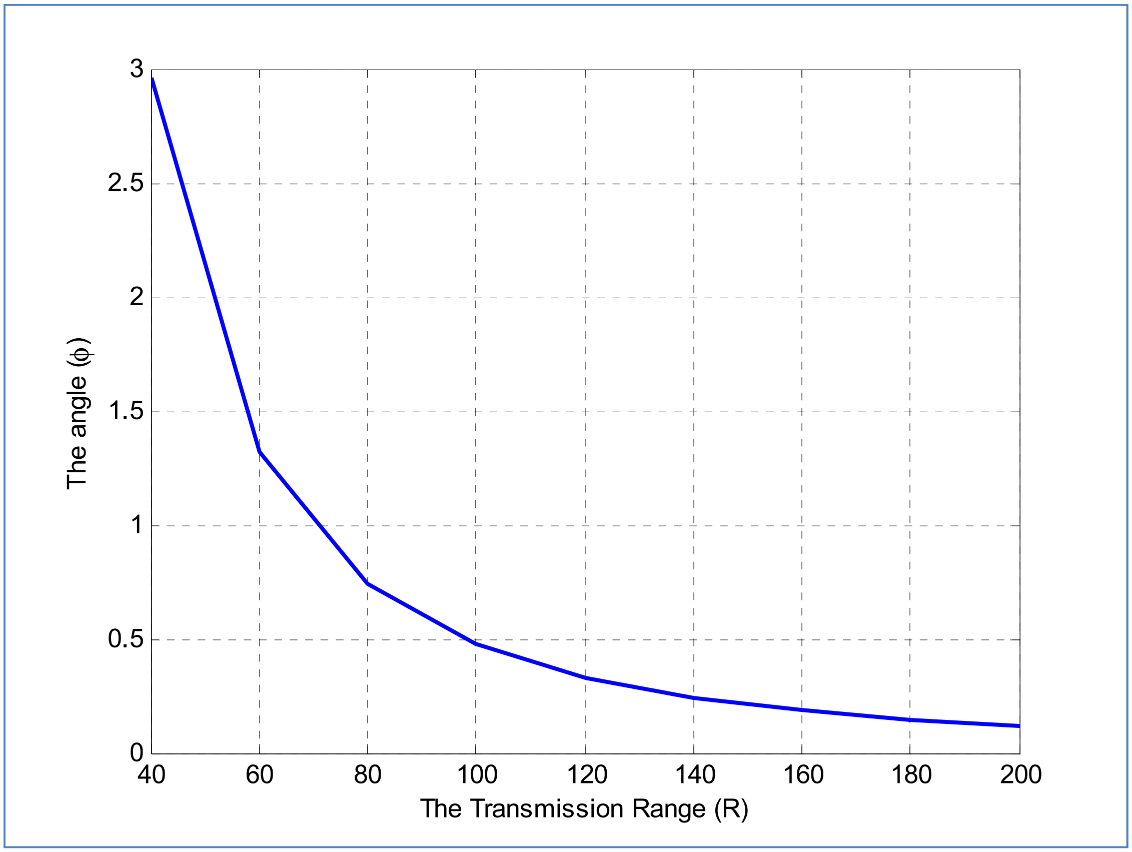

Figure 2.10 The relationship between the angle ϕ and R when the network is almost surely two-ways connected at $\rho = 0.001\ m^{-2}$

Figure 2.10 shows that there is an exponentially inverse relationship between ϕ and R. This means that if the network nodes have the potential to increase their transmission powers, they can at the same time decrease the required angle ϕ that almost ensure the network is two-ways connected. To compare the two paths case with the one path case, we plot the relationships between the angle ϕ for the one-way connectivity and the two-ways connectivity versus R when the node density is fixed at 0.001 m^{-2} in the same figure, Figure 2.11.

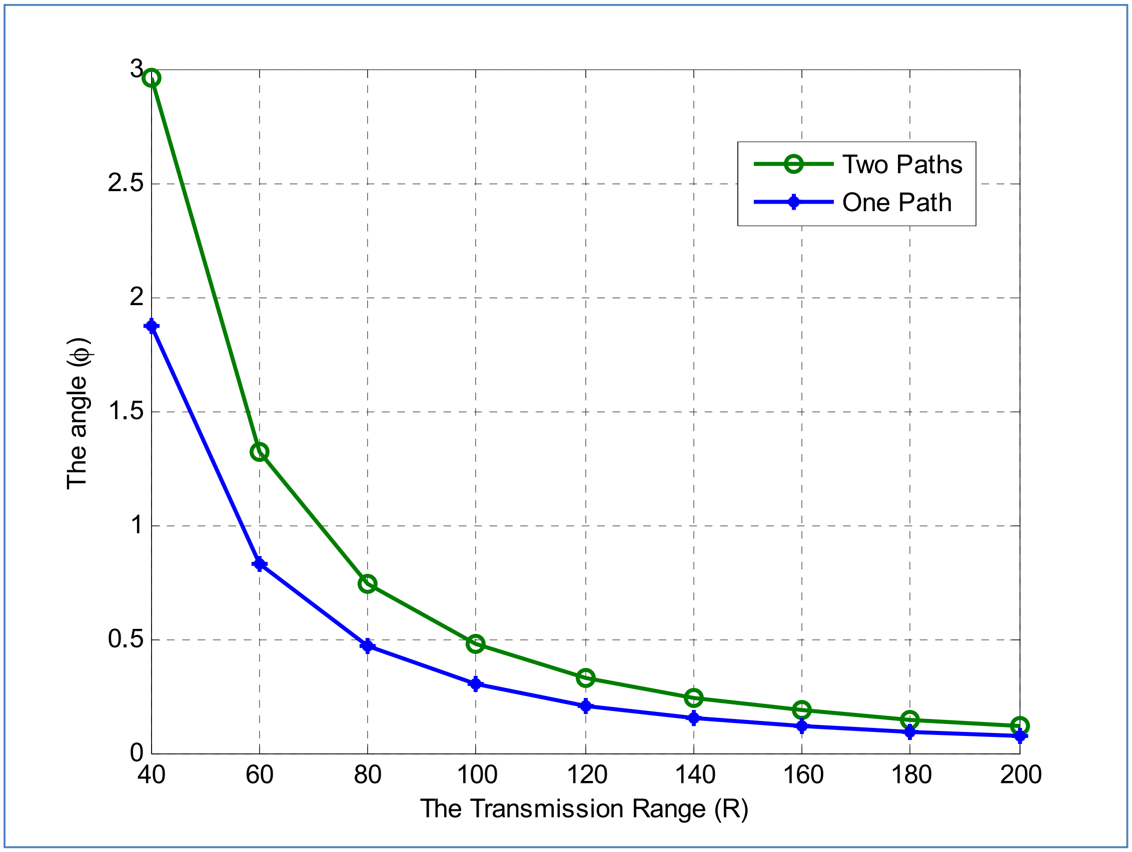

Figure 2.11 The relationship between the angle ϕ and R when the network is almost surely one-way and two-ways connected at $\rho = 0.001 m^{-2}$

Even though the angle ϕ has an exponentially inverse relationship with R in both the one route case and the two routes case, as shown in Figure 2.11, a larger angle is required for the two routes case compared to the one route case. For example, when R = 100m, the required angles to ensures the network are one-way connected and two-ways connected are 0.3 rad and 0.47 rad, respectively. The above means that the forwarding region sizes can be reduced by a factor of 5.24 and 3.34 for the one-way connectivity and the two-ways connectivity, respectively, compared to the sizes usually used in literature. To be more specific, at low transmission ranges, the angle ϕ in the two routes case is almost double the angle in the one route case. Furthermore, the ratio between the two cases decreases when R increases, because in this case the probability to find one node or two nodes is high enough and a small angle will be sufficient to almost ensure the network connectivity is one-way connected or two-ways connected.

We conclude this chapter by saying that the position-based routing protocols are more suitable to MANETs than the topology-based routing protocols, because they eliminate some of the topology-based routing protocols limitations, handle better the dynamic behavior of MANETs, and are more scalable. Among the position-based routing protocols, the greedy based routing protocol is the most used, due to its simplicity and scalability. A novel adaptive greedy forwarding strategy was proposed in this chapter. Unlike other greedy forwarding strategies, this strategy adapts the forwarding region size to the network node density. The main objective behind this strategy is to determine the forwarding region size which ensures the one-way connectivity or the two-ways connectivity.

CHAPTER 3

NETWORK RELIABILITY AND CONNECTIVITY

3.1 Introduction

Network reliability is the probability of a network performing its intended functions for a certain period under specified network conditions. In other words, network reliability is the probability that the network has no failure within a given operating period (Shooman, 2002). Usually, the availability term is used instead of the reliability term when the network recovery system is considered to fix the network failures. Network availability can be defined as the probability that the network is up at a certain point of time (Shooman, 2002). In general, since the network recovery rate is much larger than the failure rate, network reliability and network availability are used interchangeably (Shooman, 2002). Network reliability has three types that are the all-terminal reliability, the k-terminal reliability and the two-terminal reliability. The All-terminal reliability is the probability that all the network nodes can communicate to each other, whereas the k-terminal reliability is the probability that a subset of network nodes can communicate. The two-terminal reliability can be considered as a sub-case of k-terminal reliability, where k is equal to two.

3.2 Literature review

A framework for modeling, predicting and analyzing the wireless packets transmissions reliability was proposed in (Sattiraju & Schotten, 2014). This framework considered the effects of path loss, shadowing and multipath fading, while ignores other effects like nodes mobility and interference. The above reliability analysis was based on the Reliability Block Diagram (RBD) technique.

Egeland & Engelstad in (Egeland & Engelstad, 2009) introduced a method to predict the WMNs k-terminal reliability based on graph theory and the basic reliability concepts.

Specifically, this method estimated the increase in the network reliability by adding redundant nodes for static planned mesh networks and static random mesh networks. Although, this method can be used by the mesh network designers to find the required node density to achieve the target reliability, it is however very complicated to implement in real-world environments.

(Dube, Raia, Wang & Tripathi, 1997) proposed to use signal stability and location stability to measure the links reliability. In signal stability, the neighbors are classified as either strongly connected or weakly connected based on the received signal strength from them. The period of time that a link has existed determines the location stability. (Dube et al., 1997) recommends favouring the selection of paths that have stronger channels that have operating periods greater than some threshold (Jiang, He & Rao, 2001). The main drawback of using signal stability and location stability to measure the link reliability is its dependency on the links' past information that may fail to predict the future links' status especially when the nodes are highly mobile.

(McDonald & Znabi, 1999a) and (McDonald & Znabi, 1999b) propose a probabilistic model to predict the link availability, i.e. the probability that at time $t_0 + T$ the link is up given that the link is available at time t_0. In this model, the link is considered available at $t_0 + T$, even if it has failures during the interval t_0 to $t_0 + T$. This model defines the link availability as T_a / T, where Ta is the sum of all non-continuous time periods where the link is up, and T is the prediction time period. The above link availability model can be used to form a stable cluster by selecting only the reliable neighbors, and as a routing metric to choose the most stable paths.

The main drawback of the above model is that it is impractical, because when the link is considered down, the rerouting is immediately required and the corresponding nodes will not wait for the down links to become up again (Jiang, He & Rao, 2005). Thus, a continuous time period (T_c) during which the link has no failures must be used instead of the T_a parameter in order to make the above model more practical (Jiang et al., 2005). Another drawback is that this model accurately predicts the link availability when the prediction time periods are longer than tens of minutes, and substantially underestimates the link availability when the prediction time periods are less than several minutes (Jiang et al., 2005). However, the typical flow duration for data applications is often less than several minutes (Jiang et al., 2005). To overcome the above drawbacks, (Jiang et al., 2005) propose another probabilistic model to estimate the link availability.

The model proposed in (Jiang et al., 2005) consists of two parameters T_p and $L(T_p)$. T_p is the continuous time period that the link will remain up when the corresponding nodes do not change their speed and direction. On the other hand, $L(T_p)$ is the probability that the link will really remain up for the whole T_p period when the corresponding nodes may change their speed or direction. An accurate estimation of T_p can be easily calculated based on the nodes' speeds and directions, while it is more challengeable to estimate $L(T_p)$, because it involves the node speeds and directions. The authors of this model recommend to use $T_p * L(T_p)$ as a routing metric to select the most reliable links. Since usually the routing paths consist of multiple links, the flow duration depends on the link with the minimum $T_p * L(T_p)$. For this reason, the path with highest minimum $T_p * L(T_p)$ is selected as the most reliable path. However, as shown in chapter 2, this metric fails to select the truly stable route, because it does not consider the route length. The simulation results in (Jiang et al., 2005) show that the use of the above routing metric, instead of the classical routing metric that is used in DSR (the shortest path and the first selected path), significantly improves the DSR routing performance.

The mobility model used to estimate $L(T_p)$ has two properties that are the node movements are uncorrelated and the epochs (a random time interval variable during which a node does not change direction or speed) are exponentially distributed. Thus, the model proposed in (Jiang et al., 2005) is only applicable in networks where the nodes follow the above mentioned mobility model. Another weakness of this model is that it does not provide an explicit formula to estimate $L(T_p)$; instead of that it combines the theoretical analysis with on fly measurements to compensate the errors happen in the theoretical estimation of $L(T_p)$.

(An & Papavassiliou, 2002) proposed an entropy based analytical model to evaluate the MANETs stability and availability. This model used the node mobility parameters, i.e. speeds and directions, and the concept of entropy to estimate the path availability and stability. They recommended using the above model as a stability routing metric to select the most stable path. In (Wu, Liao, Tsao & Lin, 2009), (Pascoe-Chalke, Gomez, Rangel & Lopez-Guerrero, 2010) and (Namuduri & Pendse, 2012), the link duration was considered as the major criterion to estimate the path stability. The link duration was mathematically calculated, and recommended as a routing metric to select the most stable path among the available paths in the above studies.

Alvi et al. (Alvi et al., 2016) proposed a novel MAC protocol based on Time Division Multiple Access (TDMA) protocol to be used in smart cities. This protocol was Bitmap-Assisted Efficient and Scalable TDMA-Based WSN MAC (BEST-MAC) protocol. It could be used as MAC layer protocol in order to increase the data reliability and the network throughput. It was specifically designed to be used in smart cities, where the data traffic was diverse, and the packets loss and delay were unacceptable. The use of small time slots, short node addresses, and knapsack algorithm to schedule time slots are the main characteristics of BEST-MAC protocol. The objective behind the use of small size time slots is to improve the link utilization by efficiently handling the adaptive data traffic in smart cities, while the use of short node addresses reduces the energy consumption by reducing overheads. Finally, the use of knapsack algorithm decreases the average packet delay by decreasing the processing time and improving the link utilization. The simulation results in (Alvi et al., 2016) prove that BEST-MAC protocol increases the network throughput, and decreases the transmission delay and energy consumption.

3.3 Ensuring reliable communications in MANETs with uniform random distribution

As we explained in chapter 2, to adapt with the frequent link failures in MANETS and WMNs, the routing protocols shall catch more than one route, at least two routes. In the case where two routes are used, we can use the first route as the main route, while the other route is a standby route which is used upon link failures. By allowing the routing protocols catch at least two routes, the packets loss is virtually decreased to zero on the one hand. On the other hand, seamless multimedia communications over MANETs and WMNs can be assumed.

3.3.1 Mathematical model analysis

The nodes density in MANETs and WMNs must be above a certain threshold for the existence of two routes between any randomly chosen source and destination pair with high probability. In this thesis, we provide a novel mathematical model to find this node density in terms of the number of node neighbors. In addition to that, we propose some solutions in case the node density is below the required density in order to increase the node density to the required one.

A MANET with M nodes that are uniformly distributed in a square area (A) with edge length equals to a is considered. All nodes have a circular transmission range with radius R. Two nodes are considered neighbors, and can communicate directly, if the distance between them is less the transmission range. The forwarding strategy used in this network is LRD greedy forwarding strategy. Finally, assume that the mobile nodes move according to random walk mobility model (Roy, 2011), which means that the nodes are always uniformly distributed over the network area.

A. Path availability

As it is known, the node density is equal to the number of nodes divided by the network area. Thus, in our case the node density is equal to M/A. Path availability is defined as the likelihood that at least one path exist between the Source node (S) and the Destination node

(D). To have at least one path between S and D, the source node and all forwarding nodes must have at least one neighbor node inside a half circle region in the direction of D with radius equals to R. For uniform distribution, the probability that a mobile node has n neighbors inside a specific region is well approximated by the Poisson distribution (Dung & An, 2013). Thus,

$$\mathrm{P(n)} = \frac{(\rho \mathrm{C})^{\mathrm{n}}}{\mathrm{n}!}\, \mathrm{e}^{-\rho \mathrm{C}} \tag{3.1}$$

Where:

$\mathrm{P(n)}$: the probability that a mobile node has n neighbors in the specified region.

ρ : node density.

C : half-circular area.

As was said before, we are more interested to have at least two routes between S and D in order to increase the network reliability. Based on that, the source node and the forwarding nodes must have at least two neighbors inside the half-circular region. Let us define ψ as the probability that the source node or the forwarding node has at least two one hop neighbors inside a half circle. This probability can be found by using equation 3.1 with n greater than or equals to 2, that is

$$\psi = \mathrm{p(n} \geq 2) = 1 - \mathrm{e}^{-\rho \mathrm{C}} - (\rho \mathrm{C})\mathrm{e}^{-\rho \mathrm{C}} \tag{3.2}$$

As we are dealing with MANETs or WMNs, usually the routing path between S and D consists of multi-hop. Let us denote by the number of hops as k. Because the source node and the forwarding nodes independently forward the packets, the probability that at least two routes exist between S and D ($\mathrm{P_k}$) is equal to ψ^{k}, then

$$\mathrm{P_k} = \psi^{\mathrm{k}} = (1 - \mathrm{e}^{-\rho \mathrm{C}} - (\rho \mathrm{C})\mathrm{e}^{-\rho \mathrm{C}})^{\mathrm{k}} \tag{3.3}$$

Where:
P_k : the probability that two k-hop routes exist between S and D.
k : number of hops.
ψ : the probability that the source node or the forwarding node has at least two neighbors.

All the parameters in equation 3.3 are known except the k parameter. Thus, a method to estimate the number of hops (k) must be used in order to find the probability that two k-hops routes exist between S and D. The method which has been proposed in (De, 2005) and (De et al., 2006) is adopted to estimate the number of hops in a uniformly distributed MANET, which implies LRD greedy forwarding strategy as the forwarding strategy to forwards the packets. According to the above greedy forwarding strategy, the source node forwards the packets to a neighbor node inside a half circular area of radius R, in the direction of destination, that has the least remaining distance to D. Note that, when we consider the above entire half circle, the remaining distance to D is not guaranteed to be less than the current distance between the forwarding node and node D. However, the probability of this event is low for networks that have high node density as it is proven in (De et al., 2006). The above highlight another advantage of our adaptive greedy forwarding strategy which has been proposed in chapter 2. This advantage is that by reducing the expected forwarding region from the half circle region to a smaller region, we eliminate or at least minimize the probability that the forwarding node selects a neighbor node that has remaining distance to D greater than the remaining distance to D from the forwarding node itself.

B. The expected number of hops

Here, the expected number of hops based on the technique presented in (De, 2005) and (De et al., 2006) is estimated. Assume as in (De, 2005) and (De et al., 2006) that the distance between S and D is l, P is the selected forwarder node, r is the distance between S and P, θ is the angle between the line connecting P and S and the line connecting S and D, and z is the remaining distance to D, see Figure 2.1. The uniform distribution is used to characterize the location of P in polar coordinates (r,θ), because the nodes are uniformly distributed in the network area. Since r and θ are independent Random Variables (RVs), their joint pdf ($f_{r\theta}(r,\theta)$) is equal to the multiplication of their pdf's. Thus, the joint pdf of the RV r θ (P) is

$$f_{r\theta}(r,\theta) = \begin{cases} \frac{2r}{\pi R^2}, & 0 \le r \le R \ and -\frac{\pi}{2} \le \theta \le \frac{\pi}{2} \\ 0, & otherwise \end{cases} \tag{3.4}$$

The joint pdf RVs transformation transforms the RV P from the polar coordinates (r, θ) to the Cartesian coordinates (x,y). By this transformation, the RV P joint pdf in terms of (x,y) is

$$f_{xy}(x,y) = \begin{cases} \frac{2}{\pi R^2}, & 0 \le x \le R, -R \le y \le R, and\ x^2 + y^2 \le R^2 \\ 0, & otherwise \end{cases} \tag{3.5}$$

Taken from De et al. (2006, p. 5)

Again by using RVs transformation, the pdf of the RV z, which is equal to $\sqrt{(l-x)^2 + y^2}$, is

$$f_z(z) = \begin{cases} \frac{4z}{\pi R^2}[\frac{\pi}{2} - \arcsin\left(\frac{l^2 + z^2 - R^2}{2lz}\right), l - R \le z \le l \\ \frac{4z}{\pi R^2}\left[\arcsin\left(\frac{l}{z}\right) - \arcsin\left(\frac{l^2 + z^2 - R^2}{2lz}\right)\right], l \le z \le \sqrt{l^2 + R^2} \\ 0, otherwise \end{cases} \tag{3.6}$$

Taken from De et al. (2006, p. 5)

The number of potential forwarding nodes (n) must be known in order to find the minimum remaining distance to D. Since the nodes are uniformly distributed in the network area, n is equal to the node density (ρ) multiplied by the expected forwarding area ($\frac{\rho\pi R^2}{2}$), the shaded region in Figure 2.1. Assume the remaining distances to D are z_1, z_2, ..., z_n, and δ is the least remaining distance to D. Based on that, $\delta = \min(z_1, z_2, ..., z_N)$. Equation 3.7 gives us the δ pdf distribution.

$$
f_{\delta}(\delta) = \begin{cases} n\left(\frac{2}{\pi R^2}\right)^n 2\delta\left[\frac{\pi}{2} - \arcsin\left(\frac{\delta^2 + l^2 - R^2}{2l\delta}\right)\right]\left[\begin{matrix} \delta^2 \arcsin\left(\frac{\delta^2 + l^2 - R^2}{2l\delta}\right) \\ + \frac{1}{2}\sqrt{4R^2 l^2 - (\delta^2 - l^2 - R^2)^2} - R^2 \arcsin\left(\frac{(\delta^2 - l^2 - R^2)}{2lr}\right) - \frac{\pi\delta^2}{2} \end{matrix}\right]^{n-1} & , l - R \le \delta \le l \\ n\left(\frac{2}{\pi R^2}\right)^n 2\delta\left[\arcsin\left(\frac{1}{\delta}\right) - \arcsin\left(\frac{\delta^2 + l^2 - R^2}{2l\delta}\right)\right]\left[\begin{matrix} \delta^2 \arcsin\left(\frac{\delta^2 + l^2 - R^2}{2l\delta}\right) \\ + \frac{1}{2}\sqrt{4R^2 l^2 - (\delta^2 - l^2 - R^2)^2} - \\ R^2 \arcsin\left(\frac{\delta^2 - l^2 - R^2}{2lR}\right) - \delta^2 \arcsin\left(\frac{1}{\delta}\right) - l\sqrt{\delta^2 - l^2} \end{matrix}\right]^{n-1} & , l \le \delta \le \sqrt{l^2 + R^2} \\ 0 & , \quad \text{otherwise} \end{cases} \tag{3.7}
$$

Taken from De et al. (2006, p. 6)

Let us denote ε as the maximum forward progress per hop ($l - \delta$). Thus, the pdf of ε is given by $f_{\varepsilon} = f_{\delta}(l - \varepsilon)$. Substitute $f_{\delta}(\delta)$ from equation 2.7 into the above equation, we get the pdf of ε, that is

$$
f_{\varepsilon}(\varepsilon) = \begin{cases} n\left(\frac{2}{\pi R^2}\right)^n 2(l - \varepsilon)\left[\frac{\pi}{2} - \arcsin\left(1 + \frac{\varepsilon^2 - R^2}{2l(l - \varepsilon)}\right)\right]\left[\begin{matrix} (l - \varepsilon)^2 \arcsin\left(1 + \frac{\varepsilon^2 - R^2}{2l(l - \varepsilon)}\right) \\ + \frac{1}{2}\sqrt{4R^2 l^2 - (\varepsilon^2 - R^2 - 2l\varepsilon)^2} - R^2 \arcsin\left(\frac{(\varepsilon^2 - R^2 - 2l\varepsilon)}{2lR}\right) - \frac{\pi(l - \varepsilon)^2}{2} \end{matrix}\right]^{n-1} & , R \ge \varepsilon \ge 0 \\ n\left(\frac{2}{\pi R^2}\right)^n 2(l - \varepsilon)\left[\arcsin\left(\frac{l}{l - \varepsilon}\right) - \arcsin\left(1 + \frac{\varepsilon^2 - R^2}{2l(l - \varepsilon)}\right)\right]\left[\begin{matrix} (1 - \varepsilon)^2 \arcsin\left(1 + \frac{\varepsilon^2 - R^2}{2l(l - \varepsilon)}\right) \\ + \frac{1}{2}\sqrt{4R^2 l^2 - (\varepsilon^2 - R^2 - 2l\varepsilon)^2} - \\ R^2 \arcsin\left(\frac{\varepsilon^2 - R^2 - 2l\varepsilon}{2lR}\right) - (l - \varepsilon)^2 \arcsin\left(\frac{1}{1 - \varepsilon}\right) \\ -l\sqrt{\varepsilon^2 - 2l\varepsilon} \end{matrix}\right]^{n-1} & , 0 \ge \varepsilon \ge l - \sqrt{l^2 + R^2} \\ 0 & , \quad \text{otherwise} \end{cases} \tag{3.8}
$$

Taken from De et al. (2006, p. 6)

By default, the average of ε ($\overline{\varepsilon}$) which gives the average progress per one hop is

$$
\overline{\varepsilon} = \int_{l - \sqrt{l^2 + R^2}}^{R} t f_{\varepsilon}(t) dt \tag{3.9}
$$

Taken from De et al. (2006, p. 6)

The expected progress per hop ($\bar{\varepsilon}$) is almost independent of l and dependent on ρ and R only were proven in (De, 2005) and (De et al., 2006). Based on that, an approximation approach to find the average number of hops ($\bar{h}$), which greatly reduce the complexity of the exact approach, was proposed in (De, 2005) and (De et al., 2006). The approximation approach works as follows: at first $\bar{\varepsilon}$ is calculated based on equation 3.9, then to obtain the expected number of hops ($\bar{h}$), we divide the distance between S and D (l) over $\bar{\varepsilon}$ as shown in the following equation:

$$\bar{h} = \frac{l}{\bar{\varepsilon}} \tag{3.10}$$

Taken from De et al. (2006, p. 9)

Now, the probability that two k-hops routes exist between S and D (P_k) can be found by replacing the k parameter in equation 3.3 with the $\bar{h}$ parameter obtained from equation 3.10, that is

$$P_k = (1 - e^{-\rho C} - (\rho C)e^{-\rho C})^{\bar{h}} \tag{3.11}$$

3.3.2 Evaluation

Assume we have a MANET, where the network nodes are uniformly distributed in the network area. The network area is a square area with edge length (a) equals to 1000m. The transmission range (R) for all nodes is fixed at 100m. Our objective here is to find the node density in terms of the number of neighbors which is required to have two paths between any randomly chosen source and destination pair with high probability.

At first, we study the pdf of the per one hop progress (ε), which is shown in equation 3.8 and plotted in Figure 3.1. It can be seen in this Figure that the per one hop progress toward the destination is more likely to be close to R. To see how the node density in terms of the average number of neighbors affects ε average ($\bar{\varepsilon}$), we plot the relationship between $\bar{\varepsilon}$ and n in Figure 3.2.

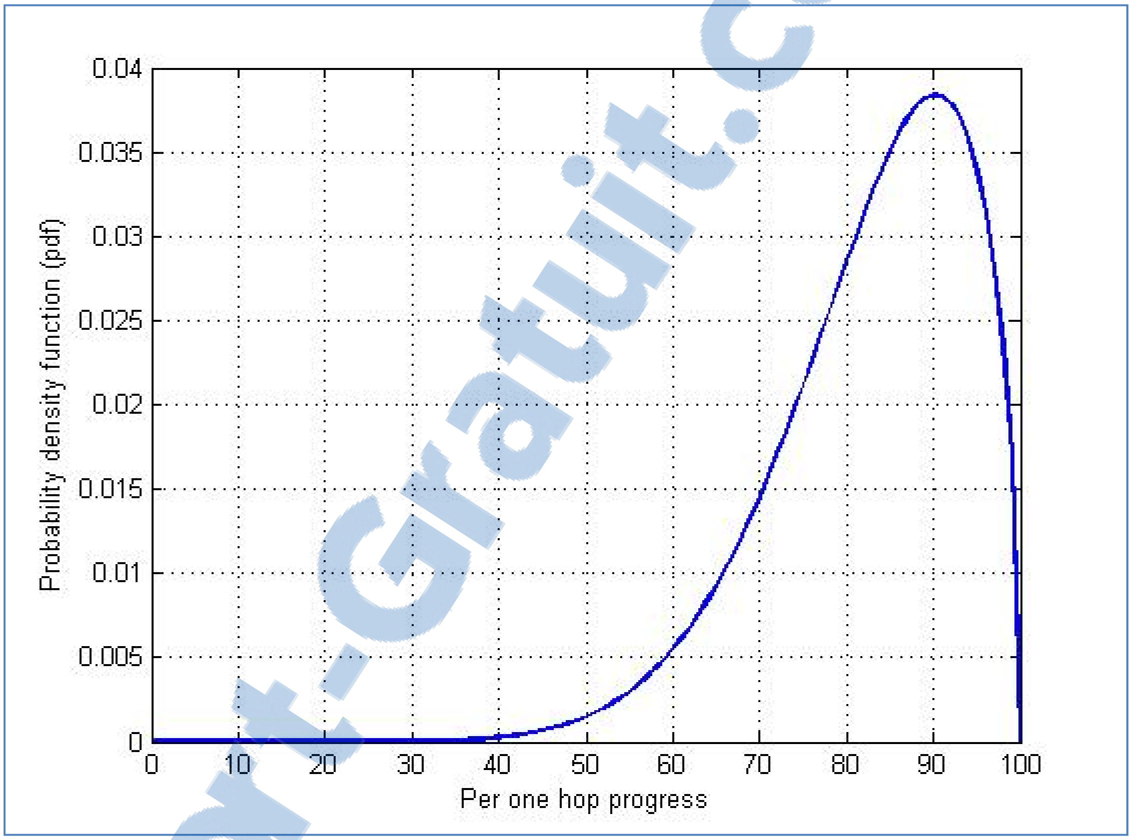

Figure 3.1 Probability density function of the per one hop progress at n = 10, R = 100m and a = 1000m

$\bar{\varepsilon}$ exponentially increases, when n increases from zero to 8, after that $\bar{\varepsilon}$ increases slowly with n, as shown in Figure 3.2. When n is small (n<8), the increase in n rapidly increases the probability of finding a forwarding node that is closer to the destination, in other words, larger $\bar{\varepsilon}$, after that $\bar{\varepsilon}$ approaches the saturation region. One may ask this question, why $\bar{\varepsilon}$ does not approach R even for high node density. This is due to the LRD optimization criterion to select the forwarding node, which chooses a neighbor node that has the minimum remaining distance to the destination node and not the maximum per one hop progress as it is the case in MHD greedy forwarding strategy.

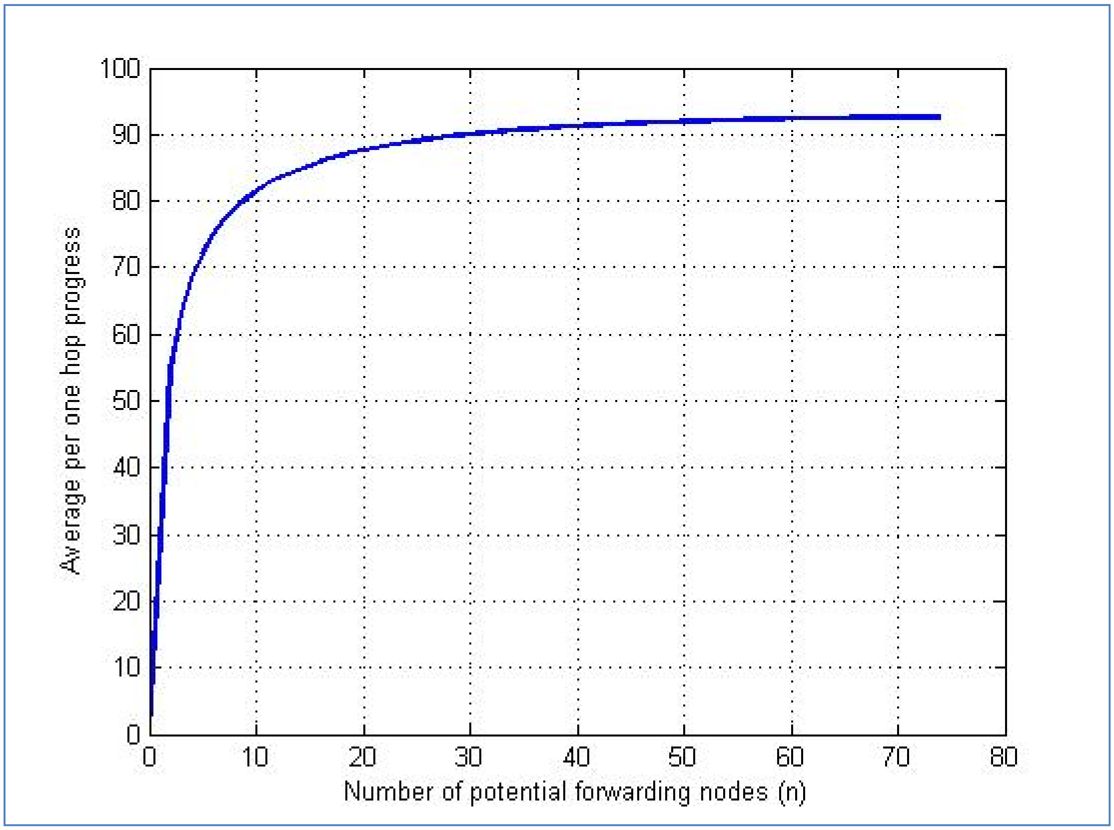

Figure 3.2 The relationship between the average per one hop progress ($\overline{\varepsilon}$) and the number of potential forwarding nodes (n) at R = 100m

Now let us turn our attention to our main objective from this analysis that is the required node density, in terms of the number of neighbors, which ensures the existence of two routes between any randomly chosen Source node (S) and Destination node (D). The probability that two k-hop routes exist between S and D (P_k) versus n is given in equation 3.11 and it is plotted in Figure 3.3. This Figure shows that P_k exponentially increases with n till it reaches the saturation region, where the increase in n brings negligible improvements in terms of two routes connectivity and may cause degradation to the network performance due to the more interference it may add to the network. As shown in Figure 3.3, the two routes connectivity is almost ensured when n equals to 8.

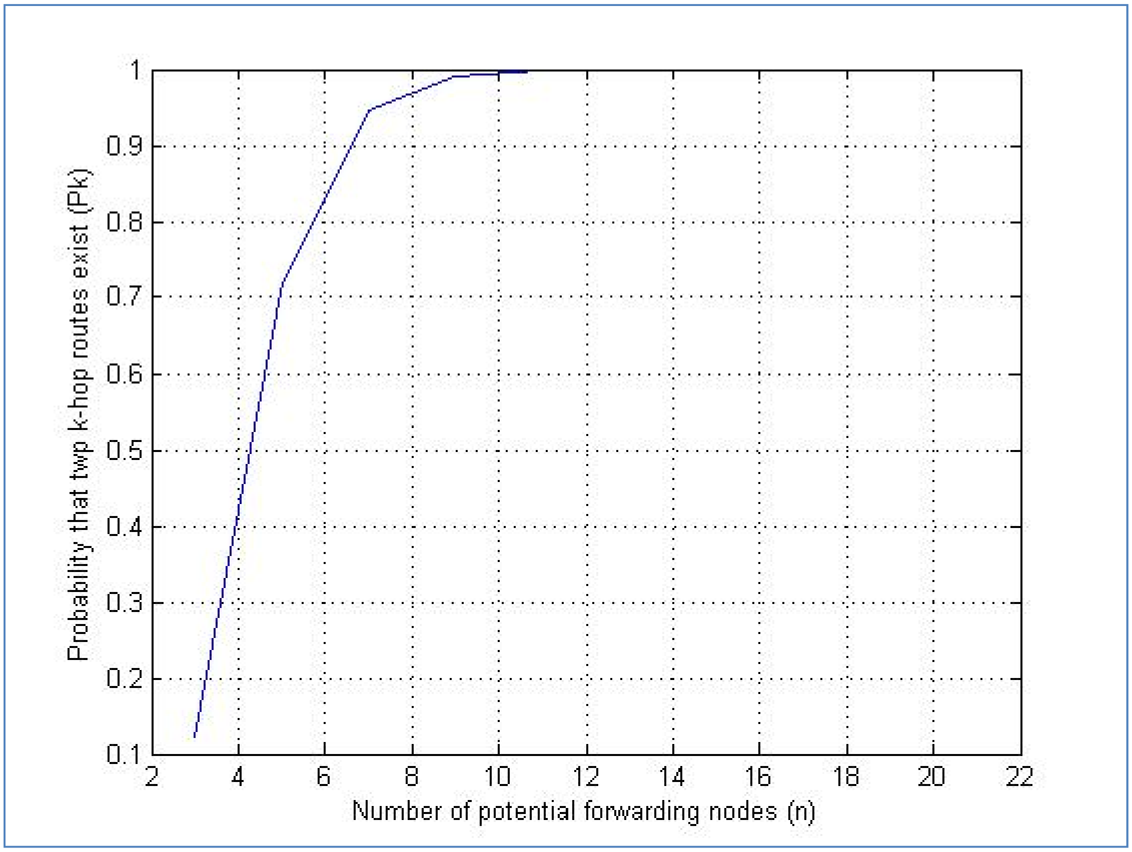

Figure 3.3 The probability that two k-hop routes exist between S and D versus the number of potential forwarding nodes (n)

It was proven early in this thesis, section 2.2, and in (Takagi & Kleinrock, 1984) that the magic number 8, i.e. n is equal to 4, is the required number of neighbors to ensure the existence of one route between any randomly chosen S and D pair. Here, we provides a novel magic number which is n equals to 8 that ensures the existence of two routes between any randomly chosen S and D pair. This magic number can encourage the MANETs and WMNs designers to take the two routes connectivity issue more seriously, when they design their networks due to the huge improvement it bring to the network performance (Hayajna & Kadoch, 2017b), (Moussaoui & Boukeream, 2015) and (Hayajna & Kadoch, 2016).

Even though we cannot force people to use the network or to give their permissions to use their devices to relay the network traffic in order to increase the node density to the required density, we still can somehow increase the node density. This thesis proposes two approaches that can be used to increase the node density to the required node density that ensures the two routes connectivity. The first approach is to add extra fixed nodes, i.e. wireless mesh routers, to the network. In this case, the MANET is turn into WMN. This can be easily done with little effort and cost due to the ease of implementation of the mesh routers and their relatively affordable cost. The implementation of wireless mesh routers costs less, because their prices are relatively low, and do not require wires to connect them to the network. Another advantage of this approach is its adaptability to the network requirements, where we can easily add or remove the wireless mesh routers (turn them off), or even change their positions. In addition, we can control the network node density by adjusting the wireless mesh routers' transmission range. The other approach is to encourage people to use the network, or give us the permission to use their devices to relay the network traffic by giving them some incentives.

3.4 The random waypoint mobility model

Node mobility in MANETs and WMNs makes their analysis more challengeable compared to other kinds of networks. To analyse the performance of MANETs and WMNs, nodes mobility models are required. The most used mobility model in the literature is Random WayPoint mobility model (RWP) (Bettstetter, Resta & Santi, 2003). In RWP, each network node chooses a random destination point uniformly. After that, the node moves to the selected destination at a speed, which is chosen uniformly from the interval $[v_{min}, v_{max}]$ (Bettstetter et al., 2003). Then, the network node pauses for a predefined pause time, before move again and repeat the same steps. It is well known that the nodes moving according to the RWP have non-uniform spatial distribution regardless of their initial spatial distribution (Bettstetter et al., 2003) and (Bettstetter & Wagner, 2002).

Even though the RWP mobility model is the most used mobility model, it has some problems as shown below. Firstly, most theoretical results regarding routing, capacity, connectivity and power saving assumes uniform node distribution. Thus, the above results cannot be directly applied to the networks where the nodes are moving according to the RWP mobility model due to its non-uniform node distribution (Bettstetter et al., 2003). Secondly, the initial uniform distribution and the short term behaviour of the RWP model are not like the actual long term behaviour, i.e. the steady state distribution, (Bettstetter et al., 2003). Based on that, many studies' simulation results available in literature that assume the nodes are moving according to RWP mobility model could be inaccurate, because they take their results after a few simulation steps (Bettstetter et al., 2003). Third, RWP mobility model has the border effect. This effect happens, because the network nodes tend to cross the middle of the network area with relatively high frequency compared to other areas (Bettstetter et al., 2003). The node distribution converges towards asymptotically stationary distribution with the maximum node density in the middle of the network area (Bettstetter et al., 2003). Finally, the nodes' average speed decreases with time and converges to a value that is less than the initial average speed, i.e. $\frac{v_{min}+v_{max}}{2}$, where v_{min} is the minimum initial speed, v_{max} is the maximum initial speed and $v_{min} \neq v_{max}$ (Bettstetter et al., 2003) and (Yoon, Liu & Noble, 2003). In addition to that, if v_{min} is equal to zero, as it is done in many studies, the average speed will be close to zero. In other words, the mobile nodes will converge to almost static nodes.

(Bettstetter et al., 2003) proposed the generalized RWP mobility model in order to overcome the above mentioned problems associated with traditional RWP mobility model. The pause time of the mobile nodes moving according to the generalized RWP mobility model is not fixed, as it is the case in the traditional RWP mobility model, and it is randomly chosen from a specified pdf. While in the traditional RWP mobility model all nodes must be mobile, in generalized RWP mobility model, some nodes are allowed to be static with specific probability from 0 to 1. To overcome the pitfall that arises when the minimum speed is equal to zero, i.e. the mobile nodes converge to static nodes, in the traditional RWP mobility model; the minimum speed in generalized RWP mobility model must be greater than zero. The purpose of putting the minimum speed (v_{min}) equals to zero in the traditional RWP mobility model is to let some nodes remain static. The generalized RWP mobility model achieves the above purpose without letting all the system converges to static system by letting some nodes actually remain static during the whole simulation duration (Bettstetter et al., 2003).

3.5 Ensuring two routes connectivity with random waypoint mobility model

We have provided in section 3.3 a probabilistic model to find the required node density to ensure the existence of two routes between any randomly chosen source and destination pair in a MANET with uniformly distributed nodes. Based on that model, we found that the number of neighbors for each node must be above 16, i.e n=8, in order to ensure the existence of two routes. The assumption in the previous section that the network nodes are uniformly distributed does not apply for all mobility models. For example, RWP mobility model has non-uniform node distribution, even when the nodes are initially uniformly distributed in the network area. This motivates us to study the case where the nodes are non-uniformly distributed in the network area. To the best of our knowledge, this thesis is the first study that mathematically determines the required node density, in terms of the number of neighbors that is required to ensure the two routes connectivity where the nodes are uniformly distributed in the network area or moving according to the RWP mobility model.

(Younes & Thomas, 2011) was the first study that mathematically estimated the hop count in mobile ad hoc network where the nodes are moving according to the generalized RWP mobility model. The greedy forwarding strategy used in that study to estimate the hop count was MHD. In the following, we rely on the analysis provided in (Younes & Thomas, 2011) to mathematically estimate the required node density in order to ensure the existence of two routes between any randomly chosen source and destination pair in MANETs where the nodes are moving according to the generalized RWP mobility model. To this end, a complete probabilistic model is proposed. We also compare MHD and LRD routing criterions' potentials to choose the shortest route.

3.5.1 The hop count

The hop count has direct impact on packet delivery ratio, per hop and end to end delay, flooding cost, network traffic load estimation, and network connectivity in MANETs (Younes & Thomas, 2011). The hop count depends on the used greedy forwarding strategy in the topology based routing protocols. (De, 2005) and (De et al., 2006) proposed an approach to estimate the hop count in mobile ad hoc networks where the nodes are uniformly distributed in the network area. The main drawback of the above approach is that it applies only for networks where the nodes are uniformly distributed in the network area. Thus, we need another approach to calculate the hop count for networks where the nodes are non-uniformly distributed. Younes and Thomas (Younes & Thomas, 2011) propose such approach to calculate the hop count for networks where the nodes are moving according to the generalized RWP mobility models, i.e. the nodes are non-uniformly distributed in the network area.

3.5.2 Mathematical analysis

To the best of our knowledge, this thesis is the first study that mathematically analyzes the two routes connectivity issue in MANETS where the nodes are moving according to the generalized RWP mobility model. Our main objective from this study is to mathematically calculate the required average number of neighbors to ensure the two routes connectivity between the network nodes. The probability that a route existence between any randomly chosen Source node (S) and Destination node (D) depends on the Euclidean distance between S and D and the hop count, in addition to node density. For the calculation of the Euclidean distance and the hop count, we use the approach presented in (Younes & Thomas, 2011).

In this analysis, we assume A MANET with square area with side length equal to L. MHD greedy forwarding strategy is the used forwarding strategy. The transmission range is a circular transmission range with radius equals to R, and it is the same for all nodes. Two nodes are considers neighbors if the distance between them is less than R.

A. The Euclidean distance between the source node and the destination node

Since the node movements are not known, a probabilistic model is needed in order to estimate the expected Euclidean distance between any randomly chosen S and D pair. (Younes & Thomas, 2011) calculates the expected Euclidean distance (d) between any two randomly chosen nodes moving according to the generalized RWP mobility model in a square network area with side length equals to L as

$$d = 0.4 * L \tag{3.12}$$

Taken from Younes & Thomas (2011, p. 149)

B. Per One Hop Progress

The number of hops (HC) between S and D depends on the Euclidean distance between them, per one hop progress, and the used forwarding strategy. The objective in MHD greedy forwarding strategy is to minimize the hop count by choosing a neighbor node in the direction of destination, which has the maximum distance to S as the rely node, i.e. has the maximum per one hop progress. The pdf of the maximum Euclidean distance between the node S and its neighbors (Ω), and the expected value of Ω (rr) are found by using equations (3.13) and (3.14), respectively.

$$f_{\Omega} = (2n) * \frac{\Omega^{2n-1}}{R^{2n}} \tag{3.13}$$

Taken from Younes & Thomas (2011, p. 152)

$$rr = \frac{2n}{2n+1} R \tag{3.14}$$

Taken from Younes & Thomas (2011, p. 152)

C. The remaining distance to the destination

Assume the relay node is located at a point on the circumference of a half circle in the direction of D with radius equals to Ω and random angle ∂ (Younes & Thomas, 2011). Since a half circle is considered, ∂ can be any value in the range of [-π/2 , π/2]. ∂ is a uniform random variable with pdf equals to 1/π. From the pdf of ∂, and the relationship between Ω, the Euclidean distance between S or the forwarding node and D and the reaming distance to D, we can find the pdf of the remaining distance to D (X) as

$$f_X(X) = \frac{2X}{\pi dr * \sqrt{1 - \left(\frac{d^2 + rr^2 - X^2}{2dr}\right)^2}} \tag{3.15}$$

Taken from Younes & Thomas (2011, p. 153)

Where:

X : the remaining distance to D.

d : the Euclidean distance between S or the forwarding node and D.

rr : per one hop progress.

The expected value of X ($\overline{X}$) is equal to

$$\overline{X} = \int_{d-rr}^{\sqrt{d^2+rr^2}} X f_x(x) dx \tag{3.16}$$

Taken from Younes & Thomas (2011, p. 153)

D. The expected hop count

An iterative procedure is introduced in (Younes & Thomas, 2011) in order to calculate the expected Hop Count (HC) .This procedure can be summarized as follows: At the beginning, S calculates the Euclidean distance to D. If this distance is less than R, then D is one of S neighbors and HC is equal to 1, otherwise S choose a relay node among its neighbors according to MHD greedy forwarding strategy to forward the packets to it. After that, the selected relay node calculates the per hop progress (rr) and the remaining distance to D ($\overline{X}$). In case $\overline{X}$ is less than R, then D is one neighbor of that relay node, and HC is equal to 2. If $\overline{X}$ is greater than R, the same steps are repeated till $\overline{X}$ falls below R, and each time HC is incremented by 1.

E. Two routes connectivity

Here, we find the node density which is required to ensure two routes connectivity between any randomly chosen source node and destination node pair. The Poisson distribution can be used to approximately estimate the probability that a mobile node has n neighbors inside a specific area (Dung & An, 2013), in our case it is a half-circular area with radius equals to R.

As explained before, to ensure the existence of two routes between S and D, the node S and all the forwarding nodes must have at least two neighbors inside a half-circular area with radius R in the direction of D, i.e. $n \geq 2$. Since S and each forwarding node independently forward the packets to a relay node until D is reached, the probability that two routes exist between S and D (P_k) is equal to $(P(n \geq 2))^{HC}$. The following equation calculates P_k:

$$P_k = (1 - e^{-\rho C} - \rho C e^{-\rho C})^{HC} \tag{3.17}$$

3.5.3 Evaluation

Consider a square area mobile ad hoc network with side length (L) equals to 1000m. The network nodes are mobile nodes moving according to the generalized RWP mobility model proposed in (Bettstetter et al., 2003). All nodes have the same transmission range (R), and follow the MHD greedy forwarding strategy.

Firstly, we study the relationship between the expected per hop progress (rr) and the node density (n), and compare rr in both MHD and LRD greedy forwarding strategies. For MHD greedy forwarding strategy, rr is calculated based on equation 3.14, while equation 3.9 calculates rr for the LRD greedy forwarding strategy. Figure 3.4 shows the relationship between the expected per hop progress in both MHD and LRD versus n based on the above two equations. We can clearly see in Figure 3.4 that rr in both MHD and LRD exponentially increases with n till it reaches the saturation region. It also shows that rr approaches R when n is high enough in MHD; in contrast to LRD where rr does not approach R, no matter how big n is. This is due to the different optimization criterions used in MHD and LRD. MHD greedy forwarding strategy tries to optimize rr, while LRD greedy forwarding strategy tries to optimize the remaining distance to D.

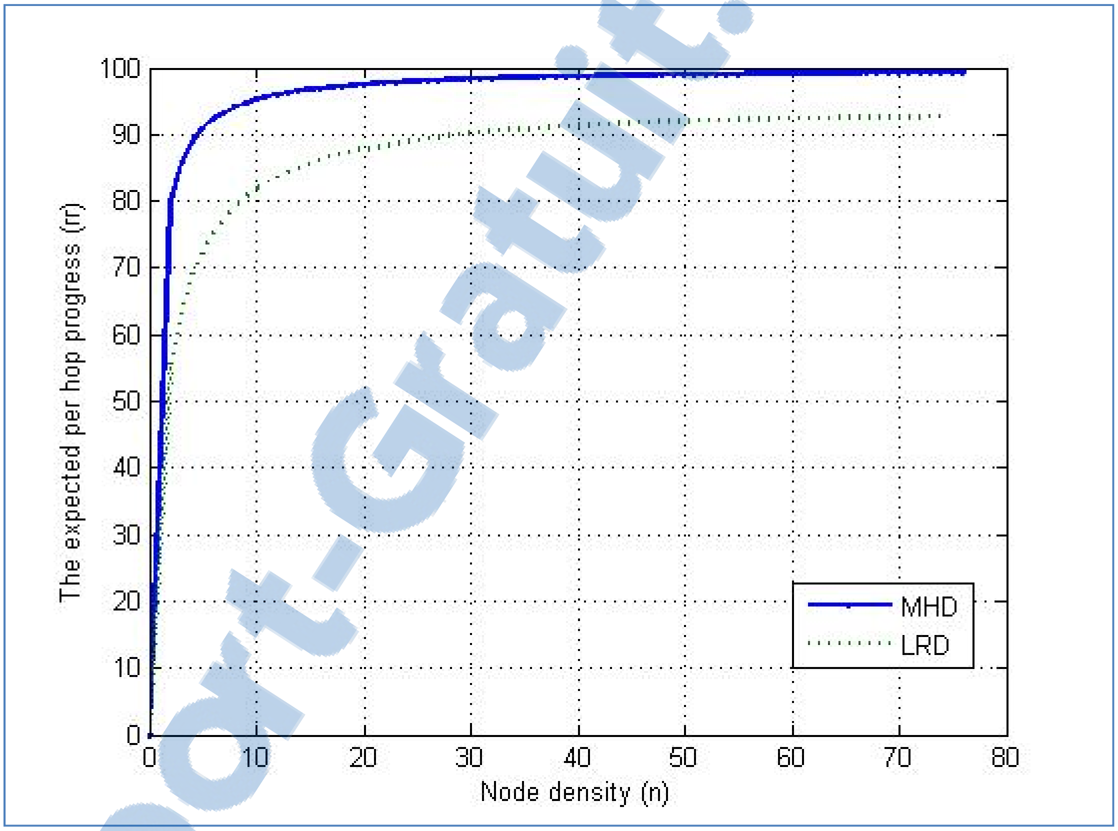

Figure 3.4 The average per one hop progress vs. the node density (n)
at R = 100m and L = 1000m for both MHD and LRD

To see which optimization criterion is better in terms of reducing the hop count, we plot the relationship between the hop count in MHD and LRD versus the node density in Figure 3.5. Actually the one that has the potential to decrease the hop count is better, because this increases the network connectivity, the packet delivery ratio, especially for less reliable networks where the link failures occur more frequently, and decreases the end to end delay and the network interference. Strangely, Figure 3.5 shows that the hop count in MHD does not depend on the node density (n). Even though for low density, MHD potentially decreases the hop count compared to LRD, but at moderate and high node density LRD performs better than MHD. This is due to the fact that MHD increases the per hop progress (rr) for each step, but the optimization criterion to select the shortest path based on rr optimization criterion fails to select the shortest path with moderate and high node density, as illustrated below. When the node density (n) increase, rr also increases. However, rr shall be located in the line connecting S and D in order to reduce the hop count. The probability of the above event is low and there is same probability that rr be perpendicular to the line connecting S and D and in this case the remaining distance is higher than the original distance between S and D. In other words, the bad location selection of the chosen relay node cancels the enhancement achieved by increasing the per one hop progress (rr).

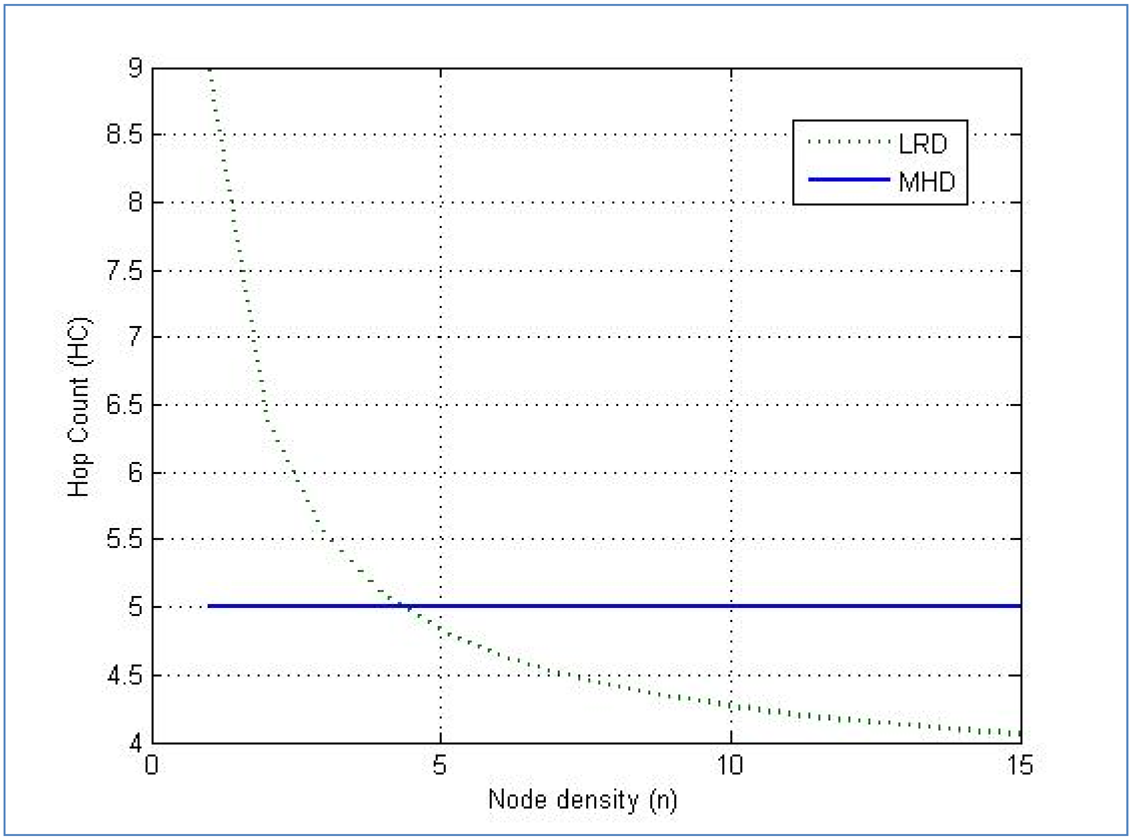

Figure 3.5 The relationship between the hop count and the node density (n)
at R = 150m and L = 1000m for both MHD and LRD

Finally, we investigate the effects of node density on the network connectivity. The relationship between the probability that two k-hop routes exist between S and D (P_k) with node density (n) is calculated based on equation 3.17 and it is plotted in Figure 3.6. As it is shown in this figure, P_k is exponentially increased with n until it reaches the saturation region, where the increase in the node density brings negligible improvement in terms of network connectivity. When n ≥ 8 almost two routes connectivity is achieved, as shown in Figure 3.6. In the previous section, we have found that the same node density (n≥ 8) ensures the existence of two routes in MANETs where the nodes are uniformly distributed in the network area. The above highlights a novel and an important conclusion that the generalized RWP mobility model has negligible effect in terms of the required node density to ensure two routes connectivity.

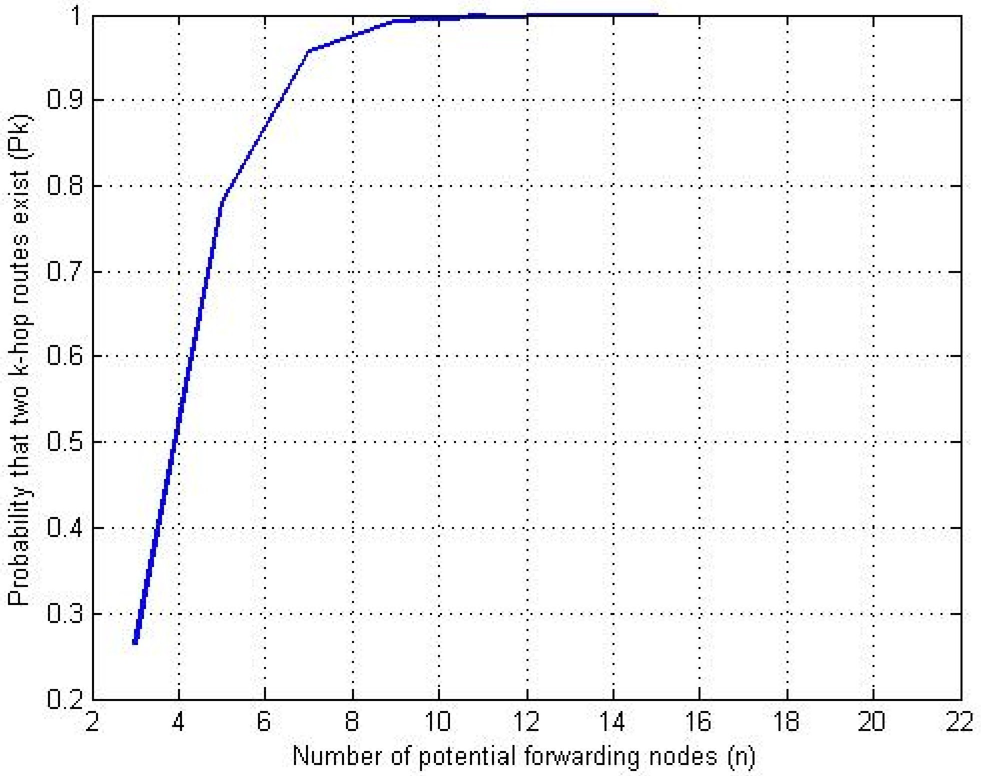

Figure 3.6 The probability that two k-hop routes exist between S and D vs. the number of potential forwarding nodes

CONCLUSION

Mobile Ad hoc NETwork (MANET) is a kind of multi-hop communication networks that is formed on the fly without the need of any kind of infrastructure. All client nodes in MANETs can operate as a host and a router at the same time, and can randomly move without any restrictions. The above characteristics make MANETS an ideal candidate to extend the cellular networks coverage, to recover from disasters, and to use them as communication networks among soldiers in the battlefield or among researchers during the conference.

On the other hand, WMN is a promising wireless technology to resolve the limitations and to improve the performance of ad hoc networks. In addition, it provides effective solutions to broadband internet access, community, small business and neighborhood networks, and industrial and building automation. WMNs have the capability to accommodate multiple radios and multiple channels in order to solve the capacity issue associated with the use of single radio and single channel. Due to its importance, industrial standards group IEEE proposed a new standardized framework, IEEE 802.11s, for WMNs in September 2011.

Link failures in WMNs and MANETs occur more frequently compared to wired communications, because of node mobility, dynamic obstacles, limited energy resources, fading, and spectrum allocations etiquette or regulations, in addition to unreserved bandwidth. These frequent failures interrupt the communications till they are fixed, and make WMNs and MANETs less reliable compared to other kinds of communication networks. Based on that, link failures detections and recoveries are important issues to investigate.

The first step to solve the link failures' problem and mitigate their impacts in WMNs and MANETs, is the link failure detections. The two main link failure detections approaches are link cross layer feedback approach and Hello based link failure detection approach. Even though the link cross layer feedback approach detects link failure faster than Hello based link failure detection approach, the later is the most used, because it is easier to implement it in the routing protocols by avoiding interlayer interaction complexity, it is link layer independent, and it requires less memory and power resources. For that reason we have concentrated in our thesis on Hello based link failure detections approach.

The Hello beacon interval (T_B) and the number of messing Hello beacons (K) are the two parameters that determine the link failure detection delay. Transient and permanent transmission errors are the two kinds of transmission errors. Non permanent interference and congestion cause transient transmission errors, while link failures cause permanent transmission errors. The cost of compensating permanent transmission errors is much higher than the cost of compensating permanent transmission errors. This is because retransmissions in the MAC layer compensate transient transmission errors; while finding and using a new path in the routing layer compensate permanent transmission errors. Based on that, it is a crucial issue to misinterpret the transient transmission errors as permanent transmission errors, and therefore, the used communication link is declared as a failed link. The incorrect declaration that the link has failed interrupts the communication till the routing protocol find an alternative route, which consumes a considerable bandwidth and power resources, congests the networks with route request messages, and causes a significant delay till another route is found. The routing protocols play a crucial role in both link failure detections and fixing these failures. Thus, the routing protocols must be carefully designed to effectively manage the link failures.

We showed in our thesis that fast and accurate link failure detections play a crucial role in maintaining WMNs and MANETs performance and increasing the packet delivery ratio. In this thesis, we analyzed Hello based link failure detection approach deployed in WMNs routing protocols that catch two routes, the primary route and the backup route. The objectives behind this analysis were to mathematically calculate the packet delivery ratio (pdr), and to find how much gain we could achieve by using two routes instead of one. The results showed an improvement of pdr of roughly 1.5 times for all sending rates. We also investigated the effect of the other parameters that affects the pdr, like link failure rate (r_{LF}). Our thesis showed that the Hello based link failure detection approach worked well in WMNs with low and medium link failure rates, and failed to work in WMNs with very high link failure rates. This conclusion opened up a new research direction, which was the investigation of other link failure detection approaches that are more suitable for WMNs and MANETs with higher link failure rates. We also showed that applying two routes was essential to cover high link failure rate values, and the need using two routes instead of one was more urgent in WMNs with higher link failure rate values, i.e. less reliable networks.

Another issue we investigated in this thesis was how we could support multimedia communications in WMNs. To this end, we provided a complete and a novel framework that could be used as a guideline to choose the proper K and T_B values based on the communications types and their QoS requirements. We showed that the use of two routes and dynamically assigning the values of K and T_B parameters based on the QoS requirements were required to support multimedia communications in WMNs and MANETs. In addition to that, we proposed a novel protocol to enhance Hello based link failure detection approach.

The routing process in MANETs is a challengeable task, because of the random movements of MANET nodes. This is because the nodes' random movements cause the network topology to change frequently, thus leading to frequent link failures. MANETs routing protocol must catch more than one route, and select the most stable routes among the available routes in order to make MANETs more resilience to the frequent link failures, to provide reliable and stable communications, and to support multimedia communications.

Position-based routing protocols eliminate some of the topology-based routing protocols' limitations, handle better the dynamic behaviour of MANET, and are more scalable. Based on that, position-based routing protocols are more suitable to MANETs than topology-based routing protocols. Three strategies are used for packets forwarding in position-based routing protocols, which are greedy packet forwarding, restricted directional flooding, and hierarchical routing. The most used strategy is greedy packet forwarding, because it is simple and scalable. The above strategy forwards the packets to only one neighbor in the direction of destination.

A novel adaptive greedy forwarding strategy was proposed in this thesis. Unlike other greedy forwarding strategies, the forwarding region in the proposed strategy is not fixed and its size is adaptive to the network node density. The above is because the connectivity of the network depends on the node density. The objective of this strategy is to determine the forwarding region size, which ensures one-way connectivity or two-ways connectivity. It was mathematically shown in this thesis that the relationships between the forwarding region size and both the node density and the transmission range are inverse relationships. It was also shown that at moderate node density, it is sufficient to use much lower forwarding region size compared to the sizes used in the literature to achieve one-way connectivity and two-ways connectivity. For example, at node density equals to 0.001 m^{-2} and transmission ranges that are greater than 100 m, the forwarding region sizes can be reduced by a factor of 5.24 and 3.34 for the one-way connectivity and the two-ways connectivity, respectively, compared to the sizes usually used in literature.

MANETs are less reliable compared to other kind of telecommunication networks, because of its lack of infrastructure and the random movements of nodes. Network node density determines if the network is connected or not. In other words, the node density must be above a certain threshold in order to ensure the network is connected, either one-way connected or two-ways connected. This thesis proposed a probabilistic model to find such node density in MANETs where the nodes are static with uniformly distributed or mobile with RWP mobility model. In addition to that, we proposed some methods to increase the network node density in case it is lower than the required node density. We proved in this thesis that the node density must not be less than 8 ($n \geq 8$) in order to ensure two-ways connectivity. Besides that it was shown that the probability of the network is two-ways connected exponentially increases with the node density till it reaches the saturation region where the increase of node density has negligible improvements in terms of network connectivity, and may has drawbacks by the additional interference they add to the network.

RECOMMENDATIONS

Fast and accurate link failure detections play a crucial role in maintaining WMNs and MANETs performance and increasing the packet delivery ratio. The two major link failure detection approaches are link layer feedback and Hello based link failure detection. Even though the cross-layer using link layer feedback is faster in detecting link failures, Hello based link failure detection approach is the most used approach. The above is because that the link layer feedback approach frequently misinterprets transient transmission errors as permanent transmission errors, and Hello based link failure detection approach is easier to implement in MANETs and WMNs routing protocols, is link layer independent, and requires less memory and power resources. Based on that, we recommend the use of Hello based link failure detection approach to detect link failures.

The use of fixed values of K and T_B as it is the case in traditional routing protocols does not optimize the network performance in terms of packet delivery ratio, average end to end delay and overhead. The Hello based link failure detection approach works well in WMNs with low and medium link failure rates, and failed to work in WMNs with very high link failure rates. This opens a new research direction, which is the proposing of a novel failure detection approach that is suitable for WMNs and MANETs with higher link failure rates. Another direction is the investigation of node mobility in the performance of Hello based link failure detection approach.

This thesis proves that the use of two routes instead of one roughly increases the packet delivery ratio by 1.5 times for the most sending rates. This increase allows WMNs and MANETs support multimedia communications. It also shows that the need using two routes instead of one is more urgent in WMNs and MANETs with higher link failure rates, i.e. less reliable networks, in order to cover the frequent link failures. Thus, we recommend the use of multi-route, at least two routes, and dynamically assigning the values of K and T_B parameters based on the QoS requirements in order to support multimedia communications over WMNs and MANETs and increase the network reliability.

The node mobility in MANETs causes the network topology to frequently change, and causes frequent link failures. This makes the routing process in MANET a challengeable task and their network reliability lower than other kind of telecommunication networks. We recommend that MANETs routing protocols catch at least two routes, and select the most stable routes among the available routes in order to make them more resilience to the changing network topology and the frequent link failures.

MANETs routing protocols are classified into two main categories that are topology-based and position-based. Topology-based routing protocols consist of proactive, reactive, and hybrid routing protocols, while position-based routing protocols consist of greedy packet forwarding, restricted directional flooding and hierarchical routing. Since position-based routing protocols eliminate some of the topology-based routing protocols limitations, handle better the dynamic behavior of MANETs and are more scalable, we recommend the use of position-based routing protocols. In particular, we recommend the use of greedy forwarding strategy, because it is simple, more scalable and can be easily implemented.

This thesis proposes a novel adaptive greedy forwarding strategy. Unlike the other kinds of greedy forwarding strategies, our strategy adapts the expected forwarding region based on the node density to find the optimum area in order to reduce the hop count, reduce network node spatial distribution, and minimize the switching from the simple greedy forwarding strategy to the complex and costly face routing. Some interesting research directions for future works are the study of the effects of the node mobility and the non-uniform node distribution in our proposed forwarding strategy

Due to the lack of infrastructure and the nodes' random movements, MANETs are less reliable compared to other kind of telecommunication networks. Thus, we recommend the use of two routes, and the selection of the most stable and reliable routes among the available routes in order to increase the network reliability. To ensure the existence of two routes between any randomly chosen source and destination nodes, the node density must be above a certain threshold. Based on that, the network designers should estimate the node density, and if it is below the required density, they should try to increase it to the required value.

This thesis suggests two approaches that can be used to increase the node density to the target density. The first approach is to add extra fixed nodes (wireless mesh routers) to the network, and in this case the MANET is turn into a WMN. Because of the ease of implementation of the mesh routers and their relatively low prices, this approach can be easily implemented with an affordable cost. In addition, wireless mesh routers do not require wires to connect them to the network, which further reduce the implementation cost of the first approach. Another reason to recommend the use of the above approach is its adaptability, where we can control the node density by adding or removing the wireless mesh routers. The other approach is to encourage people to use the network or give the permission to use their devices to relay the network traffic by giving them some incentives.

This thesis shows that the probability of having two routes rapidly increases when the node density increases till it reaches the saturation region where the increase of the node density has negligible improvements in terms of network availability, and may cause severe degradation to the network performance due to the more interference it may add to the network. The above opens a new research direction that is the joint study of the effects of the node density increase on both the network performance and the network connectivity.

This thesis investigates the effects of nodes' movements according to only random waypoint mobility model. Thus, another research direction for a future work is the investigation of the effects of other node mobility models, like Gauss-Markov mobility model, on the network connectivity.

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