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Multi-layer Traffic Engineering Framework for Inter-working Multi-hop Wireless Networks

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This thesis is submitted in partial fulfillment of the academic requirements

for the degree of

DOCTOR OF PHILOSOPHY in ELECTRICAL ENGINEERING

in the Faculty of Engineering and The Built Environment

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February 2011

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Declaration

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TO GOD BE THE GLORY.

Dedicated to the loving memory of the best mother,

Mrs Juliana Adediwura Salami.

Abstract

The interworking of multi-hop wireless networks can conveniently provide ubiquitous seamless service and continual access for network users. Ubiquity can be achieved through multi-technology mobile terminals (nodes), which enables network users to access any available network. In addition, such nodes extend network coverage by relaying traffic for each other. However, to exploit the benefits of the internetworking, it is desirable to have appropriate traffic engineering (TE) mechanisms. Taking into account the co-existence of different physical and Medium Access Control (MAC) layer standards in the individual networks, the multi-hop communication capability and the impairment-prone wireless medium, TE becomes challenging. For effective TE, nodes need to identify wireless links that will ensure an optimization of important network parameters and route traffic through such links for ubiquitous network service access and continuity. The main contributions of this research are three folds; firstly, a multi-layer framework for TE in internetworked set of multi-hop wireless networks is proposed. The hypothesis of this research is that if a strong relationship can be established between the physical and MAC layer metrics a multilayer TE framework can use the relationship to ensure an optimization of the link discovery, resource utilization and routing processes. For these processes, the research investigated the concept of connectivity in internetworked multi-hop wireless networks. This concept has not been studied before. Connectivity is taken as a probabilistic measure, and defined as a function of link availability and a link's non-impairment probability in this research. Secondly, by characterizing the network as a homogenous Poisson process, analytical models of the link availability (link discovery) and the non-impairment probability (resource optimization) were developed based on the relationship between physical/MAC layer metrics. The connectivity model was also developed and proposed as a routing metric. - Thirdly, the processes of the framework were incorporated into NS-miracle/NS2 and its performance was evaluated in an internetworked multi-hop networks scenario. The simulation report the good-put, number of packet lost, packet delivery ratio and delay for the framework's routing process with another routing process that employs hop-count. At high node density and high interference, the multi-layer framework's routing process exhibited a better performance because it considers not only the reach-ability of nodes but also the connectivity level and quality of links when forming a route.

Acknowledgements

My profound gratitude goes to my thesis advisors Professor H. Anthony Chan, Dr Antoine Bagula and Dr E.O Falowo for their support, encouragement and motivation throughout the period of this research work. It has been a unique and priceless opportunity for me to work with you. Thank you for giving me the opportunity.

I am greatly indebted to my spouse, Mobolaji Bello, for holding my hands up throughout the duration of my studies. Your constant stream of emotional support, inspiration and love are mostly appreciated. You did not let the seed die, you watered it and now it has blossomed, forging ahead with increased might, it cannot be limited.

I wish to express my gratitude to Mr Clemence Kyara (former employee of the Meraka Institute, Council for Scientific and Industrial Research (CSIR)) for his advice and guidance at the later stage of the research work.

I also acknowledge my family members. Mum, though you are not here any longer, I am very grateful for the discipline you cultivated in me; you have always been my inspiration. Dad, Oladipo, Olajide, Olawunmi, Olanrewaju and Olayemi, thank you for your invaluable support throughout the duration of my studies.

My special thanks go to every member of the Communication Research Group, Electrical Engineering department, University of Cape Town.

Finally, and most importantly I wish to thank God for the gift of life, His guidance and for His excellent Spirit who assisted me in conducting this research, and for my little bundle of joy, Moesi-Othniel who was delivered a week after the submission of this thesis.

Table of Contents

Declaration.....	iii
Acknowledgements	vi
List of Figures.....	x
List of Tables	xii
List of Equations	xiii
Glossary	xv
List of Abbreviations	xvi
List of Notations	xvii
Chapter 1 Introduction.....	1
1.1 Inter-working multi-hop wireless networks.	1
1.2 Challenges of Traffic engineering in inter-working multi-hop wireless networks.....	5
1.3 Deployment Scenario	7
1.4 Problem Statement.....	10
1.5 Research Motivation.....	11
1.5.1 Hypothesis.....	13
1.5.2 Research objectives and contributions.....	13
1.6 Research methodology	14
1.6.1 Research scope and assumptions.	16
1.7 Thesis Outline.....	16
Chapter 2 Review of Traffic engineering in multi-hop wireless networks.	18
2.1 Overview of wireless access network architectures	18
2.2 Traffic engineering in multi-hop wireless networks	23
2.2.1 The concept of connectivity in multi-hop wireless networks	28
Chapter 3 Research Methodology	34
3.1.1 Node distribution	34
3.1.2 Spatial Point Pattern.....	35
3.1.3 Poisson Point processes.....	36
3.1.5 Inter-working multi-hop wireless network model	40
3.1.6 Node degree	42

3.1.7	Node model	43
3.1.8	Propagation model	44
<u>Chapter 4 Analytical Models for the Multi-layer Traffic Engineering framework.....</u>		<u>46</u>
4.1	The concept of availability.	46
4.2	Link distance distribution	47
4.3	Availability model	48
4.3.1	Link availability model.....	48
4.3.2	Route availability model.....	51
4.4	Non-impairment probability model.	56
4.4.1	Evaluating Interference on a link.	57
4.4.2	Probability of Bit Error	67
4.5	Connectivity model	72
4.5.1	Connectivity Aware routing process	77
4.5.2	Properties of the connectivity metric.....	78
<u>Chapter 5 Simulation Based Validation.....</u>		<u>81</u>
5.1	Motivation for the use of NS-Miracle simulator	81
5.2	Simulation environment	84
5.2.1	Physical Layer	85
5.2.2	MAC Layer.....	87
5.2.3	Network Layer	87
5.3	Analysis of Simulation results for AODV-UU-HP and AODV-UU-CL	96
<u>Chapter 6 Conclusion and future work</u>		<u>107</u>
<u>Research journal publications</u>		<u>110</u>
<u>References</u>		<u>111</u>
<u>Bibliography</u>		<u>120</u>
<u>Appendix A: Transmission range estimation</u>		<u>121</u>
<u>Appendix B: Connectivity graph.....</u>		<u>122</u>
<u>Appendix C: Connectivity Aware codes</u>		<u>123</u>
C.1	Poisson_random_variable.cc.....	123
C.2	Connectivity-aware.h.....	124
C.3	Connectivity-aware-mac-802_11mr.h	124

C.4 Connectivity-aware-mac-802_11mr.cc.....	125
C.5 Connectivity-aware-mac-802_11-module.cc.....	126
C.6 Connectivity-aware-mac-802_11-module.h.....	127
C.7 Connectivity-aware-mac-802_11.tcl.....	128
Appendix D: SNIR threshold at different data rates.....	129
Appendix E: Control message format.....	130
Appendix F: Illustration of the routing process.....	132
Appendix G: TCL Simulation scripts.....	134
G.1 AODV-UU-CL tcl script.....	134
G.2 AODV-UU-HP tcl script.....	150

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List of Figures

Figure 1.1 Steps in traffic engineering processes [21].....	6
Figure 1.2 Inter-working network scenario with single mode and multi-mode nodes	8
Figure 3.1 Spatial Point Pattern	35
Figure 3.2 Nodes within a multi-hop wireless network.....	40
Figure 3.3 Inter-working multi-hop wireless network model [57]	40
Figure 3.4 Generic protocol stack architecture for a multi-technology mobile terminal	43
Figure 4.1 Link Availability (P_{link}) vs Normalized Transmission Range (R_o)	50
Figure 4.2 Link Availability vs Number of Nodes for different values of R.....	51
Figure 4.3 A Sub-network.....	51
Figure 4.4 Number of hops (l) vs distance between nodes.....	53
Figure 4.5 Inter-node Interference power vs $\beta_{k,R}$	58
Figure 4.6 Inter-node Interference power vs number of interfering nodes.....	58
Figure 4.7 Representation of the transmission from a T-node to an R-node on link l	59
Figure 4.8 Approximation of the ring created by the interference region.	62
Figure 4.9 Interfering node density vs network node density.....	65
Figure 4.10 Interference power vs Interfering node density.....	66
Figure 4.11 SNIR vs Interference power.	66
Figure 4.12 Probability of Bit Error vs. Interfering node density.....	70
Figure 4.13 Non-impairment probability vs. Interfering node's density.....	71
Figure 4.14 Connectivity vs Network node density.....	73
Figure 4.15 Isotonicity	80
Figure 5.1 Multi-layer architecture of a node within NS-MIRACLE [99].....	84
Figure 5.2. Good-put(packets/s) vs Number of nodes	98

Figure 5.3 Good-put(packets/s) vs Number of transmitting nodes.....	98
Figure 5.4 Delivery ratio vs Number of nodes	100
Figure 5.5 Delivery ratio vs Number of transmitting nodes	101
Figure 5.6 Packet lost vs Number of nodes	101
Figure 5.7 Packet lost vs Number of transmitting nodes	102
Figure 5.8 Delay vs Number of nodes	104
Figure 5.9 Delay vs Number of transmitting nodes.....	104
Figure 5.10 Delay vs Distance	105
Figure 5.11 Delay vs Transmitting power	105

University of Cape Town

List of Tables

Table 2.1 Available connection options in an integrating single-hop WWAN and	21
Table 2.2 Available connection options in an integrated single-hop WWAN and multi-hop	22
Table 2.3 Available connection options in an integrated multi-hop WWAN and multi-hop	22
Table 2.4 Summary of common routing metrics.	24
Table 4.1. Interfering node density, bit error probability and non-impairment probability	71
Table 4.2 Network node density, availability, non-impairment probability and connectivity.	75
Table 5.1 Physical Layer simulation Configuration	86
Table 5.2 Simulation parameters	97

Univ rsity of Cape Town

List of Equations

Equation 1	37
Equation 2	43
Equation 3	44
Equation 4.....	50
Equation 5.....	48
Equation 6.....	49
Equation 7	50
Equation 8.....	50
Equation 9	52
Equation 10	54
Equation 11	55
Equation 12	55
Equation 13	55
Equation 14	55
Equation 15	55
Equation 16	56
Equation 17	57
Equation 18.....	59
Equation 19a, 19b, 19c.....	60
Equation 20.....	61
Equation 21.....	61
Equation 22.....	61

Equation 23.....	62
Equation 24.....	62
Equation 25	62
Equation 26	62
Equation 27	63
Equation 28.....	63
Equation 29	63
Equation 30.....	64
Equation 31.....	67
Equation 32.....	67
Equation 33	68
Equation 34.....	68
Equation 35	68
Equation 36.....	68
Equation 37	69
Equation 38.....	73

Glossary

Availability	probability that two nodes are within the maximum transmission range of each other, so that a communication link may be established between them.
Connectivity	probability that a wireless link is available and the probability of non-impairment on it is high enough to guarantee successful transmission over it.
Impairment	a symptom of reduced quality or strength
Link	1-hop communication connection between any node pair in the network.
Mobile-terminals	wireless mobile devices
Multi-modal	operating with multiple technologies
Multi-interface	having more than one technology interface
Nodes	wireless mobile devices
Non-impairment probability	the likelihood that the radio attributes of a link have the potential to satisfy the minimum requirement for successful communication over it.
Route	multi-hop communication connection path between any source and destination pair.

List of Abbreviations

AODV	Ad-hoc On-demand Distance Vector
CSR	Complete Spatial Randomness.
IP	Internet Protocol
MAC	Medium Access Control
NND	Nearest Neighbour Distance
NS2	Network Simulator version 2
NS-Miracle	NS Multi InteRface Cross Layer Extension
PBE	Probability of Bit Error.
PHY	Physical
R.V.	Random variable
IEEE	Institute of Electrical and Electronics Engineers
SNIR	Signal to Noise and Interference Ratio

List of Notations

(x_i, y_i)	x and y co-ordinates of node i
A_l	Channel attenuation for link l
$D(.)$	Node degree of a node.
f_c	Carrier frequency
g	Speed of light
G_r	Receiver gain
G_t	Transmitter gain
k	An interfering node
l	One-hop link
L	Set of all links in the network.
L_f	System loss factor
P_{ini}	Inter-node interference power on link l
P_{int}	Total interference power experienced by the R-node at the end of link l
P_{link}	Availability of a 1-hop link for any node in the network
P_l^r	Power received by the R-node on link l
P_l^t	Power transmitted by the T-node on link l
P_o	Noise power on link l
$P^{t(k)}$	Transmitting power of an interfering node
R^2	Two-dimensional plane
R^d	d-dimensional plane
R-node	Receiver-node (destination-node)
R_o	Transmission range of nodes

S	Total number of interfering nodes.
T-node	Transmitter-node (source-node)
α	Path loss exponent
$\beta_{k,R}$	Distance between a k-node and an R-node
$\beta_{T,R}$	Distance between a T-node and an R-node
$\theta^{(l)}$	SNIR on link l
θ^{th}	SNIR threshold value
λ	Mean number of points per unit area
λ_c	Wavelength
μ	Spatial node density.
μ_{Net}	Spatial node density of the network
$\Phi^{(l)}$	Probability of bit error on link l
Ω	Denotes an inter-working multi-hop wireless network

Chapter 1 Introduction

1.1 Inter-working multi-hop wireless networks

The emergence of different types of network services (e.g. IPTV, video on demand etc), an increase in the demand for these services and most especially the desire for “more” convenient ways to access these services have led to the evolution of different wireless access networks. Over the years, several wireless networks (fixed/mobile networks, single-hop/multi-hop mobile networks, infrastructure-based/infrastructure-less networks) have been designed with more sophisticated standards than their predecessors in order to satisfy the demand cravings. Though these wireless access network technologies have been standardized and commercialized, yet no single technology can be considered as the best because they have been designed for different purposes and therefore operate with different networking standards [1]. In addition, there is a slow upgrade and migration to new wireless technologies due to the involved cost. Wireless access networks typically have distinguishing characteristics in terms of coverage range, frequency of operation, data rate and power [2]. With the increase in demand for seamless service continuity through ubiquitous broadband connectivity, the integration of multiple heterogeneous wireless access networks has become important [1]. Heterogeneity is supported with the fact that no single wireless network standard is able to optimally cover all the different wireless communication scenarios [3] [4]. The integration of wireless networks can allow the provisioning of services to mobile network users in any communication scenario.

In order to achieve the integration of wireless networks, the networks are seamlessly inter-networked. The concept of inter-working networks does not create an entirely new network; it is just an approach that enables the integration of existing network technologies into a unified platform for in order to provide an uninterrupted and consistent level of service to

network users.

Moreover, to complement the quest for access to services anytime and anywhere, mobile devices are now being equipped with multi-mode (multi-technology) capabilities, which can allow users to have access to any available network using a single mobile device. Therefore, apart from the integration of wireless networks, there is also a tendency that heterogeneous terminals (nodes) can co-exist in an inter-working wireless network.

A lot of research work has gone into the inter-working of single-hop WWAN (e.g. 3G) and single-hop WLAN (e.g. IEEE802.11). Standardization groups such as the Third Generation Partnership Project (3GPP) [5] and 3GPP2 [6] have dealt with the inter-working between 3G and WLANs. The inter-working between heterogeneous IEEE 802 networks and between IEEE 802 networks and cellular networks has also been dealt with by standardization groups. However, they have only considered the single-hop mode of operation, where only two connection options are available. These options are: 1) direct connection between a mobile terminal and a cellular Base Station (BS) or 2) direct connection between a mobile terminal and an Access Point (AP). The paradigm of multi-hop communication was not exploited. Even though coverage extension and relaying via multi-hop communication is an old concept, it has become practical only recently [7]. Practitioners expect that in the future, wireless networks will not be limited to cellular systems [8]. It is envisaged that parts of the access domain in next generation wireless networks will not be centrally organized, instead they will be infrastructure-less and provide multi-hop communication for nodes that cannot reach their destination with a single hop transmission [9]. Mobile terminals (nodes) may access network services by forming alliance with other nodes any time and any place. Such nodes could be a part of the personal, local and wide area sphere of wireless networking. The nodes would temporarily co-operate to provide

ubiquitous access and service continuity for each other [9]. In addition, to reduce the problem of dead spot in cellular networks, multi-hop cellular networks are also being considered [10].

The advent of multi-hop communications has brought about new opportunities for future wireless networks (e.g. seamless service continuity) [11]. In contrast to single hop, multi-hop capabilities allow nodes to relay traffic for each other. It introduces the concept of cooperation among nodes to allow short-range communication between them. It also achieves higher spectral efficiency, better route diversity, and significantly lower power consumption. In addition, it alleviates path loss and fading¹ issues associated with the wireless channel. Mitigating both path loss and fading and the reduction of consumed power arise from the ability of nodes to provide each other with diverse propagation paths through a series of close hops to intended destination [12]. For example, splitting a single hop connection into two hops reduces the average distance between communicating pairs of nodes. Since power consumption is proportional to distance, the reduction in distance results in the reduction of the amount of energy that would have been used to transmit the data on a single-hop. In this way, multi-hop wireless networks are able to improve the reliability of the communication between nodes and extend the network capacity [12]. In addition, because there can be diverse multi-hop routes to a destination, multi-hop communications introduce inherent redundancy, which upholds the network during random link failure.

Some applications of multi-hop communication include mesh networks, vehicular networks, and mobile ad-hoc and sensor networks. Furthermore, the recent enhancements to wireless network technologies such WiFi (Wireless Fidelity), WiMAX (Worldwide

¹ Path loss refers to the exponential decay of received average signal power with distance, while fading is caused by the random variations of instantaneously received power.

Interoperability for Microwave Access) and cellular networks include the addition of multi-hop capability. These enhanced standards are the IEEE 802.16j standards for mesh and multi-hop relay specification in Mobile WiMAX [7] [13], the 3rd Generation Partnership Project (3GPP) Opportunistic Driven Multiple Access (ODMA) which is a protocol proposed for UMTS TDD mode [14] [15], the IEEE 802.11s which is an ESS (Extended Service Set) mesh networking enhancement of IEEE 802.11, and the IEEE 802.15.5 for WPAN (Wireless Personal Area Network) mesh networking [16].

Therefore, in the light of the provisioning of ubiquitous network access to users, the inter-working of multi-hop wireless networks is a step into the future of wireless networking. Inter-working multi-hop wireless networks can substantially extend network coverage and provide unlimited and ubiquitous network access so that users can enjoy seamless handover and uninterrupted service. These networks can also be very useful in areas that are 'hard to wire', areas with no initial wire-line or wireless single hop network coverage and areas that suffer from connectivity problems e.g. isolated inhabited islands or rural areas. They are also useful for military applications and communication restoration in disaster recovery operations when cell sites may have been damaged. Another application is for Intelligent Transport Systems, which ensures road safety. In addition, inter-working multi-hop wireless networks can minimize infrastructure cost and thus provide low-cost networking.

Despite the advantages and potentials that come with the inter-working of multi-hop wireless networks, the inter-working process poses many challenges, and there is a need for solutions to these challenges. The research issues in inter-working multi-hop wireless networks covers all layers of the network protocol stack. Some of these research issues are related to traffic engineering, mobility, billing and security [17]. However, this research specifically

focuses on traffic engineering in inter-working multi-hop wireless networks in which heterogeneous mobile terminals co-exist. Since mobile terminals are now being equipped to integrate different access technologies on a single mobile device, the co-existence of single-mode and multi-mode mobile devices in a network cannot be undermined. Integrating multiple technologies on a single device allows network users to be supported by any available network. Thus, the issue of resource optimization still exists in the inter-working of multi-hop wireless networks. This research considers all terminals (single-mode or multi-mode) to have multi-hop capability.

1.2 Challenges of Traffic engineering in inter-working multi-hop wireless networks

Traffic engineering (TE) is a commonly-used technique for achieving optimal or near optimal performance in a network. Traffic engineering concepts allow a network to exercise control over the way it provides or responds to resources demand by moving the traffic offered to a network to where the network resources are available. The control is achieved with the use of protocols that influence the manner in which resources may be allocated. TE can be viewed in different ways depending upon the specific context in which they are used and the goal they serve. The optimization objective of TE can be achieved through capacity management or traffic management. Capacity management includes capacity control, routing control, and resource management. Traffic management includes nodal traffic control functions such as traffic conditioning, queue management and scheduling [18]. The manner in which traffic engineering objectives are implemented change over time as new requirements are imposed by emerging technologies. Therefore, TE concepts require continuous development of new methods to

enhance network performance as new technologies emerge. Although designing TE mechanisms for wired networks may be quite straight forward, it is complicated for wireless networks, more so in an inter-working environment [19].

There are three main steps for the designing of traffic engineering mechanisms as shown in figure 1.1. Firstly, knowledge of the underlying network parameters, associated resource constraints and the network state are needed. Secondly, an understanding and optimization of the performance measures of interest. The performance measures of a network may be in terms of traffic level QoS parameters (throughput, packet loss, delay and jitter) [20]. Thirdly, the selection of paths and routing of traffic in order to ensure that the necessary performance measures are optimized. .

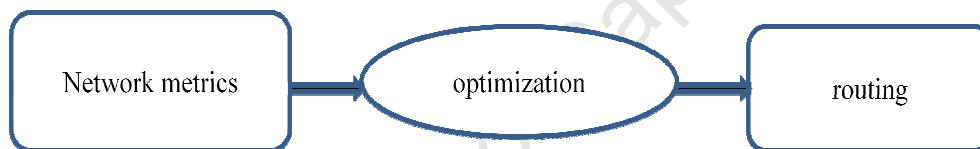


Figure 1.1 Steps in traffic engineering processes [21]

Traffic engineering functions are vital in ensuring ubiquitous access and service continuity for nodes in an inter-working multi-hop wireless network. Two of the features of these networks that significantly affect TE are the co-existence of single and multi-modal terminals and the multi-hop communication capability of the nodes.

Typically, in a wireless network, all nodes (mobile terminals) run the same set of protocols (e.g. on the lower layers: physical, link and MAC layer) and these protocols have the same goal when providing services to the upper layers. However, with the co-existence of single-mode and multi-mode nodes, nodes may implement different protocols for a given layer (e.g. physical and MAC layer protocols may differ). Thus, inter-working may cause the operation of

the protocols to conflict. For example, if different scheduling techniques are employed by the MAC protocols, the concurrent operation of these techniques in an inter-worked scenario may eventually cause inter-node interference. This occurrence may significantly affect the traffic engineering process within the network and must be taken into account [17].

Due to the multi-hop communication capability within the network, the identification of the optimal and reliable paths for traffic routing is very important. Traffic routing is mainly affected by connectivity constraint within the network. If there are no links between nodes then the performance of any TE process will be limited. The dynamic network topology and the random location of nodes make it difficult to discover and maintain reliable routes. In addition, end-to-end delay can occur due to problems at the lower layers (e.g. interference patterns on the physical layer). Thus it is necessary to consider the operations on the lower layers in traffic engineering.

In order to leverage the capabilities of inter-working multi-hop wireless networks to provide seamless service continuity and ubiquitous broadband access, appropriate traffic engineering mechanisms are needed.

1.3 Deployment Scenario

Consider a scenario in which multi-hop wireless access networks are inter-worked with partially overlapped coverage as shown in figure 1.2. These networks can belong to different or same service providers. Users' nodes (terminals) such as laptops and smart phones in the network are either single or multi-modal nodes with multi-hop capabilities. Gateway nodes (access points and base stations) provide inter-domain co-ordination between the networks as well as connection to the Internet. If single-mode nodes are out of the range of their applicable gateway, they can relay traffic through other single/multi-mode nodes. The nodes with multi-

mode capability can also connect to applicable gateway directly if they are within its range, otherwise they will relay their traffic through other nodes. As nodes move, they can enjoy ubiquitous access and seamless service continuity, assuming there is co-operation between nodes.

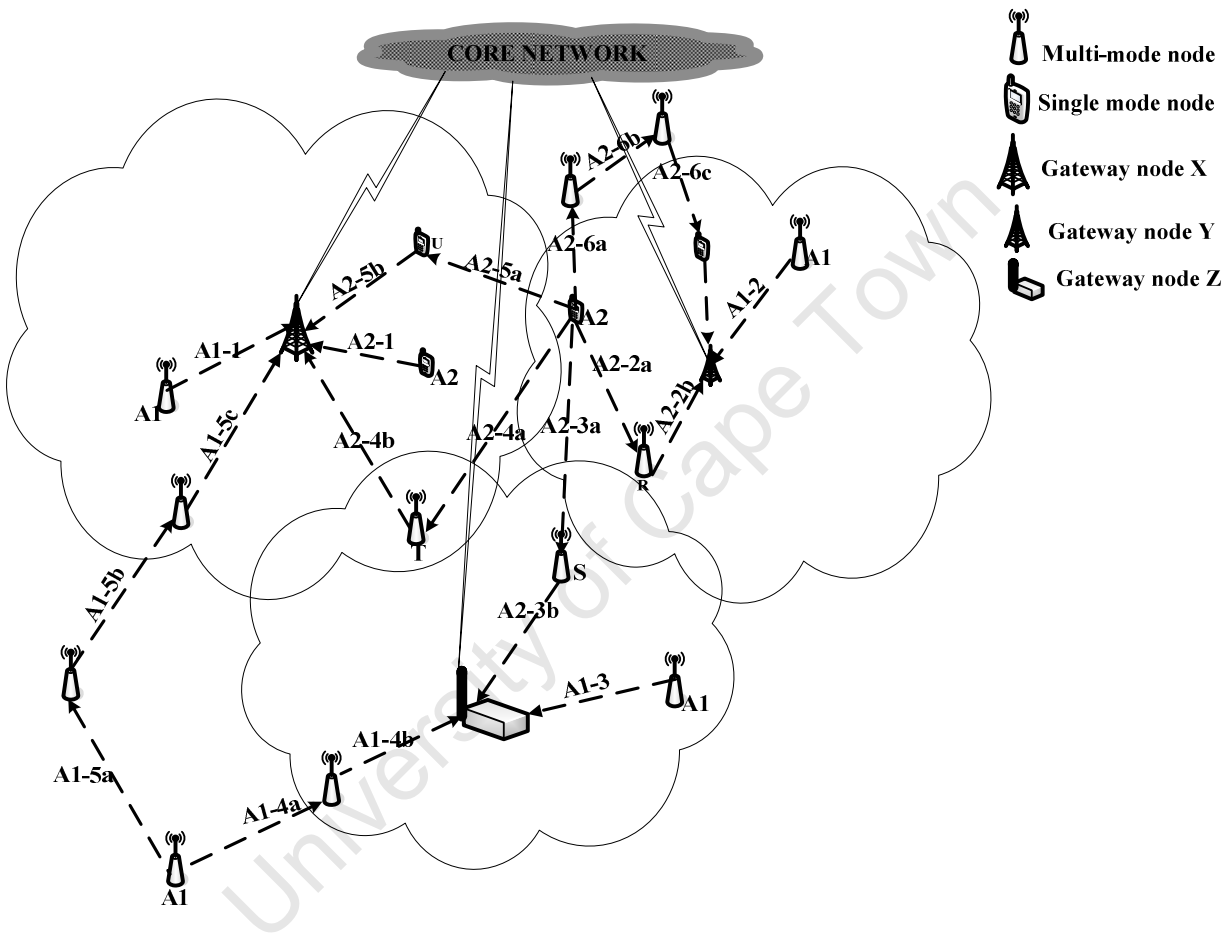


Figure 1.2 Inter-working network scenario with single mode and multi-mode nodes

Even if nodes are out of range of their applicable gateway, their traffic can still be relayed through the closest multi-hop node with similar operational mode capability. When gateway nodes are unreachable by a node, the onus of all other nodes is to ensure continuity of service for this node. Figure 1.2 illustrates some possible ubiquitous service continuity

connections in this scenario. From figure 1.2, the communication scenarios that can be considered for node A1 (a multi-mode terminal) are:

1. It can have service continuity through gateway nodes X, Y or Z if it is within their coverage range as it moves around. This is illustrated by : A1-1, A1-2 and A1-3 connections
2. If A1 happens to be out of coverage range of all the gateway nodes, it is able to continue accessing its ongoing service through either connection A1-4a and A1-4b or A1-5a, A1-5b and A1-5c connections.

If node A2 is a single-mode node;

1. It will always have service continuity as long as it is within its parent gateway node X's coverage range through A2-1 connection
2. In the event that A2 moves out of its parent gateway node's coverage range into network 2, it can have service continuity through:
 - a. Node R, a multi-mode terminal using A2-2a and A2-2b connections.
 - b. Node S, a multi-mode terminal using A2-3a and A2-3b connections.
 - c. Node T, a multi-mode terminal using A2-4a and A2-4b connections.
 - d. Node U, a single-mode terminal using A2-5a and A2-5b connections.
3. If it happens that the only node that node A2 can link with is out of the range of all gateway nodes, service continuity can be supported by other available multi-hop node through all A2-6 connections.

From the scenario described, the focus of this research is on when the multi-hop nodes within the inter-working multi-hop wireless networks are out of their parent gateway coverage and the continuity of access to service is provided through other single-mode or multi-mode nodes.

1.4 Problem Statement

As new wireless access network standards are emerging, the design of protocols continues to pose challenges at all layers of the communication stack. The advantages of inter-working multi-hop wireless networks cannot be over-stated. It conveniently brings about the ubiquity of network services required by network users. However, in order to complement the benefits of inter-working multi-hop wireless networks with reliable provisioning of services to users, it is desirable to have applicable traffic engineering operations.

The traffic engineering operations for ensuring ubiquitous service continuity in inter-working multi-hop wireless networks involves link discovery optimization, resource optimization and routing. Optimization has to do with providing the best possible network resource in the light of constraints in order to ensure that a node enjoys continuous access to its service if even it is out of its gateway node coverage area. The aforementioned operations are affected by the fact that the wireless medium may be subjected to impairment at anytime. The instability of the links makes it difficult to guarantee connection on the links that make up a multi-hop route. Nodes need to be able to identify links that will ensure an optimization of necessary network parameters and route traffic through such links. With the features of inter-working multi-hop wireless networks and taking into account the heterogeneity of physical and MAC layer standards that may exist in the network, how can nodes perform these traffic engineering operations within such network?

1.5 Research Motivation

Due to the benefits of inter-working multi-hop wireless networks, it is desirable to have an applicable traffic engineering framework for such a network. Little research work, if any, exists on TE in inter-working multi-hop wireless networks. Most prior efforts have concentrated on single multi-hop wireless networks with single-mode nodes. With the features of inter-working multi-hop wireless networks and taking into account the heterogeneity of the physical/MAC layers of nodes that may exist in the network, TE processes can be disintegrated into connectivity functions. However, connectivity has only been studied for single multi-hop wireless networks but not for inter-working multi-hop wireless networks. To the best of our knowledge, no published work has either considered connectivity as a joint function of availability and non-impairment probability or used it as a metric for multi-hop routing in inter-working multi-hop wireless networks.

In an inter-working multi-hop wireless network, a node to node connection may involve a sequence of several links and the final end-to-end connection experienced by a network user will be limited by the weakest link in this chain of connections. Thus, link discovery optimization and traffic routing techniques should select links that will optimize routing and avoid the wastage of network's resources while ensuring ubiquitous access and service continuity.

Based on the heterogeneity of the technologies that may be present in inter-working multi-hop wireless networks, a multi-layer approach will play an important role by utilizing useful lower layer information in ensuring link discovery optimization and resource optimization for the routing process. A multi-layer approach will allow traffic and resource level parameters on the lower layer to be taken into account in the optimization processes of TE. The optimization

objective is to optimize connectivity for nodes within the network.

Therefore, the motivation for this research is to propose a multi-layer framework for traffic engineering in an inter-working multi-hop wireless network. The multi-layer framework consists of a link discovery optimization process, a resource optimization process and a routing process.

In the proposed multi-layer framework, the link discovery and resource optimization processes determine the level of connectivity between two multi-hop nodes. These processes makes use of physical/MAC layer parameters such as node's transmission range, transmission power, spatial node density, interfering node density, probability of interference, signal to noise and interference ratio (SNIR) and bit error probability. During the routing process, the level of connectivity on a link is the routing cost metric. A strong connectivity level on all links that make up a multi-hop route means that reliable last mile ubiquitous service continuity can be assured. An overview of some existing metrics for multi-hop routing is presented in chapter 2.

Due to the stochastic nature of the wireless environment, in this research, the level of connectivity is taken as a probabilistic measure. In this research, connectivity has been re-defined as the probability that a wireless link is available and the probability of non-impairment on it is high enough to guarantee successful transmission over it. Therefore, connectivity is mutually dependent on the link availability and non-impairment probability. Link availability is the probability that two nodes are within at most the maximum transmission range that is sufficient for a communication link to be established between them. Link non-impairment probability indicates the likelihood that the radio attributes of a link has the potential to satisfy the minimum requirement for successful communication over it. The minimum requirement is defined by the underlying network parameters and associated resource constraints of the network

such as data rate and the SNIR threshold of the network. When fine-tuned, these attributes define by physical/MAC layer parameters that ensure the proper functioning of a link.

1.5.1 Hypothesis

Given that some of the physical and MAC layer metrics in an inter-working multi-hop wireless network influence each other and collectively, they affect ubiquitous service continuity within the network. If a strong relationship can be established between these metrics, then using this relationship, a multilayer traffic engineering framework can ensure:

- Link discovery and network resource optimization.
- An efficient routing process for the provisioning of ubiquitous network access and service continuity in an inter-working multi-hop wireless networks.

1.5.2 Research objectives and contributions

Due to the nature of next generation wireless networks, the objective of this dissertation is to develop a multi-layer traffic engineering framework for the purpose of ensuring ubiquitous access and service continuity in inter-working multi-hop wireless networks. To achieve the global objective, this research seeks to find the relationship between the necessary physical and MAC layer metrics that affects traffic engineering and use the relationship to ensure optimal link discovery, resource optimization and routing. The specific objectives and contributions of this research are:

- To analytically derive a model for determining the availability of a link in an inter-working multi-hop wireless network: this defines the link discovery process.
- To analytically derive a model for the non-impairment probability on available links. The interfering node density, probability of interference and interference power are used to

estimate the SNIR and the bit error probability on all potentially available links. The model defines the resource optimization process. Considering the effect of interference, the goal is to identify the set of nodes whose simultaneously transmission with the node of interest cannot be prohibited and estimate the impact of their transmission on available links.

- To present a connectivity model for inter-working multi-hop wireless networks based on the link availability model and the link's non-impairment probability.
- To use the connectivity model as a metric in the routing process for multi-hop nodes in inter-working multi-hop wireless networks. The routing process takes into account the level of connectivity on links to achieve optimal routing for a reliable ubiquitous access and service continuity.

For the analytical models in this research, we exploited the splitting and merging properties of the Homogenous Poisson Process to characterize the inter-working multi-hop wireless network.

1.6 Research methodology

This research work involves the derivation of analytical models that make up the proposed multi-layer traffic engineering framework and the simulation performance of the routing process.

For the link discovery and resource optimization process, we obtained connectivity as a function of the availability of links and the non-impairment probability on available links. The level of non-impairment is a function of interference and the probability of bit error on links.

Firstly, for any T-node (transmitting or source node) in the network, the probability that a link is available for it to transmit its packet is evaluated. The link may be a direct link to the intended destination node or it may be a link to intermediate nodes between the T-node and the

intended destination node. It is only after confirming the availability (existence) of a link that the non-impairment level metrics (e.g. probability of interference, interference power, SNIR, and probability of bit error) on the link can be evaluated.

Secondly, after the confirmation of the existence of a link, an interference region is defined for the R-node (a receiving node, which could be the intended destination or an intermediate node) on the link of interest. All nodes present within this region are potential interfering nodes. However, only the nodes that happen to be transmitting concurrently with the T-node will contribute to the interference power. The probability that a node in the inter-working network will contribute to the interference power is estimated.

Thirdly, using the probability of interference, the density of interfering nodes can be evaluated and also the total interference power, which is used to evaluate SNIR on the link of interest. If the SNIR on the link is less than the threshold SNIR value in the network, then there is a likelihood that transmission errors will occur on that link. The set value for SNIR threshold in the network is also used to estimate the threshold of the number of interfering nodes and the threshold value for the probability of bit error that can be tolerated in order to be able to guarantee a successful transmission. The probability of bit error is obtained as a function of the interfering node's density. Finally, an estimation of the connectivity level on that link is used for the routing process.

Simulation was carried out on NS-miracle version 1.2.2. NS-miracle is the Multi-InterfAce Cross-Layer Extension of the Network Simulator version 2. The capability of NS-miracle supports heterogeneous networks in which different networks coexist. It allows the simulation of multi-technology and multi-interface communication capabilities at all layers of the protocol stack [22].

We compared the simulation performance of the connectivity routing metric and the hop-count metric using the AODV-UU protocol, which uses hop-count and is readily available in the NS-Miracle simulator. In the interworking multi-hop network scenario, when the network is dense, (i.e. when the number of nodes in the inter-working network is increased), the connectivity metric exhibited an outstanding performance than the hop-count metric. In addition, when the number of transmitting nodes is increased (which increases the number of interfering nodes), the connectivity metric performs better in terms of good-put, packet delivery ratio, number of packet lost and delay. Due to the fact that the connectivity metrics encompasses the applicable physical layer and MAC layer metrics, it is able to choose routes that can optimize these metrics and thus avoid low quality links.

1.6.1 Research scope and assumptions

The features of the wireless networks considered in this research include; the networks are inter-working, nodes in the network are multi-hop mobile terminals, which are either multi-mode or single-mode terminals. We assume that co-operation, security and hand-off mechanisms exist within the network. The NS-miracle 1.2.2 supports IEEE 802.11 technologies for multi-hop multi-mode node, thus the simulation work was performed with IEEE 802.11 technologies.

1.7 Thesis Outline

The organization of this rest of this thesis is as follows:

Chapter 2 provides a review of literatures related to this research with specific focus on 1) different wireless access network architectures that have been in existence over the years, 2) traffic engineering in wireless networks, 3) a discussion on some existing metrics that are used to

define optimal paths during traffic engineering, and 4) previous research work on connectivity in multi-hop wireless networks.

Chapter 3 discusses the methodology used in this research. It discusses the fundamental models that provide the basis for the analytical framework presented in this research. These models are the node distribution model (using the spatial point process), Homogenous Poisson Process, inter-working network model, node degree model, node model and propagation model.

Chapter 4 presents the analytical models developed in this research for the proposed multi-layer traffic engineering framework and the numerical results obtained from these models. These are the availability, non-impairment probability, and the connectivity models.

Chapter 5 presents the simulation work carried out in this research and the simulation performance results obtained from the NS-miracle 1.2.2 on NS2.34 network simulator. The chapter also gives a background of the NS-miracle network simulator.

Chapter 6 concludes the thesis and discusses the future work on this research.

Chapter 2 Review of Traffic engineering in multi-hop wireless networks

The purpose of this chapter is to provide a review of wireless access networks and the background motivation for inter-working multi-hop wireless network, a review of traffic engineering and existing routing metrics for multi-hop wireless networks and also to discuss existing research work on connectivity in multi-hop wireless networks.

2.1 Overview of wireless access network architectures

Using the wireless wide area network (WWAN) and the wireless local area network (WLAN), below is a summary of the alternative wireless access network architectures in terms of their coverage range, data rate and their ability to provide ubiquitous connectivity for users. 3G and IEEE 802.11 are examples of representative technologies for WWAN and WLAN respectively.—Similar to the analysis in [2], wireless access network architectures can be classified as:

1. *Single-hop WWAN*: a single-hop WWAN architecture provides a high coverage range but limited data rate and cannot allow ubiquitous connectivity.
2. *Single-hop WLAN*: a single-hop WLAN architecture provides high data rate but limited coverage range and cannot support ubiquitous connectivity.
3. *Multi-hop WWAN*: this architecture provides coverage enhancement by reducing dead spots and avoids data rate degradation. Cannot single-handedly provide ubiquitous connectivity, but it can enhance the provisioning of ubiquitous connectivity. Li et al. [10] outline other benefits of a multi-hop WWAN.
4. *Multi-hop WLAN*: Extends the coverage range at high data rates and enhances ubiquitous connectivity with appropriate techniques for providing guarantees.

5. *Integrated single-hop WWAN and single-hop WLAN*: here, users can hand-over to the either WLAN or WWAN for service depending on the network within user's range. Since the coverage area of a WLAN is smaller than that of WWAN, users may end up being served by the WWAN and thus experience limited data rate. Can extend service coverage for users but cannot support ubiquitous connectivity.
6. *Integrated single-hop WWAN/WLAN and multi-hop WLAN/WWAN*: in this architecture, users can hand-off to the either WLAN or WWAN. At any given point in time, a user can strictly be served only through one of the networks. Consequently, when operating in the multi-hop WLANs, a user may enjoy a high data rate. However, when users move to the WWAN, data rate may decrease so consistent data rate may not be guaranteed. The architecture can extend service coverage for users but cannot fully provide ubiquitous connectivity.
7. *Integrated Multi-hop WWAN and Multi-hop WLAN*: Provides ubiquitous connectivity by extending service coverage range, supporting high data rate and avoiding data rate degradation with appropriate techniques for providing guarantees in terms of connectivity and QoS.

In terms of architectural integration, the last three architectures, which integrate (inter-works) heterogeneous wireless networks, are the most relevant to the provisioning of high data rates and increased coverage area. It is also necessary to identify levels of service access/service provisioning within the inter-worked environment. In terms of service level integration between heterogeneous wireless networks, four inter-working levels that have been identified by [3] are:

- **Level A: Visited Network Service Access**

In this level of inter-working, users are allowed to have access to a set of services available in a visited network while relying on their home network credentials. For example, a cellular subscriber, using multi-mode terminal (a laptop with cellular and WiMAX or/and WLAN network interfaces) would be able to connect to a WiMAX or WLAN hotspot using his/her cellular smart card credentials and get high-speed Internet access from the visited network's service provider.

- **Level B: Intersystem Service Access**

In this level, users can connect to their home network through a visited network and can have access to specific services located in the home network. A cellular subscriber using a cellular/WLAN/WiMAX laptop can enjoy his/her cellular IMS services by connecting to the WiMAX or WLAN network. As stated in [3], neither level A nor level B would support seamless service continuity when the user moves between networks.

- **Level C: Intersystem service continuity**

Level C extends, level A and B so that the user is not required to re-establish active session(s) when moving between networks. If a cellular user equipped with a multi-mode laptop begins to download a large file when connected to the WLAN hotspot and the user moves out of the WLAN coverage area, the downloading service will continue through the cellular network without the user's intervention even though a short transfer interruption might be observed during the network change.

- **Level D: Intersystem seamless service continuity**

Level D aims to offer seamless service continuity as the user moves between networks. The user with a multi-mode terminal can seamlessly continue with his/her voice over IP (VoIP) call as the user moves between networks.

For the provisioning of ubiquitous service access, extended coverage, increased data rate and seamless service continuity, the inter-working of multi-hop wireless networks (integration of multi-hop wireless networks) will be more relevant. The integrated architectures; single-hop WWAN and single-hop WLAN, and single-hop WWAN/WLAN and multi-hop WLAN/WWAN only enables a user to access a particular network depending upon the application needs and the available networks. On the other hand, the integration of heterogeneous multi-hop wireless networks provides unlimited mobility and greater flexibility but introduce a number of challenges due to its dynamic network topology.

As a summary, table 2.1, 2.2 and 2.3 outlines the connection options that may be available for single-mode and multi-mode nodes in the three integrated architectures.

Table 2.1 Available connection options in an integrating single-hop WWAN and single-hop WLAN network

Access nodes User nodes	WWAN Gateway	WLAN Gateway
Single mode WLAN	☒	☑
Single-mode WWAN	☑	☒
Multi-mode node (WLAN and WWAN)	☑	☑

From table 2.1, single mode nodes can only have access to their services through

appropriate gateway nodes; however, multi-mode nodes can have access via any available gateway node.

Table 2.2 Available connection options in an integrated single-hop WWAN and multi-hop WLAN network

Access nodes \ User nodes	WWAN Gateway	WLAN Gateway	Multi-hop single mode node (WLAN)
Single mode WLAN	☒	☑	☑
Single-mode WWAN	☑	☒	☒
Multi-mode node (WLAN and WWAN)	☑	☑	☑

Comparing table 2.1 with table 2.2, multi-hop nodes further increases service access to user nodes in network integrating single-hop WWAN and multi-hop WLAN.

Table 2.3 Available connection options in an integrated multi-hop WWAN and multi-hop WLAN network

Nodes \ Access nodes	WWAN Gateway	WLAN Gateway	Multi-hop single mode WLAN	Multi-hop single mode WWAN	Multi-hop Multi-mode (WLAN and WWAN)
Single mode WLAN	☒	☑	☑	☒	☑
Single-mode WWAN	☑	☒	☒	☑	☑
Multi-mode node (WLAN and WWAN)	☑	☑	☑	☑	☑

Comparing table 2.1, table 2.2 and table 2.3, integrated multi-hop WWAN and WLAN provides the more options for service access through greater coverage and thus allows ubiquitous and seamless service continuity. Note that the provisioning of ubiquitous access and seamless service continuity are not dependent only on inter-working mechanisms but also on the traffic engineering protocols used by the networks involved.

2.2 Traffic engineering in multi-hop wireless networks

Traditionally, traffic engineering research in wireless networks have focused on homogeneous networks, such as infrastructure-based wireless access networks, ad hoc, and mesh networks. However, recently, interest in the co-existence of different types of networks has increased. Traffic engineering operations in these types of scenarios have become challenging because the protocols that ensures traffic engineering in individual wireless networks were mainly designed for a homogeneous networking scenario. Consequently, there is a need to develop traffic engineering techniques for heterogeneous networking scenarios.

One of the main objectives of traffic engineering is to ensure expeditious movement of traffic within the network in order to avoid congestion and to ensure quality of service (QoS) for traffic. The main challenge for traffic engineering in inter-working multi-hop wireless networks is the multi-hop communication environment, which is also characterized by an unpredictable topology and medium. Thus, mechanisms are needed to dynamically make traffic benefit from available resources within the network [21].

The traffic engineering operations for ensuring ubiquitous service continuity in inter-working multi-hop wireless networks has to do with link discovery optimization, resource optimization and routing. These operations involve how to determine feasible paths based on a set of network constraints while maintaining an efficient utilization of network resources and

routing traffic through such paths. Certain optimality constraints, which are defined based on network resources are imposed on the process of identifying feasible paths. The routing process ensures that traffic is routed through optimal paths.

Several metrics can be used to define optimal paths. These metric include the number of hops, delay, throughput, signal strength, load and maximum transmission unit. Depending on the metric used, different paths, including different wireless technologies can be selected as the best option in an inter-working network. Specifically for multi-hop wireless networks, the metrics that have been proposed include hop count [23], per hop Round Trip Time (RTT) [24], Per-hop Packet Pair Delay (PktPair) [25], ETX [26], ETT [27], WCETT [28], MIC [29] [30], iAWARE [31]. Table 2.4 provides a summary of the characteristics of these routing metrics.

Table 2.4 Summary of common routing metrics

Routing metric	Characteristics
Hop count [25] [32][33][34]	Finds paths with minimum number of hops during a routing process and assumes that all links in the network are alike. Computing hop count requires no additional measurements. However, the route that minimizes the hop count does not necessarily maximize throughput. Hop count does not consider interference on links. It is the routing metric for protocols such as AODV [25], DSR [36], DSDV [37]
Per hop Round Trip Time (PH-RTT) [24]	Based on measuring the round trip delay between neighbour nodes [24]. Every node sends a probe to its neighbour so that they can estimate the RTT to their neighbours. It measures link quality by identifying high delay links within

	<p>the network, and thus such links can be avoided. A high RTT value indicates a high delay. However, it does not explicitly account for interference on a link. The routing protocol that uses this metric, selects the path with the least total sum of RTTs.</p>
<p>Per-hop Packet Pair Delay (PktPair) [25]</p>	<p>Based on estimating the delay between a pair of back-to-back probe packets sent to neighboring nodes [25]. The delay is estimated by sending a small and a large probe packet back-to-back to neighbors every two seconds. The delay between the arrivals of the two probe packets is reported to the sender.</p>
<p>Expected Transmission Count (ETX) [26]</p>	<p>Estimates the number of retransmissions needed to successfully send probe packets between pairs of neighboring nodes [26]. To compute the ETX, nodes broadcast probe packet every second. If the measurement-based probabilities of successful transmissions in the forward and reverse directions of a link are S_f, and S_r, respectively, then $ETX = 1/S_r S_f$. Smaller ETX indicates a better link. ETX of a route is the summation of the ETX of all the links along the route [32]. However, ETX based schemes do not capture the intra-flow or inter-flow interference.</p>
<p>Expected transmission time (ETT) [27]</p>	<p>It captures the data rate used by each link. The ETT of a</p>

	<p>link is the expected MAC layer duration for a successful transmission of a packet on the link. ETT is expressed as $ETT = ETX \times S/B$ where S is the packet size used and B is the bandwidth of the link. ETT captures the impact of link capacity on the performance of the link through the parameter B in the weight of path. However, ETT does not fully capture the intra-flow and inter-flow interference in the network.</p>
<p>Weighted Cumulative Expected Transmission Time (WCETT): [28]</p>	<p>Proposed for multi-hop 802.11 mesh networks, with multiple radios per node. WCETT of an n-hop path is calculated as:</p> $WCETT = (1 - \beta) \times \sum_{k=1}^n ETT_k + \beta \cdot \max_{1 \leq y \leq z} X_y$ <p>Although it takes into account the bandwidth and error rate in the path, it does not capture inter-flow interference. When there are multiple flows in the network, it will route the packet through congested areas resulting in poor throughput [32]</p>
<p>Metric of Interference and Channel Switching (MIC) [29] [30]</p>	<p>MIC considers inter-flow interference. It uses a method that scales up the ETT of links by the number of interfering neighbors in order to capture inter-flow interference. However MIC does not consider a node that is close to the sender or receiver but not involved in any simultaneous</p>

	transmission as an interferer.
Interference Aware (iAware) [31], proposed iAWARE	Considers the effect of variation in link loss-ratio, transmission rate, inter-flow and intra-flow interference for routing in mesh networks. It uses a correlation between interference and ETT. The metric is defined as: $iAware = ETT/IR$, where IR is the interference ratio of the link of interest and ETT is the expected transmission time of the link. IR is the ratio between SNIR and SNR [38]. However, it is known that iAware gives more weight to ETT compared to interference on a link.

For multi-hop wireless networks, it is necessary to consider link quality in routing metrics as links do not have the same quality. High quality links supports high bit rates and thus less transmission errors and re-transmissions are avoided on such links.

Since the design of effective routing metrics depends on the specific characteristics of the target network [39], it is necessary to consider the features that affects traffic engineering processes in inter-working multi-hop wireless networks as discussed in chapter 1. In inter-working multi-hop wireless networks, connectivity between links is a major factor that affects traffic routing. The parameters that affects connectivity includes node density, interfering node density, and transmission range of nodes. Interfering node density affects the SNIR which inturn affects probability of bit error. Therefore, these connectivity parameters should be captured dynamically and routing decisions should exploit such parameters in order to ensure reliable seamless service continuity. Thus, in this research, we analyse connectivity in terms of the connectivity parameters in inter-working multi-hop wireless networks and propose connectivity

as a routing metric in inter-working multi-hop wireless networks. The next section discusses existing research works on the concept of connectivity in multi-hop wireless networks.

2.2.1 The concept of connectivity in multi-hop wireless networks

Until recently, when the proliferation of mesh networks began, mentioning multi-hop wireless networks brings to mind networks that are used for the purpose of gathering, processing, and disseminating information. A lot of attention is now being paid to exploiting multi-hop communication for other purposes. Since nodes may have to depend on other nodes to relay their traffic due to transmission range limitations, the concept of connectivity in multi-hop wireless networks is fundamental in the study of traffic engineering in inter-working multi-hop wireless networks.

In wireless networks formed by a large number of nodes distributed according to some statistics over a limited or unlimited region of dimension \mathbb{R}^d , the theory of connectivity aims at finding the potential set of links that can connect nodes to each other, subject to some constraints such as radio resource limitations [40].

Factors that can affect connectivity in inter-working multi-hop wireless networks include the random location of nodes and the unpredictability in the conditions of the wireless link that exists between the nodes. Connectivity is provided by links and it is affected by the attributes of a link, which are determined by the physical layer and MAC layer metrics.

Although many research works on multi-hop wireless networks exists and some fundamental results have been obtained on connectivity in such networks, these have come at the price of simplistic assumptions made about the physical layer. On the other hand, other works have considered the realistic operation of the physical layer in their research. In this section, we provide a brief summary of published work and highlights the technical issues that motivates this

research.

2.2.1.1 Research works on connectivity in multi-hop wireless networks

Some of the research works based on simplistic assumptions about the physical layer include [41], [42], [43], [44] and [45]. The authors of [41] evaluated connectivity in one-dimensional stationary ad hoc wireless networks. In [42], an evaluation of the probability of k-hop connectivity in a homogeneous wireless multi-hop network was provided. The multi-hop network was modelled as a unit disk graph and the authors showed that the probability that two random nodes are k-hop neighbours and so are able to communicate is only determined by two parameters, i.e., the normalized distance and the average vertex degree. Li et al in [43] investigated the connectivity requirements in a wireless multi-hop network. A case of 1-dimensional ad hoc network was considered. The authors stated that the question of whether the network is connected or not is mathematically equivalent to testing the hypothesis that all physically adjacent nodes are within a certain distance from each other. Their study was based on the assertion that two nodes are connected directly if and only if the distance between them is less than or equal to the radio range. This assertion definitely ignores the physical layer attribute of wireless link. In [44], the authors evaluated the connectivity of a wireless multi-hop network in bounded area with a focus on the relationship between the transmission range, minimum node degree and connectivity. Other work on connectivity with simplistic physical layer assumptions includes [45]. However, some other research works based on realistic assumptions about the physical layer include [46], [47], [48], [49]. In [46], the authors focused on the impact of fading on the local and overall connectivity of nodes in static wireless ad hoc networks. Farhadi et al in [47] considered the effect of bit error rate performance on network connectivity in mobile ad-hoc networks. Kong et al in [48] provided a study of connectivity and transmission latency in wireless networks with unreliable links. In [49], the bit error rate (BER) performance and

connectivity characteristics of multi-hop ad hoc wireless networks were analyzed. The authors also analyzed the connectivity of the network, in terms of average sustainable number of hops.

2.2.1.2 Motivation for research on connectivity in inter-working multi-hop wireless networks

The analysis, models, frameworks and techniques in the mentioned research studies are not applicable in inter-working multi-hop wireless networks due to the following reasons:

Firstly, the scope of the research work is limited to single multi-hop networks with single-mode nodes, whereas, an inter-working multi-hop wireless network may consist of multiple networks operating with different networking standards e.g. physical and MAC layer techniques. As supported by [50], the results of these studies are not easily generalizable to inter-working multi-hop wireless networks due to the multi characteristics of such networks. Therefore, it is desirable to study connectivity in the light of the attributes of an inter-working multi-hop wireless network.

Secondly, similar to wired and cellular networks, the notion of connectivity in some of the mentioned research works has been taken as a case of full connectivity, where all the nodes in the network are connected to a central station and thus creating a fully connected network. The classical notion of connectivity [51] says that a network is connected so long as there is a path between any pair of nodes. However, according to [52], full connectivity in multi-hop wireless network can be very expensive, as the maximal power will have to be large enough to connect the most isolated node to the network. This could yield rather poor performances for large networks such as inter-working multi-hop wireless networks. Dousse et al in [52] also stated that some wireless multi-hop networks do not necessarily require full connectivity of all the nodes of the networks as in practice many routing protocols do not exhaustively search all the routes in a network. From our own perspective, inter-working multi-hop wireless networks can be classified

under such category. Thus, it is desirable to re-define the notion of connectivity and use connectivity as a routing metric for inter-working multi-hop wireless networks.

Third, these effort only dealt with single multi-hop networks, they did not study the effect of inter-node interference in an inter-domain multi-hop scenario. Interference is an important factor to be considered in achieving last-mile connectivity between communicating nodes in inter-working multi-hop wireless networks. For example, even if an end-to-end route exists for some time between two multi-hop nodes, channel impairments due to inter-node interference may affect the routing of traffic. Thus, end-to-end connectivity in wireless multi-hop networks may be intermittent [53]. In this case using link-to-link connectivity in order to achieve an end-to-end connectivity is desirable.

Another plausible observation in some of the research works outlined is that the multi-hop wireless network has been modeled with a deterministic model (e.g. graph model). A wireless network has been represented as graph consisting of vertices and edges. The vertices are the nodes and the edges are a set of directed links. However, such models are only applicable when the classical notion of connectivity is taken. In addition, since a wireless environment is stochastic, it cannot be adequately represented as a graph of vertices and edges. In order to be able to represent a wireless network properly, the randomness in the network must be modelled. The randomness in the network is caused by propagation conditions, interference, location of nodes etc. The graph model also forces the assumption that a transmission will be successful between two nodes once they are within each other's range and thus a network is connected if each pair of node in the network are within each other's range. These research works have modelled the multi-hop network with this assumption. Due to the nature of a wireless network, communication links can sometimes be unreliable to guarantee successful communication

between two nodes. Even when two multi-hop nodes lie within each other's transmission range, a reliable communication link may not exist between the two nodes [54]. Hence, the quality of the transmission that a link can provide needs to be considered.

For this research, we have taken into account the random location of nodes, propagation conditions, and the effect of interference on bit error probability in modelling an inter-working multi-hop network. In addition, the notion of connectivity has been redefined because the existence of a connecting link between two nodes is affected by the location of its surrounding nodes (gateway node/other multi-hop node) and also the condition of the link. If any two nodes are within each other's transmission range, then a link is available for them to communicate, however, this link will only be said to provide connectivity if the quality of the link can guarantee the minimum requirement for successful transmission in the network. Thus, in this research, connectivity is mutually dependent on the availability and reliability of a link.

In the mentioned research works, the mobile terminals in the networks are homogenous whereas the mobile terminals in an inter-working multi-hop wireless network as depicted in figure 1.2 may be heterogeneous.

Some of the research works have assumed fixed regular network topology for multi-hop wireless networks. This is not a valid assumption for a stochastic environment like multi-hop wireless networks in which nodes are randomly placed and the topology is unpredictable.

Research studies that seem related to our research includes [55] and [56]. [55] considered the inter-working of wireless mesh networks. However, the authors modeled the inter-worked networks as a graph. In [56], the authors considered the integration of both single hop and multi-hop wireless networks; however, their model did not take the effect of interference into account.

The multi-layer traffic engineering framework presented in this dissertation encompasses

metrics on the physical and MAC layer that affects traffic engineering in inter-working multi-hop wireless networks. We disintegrate the traffic engineering problem by looking into the issue of connectivity in inter-working multi-hop wireless networks, which has not been studied. We have defined connectivity as the probability that a link is available and reliable (with high non-impairment probability) enough to ensure successful transmission. We provide analytical probabilistic models for availability, non-impairment probability and connectivity in inter-working multi-hop wireless networks. Finally, we use connectivity as a metric for routing within the inter-working multi-hop wireless networks. The nodes within the network are a mix of single-mode and multi-modal nodes.

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Chapter 3 Research Methodology

Since the methodology of this research involves both analytical and simulation work, this chapter discusses and presents the fundamental models that were used for the development of the analytical models for the multi-layer traffic engineering framework presented in chapter 4 Network models.

Several factors affect the performance of an inter-working multi-hop wireless network. Some of these include node distribution, propagation condition and interference. Specifically, since the interference and the signal strength at a receiver depends on the distribution of nodes (especially the interfering transmitters) mathematical techniques are needed to explicitly model the node distribution. Therefore, this chapter discusses the fundamental models which have been used in this research. These models include a model for the spatial distribution of nodes in the inter-working network, the inter-working network model, the node protocol architecture model, and the propagation model. These models provide a background for the analytical studies of an inter-working multi-hop wireless network.

3.1.1 Node distribution

The geometry of the wireless network and its structural fluctuations are usually far from being regular and are critical parameters that greatly influence its performance. One of the factors that causes fluctuation in such networks is the distribution of nodes. In a network consisting of mobile nodes, nodes' locations are completely unknown a priori and hence their distribution is random. The irregular location of nodes, which is influenced by factors like mobility or unplanned location of the nodes may be considered as a realization of a Spatial Point

Pattern [57] [58]. The spatial point pattern model of concern in this research is the Poisson Point Process, which is discussed in the next sub sections.

3.1.2 Spatial Point Pattern

To capture the stochastic nature of an inter-working multi-hop wireless networks it is necessary to appropriately represent the components of the network. This can be done with probabilistic models based on spatial point patterns. A probabilistic model adequately reflects the network variability, which is particularly relevant for multi-hop networks.

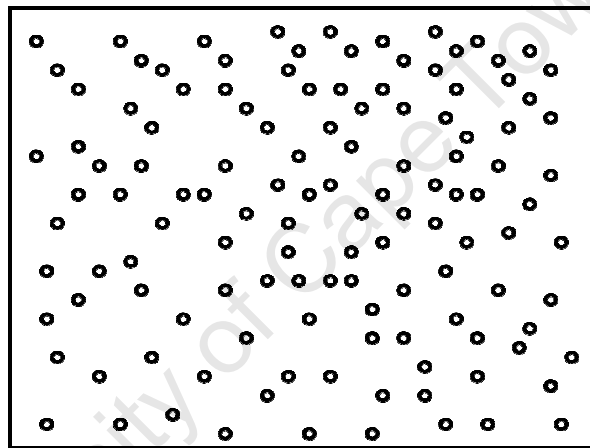


Figure 3.1 Spatial Point Pattern

Stochastic patterns are said to be formed by a set of points that are irregularly distributed within a region of space. Such patterns are known as spatial point pattern as illustrated in figure 3.1. The lack of independence between the points that make up the pattern is called complete spatial randomness (CSR) [59]. The theories of CSR are used to analyze spatial point patterns in biological sciences and are also applicable to wireless networks [60].

A spatial point pattern can be referred to as a finite or countably-infinite set of points or events, irregularly or randomly distributed within a designated region and presumed to have been

generated by some form of stochastic mechanism [59][60]. In most applications, the designation is essentially on planar \mathbb{R}^d (e.g. $d=2$ for two-dimensional) Euclidean space [59].

A point process is a statistical model that captures the characteristics of spatial point patterns in a finite number of parameters [61]. It is a random process whose values are composed of spatial point patterns on a set S . For a complete spatial random process, each point is an “event” and events corresponding to such a process are independent. Theoretically, a point process can be defined as:

Definition 3.1.2

$Y = \{Y_s\}_{s \in S}$ is a point process in the Euclidean space of \mathbb{R}^2 , if $\{Y_s\}$ is a sequence of random events with values and located in \mathbb{R}^2 , and $Y(W) = \#\{s: Y_s \in W\}$ denotes the number of points Y_s of Y located in a window $W \subset \mathbb{R}^2$ [62].

3.1.3 Poisson Point processes

The point process is a Poisson Point Process if the number of events in any fixed observation window is Poisson distributed[62]. In a Poisson point process, points are independently scattered, implying complete spatial randomness. As a result, only a single parameter, the intensity λ (the mean number of points per unit area), is necessary to characterize a Poisson point process [63].

Definition 3.1.3

A point process Y is called a Poisson point process with intensity λ if the random variable $Y(W)$ is Poisson distributed with expectation $\lambda|W|$ for any window $W \subset \mathbb{R}^2$, where $|W|$ denotes the area of W and the random variables $Y(W_1), Y(W_2), \dots, Y(W_n)$ are independent for any sequence of pair-wise disjoint windows W_1, W_2, \dots, W_n [62].

According to the theory of CSR for a spatial point pattern, it follows that the probability of $Y(W)$ points being inside a \mathbb{R}^2 Euclidean plane, given by equation 1 depends on the area of the region $|W|$ and not on the shape or location of the plane.

$$\Pr(Y(W) \text{ in } \mathfrak{R}^2) = \frac{(\lambda |W|)^{Y(W)}}{(Y(W))!} e^{-\lambda|W|}, Y(W) > 0. \quad \mathbf{1}$$

From theory, these points can be said to form a realization of a Homogeneous Poisson Point Process (HPPP).

3.1.4 Properties of Poisson Point Process

Two properties of the homogeneous Poisson point process which are applicable in the context of this dissertation are the merging and splitting of Poisson processes.

3.1.4.1 Merging Poisson Point process

Theorem 3.1.4.1

For all $d > 1$ and for all $\lambda > 0$, the superposition or merging of N independent homogeneous Poisson process on \mathbb{R}^d with intensities λ_i (for $i = 1, 2, 3, \dots, N$) is a Poisson process with intensity $\lambda = \sum_i \lambda_i$.

Consider two Poisson processes Y_1 , with intensity λ_1 and Y_2 , with intensity λ_2 . Merging these two independent Poisson processes creates a Poisson process $Y = Y_1 + Y_2$, with intensity $\lambda_1 + \lambda_2$ [64].

Proof: adapted from [65].

Let $Y_1 \sim \text{Poisson}(\lambda_1(\tau))$ and $Y_2 \sim \text{Poisson}(\lambda_2(\tau))$

Characteristic function:

$$\psi_{Y_1}(z) = e^{\lambda_1 \tau (z-1)}$$

$$\begin{aligned}\psi_{Y_2}(z) &= e^{\lambda_2\tau(z-1)} \\ \psi_Y(z) &= \psi_{Y_1}(z)\psi_{Y_2}(z) \\ &= e^{\lambda_1\tau(z-1)}e^{\lambda_2\tau(z-1)} \\ &= e^{(\lambda_1+\lambda_2)\tau(z-1)}\end{aligned}$$

Therefore, $Y \sim \text{Poisson}((\lambda_1+\lambda_2)\tau) \Rightarrow$ Poisson process Y has intensity $\lambda_1+\lambda_2$.

3.1.4.2 Splitting Poisson process

Given a homogeneous Poisson process on \mathbb{R}^d with intensity λ , it is possible to partition the points into several sets of points so that each set of points forms a homogeneous Poisson process, with a given intensity all summing to λ [66][67].

Theorem 3.1.4.2

For all $d > 1$ and for all $\lambda > \lambda_i > 0$, if a homogeneous Poisson point process Y on \mathbb{R}^d with intensity λ is randomly split into N independent sub-processes with probabilities P_i for $i = 1, \dots, N$, such that, $P_1 + P_2 + P_3 + \dots + P_N = 1$, then these sub-processes are mutually independent homogeneous Poisson processes on \mathbb{R}^d with intensities $\lambda_i = \lambda P_i$ where $\lambda = \lambda_1 + \lambda_2 + \lambda_3 + \dots + \lambda_N$ [64].

Consider a Poisson processes Y with intensity $\lambda(z)$. Randomly splitting Y into two sub-processes Y_1 with probability p and Y_2 with probability $1-p$, creates two Poisson processes with intensity λp and $\lambda(1-p)$.

Proof: adapted from [65]

Let $Y \sim \text{Poisson}(\lambda\tau)$

$$(Y_1, Y_2 | Y) \sim \text{Multinomial}(Y, p, 1 - p)$$

$$\psi_{Y_1 Y_2}(z_1 z_2 | Y) = E(z_1^{Y_1} z_2^{Y_2} | Y)$$

$$\begin{aligned}
&= (pz_1 + (1-p)z_2)^Y \\
\psi_{Y_1 Y_2}(z_1 z_2) &= E_Y(\psi_{Y_1 Y_2}((z_1 z_2 | Y)) \\
&= E(pz_1 + (1-p)z_2)^Y \\
&= \psi_Y(pz_1 + (1-p)z_2) \\
\psi_Y(z) &= e^{\lambda\tau(z-1)} \\
\psi_{Y_1 Y_2}(z_1 z_2) &= \psi_Y(pz_1 + (1-p)z_2) \\
&= e^{\lambda\tau[(pz_1 + (1-p)z_2) - 1]} \\
&= e^{\lambda\tau[p(z_1 - 1) + (1-p)(z_2 - 1)]} \\
&= e^{p\lambda\tau(z_1 - 1)} e^{(1-p)\lambda\tau(z_2 - 1)}
\end{aligned}$$

Therefore, $Y_1 \sim \text{Poisson}(p\lambda\tau) \Rightarrow$ Poisson process Y_1 has intensity $p\lambda$ and

$Y_2 \sim \text{Poisson}((1-p)\lambda\tau) \Rightarrow$ Poisson process Y_2 has intensity $(1-p)\lambda$

Where, Y_1 and Y_2 are two independent homogeneous Poisson point sub-processes.

Since nodes are independently located and their location are unknown a priori, in this research we assume that nodes' positions are completely random and are distributed according to a homogeneous Poisson point process (HPPP) in two dimensional plane (\mathbb{R}^2). Therefore, only a single parameter, μ (which denotes the mean number of nodes per unit area in the two dimensional space) is necessary to characterize the node distribution process. HPPP is a fundamental point process that is easy to handle analytically and its use leads to interference models that are more general than the Gaussian model and better suited to the multi-hop network [68][69]. Poisson process' application to nodes' positions modelling in wireless environments was firstly done in [68] and then in [70]. It is a widely accepted model for characterizing the

spatial distribution of nodes in wireless networks [69] [71] [72] [73] [74] [75]. The authors of [69] proved that if the node positions are modelled with Poisson point process, parameters such as the spatial distribution of nodes, transmission characteristics and the propagation characteristics of the wireless link can be easily accounted for.

3.1.5 Inter-working multi-hop wireless network model

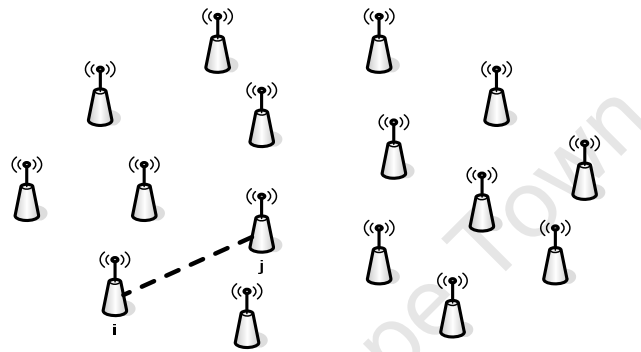


Figure 3.2 Nodes within a multi-hop wireless network

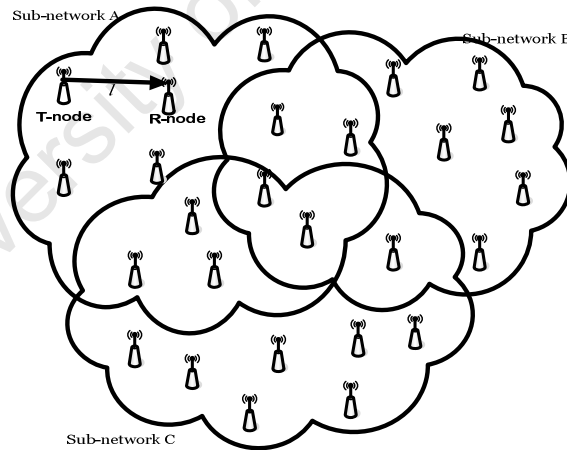


Figure 3.3 Inter-working multi-hop wireless network model [57]

In this section, the inter-working multi-hop wireless network model developed for the purpose of this research is briefly presented. The model is based on the properties of the Poisson process discussed in the previous sections. Figure 3.2 represents the single multi-hop wireless networks (i.e. sub-networks W, X, Y), that are inter-working. The inter-working network is

represented by Ω . The nodes in each network are contained in a Euclidean space of 2-dimensions (\mathbb{R}^2), and the total number of nodes in the inter-working network (Ω) is denoted by N_{Ω} . The number of nodes in each sub-networks are W_a , X_b and Y_c respectively, where $W_a + X_b + Y_c = N_{\Omega}$. The mean number of nodes per unit area (spatial node density) of each sub-network is given by μ_W , μ_X , μ_Y (μ is in nodes /unit square and it is given by *(number of nodes in a sub-network)/(coverage area of the sub-network)*).

The sub-networks W , X , Y are independent Poisson point processes and each contain random and independently positioned nodes. Each network has a set of independently positioned nodes that it services as in figure 3.2. When these networks overlap as illustrated in figure 3.3, the nodes that are being served remain independently positioned. The fact that the networks are overlapping does not necessarily mean that the nodes being serviced by sub-network W can be serviced directly by sub-network X . However, nodes can be serviced by any sub-network when the networks are inter-networked to create the deployment scenario described in figure 1.2. Therefore, in order to create the deployment scenario in figure 1.2, we apply theorem 3.1.4.1 to merge sub-networks W , X , and Y to create an inter-working multi-hop wireless network. As stated in theorem 3.1.4.1, initially independent Poisson point processes such as sub-networks W , X , and Y can be merged to form a single Poisson point process. Thus, after these networks (independent Poisson Point processes) are merged, the spatial node density of the inter-working network can be expressed as $\mu_{Net} = \mu_W + \mu_X + \mu_Y$.

An inter-domain co-ordination exists between these networks and nodes in the network may communicate in a multi-hop manner. A node that originates traffic (source-node) at any point is referred to as the transmitter-node (T-node) while a node for which the traffic is destined (destination-node) is referred to as the receiver-node (R-node). The links between nodes are

represented by $\{l : l = 1, 2, \dots\} \subseteq L$, where L is the set of all links in the entire network. The length of a communication link is represented by $\beta_{T,R}$ (T denotes the transmitter-node and R denotes the receiver-node on the link). The transmission range of each of the nodes is R_o and the distance ($\beta_{T,R}$) between any T -node and R -node in the network is given by $\beta_{T,R} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$ where (x_i, y_i) and (x_j, y_j) represents the location of the T -node and R -node respectively. Note that $\beta_{T,R}$ refers to the distance between specific communicating node pairs. The distance may be a single hop distance between the nodes and it may be the total of the single hop distance that make up the multi-hop distance between any source-destination pair.

3.1.6 Node degree

Concerning the analysis of spatial point pattern, the distribution theory of the nodes under complete spatial randomness is well known under the theory of the Nearest Neighbor Distance (NND) [66]. The degree of a node in wireless multi-hop networks is defined as the number of neighbour nodes that it has [76]. A node is said to be a neighbour node to another node if the distance between the two nodes is less than or equal to their transmission range, which means that both nodes have a direct link (1-hop link) to each other. Therefore, a node's degree is the number of nodes within its transmission range or the number of nodes within its 1-hop vicinity.

The degree of a node is denoted by $D(\cdot)$. In an instance where for a node, $D(\cdot)=0$, the node is termed a "lone node". The existence of a "lone node" in a multi-hop wireless network is an undesirable condition [54]. Although a lone node may be useless in terms of connectivity in a static multi-hop wireless network, yet in a mobile scenario, it becomes useful as it moves into the transmission range of another node or when another node moves into the node's transmission

range . The desirable condition for connectivity in a multi-hop wireless network is for all nodes to have $D(.) > 0$. The probability that $D(.) > 0$ for any node is given by equation 2 [57]. R_o is the transmission range of the node and $f(x)$ is the probability density function (PDF) of the distance between any two nodes in an inter-working multi-hop wireless network.

$$\Pr(D(.) > 0) = \int_0^{R_o} f(x) dx \quad 2$$

$f(x)$ depends on the distribution of the nodes in the network. Equation 2 provides a foundation for the link availability model developed in chapter 4.

3.1.7 Node model

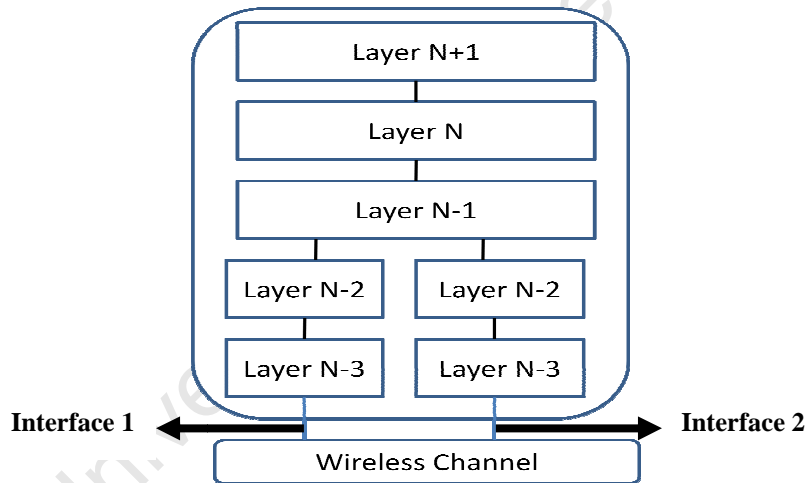


Figure 3.4 Generic protocol stack architecture for a multi-technology mobile terminal

This section describes the communication protocol architecture of multi-technology mobile terminals. Figure 3.4 shows a generic communication protocol architecture for a multi-technology mobile terminal (node) with two interfaces. For the purpose of this research, some nodes are single-mode nodes while others are multi-mode. Multi-mode nodes are mobile terminals equipped with multiple communication interfaces with each interface operating a different wireless communication technology standard. In other words, these nodes have the

ability to operate in multiple modes. For example, these nodes can have multiple interfaces that could be a combination of any of the 3G, WiMAX or IEEE 802.11 standards. Thus, a node may consist of dual physical and medium access control (MAC) layers as shown in figure 3.4. Single-mode nodes have only one communication interface and operates with only one wireless communication technology standard.

A network scenario in which nodes have the same physical layer design is termed homogeneous. A heterogeneous case occurs when nodes use different physical layer techniques. In this dissertation, nodes are able to transmit signals at power levels, which are random and independent between nodes.

3.1.8 Propagation model

The received signal strength per node is predicted with the free space propagation model. For any packet transmitted by a T-node and received by an R-node on link l , the Friis equation in 3 gives the actual received power at the R-node.

$$P_l^r = c P_l^t A_l = c P_l^t (\beta_{T,R})^{-\alpha}$$

$$\left[c = \frac{G_t G_r \lambda_c^2}{(4\pi)^2 L_f} \right] \quad 3$$

On link l , P_l^t is the power transmitted by the T-node, P_l^r is the power received by the R-node, G_t and G_r are the transmitter and receiver gain respectively. The wavelength, $\lambda_c = c/f_c$ (where c is the speed of light and f_c is the carrier frequency) and L_f is the system loss factor (where $L_f \geq 1$).

To account for path-loss, the channel attenuation for link l is denoted by A_l . Path-loss is an attenuation effect, which results in the reduction of the transmitted signal power in proportion to the propagation distance over a certain link. It is typically given that the received power from a T-node at distance $\beta_{T,R}$ from the R-node decays exponentially as $(\beta_{T,R})^{-\alpha}$. The path loss

exponent (α) represents the exponential decay of the transmitted power. It depends on the environment and could be a constant between 2 and 6.² Taking $\alpha=2$, then, $A_I = (\beta_{T,R})^{-2}$. The exponential decay of power makes it possible to consider interference from nodes located at a far distance from the R-node as negligible.

In this dissertation, it is assumed that the randomness in the distance between nodes, irrespective of the topology of the network captures the movement of nodes. The movement of a node from one point to another changes its location and consequently its distance to a reference node³. Thus, the variation in the distances between any T-node and an R-node is highly coupled with the movement of the nodes [77].

² In free space $\alpha=2$

³ Reference node refers to the receiver node (R-node) on the link for which interference is being measured.

Chapter 4 Analytical Models for the Multi-layer Traffic Engineering framework

This chapter presents the analytical models that is derived for the multi-layer traffic engineering framework for inter-working multi-hop wireless networks and the numerical results obtained. These models are the link availability model, a model for determining the non-impairment probability on available links and the connectivity model. The connectivity model provides the connectivity metric for routing in inter-working multi-hop wireless networks. The chapter has three main sections. As a link's availability must first be determined before evaluating the non-impairment probability on such links, the first section presents the mathematical analysis leading to the link and route availability models. The second section provides the analysis for the non-impairment probability while the last section presents the connectivity model.

4.1 The concept of availability

In this research, availability means that two node pairs are within at most the maximum transmission range that is sufficient for a communication link to be established between them. Ultimately, it is determined by the probability that at least a node exists within a certain distance range (equal to the maximum transmission range) of/from a particular node [57]. In a wireless network, the availability of a link between node pairs depends on the distance between them, their transmission range and the network's node density. It is only after confirming the availability (existence) of a link that the non-impairment level metrics (e.g. probability of interference, interference power, SNIR, and probability of bit error) on the link can be evaluated. The probability that a route is available between source-destination pair depends on the probability that intermediate nodes en-route to the destination have a link to another node closer

to the destination node. Route availability is the probability that adequate links exist in order to form a communication path between a source-destination pair exists [57].

In the next subsections, an analysis of link distance distribution, the link availability model and the inter-dependency that exists between link and route availability in inter-working multi-hop wireless networks are presented. The analysis is needed to determine the availability of a route for packet transmission. To avoid ambiguity, a link refers to the 1-hop communication connection between any node pair in the network, while a route refers to the multi-hop communication connection path between any source and destination pair [54]. If the 1-hop receiver node is not the final destination then a multi-hop communication path will be established.

4.2 Link distance distribution

The knowledge of inter-nodal distance distribution (link distance distribution) between nodes in a multi-hop wireless network is essential for the design of optimal network protocols and algorithm. Also, it is known that the strength of the received signal at an R-node decreases with distance according to the power law and consequently impacts the SNIR and non-impairment probability on a link. Therefore, having information about the inter-nodal distances can allow an optimization of the routing process in multi-hop networks.

Theorem 4.2.1

For a Homogeneous Poisson Point Process in \mathbf{R}^2 , the probability that there are no nodes within a distance x of an arbitrary node is $e^{-\lambda\pi x^2}$, where the parameter λ is the mean number of points per unit area [57] [58].

With $\beta_{(T,R)}$ being the link distance between a T-node and its nearest neighbor (a potential R-node), using theorem 4.2.1 stated above, the probability that $\beta_{T,R} > R_o$ and the $\beta_{T,R} \leq R_o$ is

evaluated. For any t-node within the network in figure 3.3, theorem 4.2.1 applies in the following ways:

- 1) The probability that a T-node has no neighbour, i.e., the probability that there are no nodes within a distance $\beta_{(T,R)} \leq R_o$ or the distance between a T-node and its nearest neighbour nodes is greater than the T- node's transmission range, is given by [57]:

$$\Pr(D(.) = 0) \Rightarrow \Pr(\beta_{T,R} > R_o) = e^{-\mu_{Net}\pi R_o^2} \quad \forall R_o > 0 \quad \mathbf{4}$$

- 2) The probability that a T-node has at least one neighbour (i.e. the probability that there are nodes within a distance $\beta_{(T,R)} \leq R_o$ or the distance between a T-node and its nearest neighbour nodes is less than the T- node's transmission range) is given by [57]:

$$\Pr(D(.) > 0) \Rightarrow \Pr(\beta_{T,R} \leq R_o) = 1 - e^{-\mu_{Net}\pi R_o^2} \quad \forall R_o > 0 \quad \mathbf{5}$$

Equation 5 represents the cumulative distribution function (CDF) of the distance between any two randomly positioned nodes in the network in figure 3.3. The CDF is represented by $F_\beta(R_o)$. Equation 5 also represents the probability that a link exists between a T-node and an R-node. Assuming that links become non-existent independently, this quantity can be taken as the probability that a link exists in a binomial trial. If a trial is repeated q times, then we can estimate the number of existing links for any node as $q \times F_{\beta_{T,R}}(R_o)$.

4.3 Availability model

4.3.1 Link availability model

A probabilistic model that provides knowledge about the availability of communication path could decrease the frequency of path failure that may be experienced during a routing

process. Routing metrics based in part on such probabilistic model can enhance the provisioning of ubiquitous service continuity in inter-working multi-hop wireless networks.

The probability that a communication link is available for any node is related to the link distance distribution [78]. In addition, the probability that a multi-hop communication path is available is related to the availability of the individual links that make up the path. This section presents the link and route availability models.

As long as $\beta_{T,R} \leq R_o$, a link is available (exists) between any two arbitrary nodes. Therefore, the CDF of the link distance $\beta_{T,R}$ can be taken as the probability that at least a link is available for transmission. Thus, the availability of a link in a network is a function of R_o , $\beta_{T,R}$ and μ_{Net} in the network [57]. If P_{link} represents the availability of a 1-hop link for any node in the network, then, P_{link} can be expressed as:

$$\therefore P_{link} = \begin{cases} 1 - e^{-\mu_{Net} \pi R_o^2} & \forall 0 < \beta_{T,R} \leq R_o \\ 0 & \forall \beta_{T,R} > R_o \end{cases} \quad \mathbf{6}$$

Considering the network scenario of figure 3.3 with spatially located nodes in which $N_\Omega = 20$ nodes in a 10 square units area, figure 4.1 illustrates the availability of a link as the value of R_o increases. When $R_o = 0.2$, only 22.2% of the total nodes are available for a one-hop link to any node and 99.8% of nodes are available if $R_o = 1$. All (100%) of the links are available once $R_o > 1$, which means that every node has a link to all other nodes in the network. The network is fully connected if all nodes have a link to every other node in the network. At high transmission power, more nodes are available.

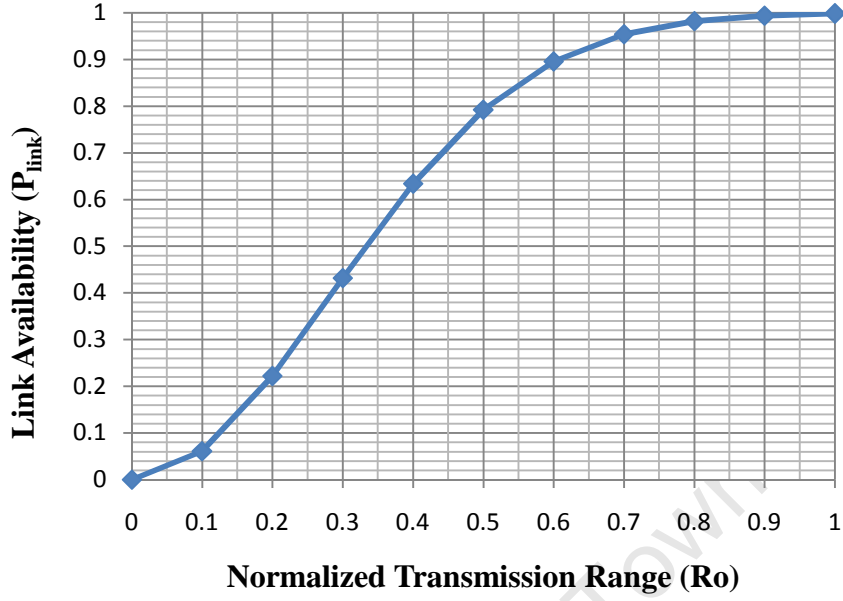


Figure 4.1 Link Availability (P_{link}) vs Normalized Transmission Range (R_o)

Figure 4.1 shows that P_{link} is a monotonically increasing function. Consequently, in a multi-hop network, as R_o increases, P_{link} increases. The number of potentially available 1-hop link for a T-node, given its transmission radius can be expressed as $q \times P_{link}$ (where $q=N_{\Omega}-1$). q is the maximum number of nodes that any other node can potentially have a 1-hop communication with.

From Poisson distribution, equation 5 is analogous to equation 7, which is the probability of at least one node within a node's radio coverage area of πR_o^2 , for any value of $R_o > 0$. The probability that the degree of a node is equal to n is expressed in equation 8.

$$\Pr(D(.) > 0) = \sum_{n=1}^{N-1} \frac{(\mu_{Net} \pi R_o^2)^n}{n!} e^{-\mu_{Net} \pi R_o^2} \quad \forall R_o > 0 \quad 7$$

$$\Pr(D(.) = n) = \frac{(\mu_{Net} \pi R_o^2)^n}{n!} e^{-\mu_{Net} \pi R_o^2} \quad \forall R_o > 0 \quad 8$$

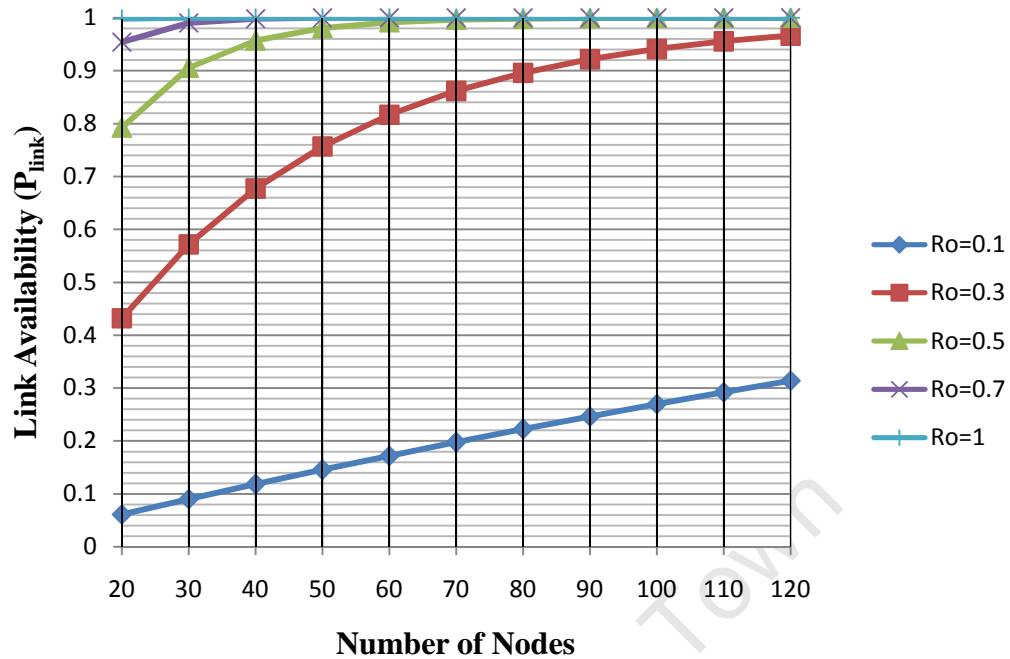


Figure 4.2 Link Availability vs Number of Nodes for different values of R

Figure 4.2 gives a plot of P_{link} at fixed R_o of values 0.1, 0.3, 0.5, 0.7 and 1 as the number of nodes in the network increases from 20 nodes to 120 nodes. Generally, P_{link} increases as the number of nodes increases; indicating that the probability of having an available link is higher in dense networks. For high values of R_o , the P_{link} is at very high values for high number of nodes in the network. Assuming R_o is the same for all nodes, then $\beta_{T,R}$ takes on values upper bounded by R_o if P_{link} is greater than zero.

4.3.2 Route availability model



Figure 4.3 A Sub-network

The route availability model presented here does not yet take into consideration the quality of links. The model only shows the probability that a route of specific number of hops could be available between two nodes taking into consideration the transmission range, distance between nodes and node density. We also provide a model to find the probability that at least a route will exist between two communicating nodes irrespective of the number of hops on the route.

If $\beta_{T,R}$ is greater than R_o , then from equation 6, $P_{link}=0$. Therefore a multi-link (multi-hop) route has to be utilized for packet transmission. In this case, multi-hop routes in the direction of the final destination are used. To ensure end to end route availability, each intermediate node on the route must have at least two neighbour nodes as shown in figure 4.3. These two neighbours are for the purpose of packet reception from the preceding node and packet transmission to the subsequent node [54]. For simplicity, we denote all inter-nodal distance greater than R_o by β .

Let ℓ represent the links (or hops) between any two nodes in the network, where $l \in L$ and L is the set of all links that exists in the network. If a transmitted packet from a node have to hop on a total of ℓ links before arriving at the destination node, $\ell-1$ intermediate nodes would be required on this route. The number of hops depends on the multi-hopdistance between the two nodes (β) and the transmission range (R_o) of the T-node and the intermediate nodes. For analytical tractability, the transmission ranges of all nodes in the network are assumed to be the same. Thus, the minimum number of links (hops) that can connect any two nodes together is:

$$\ell = \left\lceil \frac{\beta}{R_o} \right\rceil \quad \mathbf{9}$$

With the assumption that R_o for all nodes are equal, a bound exists for ℓ . The bound occurs when β is equal to β_{max} , where β_{max} is the maximum multi-hop distance that can be

between any source and destination node pairs in the network. In this case, the maximum number of hops $\ell_{\max} = \beta_{\max} / R_o$ cannot be exceeded.

Figure 4.4 shows a plot of the number of hops versus the distance between a source-destination node pair. As in section 4.3.1, a 20 node network with an area of 10 square units has been considered. The value of β was increased from 0.2 units to 1.8 units, while the number of hops was observed for constant transmission range ($R_o = 0.2, 0.3, 0.6$ and 0.7). Figure 6 confirms that the longer the distance between node pairs relative to their transmission range, the more the number of hops (links) that will be utilized to transmit a packet from source to destination. Equation 10 summarizes the minimum number of hops (ℓ_{\min}) for different values of β , and a general expression for evaluating ℓ_{\min} is obtained.

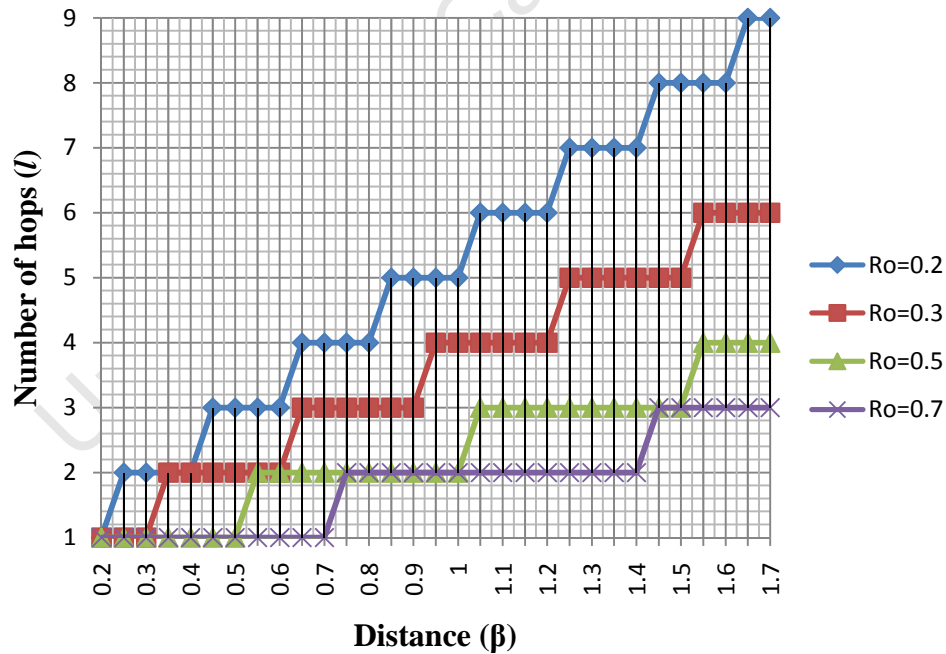


Figure 4.4 Number of hops (l) vs distance between nodes

$$\sum_{n=1}^{N-1} \frac{(\mu_{Net} \pi(\ell R_o)^2)^n}{n!} e^{-\mu_{Net} \pi(\ell R_o)^2} - \sum_{n=1}^{N-1} \frac{(\mu_{Net} \pi((\ell-1)R_o)^2)^n}{n!} e^{-\mu_{Net} \pi((\ell-1)R_o)^2} \quad \mathbf{11}$$

For condition (3), let A_{int} be the area of intersection of the transmission ranges of any two nodes along the route, which are 2-hops away from each other. From [79] A_{int} can be expressed as:

$$A_{\text{int}} = R_o^2 \left[2 \cos^{-1} \left(\frac{\beta}{2R_o} \right) - \sin \left(2 \cos^{-1} \left(\frac{\beta}{2R_o} \right) \right) \right] \quad \mathbf{12}$$

The probability of at least one node in area A_{int} , where n_{int} is the number of nodes in area (A_{int}) is:

$$\Pr(n_{\text{int}} > 0) = 1 - e^{-\mu_{Net} A_{\text{int}}} \quad \forall A_{\text{int}} > 0 \quad \mathbf{13}$$

For an ℓ -hop route, equation 13 is expressed as:

$$\Pr(n_{\text{int}} > 0) = (1 - e^{-\mu_{Net} A_{\text{int}}})^{\ell-1} \quad \forall A_{\text{int}} > 0 \quad \mathbf{14}$$

Finally, the probability of an ℓ -hop route, ($P_{\ell\text{-hop route}}$) between X_i and X_j is given by the multiplication of equation 11 and 14. However, as the network's node density increases, for constant R_o , equation 14 tends towards 1. From equation 4, 7 and 11, an asymptotic probability for an ℓ -hop route can be evaluated with equation 15.

$$\begin{aligned} P_{\ell\text{-hop route}} &= \left(1 - e^{-\mu_{Net} \pi(\ell R_o)^2} \right) - \left(1 - e^{-\mu_{Net} \pi((\ell-1)R_o)^2} \right) \\ &= e^{-\mu_{Net} \pi((\ell-1)R_o)^2} - e^{-\mu_{Net} \pi(\ell R_o)^2} \end{aligned} \quad \mathbf{15}$$

When $\ell=1$, equation 15 gives the availability of a 1-hop link (P_{link}) in equation 6.

Let P_{route} denote the availability a route irrespective of the number of hops between the source and destination node. Equation 16 gives the route availability irrespective of the number of hops for $\beta/R_o \leq \ell \leq \ell_{\text{max}}$. P_{route} is the probability of having at least a 1-hop route between any pair of

source-destination node in the inter-working multi-hop wireless network. It depends on β (multi-hop distance between the source-destination nodes) and R_o (transmission range of nodes). Note this is based on an assumption that R_o is the same for all nodes.

$$P_{route} = \sum_{\ell=\frac{\beta}{R_o}}^{\ell_{max}} P_{\ell-hop\ route} \quad 16$$

4.4 Non-impairment probability model.

In multi-hop wireless networks, the choice of the next hop depends on the availability of a link between a node and its nearest neighbour node. Most importantly, an available link must also be reliable for a good quality communication between node pairs. One major characteristic of the wireless channel that affects the quality of communication is the variation in its strength over time and frequency. As a result of the variation, communication links in wireless networks tend to be unpredictable. Moreover, this variation affects the connectivity between two communicating nodes. This section presents the analytical model for the non-impairment probability developed in this research. In order to determine the non-impairment probability, the interference at the R-node on a link and the probability of bit error were analysed.

Non-impairment probability indicates the likelihood that the radio attributes of a link has the potential to satisfy the minimum requirement for successful communication over it. The minimum requirement is defined by the underlying network parameters and associated resource constraints of the network such as data rate, bit error probability and the signal to noise and interference ratio of the network. When fine-tuned, these network parameters physical and MAC layer parameters ensure the proper functioning of a link.

4.4.1 Evaluating Interference on a link

A link's signal to interference and noise ratio is evaluated using the SNIR model from [80] in equation 17. A transmitted signal (packet) at a data rate Ψ bps can only be correctly decoded by the R-node on link l if $\theta^{(l)}$ is not less than an appropriate threshold $\theta^{(th)}$ throughout the duration of transmission as stated in [81] and [82].

$$\theta^{(l)} = \frac{P_l^r}{P_{int}} = \frac{P_l^r}{P_{ini} + P_o} = \frac{cP_l^t (\beta_{T,R})^{-2}}{\sum_{k=1}^S cP^{t(k)} (\beta_{k,R})^{-2} + P_o} \quad 17$$

The total interference power experienced by the R-node at the end of link l (the link of interest) is represented by P_{int} . It is the sum of the noise power (P_o) and the inter-node interference power (P_{ini}). P_{ini} is the cumulative of the interference power that the R-node experiences from nodes concurrently transmitting with T-node. k (for all $k= 1, 2, 3, \dots, \infty$) represents potential interfering nodes while S is the total number of simultaneously transmitting nodes that contributes to the effective interference power. The transmitting power of a potential interfering node is given by $P^{t(k)}$ and $(\beta_{k,R})^{-2}$ is the distance between a potential interfering node and the R-node. For the evaluation of P_{ini} important parameters include, the probability of interference, the interfering node density, the distance between any potential interfering node and the R-node on link l , and interfering nodes' transmission power.. The noise power level at the R-node on link l is represented by P_o . This is given by: $P_o = FkT_oB$ where k is the Boltzman constant (1.38×10^{-23} J/°K/Hz), where T_o is the ambient temperature, B is the transmission bandwidth and F is the noise figure [83].

From the denominator of equation 17, inter-node interference contributes significantly to SNIR [84]. Using $G_t = G_r = 1$, $L_f = 1$, $f_c = 5.8$ GHz and keeping the transmission power of all

interfering node the same at 100mW (20dBm), figure 4.5 and 4.6 shows the effect of the increase in $\beta_{k,R}$ and S respectively on P_{ini} . If the power received by the R-node on the link of interest and the noise power level are constant, $\beta_{k,R}$ values are independent and identically distributed random variables (R.V.), which are distributed within the area of interference [84].

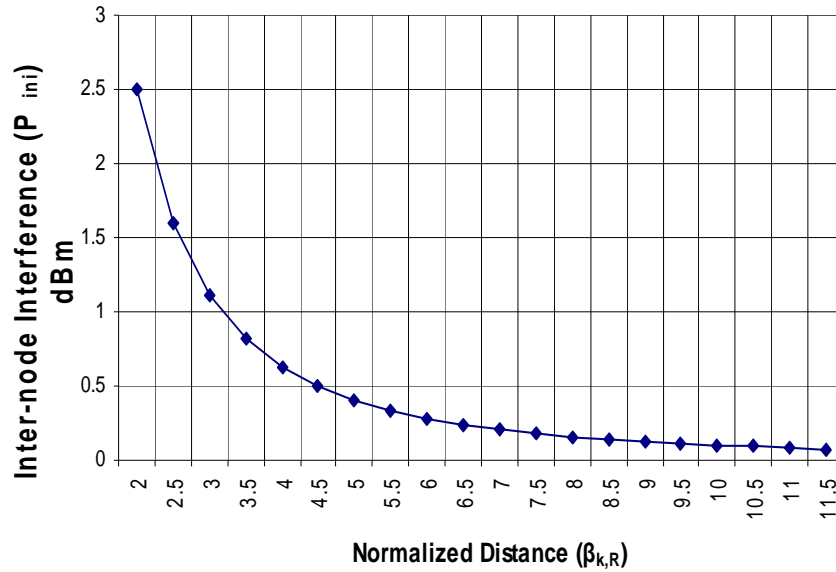


Figure 4.5 Inter-node Interference power vs $\beta_{k,R}$

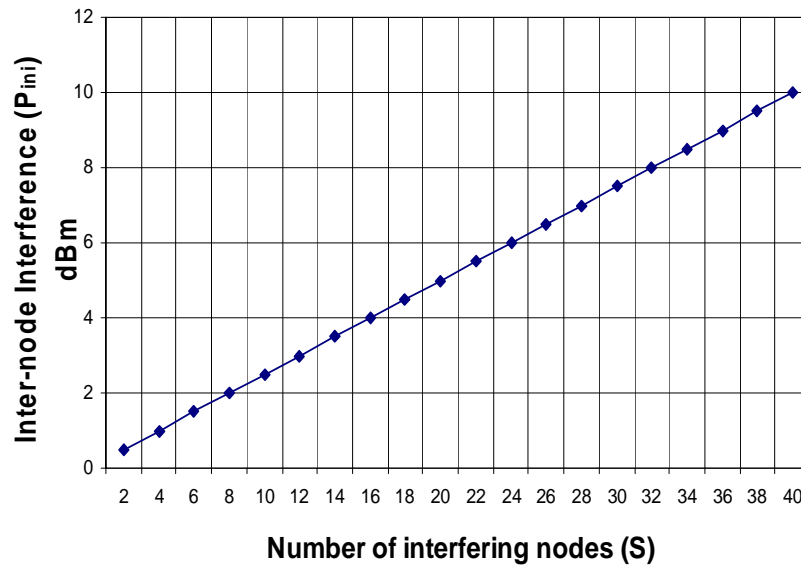


Figure 4.6 Inter-node Interference power vs number of interfering nodes

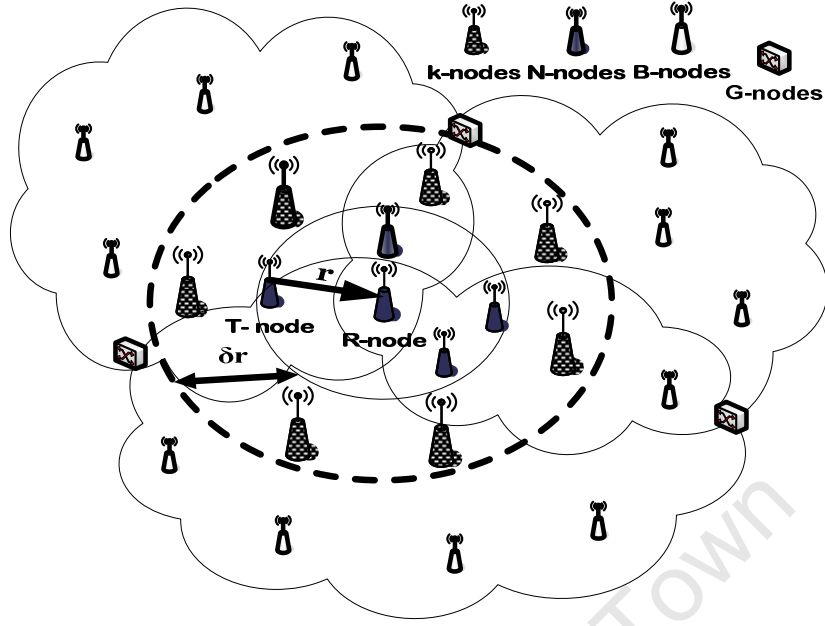


Figure 4.7 Representation of the transmission from a T-node to an R-node on link l with interfering nodes (k-nodes), non-interfering nodes (N-nodes), nodes beyond δr (B-nodes) and gateway nodes (G-nodes). $r = R_0$

Figure 4.5 shows the effect of these R.V's on P_{ini} . With a constant number of interfering nodes and varying $(\beta_{k,R})$, it can be observed that the higher the value of $\beta_{k,R}$, the smaller the P_{ini} . Figure 4.6 confirms that as S (the total number of k-nodes) increases, intuitively, P_{ini} increases. From here, an interference constraint can be defined for the inter-working network. Figure 4.7 illustrates the constraint, which is that nodes beyond a boundary $(r+\delta r)$ contribute negligible interference due to the exponential decay of power caused by signal attenuation. With this constraint, an inter-node interference region bounded by equation 18 is defined.

$$r < |\beta_{k,R}| \leq r + \delta r \tag{18}$$

For a particular link, an interference region (δr) is defined for the R-node on the link. Regardless of the position of the T-node, a node outside δr will not interfere with R-node's reception [84]. As shown in figure 4.5 and 4.7, a node will only interfere with the reception of

the R-node on link l if the distance of the node to the R-node fulfils the constraint in equation 18. $r = R_o$ represents the T-node's transmission range. According to [85] these nodes effectively contribute to the value of P_{ini} irrespective of the network topology or medium access technique. Normally, whenever a link is established between a T-node and an R-node, the MAC technique will prohibit nearby nodes in the network from simultaneous transmission. The portion of the network occupied by these nearby nodes is directly related to the size of r around the R- node [86].

Using the splitting property of the Poisson process in theorem 3.1.4.2⁴, let all nodes in the inter-working network, with spatial density μ_{Net} be sorted independently into 3 types, k-nodes, N-nodes, and B-nodes. If the probability of a node being an k-node, N-node or a B-node is P_I , P_N , or P_B respectively such that $P_I+P_N+P_B=1$, these three types of nodes are mutually independent Poisson processes with spatial densities: $\mu_I = P_I \mu_{Net}$, $\mu_N = P_N \mu_{Net}$, $\mu_B = P_B \mu_{Net}$ where $\mu_{Net} = \mu_I + \mu_N + \mu_B$. μ_I represents the spatial density of k-nodes (interfering nodes), μ_N is the spatial density of the N-nodes and μ_B is the spatial density of nodes beyond δr . From here, the effective density of k-nodes can be derived. If $\beta_{x,R}$ represents the link distance between the R-node and an arbitrary node x in the network, then:

$$\Pr(x \in N - nodes) = \Pr(|\beta_{x,R}| \leq r). \quad \mathbf{19a}$$

$$\Pr(x \in k - nodes) = \Pr(r < |\beta_{x,R}| \leq r + \delta r). \quad \mathbf{19b}$$

$$\Pr(x \in B - nodes) = \Pr(|\beta_{x,R}| > r + \delta r). \quad \mathbf{19c}$$

Note that if node x is a k-node, the $\beta_{x,R}$ becomes $\beta_{k,R}$. Due to the random geographic dispersion of nodes, P_{ini} also has a stochastic nature. Since several nodes can simultaneously

variations of instantaneously

transmit in the δr region and they altogether influence the value of P_{ini} , then $\theta^{(l)}$ (the SNIR on a link) can be estimated using the expected value of P_{ini} .

$$E[P_{ini}] = cP^{t(k)}E\left[\sum_{k=1}^S(\beta_{k,R})^{-2}\right]. \quad 20$$

In order to solve equation (20), the distribution function of the distance between the R-node and the k-nodes ($\beta_{k,R}$), given by $f_{\beta_{k,R}}(r)$, is of particular interest.

4.4.1.1 Distribution Function of $\beta_{k,R}$

As shown in figure 4.5, nodes that can potentially interfere with the R-node's reception lie in the region outside the range r . However, nodes beyond the region $(r+\delta r)$ cause negligible interference [87]. The region within δr consists of the effective k-nodes. In order to find the probability that the distance between the R-node and all k-nodes fulfill the condition in (18), two events are defined:

$$\xi_1 = \{\text{no k-node exist within distance } r\}.$$

$$\xi_2 = \{\text{at least one k-node exist within } \delta r\}.$$

Similar to the nearest neighbour analysis in [88], the probability that concurrently transmitting nodes fulfil the condition in (18) is given by:

$$(\Pr[(\xi_1) \cap (\xi_2)]) = (\Pr(\xi_1))(\Pr(\xi_2)) \quad 21$$

$$\Pr(\xi_1) = e^{-\mu_1 \pi r^2} \quad 22$$

To evaluate $\Pr(\xi_2)$, the interference cluster is laid as a strip with length $2\pi r$ and width δr as shown in figure 4.8.

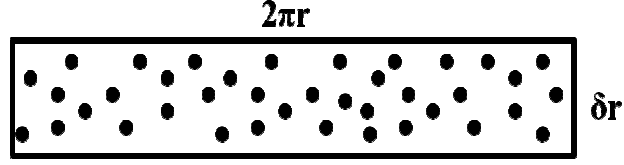


Figure 4.8 Approximation of the ring created by the interference region

As δr approaches zero, the area of the annulus can be approximated by $2\pi r \delta r$. It follows from Poisson distribution that the probability of at least one node in the annulus is:

$$\Pr(\xi_2) = 1 - e^{-\mu_1 2\pi r \delta r} \quad 23$$

From the first and second term of the Taylor's series [88], $1 - e^{-\mu_1 2\pi r \delta r} = \mu_1 2\pi r \delta r$.

Therefore, the probability of having at least a k-nodes within δr is:

$$(\Pr(\xi_1))(\Pr(\xi_2)) = (2\mu_1 \pi r \delta r) (e^{-\mu_1 \pi r^2}) \quad 24$$

Since all k-nodes have been considered to fulfil equation 19b, equation 24 can also be expressed as the probability of at least a nodes with link distance $\beta_{k,R}$ to the R-node [87]., this is given as:

$$\Pr(r < |\beta_{k,R}| \leq r + \delta r) = (2\mu_1 \pi r \delta r) (e^{-\mu_1 \pi r^2}) = f_{\beta_{k,R}}(r) \delta r$$

$$\therefore f_{\beta_{k,R}}(r) = 2\mu_1 \pi r e^{-\mu_1 \pi r^2} \quad 25$$

The detailed proof to substantiate equation 25 is provided in [89]. Now that the distribution of $\beta_{k,R}$ has been evaluated, the expected value of the summation of the negative-second moment of $(\beta_{k,R})$, can be solved. So from equation 20:

$$E\left[\sum_{k=1}^S (\beta_{k,R})^{-2}\right] = \sum_{k=1}^S E[(\beta_{k,R})^{-2}] = \sum_{k=1}^S \omega \quad 26$$

ω is an approximate solution for the negative moment of $\beta_{k,R}$ (a Poisson R.V). The Tiku's

solution [90] has been adopted to find ω .

$$\omega \approx \frac{1}{(\mu_I - 1)(\mu_I - 2)\dots\dots\dots (\mu_I - \tau)}. \quad 27$$

For the τ^{th} negative moment of $\beta_{k,R}$ (τ represents the positive value of the power of $\beta_{k,R}$)⁵, $\mu_I = P_I \mu_{Net}$ where P_I is the probability of interference [87].

4.4.1.2 Probability of Interference

As long as the transmission range of the T-node on a link overlaps with the transmission range of a k-node, the receiver node on the link on which the T-node transmits will experience interference. In practice, not all nodes within δr will transmit at the same time, with the T-node on link l , therefore P_I is defined by two events:

$\xi_{3=}$ at least a node exist within δr and

$\xi_4 =$ the node is transmitting.

For an inter-working multi-hop wireless network with spatial density μ_{Net} , $\Pr(\xi_3)$ is the probability that > 0 nodes exist within δr of the R-node and it is given by: $1 - e^{-\mu_{Net} A_I}$ where A_I is the area of δr for the R-node [87].

$$\Pr(\xi_4) = \begin{cases} 1, & \text{if } P^{(k)} > 0 \\ 0, & \text{if } P^{(k)} = 0 \end{cases} \quad \forall P^{(k)} \geq 0. \quad 28$$

Thus: $P_I = \Pr(\xi_3) \Pr(\xi_4) = 1 - e^{-\mu_{Net} A_I} \quad \forall P^{(k)} > 0$. Now, the expected value of P_{ini} in equation 20 can be solved by equation 29 and the $\theta^{(l)}$ in equation 17 can be evaluated with equation 30.

$$E[P_{ini}] \approx c P^{(k)} \times S \times \omega. \quad 29$$

$S \approx P_I \times N_\Omega$, N_Ω is the total number of nodes in the network. Equation 29 expresses the

⁵ τ can take on any value depending on the path-loss exponent value

expected (mean) value of the effective P_{ini} experienced on a link. P_{ini} is dependent on the spatial density of the interfering nodes (μ_i) and the interfering nodes' transmitting power. In order to validate equation 29, it has been used to estimate the value of $\theta^{(l)}$ and numerical results have been obtained as shown in figure 4.9 , 4.10 and 4.11. Thus, $\theta^{(l)}$ can be approximated as:

$$\theta^{(l)} \approx \frac{cP_i^t (\beta_{T,R})^{-2}}{cP^{t(k)} \times S \times \varpi + P_o} . \quad 30$$

To illustrate, consider a case of inter-working multi-hop networks with 25nodes in a 25000 unit square circular area. G_t and G_r , the transmitter and receiver gains respectively are assumed to be equal to 1, $L_f=1$ and $P_o= -101dBm$. Nodes in the network have transmission power of $100mW^6$. The interference region covers 1000 unit square area as depicted by figure 4.7 and 4.8. The evaluation of the interference power has been done with respect to an R-node on a link of interest (in figure 4.7) in the inter-working multi-hop wireless network. The number of nodes in the inter-working network was increased. As the network node density increases, more nodes are likely to fall in the interference region of the R-node on the link of interest. Assuming that all nodes in the interference region transmit simultaneously, then the μ_i around the link of interest tends to increase with increase in μ_{Net} as illustrated in figure 4.9.

⁶ Formula for the conversion of mW to dBm is given: $P_{(dBm)} = 10 \cdot \log_{10}(P_{(mW)})$

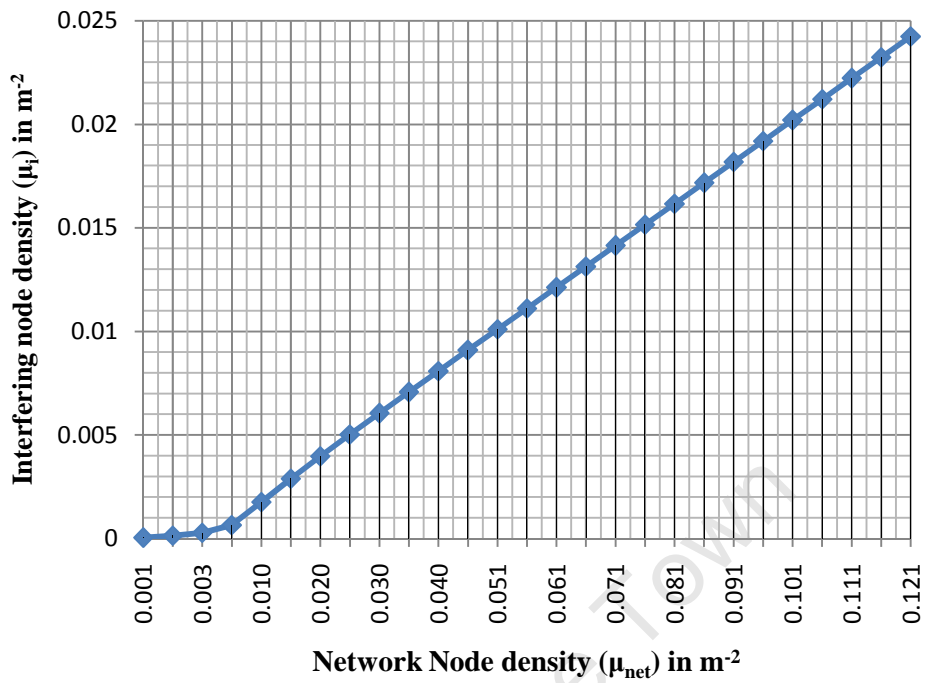


Figure 4.9 Interfering node density vs network node density

By keeping the interfering nodes' transmitting power at a fixed value, interference power (P_{ini}) rises as the density of interfering nodes' increases as in figure 4.10. Figure 4.11 shows that the SNIR on the link of interest decreases as interference power increases.

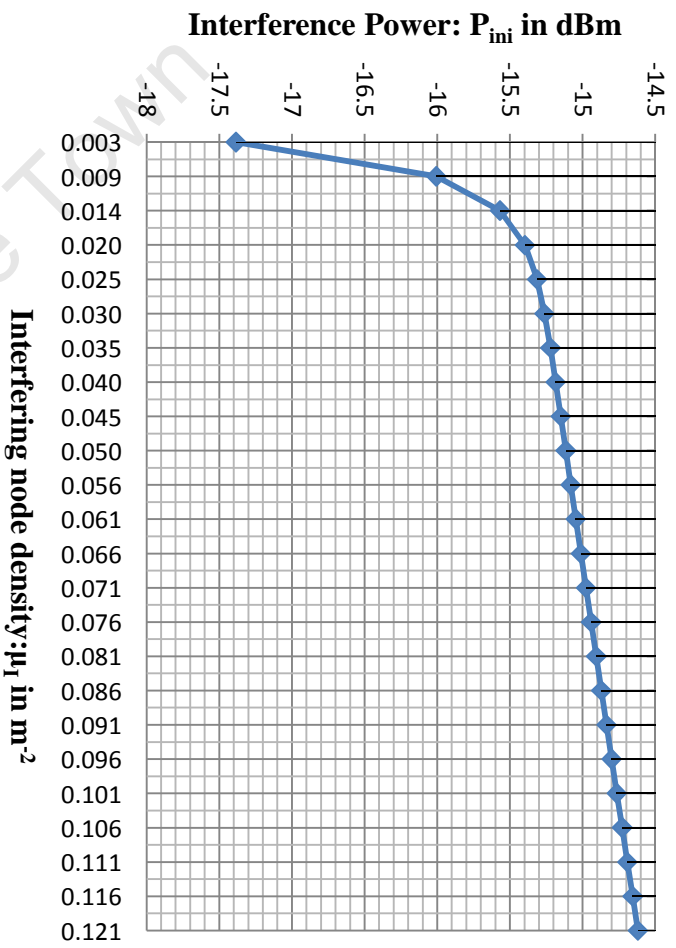


Figure 4.10 Interference power vs Interfering node density

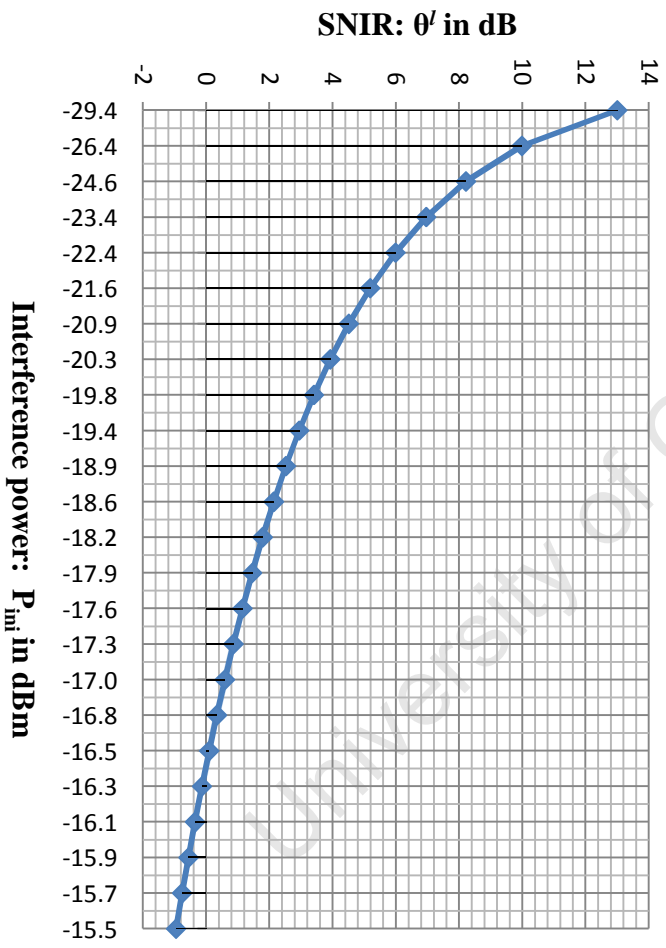


Figure 4.11 SNIR vs Interference power.

4.4.2 Probability of Bit Error

This section explains the relationship between the probability of bit error on link l denoted by $\Phi^{(l)}$ and the link's SNIR, denoted by $\theta^{(l)}$. The decoding performed at the R-node on a link is a probabilistic process which determines the success or failure of any transmission [87]. Due to potential interference, communication may not be totally error-free; hence success is specified in terms of an acceptable value for $\Phi^{(l)}$. $\Phi^{(l)}$ expresses the success or failure of a transmitted signal (packet) in terms of probability and it depends on the value of $\theta^{(l)}$. In order for an R-node to correctly decode a transmission, the value of $\theta^{(l)}$ must be greater than or equal to a SNIR threshold value (θ^{th}) as expressed in equation 31. The threshold value is a pre-set value that is used to ensure successful transmission in a network.

$$E(\theta^{(l)}) \geq \theta^{th} \quad 31$$

$E(\theta^{(l)})$ is the expected value of $\theta^{(l)}$. According to [91], the mean signal strength over the separation distance between a T-node and an R-node is appropriate for estimating the transmission strength of the link. Measures of signal variability are only appropriate in system design issues such as antenna diversity and signal coding. Hence, the mean value of $\theta^{(l)}$ will be used for the estimation of $\Phi^{(l)}$. Since θ^{th} is the minimum SNIR that is required for successful packet reception at the R-node, a transmission error can be declared once there is a probability that $E(\theta^{(l)})$ is below θ^{th} [87]. Therefore:

$$\Phi^{(l)} = \Pr(E(\theta^{(l)}) < \theta^{th}) = 1 - \Pr(E(\theta^{(l)}) \geq \theta^{th}) \quad 32$$

For the evaluation of $E(\theta^{(l)})$, the noise power level (P_o) on link l is considered negligible compared to the expected (mean) value of P_{ini} . Simultaneous transmission with that of T-node will not interfere with the reception at the R-node if the distance between these nodes and the R-node exceeds the upper bound for $\beta_{k,R}$ which is expressed as equation 33. Note that S is the

number of interfering nodes.

$$r + \delta r = \sqrt{\frac{SP^{t(k)}\theta^{th}}{P_l^t}}(\beta_{T,R}) \quad 33$$

Therefore, equation 18 now becomes:

$$r < |\beta_{k,R}| \leq \sqrt{\frac{SP^{t(k)}\theta^{th}}{P_l^t}}(\beta_{T,R}) \quad 34$$

However, not all nodes within δr will interfere since some of them will not even transmit when the T-node is transmitting. Now, what is the maximum of the number of interfering nodes that can be within δr such that a transmission error is declared if the number of interfering nodes exceeds this value? Note that in order to maintain a target SNIR threshold, there is a maximum number of interfering users that can be supported [92]. Let S_{th} represent the maximum number of interfering nodes, which has their distance to the R-node ($\beta_{k,R}$) fulfilling equation 34. For analytical tractability, let the interfering nodes' power be the same. Since unsuccessful transmission is declared when $E(\theta^{(l)}) < \theta^{th}$, then there is a probability of bit error at the receiver node if:

$$S > S_{th} \quad 35$$

There is a maximum allowable interference power (P_{ini}) that can sustain $E(\theta^{(l)}) \geq \theta^{th}$ and thus there is an amount of interferers that can be allowed in the interference region for successful transmission to maintained. In order words, $E(\theta^{(l)})$ becomes less than θ^{th} as S increases beyond S_{th} and there is a probability of bit error when $E(\theta^{(l)}) < \theta^{th}$ [87]. Therefore,

$$\Phi^{(l)} \approx \Pr(S > S_{th}) = 1 - \Pr(S \leq S_{th}) \quad 36$$

$\Phi^{(l)}$ can be estimated as:

$$\Phi^{(l)} \approx 1 - \sum_{k=0}^{S_{th}} \frac{(\mu_I A_I)^k}{k!} e^{-\mu_I A_I} \quad 37$$

μ_I is the density of interfering nodes in the interference region of area A_I . Equation 37 approximates $\Phi^{(l)}$ as a function of the number of interfering nodes. Thus irrespective of the network's topology or the multiple access technique, only the effective density of interfering nodes is considered in estimating $\Phi^{(l)}$ [87]. The maximum number of interfering nodes that can be supported to maintain the threshold for $\Phi^{(l)}$ is S_{th} . Once the number of interfering nodes exceeds this maximum value, then the allowable P_{ini} is exceeded and unsuccessful transmission is more likely to occur.

A link's non-impairment probability is represented by $\Phi^{(l)}$ and is given by the complement of equation 37, which can be determined by subtracting the bit error probability from one. Thus if the bit error probability is high, the non-impairment probability on that link is low and vice-versa. Non-impairment probability refers to the level of reliability of a link and. The goal is to utilize links with high non-impairment probability. A link with a high non-impairment probability is a reliable link.

Consider three inter-worked wireless multi-hop networks as shown in figure 4.7; with 25 nodes (7nodes, 8nodes and 10nodes respectively), covering an area of 25000unit square. The transmission power of nodes is 10mW or 10dBm and transmission range is 100unit⁷. G_t and G_r , the transmitter and receiver gains are assumed to be equal to 1, $L_f=1$, and θ^{th} is 6dB. The interference region is 1000unit square. Figure 4.12 shows the trend of $\Phi^{(l)}$ between the T-node and the R-node as μ_I increases gradually. In this network scenario, the value of $\Phi^{(l)}$ increases continually as the density of interfering nodes grows. $S_{th}=5$, thus the probability of bit error is

⁷ Transmission range is estimated with formulae provided in appendix A

considered low for all values of $S \leq S_{th}$ and the threshold for $\Phi^{(l)}$ is $2.019E-03$ (when $S=S_{th}$).

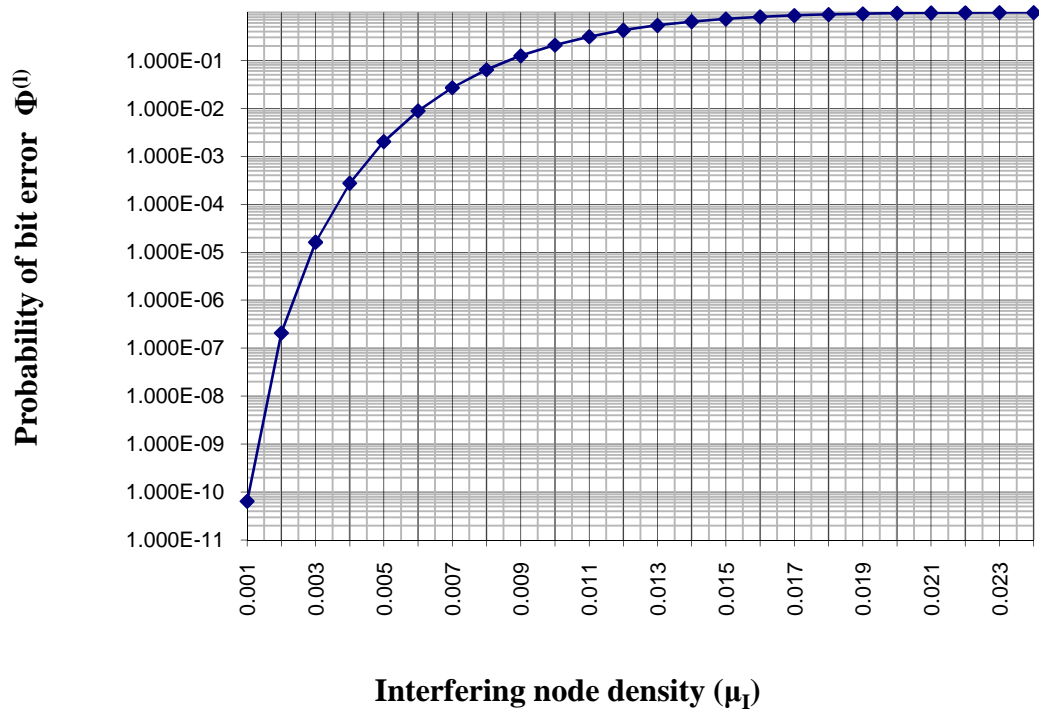


Figure 4.12 Probability of Bit Error vs. Interfering node density

For each μ_I , $\Phi^{(l)}$ is calculated using equation 37. Consequently, successful transmission on the link of interest in the inter-working network cannot be guaranteed any longer for values of $\Phi^{(l)} > 2.019E-03$. With the pre-set θ^{th} for the network, an acceptable $\Phi^{(l)}$ can be determined. If $\Phi^{(l)}$ for a link is higher than the acceptable value, the link's non-impairment (reliability) level will not guarantee a successful transmission. In this way, unreliable links are identified and optimized traffic routing decisions can be made in inter-working multi-hop wireless networks irrespective of the link/MAC layer technologies of the inter-working networks. Figure 4.13 and table 4.1 shows the non-impairment probability of the link considered in the network scenario as the density of interfering nodes increases.

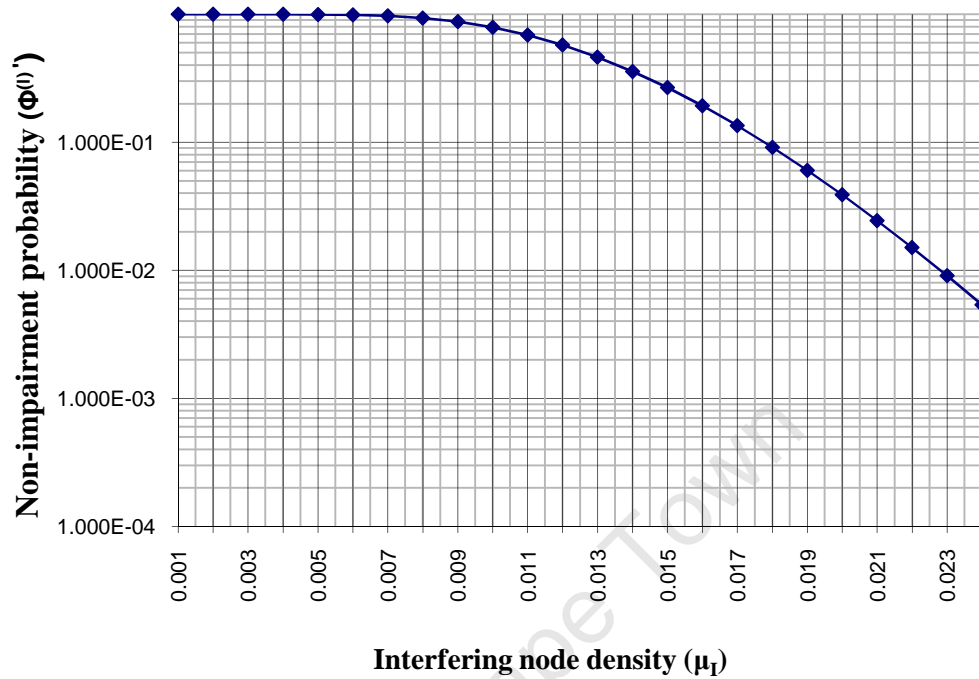


Figure 4.13 Non-impairment probability vs. Interfering node's density

Table 4.1. Interfering node density, bit error probability and non-impairment probability

μ_1	$\Phi^{(1)}$	Non-impairment probability	μ_1	$\Phi^{(1)}$	Non-impairment probability
0.001	6.360E-11	1.000E+00	0.013	5.369E-01	4.631E-01
0.002	2.073E-07	1.000E+00	0.014	6.415E-01	3.585E-01
0.003	1.615E-05	1.000E+00	0.015	7.324E-01	2.676E-01
0.004	2.737E-04	9.997E-01	0.016	8.069E-01	1.931E-01
0.005	2.019E-03	9.980E-01	0.017	8.650E-01	1.350E-01
0.006	8.827E-03	9.912E-01	0.018	9.083E-01	9.167E-02
0.007	2.700E-02	9.730E-01	0.019	9.394E-01	6.056E-02
0.008	6.380E-02	9.362E-01	0.02	9.610E-01	3.901E-02
0.009	1.242E-01	8.758E-01	0.021	9.755E-01	2.455E-02
0.01	2.084E-01	7.916E-01	0.022	9.849E-01	1.512E-02
0.011	3.113E-01	6.887E-01	0.023	9.909E-01	9.122E-03
0.012	4.240E-01	5.760E-01	0.024	9.946E-01	5.402E-03

4.5 Connectivity model

Connectivity theory in wireless networks states that it is possible to find a set of potential links that can connect nodes to each other subject to some network resource constraints [40]. Most research works state that there is connectivity between any two nodes as long as they are within each other's transmission range. However, we have defined connectivity in inter-working multi-hop wireless networks as the probability that a wireless link is available and its non-impairment probability is high enough to guarantee a successful transmission over it. Note that a link must firstly be available before its non-impairment probability can be evaluated [93].

Connectivity is considered as a probabilistic measure, as the state of the wireless link at any moment cannot be explicitly predicted. The probabilities (availability and non-impairment) are associated with a wireless link. Factors considered in determining connectivity includes the distance between two communicating nodes on a link of interest and the state of the link in terms of the transmission quality it can provide. Since the movement of nodes changes the location of nodes and consequently the distance between nodes, our assumption is that the distance between nodes captures the instantaneous location of nodes. No matter the movement pattern of nodes, their instantaneous location if the node degree of any node in the network is evaluated, it will be possible to determine if it has potential nodes with which it can possibly communicate. Nodes can send periodic 'hello' message transmissions in order to find their node degree.

The connectivity model presented in this section gives an indication of the level of connectivity that a link can provide in terms of its availability and non-impairment probability. The quality of a transmission is specified by metrics that defines the state of a link e.g. probability of interference, interference power, SNIR, and bit error probability.

Firstly, for any T-node, the probability that a link is available for it to transmit its packet is given by equation 6. The link may be a direct link to the intended destination node or it may be a link to intermediate nodes between the T-node and the intended destination node. Secondly, an interference region is defined for the R-node (intended destination or intermediate node) on the link of interest. The probability that a node in the inter-working network will contribute to the interference power is given in section 4.4.1. Thirdly, using the probability of interference, the density of interfering nodes can be evaluated and also the total interference power, which is used to evaluate $E(\theta^{(l)})$ on the link of interest. If $E(\theta^{(l)})$ on the link is less than θ^{th} , then there is a likelihood that transmission errors will occur on that link. The allowable value for $\Phi^{(l)}$ is estimated and the non-impairment probability is estimated with the compliment of equation 37 and finally, connectivity can be estimated using:

$$P_{con} = P_{link} * (1 - \phi^{(l)}) \quad 38$$

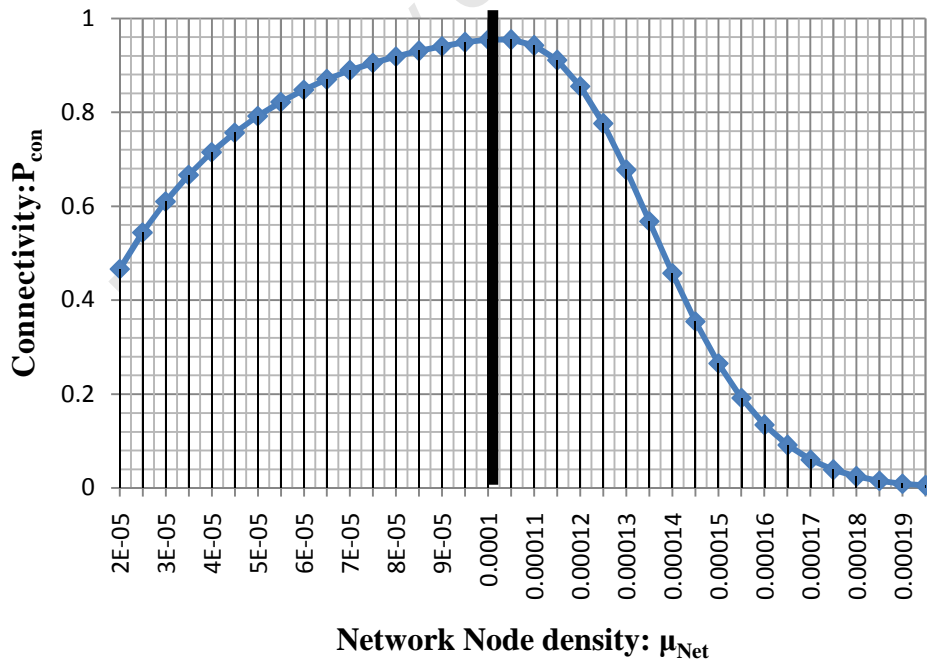


Figure 4.14 Connectivity vs Network node density

Figure 4.14 shows the evaluation of the connectivity levels on link l between a T-node and possible potential R-nodes as μ_{Net} increases for the same network scenario illustrated in the previous sub-section.

All potential R-nodes have the same interference area and nodes have the same transmission power. So $E(\theta^{(l)})$ ⁸, S_{th} , $\Phi^{(l)}$, and consequently, non-impairment probability estimation for links connecting to all potential R-nodes within the T-node's range will be the same. In other words, all links connecting to potential R-nodes are identical. This assumption is made for the sake of analytical tractability.

From figure 4.14. at very low network node density and the given transmission power, the availability of nodes in the network is very low and the T-node can barely reach other nodes.

As μ_{Net} slowly increases, a reasonable number of links becomes available for the T-node and non-impairment probability on such links is high. However, the connectivity level on these links is quite low. At high values of μ_{Net} , link availability increases and though non-impairment probability reduces yet connectivity level rises. The reduction in non-impairment probability is due to the rise in μ_I . However, the rise in μ_I does not reduce the connectivity level because the amount of interfering nodes (S) is still keeping $E(\theta^{(l)})$ less than or equal to the threshold value and thus the bit error probability $\Phi^{(l)}$ is still good enough for useful transmission.

At higher values of μ_{Net} , link availability continues to rise and non-impairment probability reduces still. At this stage, connectivity begins to decline because the rise in μ_{Net} , causes the amount of interfering nodes to surpass the tolerable amount. Therefore, connectivity cannot be guaranteed any longer at this stage.

⁸ $P^{(0)k} > 0$ for all nodes in the interference region.

Table 4.2 Network node density, availability, non-impairment probability and connectivity

μ_{Net}	P_{link}	$\Phi(l)$	P_{con}	μ_{Net}	P_{link}	$\Phi(l)$	P_{con}
0.00002	0.466342	1.00E+00	0.466342	0.00011	0.968381	9.73E-01	0.942235
0.000025	0.54388	1.00E+00	0.54388	0.000115	0.972975	9.36E-01	0.910902
0.00003	0.610153	1.00E+00	0.610153	0.00012	0.976902	8.76E-01	0.855545
0.000035	0.666796	1.00E+00	0.666796	0.000125	0.980258	7.92E-01	0.775929
0.00004	0.715209	1.00E+00	0.715209	0.00013	0.983126	6.89E-01	0.677076
0.000045	0.756588	1.00E+00	0.756588	0.000135	0.985578	5.76E-01	0.567659
0.00005	0.791955	1.00E+00	0.791955	0.00014	0.987673	4.63E-01	0.457396
0.000055	0.822183	1.00E+00	0.822183	0.000145	0.989464	3.58E-01	0.354682
0.00006	0.848019	1.00E+00	0.848019	0.00015	0.990995	2.68E-01	0.265201
0.000065	0.870101	1.00E+00	0.870101	0.000155	0.992304	1.93E-01	0.191635
0.00007	0.888975	1.00E+00	0.888975	0.00016	0.993422	1.35E-01	0.134136
0.000075	0.905106	1.00E+00	0.905106	0.000165	0.994378	9.17E-02	0.091154
0.00008	0.918894	1.00E+00	0.918894	0.00017	0.995195	6.06E-02	0.06027
0.000085	0.930678	1.00E+00	0.930678	0.000175	0.995893	3.90E-02	0.038852
0.00009	0.940751	1.00E+00	0.940735	0.00018	0.99649	2.45E-02	0.024463
0.000095	0.949359	1.00E+00	0.949099	0.000185	0.997	1.51E-02	0.015071
0.0001	0.956717	9.98E-01	0.954786	0.00019	0.997436	9.12E-03	0.009099
0.000105	0.963006	9.91E-01	0.954505	0.000195	0.997808	5.40E-03	0.005391

Generally, from literature, connectivity for a T-node is evaluated based on either

- 1) The amount of potential R-nodes it can reach (i.e. the greater the number of nodes within its reach, the higher the connectivity) [41] [43] [44] or
- 2) The amount of interference/ bit error probability on link between itself and potential R-nodes (i.e. the lower the interference, the higher the connectivity).

However, it can be observed that there is a trade-off between availability and non-impairment

probability (affected by interference and probability of bit error). Figure 4.14 and table 4.2 illustrate this trade-off as follows:

- At low network node density, non-impairment probability is high (i.e. interference/ bit error probability is low) but very few potential R-nodes can be reached (link availability is low).
- At high network node density, more potential R-nodes can be reached (link availability is high), however, non-impairment probability is low (interference and probability of bit error is high).

However, there is an issue with being predisposed to any of these two notions because low link availability may lead to difficulty in finding potential R-nodes while high link availability may lead to an unreliable network. The connectivity model presented in this section solves this trade-off issue by combining availability and non-impairment in the evaluation of connectivity. Focusing on left portion of figure 4.14, the model evaluates connectivity as follows:

- At very low network node density connectivity is taken as nonexistent as the T-node can barely reach other nodes.
- At low link availability, even though non-impairment probability is high, the connectivity level on a link is termed low.
- At high link availability, non-impairment probability is favourable and link connectivity level is optimal. It is desirable to route traffic through links with optimal connectivity.

This model can be used as a metric for traffic routing in order to avoid wasteful transmissions on low quality links in order to ensure seamless continuous ubiquitous service in inter-working multi-hop wireless networks. Note that connectivity can no longer be guaranteed as the level of connectivity inclines towards the right of figure 4.14 because the non-impairment

probability becomes unfavourable due to the high interference level caused by high node density. An illustration of the connectivity graph is available in appendix B.

4.5.1 Connectivity Aware routing process

A dynamic reaction to the changes in the wireless channel is required for traffic routing within an inter-working multi-hop wireless network [93]. The routing process uses connectivity as a metric. The metric is based on the pre-calculation of the connectivity level on a link between a T-node a potential R-nodes using the connectivity model presented in the previous section. Note that a T-node is a transmitting node and an R-node is a receiving node. The T-node could be the initial source of a transmission or an intermediate node transmitting to another node on a link of interest en-route to the final destination node. The R-node could be the intended final destination for a transmission or an intermediate node receiving a transmission on a link of interest en-route to the final destination node.

For nodes, the first step in the routing process is the calculation of link availability in order to identify 1-hop nodes. For each link that is available, the second step is to obtain the probability of interference at the R-node on the link, the SNIR and the probability of bit error. Since a change in link quality levels affects connectivity between nodes, these parameters allow the routing process to consider link quality in the computation of the routing metric. The third step is to evaluate the non-impairment probability (reliability) on each potentially available link. The fourth step is to use the availability and non-impairment probability to obtain the connectivity level on each link. The routing process chooses links that can provide optimal level of connectivity as dictated by the transmission range, node density, SNIR threshold and the bit error probability threshold. Non-impairment probability is termed low once bit error probability is below the threshold. Connectivity levels estimated over individual links are multiplied to get

the overall connectivity for all potential routes.

The routing process is well suited for inter-working multi-hop wireless networks where the wireless channel is unstable. The routing process not only estimates the quality of wireless links with measures such as the probability of interference, probability of bit error and SNIR, but also adapt to the temporal dynamics of the links and prevents wasteful transmissions over low connectivity links [93].

The simulation performance of the connectivity routing process is presented in chapter five. The AODV-UU routing process was modified by incorporating the connectivity metric into the routing process.

4.5.2 Properties of the connectivity metric

These properties of the connectivity aware metric have been identified based on the taxonomy for routing metrics in [94].

- **Factors of influence**

There are two different types of factors that could influence a metric. These are environmental factors and network-immanent factors. The environmental factors of influence for the connectivity aware metric include attenuation and node's position and the network-immanent factors include inter-node interference.

- **Mathematical Properties**

- a. **Link concatenation Operator:** Link metrics are multiplied in order to attain the metric of a route.
- b. **Dynamic vs. Static:** The metric is a dynamic metric.
- c. **Symmetric vs. Asymmetric:** The metric is asymmetric. Connectivity level on a link between node A to node B may not be the same as the connectivity level from node B

to node A. This is because the non-impairment probability on link $l_{a,b}$ may differ from that on $l_{b,a}$ as a result of the interference level around node b and a respectively. Moreover, availability may also differ due to the transmission range of each node. If node A can reach node B on $l_{a,b}$, it does not mean that node B can reach node A on link $l_{b,a}$. Note that neighbourhood is not necessarily reciprocal in wireless networks [94].

- **Design Perspective**

- a. **Target Platform:** Inter-working multi-hop wireless networks with single mode and multi-modal nodes.
- b. **Purpose:** ensure seamless service continuity and ubiquitous services access within Inter-working multi-hop wireless networks.
- c. **Optimization Goal:** The optimization objectives are to maximize connectivity and the reliability of links in ensuring seamless ubiquitous access to service. It is possible to use the metric as a link routing constraints such that only routes that optimizes the metric are utilized in the routing process.

- **Implementation Characteristics**

- a. **Layer:** This property describes which OSI layer provides the required information [94]. The physical, MAC and network layers provide information for the connectivity metric.
- b. **Analytically vs Empirically-defined Metrics:** The metric is based on analytically defined network parameters. Analytical metrics are metrics suitable for mathematical analysis /theoretical description [95].

c. Information Acquiring Method: Control packets are used to gather information about the properties of a link.

- **Isotonicity:**

The isotonic property means that the relationship between the weights of any two routes with the same origin is preserved when both are extended to the same node [96] [97].

This implies that the order of the connectivity weights on route a, (links l_1 - l_2) and route b (link l_3 - l_4) should be preserved if the weight of each route is concatenated with a common third link (link l_5) as illustrated in figure 4.15.

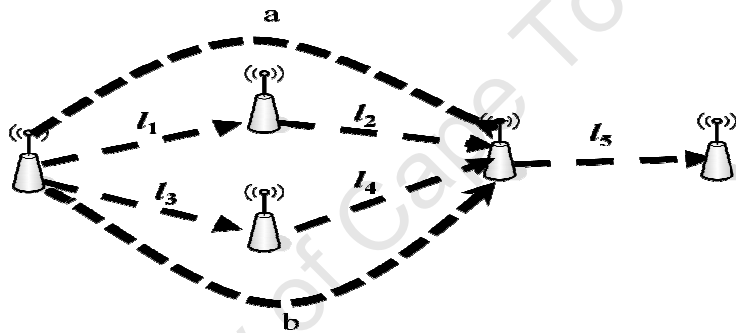


Figure 4.15 Isotonicity

If $P_{con}(a)$ and $P_{con}(b)$ denotes the connectivity on route a and b respectively; and $*$ denotes the concatenation operation such that the concatenation of x and y is given by $x*y$. Then by the definition of isotonicity, the metric, P_{con} is isotonic if: $P_{con}(a) < P_{con}(b)$ implies that $P_{con}(a*c) \leq P_{con}(b*c)$ for all a, b, c. This is true for P_{con} , because the order of the weight of the connectivity of two routes remains the same even if a common third link is concatenated with these routes, thus P_{con} is isotonic.

Chapter 5 Simulation Based Validation

This chapter presents the validation work carried out and the simulation results obtained in this research work. . A brief introduction to the features of NS-miracle, which motivates its use for this research, is also provided. The simulation has been performed using the NS-Miracle, which is the Multi InteRface Cross Layer Extension of the popular NS2 Simulator. NS2 is a discrete event simulator that supports the simulation of network protocols and optimization techniques. The extensions provided by NS-miracle are frameworks that facilitate the simulation of multi technology networks. The AODV-UU protocol is used as a baseline for comparison. A discussion of the simulation environment, necessary modifications made to the C++ code of the AODV-UU and the TCL code and the simulation results are presented. The MAC code of the AODV-UU has been modified to create the connectivity aware MAC code needed for this research. The connectivity aware MAC code incorporates the dynamic computation of the probability of bit error. The routing codes of the AODV-UU (i.e. aodv-uu.cc, aodv-uu.h and aodv_socket.cc) were modified to obtain P_{link} , $\Phi^{(l)}$ and P_{con} during the routing process.

5.1 Motivation for the use of NS-Miracle simulator

The NS-Miracle was developed based on the premise that it is now possible to integrate different technologies in a single mobile terminal. It is a set of libraries designed to enhance the functionalities provided by the Network Simulator NS2. It enables the co-existence of multiple modules within each layer of the protocol stack. Multiple IP, link, MAC or physical (PHY) layers can be specified and used within the same node. It allows the testing and understanding of new networking protocols for multi-network environment. It was developed by Nicola Baldo et al of the SIGNET lab at the University of Padova to address issues peculiar to the multi-technology networking environment [22]. Issues stated in [22], which are of relevance to this

research and provides the motivation for the use of NS-miracle for this research include:

- 1) *Accurate channel and lower layer (PHY and MAC) modeling*: the accurate modeling of the wireless channel and the lower layers is very essential. Simulators should allow realistic representations of the signal propagation and reception processes. Popular models such as the disk propagation model provide limited representation. The NS-Miracle lower layer framework has been explicitly designed to accurately model these layers [22].
- 2) *Modeling of a complete system*: due to the increasing complexity of communication systems, subtle interactions among the network layers play an important role in determining its overall performance. Thus, these interactions cannot be modeled in isolation. Therefore, a network simulator is expected to provide means to model the interactions among all layers in the network. NS-Miracle provides capabilities that allows the simulation of such interactions between the layers [22].
- 3) *Rapid simulation of new wireless access technologies*: new wireless access technologies are being proposed, standardized and released, but appropriate simulation tools are not available in time to study these technologies as they emerge. Simulators should provide reusable codes and modules to allow easier development. The modularity of NS-Miracle allows the codes to be portable, re-usable and extensible [22].
- 4) *Inter-technology interference*: this applies to the case of popular wireless communication technologies such as IEEE 802.11, Bluetooth, and WiMAX. Simulation of Inter-technology interference requires that all technologies use the same representation of interference and simulators should support this. NS-Miracle provides the class that supports functionalities shared by different wireless technology implementations [22].

- 5) *Multi-technology multi-interface communication capabilities*: as more and more devices nowadays are equipped with multiple interfaces using different communication technologies, network simulators should provide support for proper modelling of these scenarios. NS-Miracle allows the simulation of networks in which nodes may have multiple interfaces, communicate over multiple channels on multiple routes to a destination node. It allows the placement of multiple modules on each layer of the network stack and allows the exchange of information between modules of different layers or same layer [22].
- 6) *Support for heterogeneous networks*: research in wireless networking has mainly focused on homogeneous network (e.g. infrastructure, ad hoc, and mesh wireless networks). However, recently, there has been an increasing interest in scenarios in which different wireless networks co-exist. The simulation of these scenarios can be challenging because the routing layer of simulators is mainly designed for homogeneous networks. NS-Miracle supports the simulation of co-existing wireless networks [22].

Another component of the NS-miracle framework is the Miracle Routing framework, which enables the integration of different routing schemes in a multi-tier architecture to provide support for the simulation of multi-technology and heterogeneous networks [98]. It is now possible to carefully simulate complex network architectures potentially at all the OSI layers, from the physical reception model to standard applications, which allows a comprehensive view of all the networks interactions. More information on the features and capabilities of NS-Miracle are available in [22], [98] and [99]. Figure 5.1 illustrates the multi-layer architecture of a node within the NS-Miracle framework.

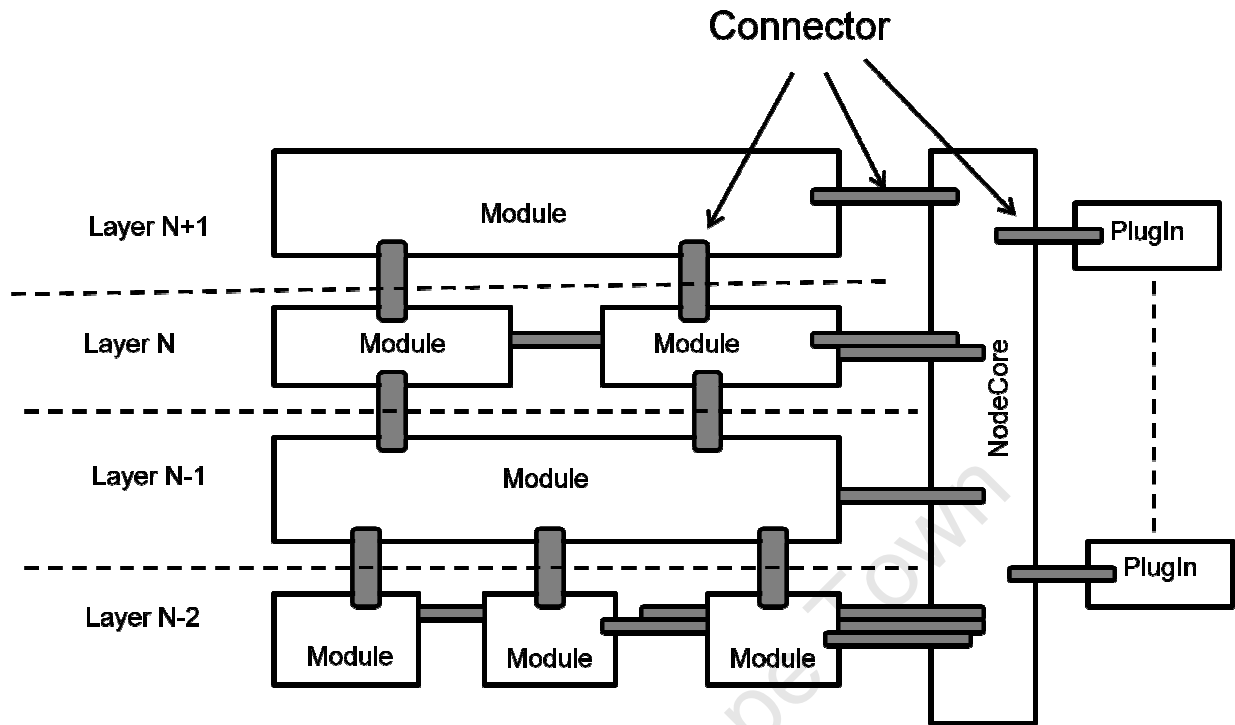


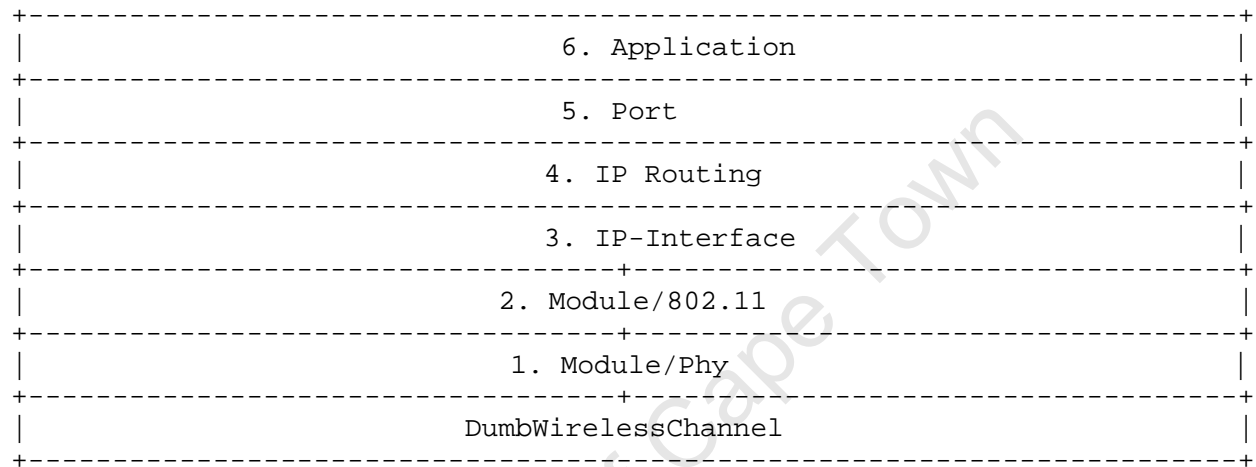
Figure 5.1 Multi-layer architecture of a node within NS-MIRACLE [99]

5.2 Simulation environment

For the simulation, the NS-Miracle-1.2.2 and NS2.34 versions have been installed on Ubuntu 9.10. An inter-working multi-hop wireless network in which nodes have either a single mode or multi-mode/multi-technology capability has been simulated. Specifically, nodes are single or dual mode nodes operating with either the IEEE802.11a or IEEE 802.11b or both technologies. The physical and MAC layer configuration of IEEE802.11b is readily available in NS2.34 while the configurations for IEEE802.11a have been added to suit the validation of this proposed traffic engineering approach. For example, to ensure the proper functioning of the MAC layer, the packet error rate (PER) information for IEEE802.11a at applicable data rates adapted from [100] has been incorporated.

The IEEE802.11 standard is the only technology with multi-hop capability that is readily available on NS-Miracle simulator and thus were used. For this research, it should be noted that the code has been created by making appropriate and relevant changes to the original code available in NS 2.34/NS-Miracle-1.2.2.

The layers within a node are as represented below:



Nodes have multi-hop capability and may have single or dual physical and MAC interfaces. Node's locations are generated with the Poisson distribution codes in appendix C.1. The network area is 1500m by 1500m.

5.2.1 Physical Layer

In NS-miracle 1.2.2, the Physical Layer Transmission (PLT) of a packet is characterized by attributes such as:

- P_t : characterizes the transmission power of a PLT, as set by the physical layer of the T-node.
- P_r : characterizes the received power when a PLT is received at the R-node. It is obtained by mathematical operations performed on the P_t attribute.
- Position: characterizes the geographical position of the T-nodes (`srcPosition`) and that of the R-node (`dstPosition`).

- P_n : characterizes the noise power at the R-node.
- P_i : characterizes the interference power, which is calculated with respect to a specific PLT being received at the R-node.

The Miracle Physical Layer (MPhy) module calculates the SNIR for all received packets by considering received signal strength, noise, all simultaneous transmissions overlapping in time, path loss, and propagation gains. MPhy implements the MInterference class, which tracks all currently active ongoing transmissions. MInterference calls the `addToInterference(Packet* p)`, at the beginning of a PLT to add the power of the set of ongoing PLTs and it uses the `getInterferencePower(Packet* p)` to return the interference caused by these ongoing PLTs on the target R-node. Thus, the probability of bit error can be obtained with these SNIR values. The simulation configuration of the physical layer parameters are provided in table 5.1.

Table 5.1 Physical Layer simulation Configuration

Channel propagation model	Free space
Frequency of transmission IEEE 802.11a	5180e6MHz
Frequency of transmission IEEE 802.11b	2437e6MHz
Transmission rate for IEEE 802.11a	6Mbps
Transmission rate for IEEE 802.11b(confirm all yellow from TCL script)	5.5Mbps
Transmission power	0.01W
Noise power	-96dBm

The SNIR threshold information for IEEE 802.11a and IEEE 802.11b adapted from [101] are in appendix D.

5.2.2 MAC Layer

In NS-miracle, error rate is calculated using pre-determined curves, which can be specified via TCL. However, because the connectivity routing metric requires error probability information dynamically from the network, additional code is incorporated to obtain error information dynamically from the network. The MAC code has been modified to create the connectivity aware MAC, specifically, changes have made to the files `Connectivity-aware-mac-802_11-module.cc`, `connectivity-aware-mac-802_11-module.h`, `connectivity-aware-mac-802_11mr.cc` and `connectivity-aware-mac-802_11mr.h`. These files are included in appendix C. The “`connectivity-aware-mac-802_11mr.cc`” provides the probability of bit error ($\Phi^{(l)}$). The `connectivity-aware-mac-802_11.tcl` is the modified TCL code for creating a `ConnectivityAware802_11MacModule`, which provides the 802.11 MAC interface during the simulation process.

5.2.3 Network Layer

For the routing process, the connectivity metric has been incorporated into the AODV-UU protocol. AODV-UU is readily supported by the NS-miracle and it is a variation of the Ad hoc On-Demand Distance Vector (AODV), developed by Uppsala University, Sweden [102]. The AODV-UU was ported into NS-miracle by Erik Andersson et al of the Karlstad University in order to support the simulation of multi-interface network technologies [103].

Modifications have been made to the C++ code of the AODV-UU routing protocol to obtain the simulation performance of the multi-layer framework’s routing process. These changes are explained in sections 5.1.3.1 and 5.1.3.2. The AODV is a typical dynamic and on-demand routing protocol, which has been studied and implemented in real networks and is

supported in the NS2 simulator. A route is discovered and created only when needed in order to adapt to dynamic network conditions (e.g. propagation and topology). However, NS2 does not meet the requirement for simulating a multi-environment and AODV is not supported on NS-miracle. Therefore a variant of the AODV, which is the AODV-UU has been ported into the NS-miracle modules by [103]. AODV-UU has internet gateway and multiple interface support.

In this research, the AODV-UU files were tailored to make use of the connectivity metric in the routing process between single-mode and multi-mode nodes in the inter-working multi-hop network. Hop count is replaced with the connectivity metric. The routing process obtains information from lower layers.

5.2.4 Changes to the routing protocol code

The excerpts of the inline listings of the codes added to aodv-uu.h, aodv_socket.cc and aodv-uu.cc files are shown in this section. The added codes are meant for obtaining the P_{link} , $\Phi^{(l)}$ and P_{con} .

The aodv-uu.h incorporates codes for calling the methods to obtain the connectivity level during a routing process.

ADDITIONS TO AODV-UU.H

```

.....9
/* Constants for connectivity awareness */
#define PI 3.14
#define NODE_DENSITY 0.00016 // subject to change
#define DECIMAL_PLACES 100000
.....

void initInterface(in_addr_t ipaddr, in_addr_t subnet, int ifindex, IConnectivityAware* icw = 0);
        nsaddr_t str2addr(const char *str);
.....
/* Methods for connectivity awareness */

```

⁹Throughout this chapter, “.....” indicates that there are other lines of codes before or after this line.

```

double calculate_link_availability(Packet* p);
double calculate_impairment_level(nsaddr_t dst, unsigned int ifindex);
int calculate_connectivity_level(Packet* p, unsigned int ifindex);

```

.....

The aodv_socket.cc provides the socket used for sending and receiving the control messages during the routing process. It incorporates line of codes for updating the connectivity level. The calculate_connectivity_level(Packet* p, unsigned int ifindex) is an NS_class, which is incorporated in aodv-uu.cc.

ADDITIONS TO AODV_SOCKET.CC

```

.....
{ void NS_CLASS aodv_socket_process_packet(AODV_msg * aodv_msg, int len,
                                           struct in_addr src,
                                           struct in_addr dst,
                                           int cl10, int ttl, unsigned int ifindex)
}

```

.....

Under /* If this was a HELLO message... Process as HELLO. */ the following were added:

```

.....
/* Make sure we add/update neighbors */
neighbor_add(aodv_msg, src, cl, ifindex);
.....

```

Under /* Check what type of msg we received and call the corresponding function to handle the msg */

```

.....
case AODV_RREQ: {
.....
/* Update of connectivity level here*/
rreq_process((RREQ *) aodv_msg, len, src, dst, ttl, cl, ifindex);
break;
.....
/* Calculate the connectivity level for this packet on the given interface */
int cl = calculate_connectivity_level(p, ifindex);
.....

```

¹⁰ cl means connectivity level.

ADDITIONS TO AODV_SOCKET.H

```
.....  
void aodv_socket_process_packet(AODV_msg * aodv_msg, int len, struct in_addr src, struct in_addr dst,  
int cl, int ttl, unsigned int ifindex);  
.....
```

The aodv-uu.cc provides the AODV-UU as the protocol for routing during the simulation. Codes for computing the link availability, non-impairment probability and connectivity level are incorporated in the aodv-uu.cc.

ADDITIONS TO AODV-UU.CC

```
.....  
#include <node-core.h>  
#include <wirelessphy-module.h>  
#include "aodv-uu.h"  
.....
```

Under /* Interpreter for commands from Tcl */ the following were added:

```
.....  
else if (argc == 4) {  
    if (strncasecmp(argv[1], "add-if") == 0) {  
  
        IPModule* ipif = dynamic_cast<IPModule*>(TclObject::lookup(argv[2]));  
        IConnectivityAware* icw = dynamic_cast<IConnectivityAware*>(TclObject::lookup(argv[3]));  
        if (ipif && icw)  
        {  
            tcl.evalf("%s addr", ipif->name());  
            nsaddr_t ipaddr = (in_addr_t) atoi(tcl.result());  
            tcl.evalf("%s subnet", ipif->name());  
            nsmask_t subnet = (in_addr_t) atoi(tcl.result());  
            initInterface(ipaddr, subnet, ipif->getId(), icw);  
            return TCL_OK;  
        }  
  
        return TCL_ERROR;  
    }  
.....
```

Under: /*Replacement for if_indextoname()*/ the following were added.

```
.....
```

```
void NS_CLASS initInterface(in_addr_t ipaddr, in_addr_t subnet, int ifindex, IConnectivityAware* icw)
.....
```

Under: /* Set network interface parameters */ the following were added.

```
.....
DEV_NR(dev_nr).cw = icw;
.....
```

- For the link discovery process (obtaining availability), the following codes were added to aodv-uu.cc.

```
double NS_CLASS calculate_link_vailability(Packet* p) {
    double linkAvailability = 0.0;
    hdr_MrclWrIPhy* ph = HDR_MRCLWRLPHY(p);

    double dX = ph->sourcePos_->getX() - ph->destPos_->getX();
    double dY = ph->sourcePos_->getY() - ph->destPos_->getY();
    double distance = sqrt(dX * dX + dY * dY);

    if (distance <= transmissionRange) {
        linkAvailability = 1 - exp(-1 * NODE_DENSITY * PI * pow(transmissionRange, 2));
        fprintf(stdout, "link_availability: link %.6f\n", linkAvailability);
    }
    else {
        fprintf(stdout, "link_availability: no link available\n");
    }

    return linkAvailability;
}
```

- For the resource optimization process (obtaining non-impairment probability), the following code has been added to aodv-uu.cc. At this stage, the probability of bit error obtained from the connectivity aware MAC module as specified in section 5.1.2 is used for the computation of the non-impairment probability on the links. The excerpt of the C++ implementation code for this process is as below:

```

double NS_CLASS calculate_nonimpairment_level(nsaddr_t dst, unsigned int ifindex) {
    double nonimpairmentLevel = 0.0;

    if ((DEV_IFINDEX(ifindex)).cw) {
        double ber = (DEV_IFINDEX(ifindex)).cw->getBER();
        double per = convert_ber_to_per(ber);
        nonimpairmentLevel = 1 - ber;

        fprintf(stdout, "nonimpairment_level: interface %d BER %.6f PER %.6f NONIMPAIRMENT %.6f\n",
ifindex, ber, per, nonimpairmentLevel);
    } else {
        fprintf(stdout, "nonimpairment_level: interface %d no connectivity aware interface\n", ifindex);
    }

    return nonimpairmentLevel;
}

```

- The excerpt of the C++ codes for computing the connectivity level as in equation 38 is added as below:

```

int NS_CLASS calculate_connectivity_level(Packet* p, unsigned int ifindex) {
    struct hdr_cmn *ch = HDR_CMN(p);
    int connectivityLevel = 0;
    double linkAvailability, impairmentLevel;

    if (DEV_IFINDEX(ifindex).enabled) {
        nonimpairmentLevel = calculate_nonimpairment_level(ch->prev_hop_, ifindex);
        linkAvailability = calculate_link_vailability(p);
        connectivityLevel = floor(nonimpairmentLevel * linkAvailability * DECIMAL_PLACES);

        fprintf(stdout, "connectivity_level: interface %d connectivity %d\n", ifindex, connectivityLevel);
    } else {
        fprintf(stdout, "connectivity_level: interface %d disabled\n", ifindex);
    }

    return connectivityLevel;
}

```

5.2.5 Control messages and Routing process

This section explains the control messages of the AODV protocol and the modifications that have been made to these control messages in order to achieve the connectivity aware routing process.

Hello messages:

The Hello messages are beamed at intervals by nodes in order to know active 1-hop neighbour nodes. Nodes detect inactive links when Hello messages are not received within a specific time interval and thus consider links to such a neighbor as non-existent.

Route requests:

- When a node wants to reach a destination node and does not have the route, it sends a route request packet to neighboring nodes. A route request packet is composed of an ID (identifies the route request packet), destination and source address; and sequence numbers (ensures the freshness of the route request packet and loop-free routing), the connectivity level update of the link it traverses (*this is a modification to the normal aodv-uu implementation, hop count has been replaced with connectivity level on links that the route request traverses*) and control flags. The connectivity level is updated on the route request packet as the route request traverses each link en-route to the destination. The connectivity level is calculated at the interface of the receiving node on the link. The ID and the source address serve as the unique identifier for each route request packet. For the route request packet creation, the connectivity level is initialized with the code below:

ADDITION TO AODV-RREQ.C

```
-----  
.....  
rreq->cl = 0;
```

.....

- Any neighbour that receives the route request checks if it is the destination node. If it is the destination node, it sends a route reply to the source node that sent the route request. Route reply packets contain the destination sequence number, source and destination address and the route's time to live.
- If the node is not the destination, it updates the connectivity level, creates a reverse path to the source of the route request, and then forwards the route request to its neighbor nodes.

For the route request packet processing section, the following were added.

```
void NS_CLASS rreq_process(RREQ * rreq, int rreqlen, struct in_addr ip_src, struct in_addr ip_dst, int ip_ttl, int cl, unsigned int ifindex)
{
    .....
    u_int32_t rreq_new_cl;
    .....
    rreq_new_cl = rreq->cl * cl;
    .....
}
```

- Any intermediate node receiving this route request for the first time and is neither the destination node nor has a valid route to the destination also updates the connectivity level, creates a reverse path to neighbor node from which it received the route request and forwards the route request to its neighbor nodes. An intermediate node can send route reply if it has an active route toward the destination. If a node receives another route request with the same source address and ID but with a lower connectivity update, the new route request is discarded. If the new route request contains a better connectivity update, the reverse route

that was initially created is updated accordingly. If this node receives a route reply later, the route reply is sent via the reverse route created to the source node as indicated in the code below.

```

.....
if (rev_rt->dest_seqno == 0 ||
    (int32_t) rreq_orig_seqno > (int32_t) rev_rt->dest_seqno ||
    (rreq_orig_seqno == rev_rt->dest_seqno &&
     (rev_rt->state == INVALID || rreq_new_cl > rev_rt->cl))) {
    rev_rt = rt_cache_update(rev_rt, ip_src, rreq_new_cl,
.....
}

```

- Once the route request gets to the destination node or any node that has a valid route to the destination, a reverse route is created and this node sends a route reply packet to the neighbour node from which it received the first route request via the reverse route created. *Another modification to the normal AODV-UU is that since we are concerned about the connectivity on forward links from a T-node to the R-nodes (intermediate nodes) on links en-route to the final destination, connectivity is only updated on route request packets and not on route reply packets.* Intermediate nodes forward the route reply packet through the reverse route created. The route reply packet generated by the destination is unicast along the reverse path created till the source of the route request is reached. After receiving the route reply, the source node starts transmitting its data to the destination node.
- A route remains active if there is continued transmission of packets along it. If the source stops transmitting, the route times out and is deleted from the intermediate nodes' cache.
- If a neighbor node is unreachable or a node along a detected route changes location and there is a link breakage, a corrective action is taken by its upstream neighbor. The upstream neighbour generates and forwards a route error packet to neighbor nodes on that route. A

route error packet contains the unreachable destination address and its sequence number. Further upstream nodes also receive this route error packet until the source node is reached and the source may re-initiate route discovery.

The control messages format are provided in appendix E while an illustration of the routing process is in appendix F. For multi-mode/multi-technology nodes, control packets are sent through each interface. The IP interface is able to identify the MAC module from which a control packet or any other packet is received with an index for each interface.

5.3 Analysis of Simulation results for AODV-UU-HP and AODV-UU-CL

The performance of the hop count metric used by the AODV-UU-HP protocol and the connectivity metric used by the AODV-UU-CL protocol are compared. The metrics considered in the simulation are:

- **Goodput:** The total number of application layer packets that were successfully transmitted in the network per second.
- **Packets Lost:** The number of packets that were lost due to the effect of simultaneously transmitting nodes.
- **Packet delivery ratio/percentage:** The ratio between the number of data packets successfully received by destination nodes and the total number of data packets sent by source nodes.
- **Delay:** The time (in seconds) taken by the data packets to reach their respective destinations.

Table 5.2 Simulation parameters

Simulation Parameters	Constant
Simulation time	450secs
Number of nodes	60
Number of transmitting nodes	12
Distance between nodes	150m
Transmitting power	10mW

Using a mix of single-mode and multi-mode nodes, simulation experiments were performed by varying some simulation parameters while other parameters remain constant as indicated in table 5.2. Firstly, the number of nodes in the network (network node density (μ_{Net})) was varied from 20 to 180 with an increment of 20, while other simulation parameters remain as indicated in table 5.2. Secondly, the number of nodes transmitting at a time (interfering node density (μ_I)) was increased from 2 to 20 at increments of 2 and other simulation parameters remain as in table 5.2.

The network topology is randomly generated with nodes locations being Poisson distributed. In order to create a balanced spread of nodes to cover the entire network deployment area, the x and y co-ordinates of nodes' location were Poisson distributed with an imposed inter-node distance of 150m. This nodes deployment strategy avoids the isolation of some nodes and the unnecessary clustering of nodes within a particular network region. The transmitting power of nodes remains fixed as in table 5.2.

For each of these simulations, the four metrics were observed. The simulation TCL scripts are in appendix G.

1. Goodput

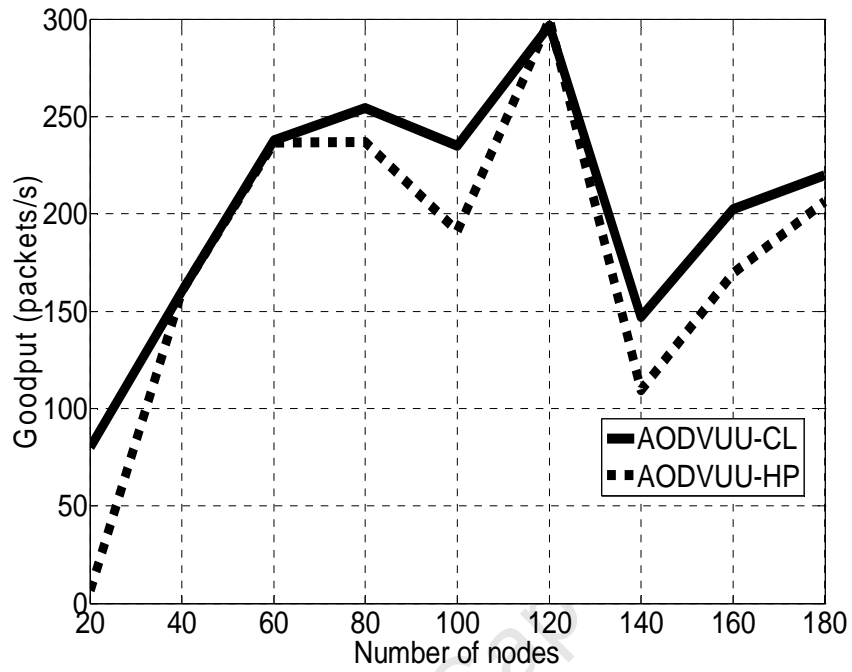


Figure 5.2. Good-put(packets/s) vs Number of nodes

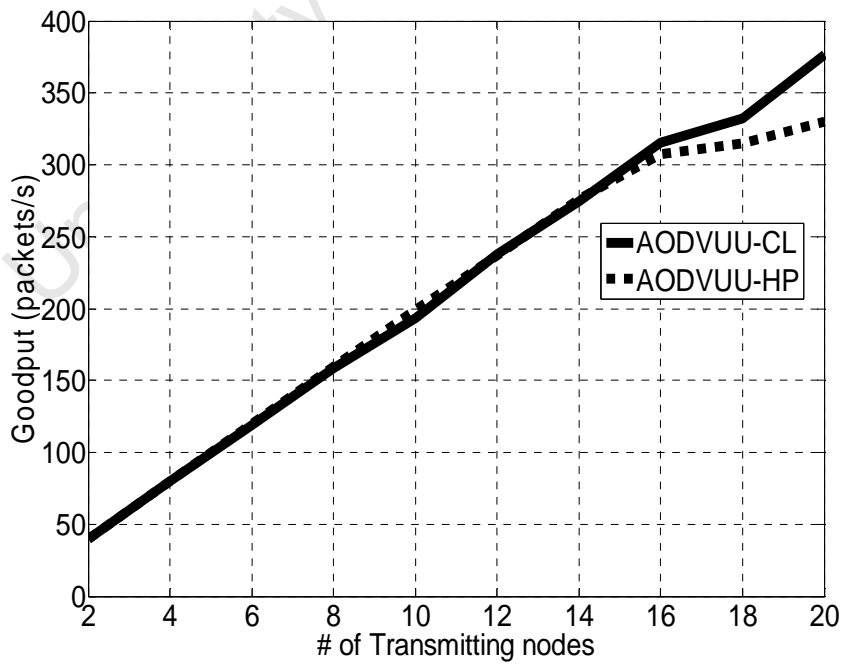


Figure 5.3 Good-put(packets/s) vs Number of transmitting nodes

Goodput is better with AODV-UU-CL as the number of nodes in the network increases even though the performance of the two metrics fluctuates as shown in figure 5.1. AODV-UU-CL is sensitive, keeps track of network link conditions to choose optimal connectivity routes during the routing process, and thus is able to successfully transmit more packets than AODV-UU-HP, which is oblivious to network link conditions during its routing process. Therefore, in an inter-working multi-hop wireless network scenario, AODV-UU-CL can maintain reliable ubiquitous service continuity and network access for nodes.

In figure 5.2, both metrics tend to choose equally good links for transmission with a low number of simultaneously transmitting nodes. However, as the number of transmitting nodes increase beyond 14 nodes, the connectivity metric distinguishes itself by increasingly transmitting more packets with success. At this stage, the goodput of the hop count metric tends to begin to decline gradually because it chooses routes without considering the network link quality. Figure 5.2 illustrates that although more simultaneously transmitting nodes reduces the non-impairment probability on network links, yet the connectivity metric is still able to avoid impaired links more than the hop count metric. Low hop-count does not necessarily indicate that a route will allow reliable transmission as links may have been chosen around the interfering nodes.

2. Packet delivery ratio/percentage

At low node density, the performance of both metrics is comparable in terms of packet delivery ratio with a distinction in performance demonstrated when the number of nodes increases, as illustrated in figure 5.3. The delivery ratio is higher under AODV-UU-CL for dense networks, this is also because the connectivity metric is keen to avoid links that have been impaired, while AODV-UU-HP has no way of evading such links. On the average, the packet

delivery ratio for AODV-UU-CL is higher than that of AODV-UU-HP under a random network topology. In figure 5.4, the delivery ratio for both routing metrics begins to decrease after 14 transmitting nodes within the network, yet the delivery ratio for AODV-UU-CL remains higher than that of AODV-UU-HP after 14 nodes even though it started with a negligibly lower delivery ratio than AODV-UU-HP.

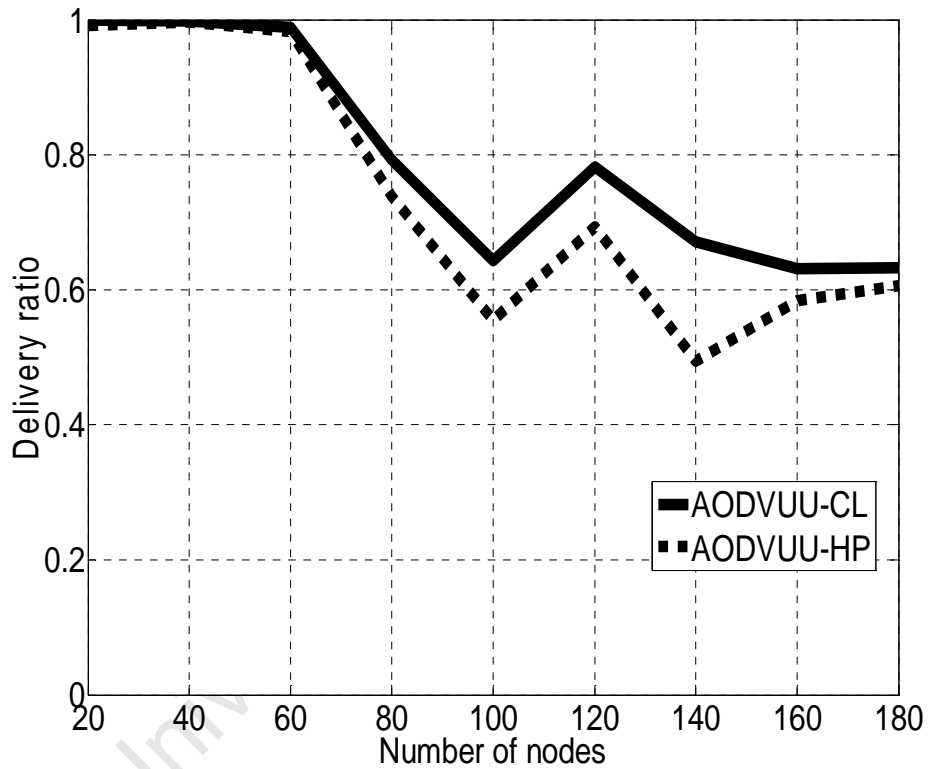


Figure 5.4 Delivery ratio vs Number of nodes

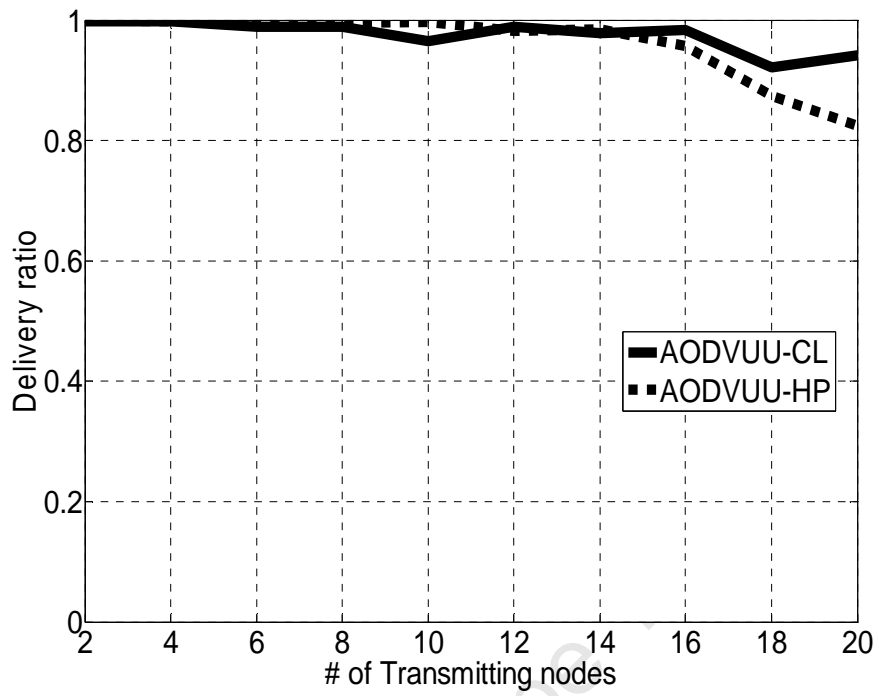


Figure 5.5 Delivery ratio vs Number of transmitting nodes

3. Packets Lost

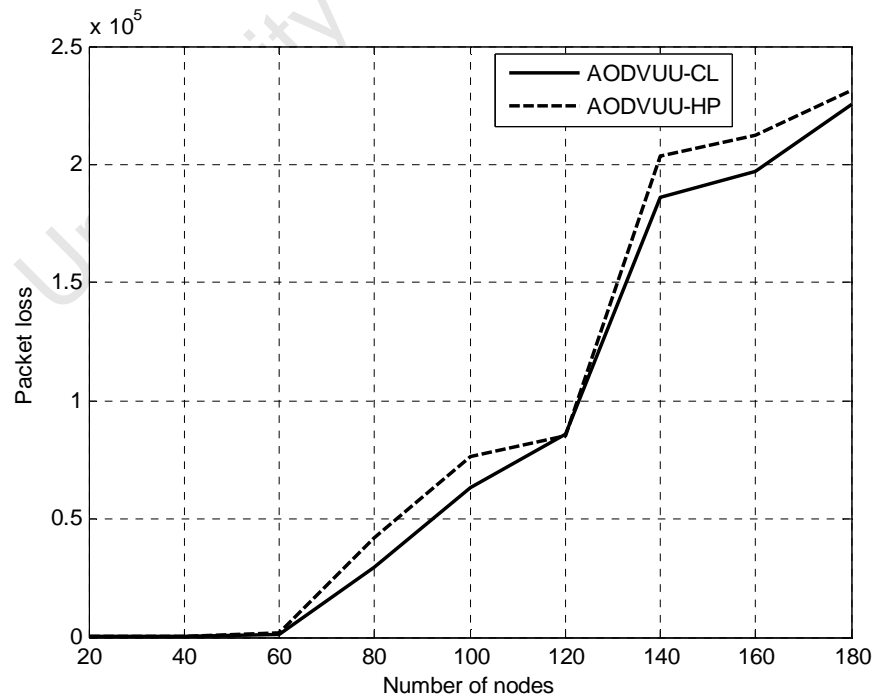


Figure 5.6 Packet lost vs Number of nodes

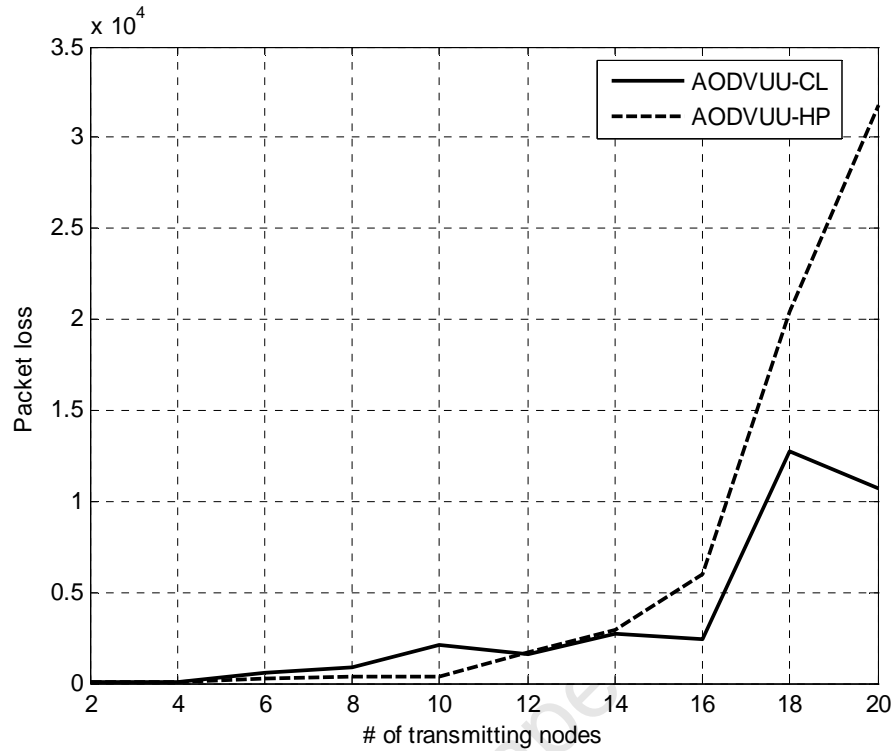


Figure 5.7 Packet lost vs Number of transmitting nodes

In figure 5.5, more packets are lost with AODV-UU-HP as the number of nodes increases beyond 60 nodes and as the number of transmitting nodes rise above 10 nodes. With AODV-UU-CL, the number of packets lost increases as the number of nodes increases but it remains significantly lower than the amount lost by AODV-UU-HP beyond 60 nodes and 120 nodes in the network .

Initially, in figure 5.6, a negligibly higher number of packets are lost by AODV-UU-CL at low number of transmitting nodes, however a great distinction in the performance of the connectivity metric can be seen after 14 transmitting nodes. With the existence of more than 14 simultaneously transmitting nodes within the network, AODV-UU-CL incurs much lesser packet loss than the AODV-UU-HP.

As the network becomes dense and as the interference level increases, AODVUU-CL is able to reduce the number of packets lost during transmission because a link's non-impairment probability is considered before it is chosen. The non impairment probability used in the computation of the connectivity level allows AODVUU-CL to use only reliable links to form routes, in order to avoid wasteful transmissions on low quality links. However, AODVUU-HP does not consider a link's reliability before it is chosen to form a route, thus more packets are lost as the the network becomes dense and as the interference level increases.

4. Delay

The delay performance of both metrics fluctuates as the number of nodes in the network increases beyond 60 nodes. Initially, the delay performance of the AODV-UU-CL is slightly lower than that of AODV-UU-HP until after 60 nodes in the network as demonstrated in figure 5.7. However, as the number of network nodes increases beyond 120 nodes in the random network topology, more nodes become available so, link availability is high and because non-impairment probability is favourable, AODV-UU-CL is able to choose links with optimal connectivity, thus averagely reducing delay during the transmission of packets. AODV-UU-HP chooses lower hop-count route irrespective of the quality of the link and its performance fluctuates with higher values of delay averagely as compared to AODV-UU-CL.

In figure 5.8, as the number of transmitting nodes increase, delay also fluctuates with both AODV-UU-HP and AODV-UU-CL. AODV-UU-HP begins to highly decline in performance, while the performance of AODV-UU-CL does not decline as much as AODV-UU-HP. This is because the connectivity metric is able to allow the protocol to choose links that can provide optimal connectivity levels (a link with high availability and high non-impairment probability).

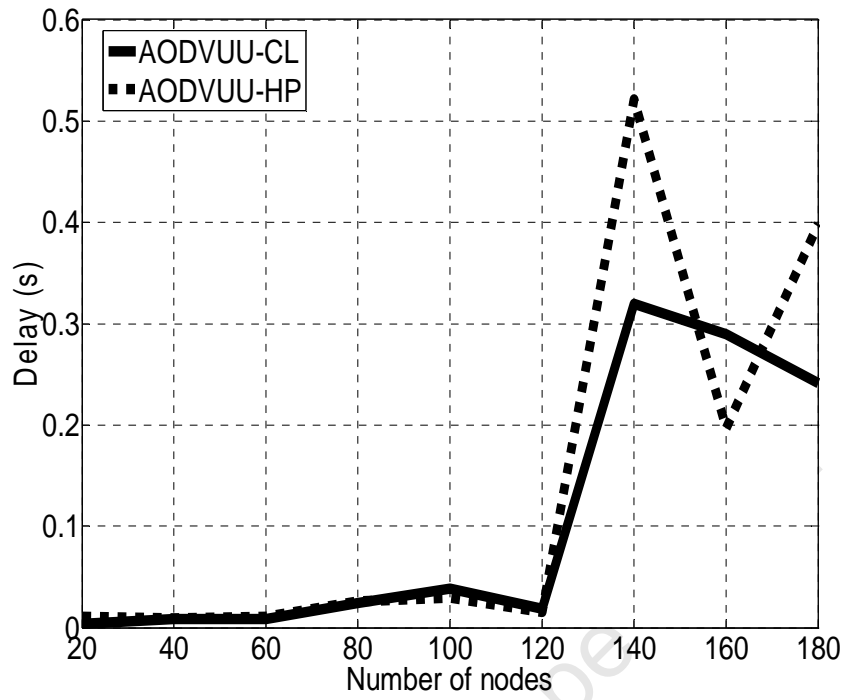


Figure 5.8 Delay vs Number of nodes

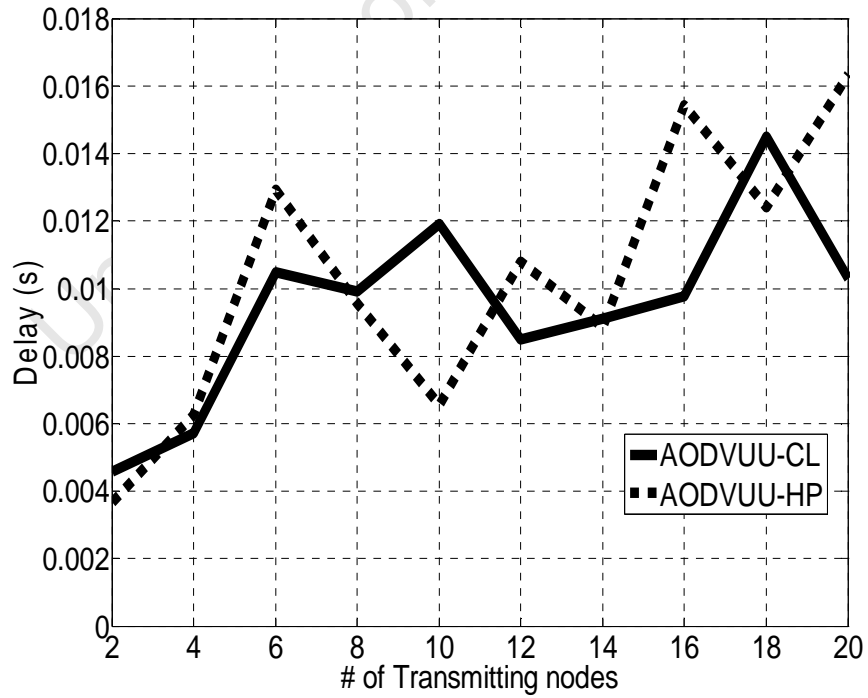


Figure 5.9 Delay vs Number of transmitting nodes.

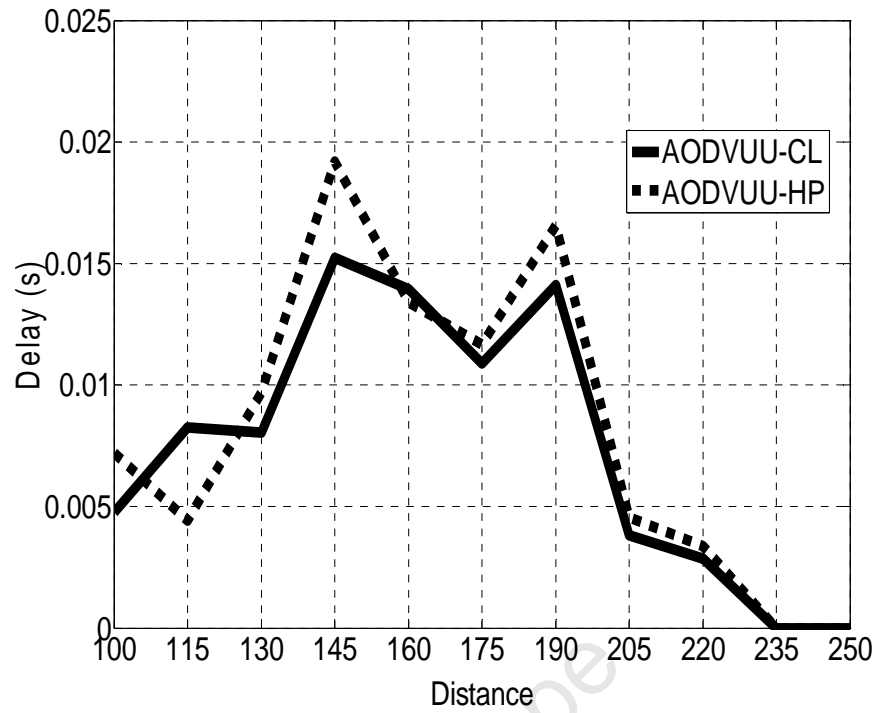


Figure 5.10 Delay vs Distance

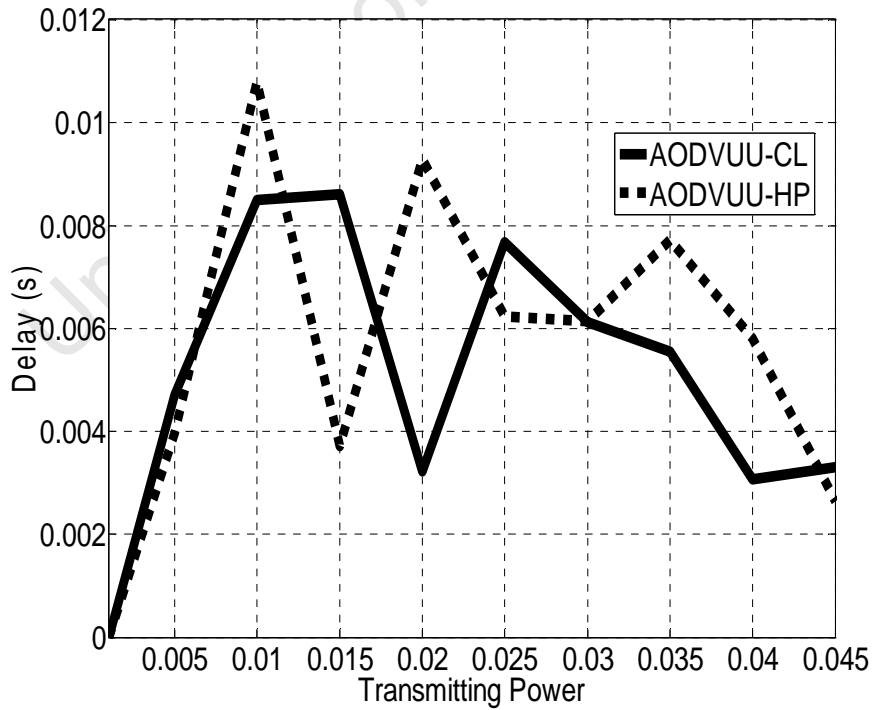


Figure 5.11 Delay vs Transmitting power

Figure 5.9 and 5.10 shows further simulations results obtained to observe the delay simulation metric. The distance between nodes and the transmission power of nodes were varied while the number of nodes and number of transmitting nodes in the network remained fixed at 60 nodes and 12 nodes respectively. The delay performance of both metrics under varying nodal distances and transmission power also fluctuates. However, from figure 5.9 and 5.10, AODV-UU-CL improves the delay experienced by nodes in the network more than AODV-UU-HP. Generally for AODVUU-CL and AODVUU-HP, an increase in the distance between nodes decreases the hop distance between nodes (i.e. shorter distances means more hops and longer distances means lesser number of hops), thus delay reduces as distance increases. At higher transmission power, delay is reduced.

In figure 5.1 to figure 5.8, the distinction in the performance of the two routing metrics becomes clearer as the network node density (number of nodes within the network) and the interfering node density (number of transmission nodes) becomes increasingly high. In the inter-working multi-hop network scenario, as the network gets denser, (i.e. when the number of nodes in the inter-working network is increased), AODV-UU-CL exhibited an outstanding performance than AODV-UU-HP. In addition, when the number of transmitting nodes is increased (which increases the number of interfering nodes), AODV-UU-CL performs better in terms of goodput, packet delivery ratio, number of packet lost and delay.

Chapter 6 Conclusion and future work

In this dissertation, a multi-layer traffic engineering framework has been proposed for inter-working multi-hop wireless networks. The multi-layer traffic engineering framework ensures ubiquitous service access and continuity through a link discovery optimization process (with the link availability model), a resource optimization process (with the non-impairment probability model) and a routing process (using the connectivity model as a routing metric).

The hypothesis posed is that if a strong relationship can be established between the physical and MAC layer metrics a multilayer TE framework can use the relationship to ensure an optimization of the link discovery, resource utilization and routing processes,. Thus, the research work exploited the relationship between physical and MAC layer metrics for the models.

For the link discovery process, we have used the homogenous Poisson point process to develop a relationship between a T-node's transmission range (R_o), (dictated by the transmission power), the distance between the T-node and the intended R-node ($\beta_{T,R}$), the network node spatial density μ_{Net} and the T-node's degree $P(D(.))$. This relationship is given by the link availability model (P_{link}). The available link may be a direct link to the intended destination node or it may be a link to intermediate nodes between the transmitting node and the intended destination node.

After confirming the availability (existence) of links, the resource optimization process finds the link that can provide quality communication based on available network resources. For this process, the relationship between the probability of interference, transmission power, SNIR, and probability of bit error is exploited. The splitting and merging properties of the homogenous

Poisson process is used to identify different the types of nodes in the network. We have established a relationship between P_I , P_{ini} , SNIR and $\Phi^{(l)}$ as a function of the interfering nodes' density μ_p , the threshold of interfering nodes S_{th} , and the area of the interference region A_I . This relationship is given by the non-impairment probability model.

For the routing process, the connectivity level on a link is computed using the link availability and non-impairment probability as inputs. Link that optimizes connectivity are chosen to form routes within the network.

The performance of the framework has been evaluated using the NS2.34/NS-Miracle 1.2.2 simulator. The findings indicate that with an increase in the network node density and interfering node density, which degrades network performance, the framework is able to achieve improved QoS at the traffic level. It successfully delivers more packets to the application layer. It is able to reduce the number of packets lost during transmission and the percentage of packets delivered also increases. Though the delay performance fluctuates as the network gets more congested with nodes or interfering nodes, it still provided lower delay values in comparison with the framework that employs hop-count. Lastly, the improved performance can be attributed to the choosing of links with optimal connectivity level to make up a multi-hop route. The overall performance shows that it can be used to ensure better and reliable last mile ubiquitous service access and continuity in an inter-working multi-hop wireless networks with heterogeneous mobile terminals (single-mode and multi-mode nodes).

With regards to future work, firstly, the framework can be extended for use in cognitive radio networks by including spectrum information in the link discovery process.

Secondly, since only link metrics were considered in this research, another future research work on the framework is to consider the inclusion of node metrics such as energy or

power levels and memory or workload in the connectivity model.

Thirdly, since communication conditions when nodes are within the range of their parent gateway node's coverage may differ from when they are out of range, it may be desirable to employ flexibility in the choice of protocol for routing. Even though we did not implement multi-routing capability for nodes in the simulation, it will be interesting to enhance nodes with multi-routing capabilities. Multi-routing capabilities in nodes will allow nodes to adaptively switch routing functions depending on the network scenario in which they are (i.e. if they are in or out of their gateway node range). They can use an applicable routing process when they are within the range of their gateway nodes and use the proposed routing process when they are outside their gateway node's coverage (i.e. using other nodes to relay their traffic).

Research journal publications

- 1) Oladayo Salami, Antoine Bagula and H. Anthony Chan. "Framework for Link Reliability in Interworking Multi-hop Wireless Networks," Special issue on Recent Advances in Simulation and Mathematical Modeling of Wireless Networks, Mathematical and Computer Modeling, vol. 53, Issues 11-12, pp 2219-2228, ISSN 0895-7177, DOI:10.1016/j.mcm.2010.08.027, Elsevier press, June 2011.
- 2) Oladayo Salami, Antoine Bagula and H. Anthony Chan. "Route Availability model for Inter-working multi-hop wireless networks," International Journal of Electronics and Telecommunication, vol. 56, No2, pp 185-190. ISSN: 0867-6747, Verista Press, 2010.
- 3) Oladayo Salami, Antoine Bagula, and H. Anthony Chan," A framework for connectivity in Interworking Multi-hop Wireless Network," Smart Spaces and Next generation wired/wireless networking, Lecture Notes in Computer Science, vol. 6294/2010, pp 335-352. ISBN/DOI:10.1007/978-3-642-14891-0_30, Springer Publications, 2010.
- 4) Oladayo Salami, Antoine Bagula, and H. Anthony Chan, "A model for Interference on Links in Interworking Multi-hop Wireless Networks," Advances in Computer Science and Information Technology, Lecture Notes in Computer Science, vol. 6059/2010, 264-278. ISBN/DOI:10.1007/978-3-642-13577-4_23, Springer Publications, 2010.
- 5) Oladayo Salami, Antoine Bagula and H. Anthony Chan. "Evaluation of Interference in Interworking Multi-hop Wireless Network," International Journal of Security and its Application, vol 4, issue 4, pp27-42, ISSN: 1738-9976, 2010.

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Appendix A: Transmission range estimation

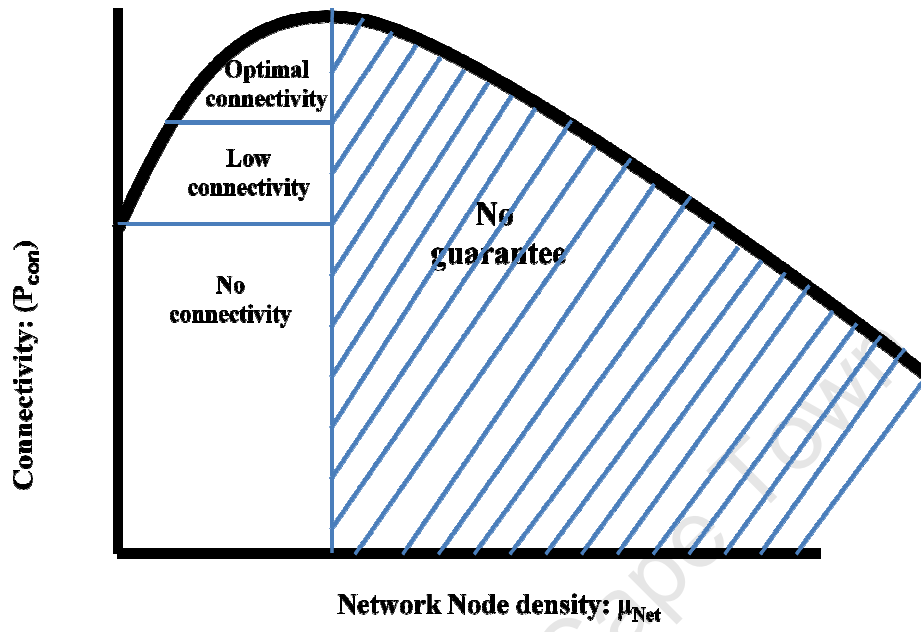
Parameter	Value
P_t	10dBm
P_r	-76dBm
G_t	1dBi
G_r	1dBi
f_c	5800MHz

$$R_o = \frac{10^{(P_t + G_t + G_r - P_r)}}{41.88 \times f_c}$$

Using the wireless specification as above and the equation as above, the transmission range (R_o) of a node is estimated. The equation for R_o is adapted from:

http://www.moxa.com/newsletter/connection/2008/03/Figure_out_transmission_distance_from_wireless_device_specs.htm on 23rd October, 2009.

Appendix B: Connectivity graph.



Appendix C: Connectivity Aware codes

C.1 Poisson_random_variable.cc

```
#include <cmath>
#include "poisson_random_variable.h"
static class PoissonRandomVariableClass: public TclClass {
public:
    PoissonRandomVariableClass() :
        TclClass("RandomVariable/Poisson") {
    }

    TclObject* create(int, const char* const *) {
        return (new PoissonRandomVariable());
    }
} class_exponentialranvar;

PoissonRandomVariable::PoissonRandomVariable() {
    bind("avg_", &avg_);
}

PoissonRandomVariable::PoissonRandomVariable(double avg) {
    avg_ = avg;
}

double PoissonRandomVariable::avg() {
    return avg_;
}

double PoissonRandomVariable::value() {
    return generatePoissionBasedUponMultiplicationOfUniformVariates();
}

double PoissonRandomVariable::generatePoissionBasedUponExponentialInterArrivalTime() {
    double k = 0;
    double sum = 0;

    do {
        k = k + 1;
        sum = sum + rng_->exponential();
    } while (sum < avg_);

    return k - 1;
}

double PoissonRandomVariable::generatePoissionBasedUponMultiplicationOfUniformVariates() {
    double k = 0;
    double p = 1;
    double L = exp(-avg_);
    do {
        k = k + 1;

```

```

    p = p * rng_->uniform(0, 1);
} while (p > L);
return k - 1;
}

```

C.2 Connectivity-aware.h

```

#ifndef _CA_
#define _CA_
#include <packet.h>
class IConnectivityAware {
public:
    virtual double getBER() = 0;
protected:
    virtual ~IConnectivityAware() {}
};
#endif /* __connectivity-aware_h__ */

```

C.3 Connectivity-aware-mac-802_11mr.h

```

#ifndef _CAMAC80211MR_
#define _CAMAC80211MR_

#include <mac-802_11mr.h>

#include "connectivity-aware.h"

#define BITS_PER_FRAME (1500 * 8)

class ConnectivityAwareMac802_11mr: public Mac802_11mr,
    virtual public IConnectivityAware {
public:
    ConnectivityAwareMac802_11mr();
    virtual ~ConnectivityAwareMac802_11mr();

    virtual int command(int argc, const char* const * argv);

    virtual double getBER();

    double getFER();

protected:
    inline double getTargetSNR(PhyMode mode) {
        switch (mode) {
            case Mode1Mb:
                return 1e6;
            case Mode2Mb:
                return 2e6;
            case Mode5_5Mb:
                return 5.5e6;
        }
    }
};

```

```

    case Mode11Mb:
        return 11e6;
    case Mode6Mb:
        return 6e6;
    case Mode9Mb:
        return 9e6;
    case Mode12Mb:
        return 12e6;
    case Mode18Mb:
        return 18e6;
    case Mode24Mb:
        return 24e6;
    case Mode36Mb:
        return 36e6;
    case Mode48Mb:
        return 48e6;
    case Mode54Mb:
        return 54e6;
    default:
        return 0.0;
    }
}
};

#endif /* _CAMAC80211MR_ */

```

C.4 Connectivity-aware-mac-802_11mr.cc

```

#include <cmath>
#include <mac-802_11mr.h>

#include "connectivity-aware-mac-802_11mr.h"

static class ConnectivityAwareMac802_11mrClass: public TclClass {
public:
    ConnectivityAwareMac802_11mrClass() :
        TclClass("Mac/802_11/Multirate/CA") {
    }

    TclObject* create(int, const char* const *) {
        return (new ConnectivityAwareMac802_11mr());
    }
} class_ConnectivityAwareMac802_11mr;

ConnectivityAwareMac802_11mr::ConnectivityAwareMac802_11mr() :
    Mac802_11mr() {
}

ConnectivityAwareMac802_11mr::~ConnectivityAwareMac802_11mr() {
}

```

```

int ConnectivityAwareMac802_11mr::command(int argc, const char* const * argv) {
    return Mac802_11mr::command(argc, argv);
}

double ConnectivityAwareMac802_11mr::getBER() {
    double ber = 0.0;
    double fer = getFER();
//TODO: Convert to BER
    ber = 1 - pow(10, (log10(1 - fer) / BITS_PER_FRAME));

    fprintf(stdout, "BER %.6f\n", ber);

    return ber;
}

double ConnectivityAwareMac802_11mr::getFER() {
    double dataFrameErrors = macmib_.getDataFrameErrors();
    double dataFrameReceives = macmib_.getDataFrameReceives();
    double fer = 0.0;

    if (dataFrameErrors > 0 || dataFrameReceives > 0) {
        fer = dataFrameErrors / (dataFrameErrors + dataFrameReceives);
        fprintf(stdout, "ERROR: %.2f, RECEIVED: %.2f, FER %.6f\n", dataFrameErrors, dataFrameReceives, fer);
    }

    return fer;
}

```

C.5 Connectivity-aware-mac-802_11-module.cc

```

#include <cstring>
#include <cstdlib>

#include "connectivity-aware-mac-802_11mr.h"
#include "connectivity-aware-mac-802_11-module.h"

static class ConnectivityAwareMac802_11ModuleClass: public TclClass {
public:
    ConnectivityAwareMac802_11ModuleClass() :
        TclClass("Module/802_11/CA") {
    }
    TclObject* create(int, const char* const *) {
        return (new ConnectivityAwareMac802_11Module());
    }
} class_ConnectivityAwareMac802_11;
ConnectivityAwareMac802_11Module::ConnectivityAwareMac802_11Module() {
}
ConnectivityAwareMac802_11Module::~ConnectivityAwareMac802_11Module() {
}
int ConnectivityAwareMac802_11Module::command(int argc, const char* const * argv) {
    Tcl& tcl = Tcl::instance();

```

```

if (argc == 2) {
    if (strcasecmp(argv[1], "getBER") == 0) {
        if (mac_) {
            tcl.resultf("%.4f", getBER());
            return TCL_OK;
        } else {
            fprintf(stderr, "No mac defined");
            return TCL_ERROR;
        }
    }
}
return MacModule802_11::command(argc, argv);
}
void ConnectivityAwareMac802_11Module::recv(Packet *p) {
    MacModule802_11::recv(p);
}
void ConnectivityAwareMac802_11Module::recv(Packet *p, Handler *callback) {
    MacModule802_11::recv(p, callback);
}
double ConnectivityAwareMac802_11Module::getBER() {
    ConnectivityAwareMac802_11mr* macMr =
        dynamic_cast<ConnectivityAwareMac802_11mr*> (mac_);
    return macMr->getBER();
}

```

C.6 Connectivity-aware-mac-802_11-module.h

```

#ifndef _CAMAC80211MODULE_
#define _CAMAC80211MODULE_

#include <packet.h>
#include <802.11-module.h>
#include "connectivity-aware.h"

class ConnectivityAwareMac802_11Module: public MacModule802_11,
    virtual public IConnectivityAware {
public:
    ConnectivityAwareMac802_11Module();
    virtual ~ConnectivityAwareMac802_11Module();

    virtual int command(int argc, const char* const * argv);

    virtual void recv(Packet*, Handler* callback);
    virtual void recv(Packet *p);

    virtual double getBER();
};
#endif /* _CAMAC80211MODULE_ */

```

C.7 Connectivity-aware-mac-802_11.tcl

```
MacInterface set debug_ 0
LogInterface set debug_ 0
LLInterface set debug_ 0

Mac/802_11/Multirate/CA set basicRate_ 1Mb
Mac/802_11/Multirate/CA set dataRate_ 1Mb

Mac/802_11/Multirate/CA set debug_ 0
Module/802_11/CA set debug_ 0

proc createConnectivyaWare802_11MacModule {llname ifqName ip {qlen ""}} {
    set module [new Module/802_11/CA]
    set ll [new $llname]
    set mac [new Mac/802_11/Multirate/CA]
    set ifq [new $ifqName]
    set macinterface [new MacInterface]
    set llinterface [new LLInterface]
    set loginterface [new LogInterface]

    set god [God instance]
        set arptable_ [new ARPTable/Mrcl $ip $mac]
        # FOR backward compatibility sake, hack only
        $arptable_ drop-target $macinterface
        $ll arptable $arptable_
        $ll mac $mac
        $ll down-target $ifq
        $ll up-target $llinterface

        $ifq target $mac
        if {$qlen != "" } {
            $ifq set limit_ $qlen
        }
        $mac nodes [$god num_nodes]
        $mac up-target $ll
        $module setMac $mac
        $module setIfq $ifq
        $module setll $ll
        $module setMacInterface $macinterface
        $module setLogInterface $loginterface
        $module setLLInterface $llinterface

    return $module
}
```

Appendix D: SNIR threshold at different data rates

802.11 a		802.11 b	
SNIR threshold (dB)	Rate (Mbps)	SNIR threshold (dB)	Rate (Mbps)
6	6	2	1
7.8	9	5	2
9	12	9	5.5
10.8	18	12	11
17	24		
19	36		
24	48		
24.6	54		

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Appendix E: Control message format

Route Request message format:

Route Request ID	Source Address	Source Sequence Number	Destination Address	Destination Sequence Number	Connectivity Level Update
------------------	----------------	------------------------	---------------------	-----------------------------	---------------------------

- Route request ID: a unique number that identifies a particular route request when taken together with the source address.
- Source address: address of the originator of the request.
- Source sequence number: the current sequence number pointing to the request originator.
- Destination address: the address of the destination to which route is needed.
- Destination sequence number: latest sequence number in the source cache pointing to the destination.
- Connectivity level update: the connectivity level of all the links that the route request has traversed.

Route Reply message format:

Destination Address	Source Address	Destination Sequence Number	Life Time
---------------------	----------------	-----------------------------	-----------

- Destination address: the address of the destination for which the route is given.
- Source address: address of the originator of the request to which the route is given.
- Destination sequence number: sequence number pointing to the destination for which route is given.
- Lifetime: the duration for which route is considered valid.

Route Error message format:

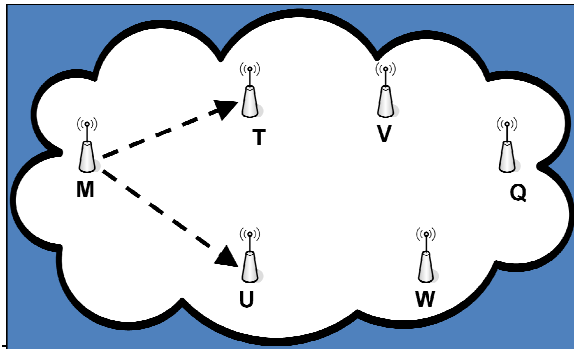
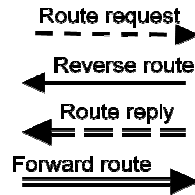
Unreachable Destination Address	Unreachable Destination Sequence number	Additional Unreachable Destination Address	Additional Unreachable Destination Sequence number	Number of Unreachable Destinations
--	--	---	---	---

- Unreachable destination address: address of the node that has become unreachable.
- Unreachable destination sequence number: sequence number of the node that has become unreachable
- Additional unreachable destination addresses and sequence number: these are added if needed.
- Number of unreachable destinations: the count of unreachable destination in the message, which must be at least one..

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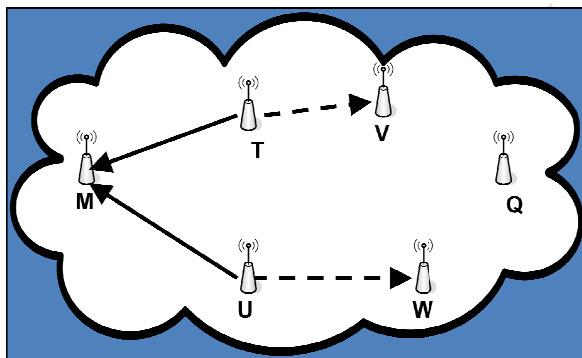
Appendix F: Illustration of the routing process.

- During the routing process, links with CL within the optimal range are preferred. If available links have CL within the low range, the link with the highest CL of these low range is used.
- CL within the optimal range will always provide optimal connectivity.



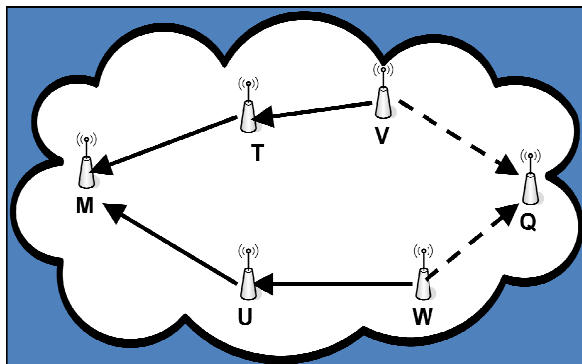
Source node M wants to transmit to destination node Q.

- M creates a route request packet and sends it to both T and U.



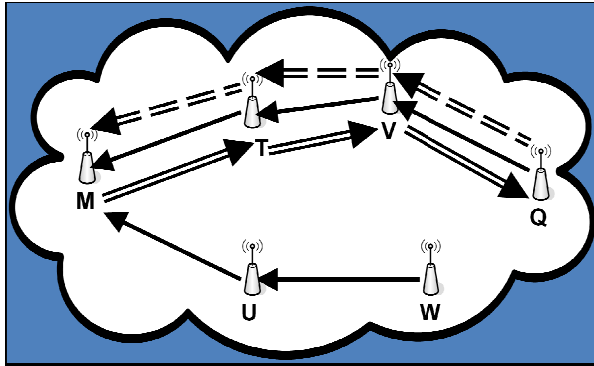
T and U are not the destination node.

- T and U update the CL on the route request packet received respectively.
- T and U each create a reverse route to M.
- They forward the request to their neighbour nodes.
- Subsequent route request with the same request ID and source address received by V and W and with lower CL are discarded. If subsequent route request shows better CL than the already processed route request, reverse route is updated to reflect the link to the source of the route request with the better CL.



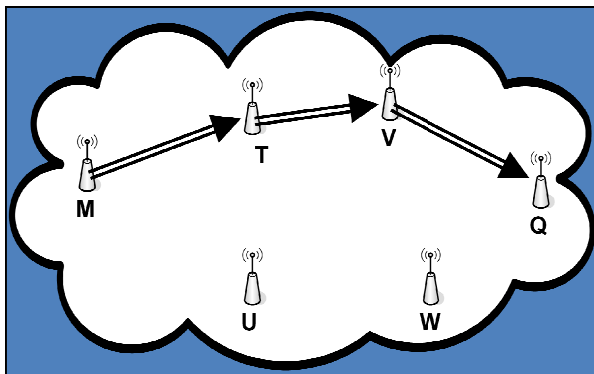
V and W are not the destination node.

- V and W each update the CL, create a reverse route to T and U respectively and forwards route request packet to Q.
- Subsequent requests with the same request ID, source address and lower CL received by Q after the first request has been processed are discarded.
- Also in case T or U receives this same request from V or W, it is discarded.



Q is the destination node.

- Q creates a reverse route to V, and a route reply packet. The route reply packet is forwarded to M through the reverse route created.
- Forward path to Q is set up as route reply travels to M.



M transmits packet to Q

- M uses route M-T-V-Q to transmit data to Q

University of Cape Town

Appendix G: TCL Simulation scripts.

G.1 AODV-UU-CL tcl script

```
#####
# Command-line parameters
#####
if {$argc == 0} {
    set opt(run) 1
    set opt(nn) 60
    set opt(ns) 4
    set opt(duration) 450
    set opt(sampling) 1.0
    set opt(distance) 150
    set opt(txpower) 0.01
} elseif {$argc == 6 || $argc == 7} {
    set opt(run) [lindex $argv 0]
    set opt(nn) [lindex $argv 1]
    set opt(ns) [lindex $argv 2]
    set opt(duration) [lindex $argv 3]
    set opt(sampling) [lindex $argv 4]
    set opt(distance) [lindex $argv 5]

    if {$argc == 7} {
        set opt(txpower) [lindex $argv 6]
    } else {
        set opt(txpower) 0.01
    }
} else {
    puts "invalid args"
}
#####
# Scenario Configuration
#####
set opt(xmax) 1500
set opt(xmin) 0
set opt(node_density) [expr $opt(nn) / ($opt(xmax) * $opt(xmax))]

# starting time of each transmission
set opt(start_min) 0
set opt(start_max) 0.05

set opt(resultfname) "$argv0-$opt(nn)-$opt(ns)-$opt(duration)-$opt(distance)-$opt(txpower).log"
set opt(tracefname) "$argv0-$opt(nn)-$opt(ns)-$opt(duration)-$opt(distance)-$opt(txpower).tr"
set opt(thrfname) "$argv0-$opt(nn)-$opt(ns)-$opt(duration)-$opt(distance)-$opt(txpower).thr"
set opt(perfname) "$argv0-$opt(nn)-$opt(ns)-$opt(duration)-$opt(distance)-$opt(txpower).per"
set opt(fttfname) "$argv0-$opt(nn)-$opt(ns)-$opt(duration)-$opt(distance)-$opt(txpower).ftt"
#####
# Module Libraries
#####
# The following lines must be before loading libraries and before instantiating
# the ns Simulator
#remove-all-packet-headers
source dynlibutils.tcl

dynlibload ns_tools_extensions
dynlibload Miracle
dynlibload miracleport
dynlibload miraclecbr
dynlibload cbrtracer
dynlibload miraclelink
dynlibload MiracleBasicMovement
dynlibload MiracleWirelessCh
dynlibload MiraclePhy802_11
dynlibload dei80211mr /home/oladayo/Dev/ns2/ns-allinone-2.34/dei80211mr-1.1.4/src/.libs
dynlibload connectivityawaremac802_11
dynlibload aodvuuc1
```

```

#####
# Tracers
#####
dynlibload Trace
dynlibload cbrtracer
dynlibload aodvuuc1tracer
dynlibload phytracer
#####
# NS-2 Instance & Trace Files
#####
set ns [new Simulator]
$ns use-Miracle

set tf [open $opt(tracefname) w]
$ns trace-all $tf

set hf [open $opt(thrfname) w]
set pf [open $opt(perfname) w]
set ff [open $opt(fttfname) w]
#####
# Random Number Generators
#####
# seed the default RNG
global defaultRNG
$defaultRNG seed 9999

set startRNG [new RNG]
set typeRNG [new RNG]
set neighbourRNG [new RNG]
set positionRNG [new RNG]
set tx_pairRNG [new RNG]

# Create the RNGs and set them to the correct substream
for {set j 1} {$j < $opt(run)} {incr j} {
    $defaultRNG next-substream
    $startRNG next-substream
    $typeRNG next-substream
    $neighbourRNG next-substream
    $positionRNG next-substream
    $tx_pairRNG next-substream
}

set start_ [new RandomVariable/Uniform]
$start_ set min_ $opt(start_min)
$start_ set max_ $opt(start_max)
$start_ use-rng $startRNG

set type_ [new RandomVariable/Uniform]
$type_ set min_ 0
$type_ set max_ 1
$type_ use-rng $typeRNG

set neighbour_ [new RandomVariable/Uniform]
$neighbour_ set min_ 0
$neighbour_ set max_ $opt(nn)
$neighbour_ use-rng $neighbourRNG

set distance_ [new RandomVariable/Poisson]
$distance_ set avg_ $opt(distance)
$distance_ use-rng $positionRNG

set direction_ [new RandomVariable/Uniform]
$direction_ set min_ 0
$direction_ set max_ 1
$direction_ use-rng $positionRNG

set tx_type_ [new RandomVariable/Uniform]
$tx_type_ use-rng $typeRNG

set tx_pair_ [new RandomVariable/Uniform]
$tx_pair_ use-rng $tx_pairRNG

```

```

#####
# Functions
#####
# Create nodes
proc create_nodes {id posX posY posZ} {
    puts "Creating node $id at $posX, $posY"
    # +-----+
    # |                                     4. AODVUU                               |
    # +-----+
    # |                                     3. IP/AODVUU Interface                       |
    # +-----+

    global ns nodes nodes_aodvuu nodes_ipif nodes_ll nodes_ll_count nodes_pos

    set nodes($id)          [$ns create-M_Node]

    set nodes_aodvuu($id)   [new Module/AODVUU]
    set nodes_ipif($id)     [new Module/IP/AODVInterface]

    set nodes_ll_count($id) 0

    # Use default IP addressing i.e. 0, 1, 2, 3 etc

    # Add modules
    $nodes($id) addModule 4 $nodes_aodvuu($id)      3 "n0_AODV"
    $nodes($id) addModule 3 $nodes_ipif($id)        3 "n0_IP"

    # Connect modules
    $nodes($id) setConnection $nodes_aodvuu($id)   $nodes_ipif($id)    1

    # Set position
    set nodes_pos($id) [new "Position/BM"]
    $nodes($id)        addPosition $nodes_pos($id)
    $nodes_pos($id)    setX_ $posX
    $nodes_pos($id)    setY_ $posY

    puts [format "\tMesh Node \t$id : X = %.2f, Y = %.2f" \
                $posX $posY]
}

proc attach_cbr_source_to_node {id} {
    puts "Attaching CBR source to node $id"
    # +-----+
    # |                                     6. CBR                               |
    # +-----+
    # |                                     5. Port                               |
    # +-----+

    global ns nodes nodes_port nodes_cbr nodes_cbr_port nodes_aodvuu

    set nodes_cbr($id)      [new Module/CBR]
    set nodes_port($id)     [new Module/Port/Map]

    # Set CBR rate
    $nodes_cbr($id) set period_ 0.05

    # Add modules
    $nodes($id) addModule 6 $nodes_cbr($id)          3 "n0_CBR"
    $nodes($id) addModule 5 $nodes_port($id)         3 "n0_PORT"

    # Connect modules
    $nodes($id) setConnection $nodes_cbr($id)       $nodes_port($id)    1
    $nodes($id) setConnection $nodes_port($id)      $nodes_aodvuu($id)  1

    set nodes_cbr_port($id) [$nodes_port($id) assignPort $nodes_cbr($id)]
}

proc attach_cbr_sink_to_node {id} {
    global ns nodes nodes_cbr nodes_port nodes_cbr_port nodes_aodvuu

```

```

set nodes_cbr($id)      [new Module/CBR]
set nodes_port($id)    [new Module/Port/Map]

# Set CBR rate
$nodes_cbr($id) set period_ 0.05

# Add modules
$nodes($id) addModule 6 $nodes_cbr($id) 3 "n0_CBR"
$nodes($id) addModule 5 $nodes_port($id) 3 "n0_PORT"

# Connect modules
$nodes($id) setConnection $nodes_cbr($id) $nodes_port($id) 1
$nodes($id) setConnection $nodes_port($id) $nodes_aodvuu($id) 1

set nodes_cbr_port($id) [$nodes_port($id) assignPort $nodes_cbr($id)]
}

proc connect_source_and_sink {sourceId sinkId source_cbr_start} {
    global ns opt nodes nodes_cbr nodes_port nodes_cbr_port nodes_aodvuu nodes_ipif

    $nodes_cbr($sourceId) set destAddr_ [$nodes_ipif($sinkId) addr]
    $nodes_cbr($sourceId) set destPort_ $nodes_cbr_port($sinkId)

    $nodes_cbr($sinkId) set destAddr_ [$nodes_ipif($sourceId) addr]
    $nodes_cbr($sinkId) set destPort_ $nodes_cbr_port($sourceId)

    set source_cbr_stop [expr $source_cbr_start + $opt(duration)]

    $ns at $source_cbr_start "$nodes_cbr($sourceId) start"
    $ns at $source_cbr_stop "$nodes_cbr($sourceId) stop"
}

proc attach_mac80211a_interface_to_node {id} {
    puts "Attaching IEEE 802.11a interface to node $id"
    # +-----+
    # |                2.n LL                |
    # +-----+
    # |                1 PHY                  |
    # +-----+

    global ns nodes nodes_aodvuu nodes_ipif nodes_ll nodes_ll_count nodes_phy nodes_pp channel
    pmodel per_a

    set nodes_ll($id,$nodes_ll_count($id)) [createConnectivityAware802_11MacModule "LL/Mrc1"
"Queue/DropTail/PriQueue" [$nodes_ipif($id) addr] 100]
    set nodes_phy($id) [createPhyModule "Phy/WirelessPhy/PowerAware" $pmodel
"Antenna/OmniAntenna" $nodes_ll($id,$nodes_ll_count($id)) ""]

    set mac [$nodes_ll($id,$nodes_ll_count($id)) getMac]
    set phy [$nodes_phy($id) getPhy]
    $mac basicMode_ Mode6Mb
    $mac dataMode_ Mode6Mb
    $mac per $per_a

    $phy set CStresh_ 6.31e-12
    $phy set freq_ 5.18e+9

    set nodes_pp($id) [new PowerProfile]
    $mac powerProfile $nodes_pp($id)
    $phy powerProfile $nodes_pp($id)

    # Add modules
    $nodes($id) addModule 2 $nodes_ll($id,$nodes_ll_count($id)) 3 "n${nodes_ll_count(0)}_LL"
    $nodes($id) addModule 1 $nodes_phy($id) 3 "n0_PHY"

    # Connect modules
    $nodes($id) setConnection $nodes_ipif($id)
$nodes_ll($id,$nodes_ll_count($id)) 1
    $nodes($id) setConnection $nodes_ll($id,$nodes_ll_count($id)) $nodes_phy($id)
1

```

```

# Add to channel
$nodes($id) addToChannel $channel $nodes_phy($id) 1

$nodes_aodvuu($id) add-if $nodes_ipif($id) $nodes_ll($id,$nodes_ll_count($id))
$nodes_aodvuu($id) if-queue [$nodes_ll($id,$nodes_ll_count($id)) getQueue]

incr nodes_ll_count($id)
}

proc attach_mac80211b_interface_to_node {id} {
puts "Attaching IEEE 802.11b interface to node $id"
# +-----+
# |                2.n LL                |
# +-----+
# |                1 PHY                  |
# +-----+

global ns nodes nodes_aodvuu nodes_ipif nodes_ll nodes_ll_count nodes_phy nodes_pp channel
pmodel per_b

set nodes_ll($id,$nodes_ll_count($id)) [createConnectivityAware802_11MacModule "LL/Mrc1"
"Queue/DropTail/PriQueue" [$nodes_ipif($id) addr] 100]
set nodes_phy($id) [createPhyModule "Phy/WirelessPhy/PowerAware" $pmodel
"Antenna/OmniAntenna" $nodes_ll($id,$nodes_ll_count($id)) ""]

set mac [$nodes_ll($id,$nodes_ll_count($id)) getMac]
set phy [$nodes_phy($id) getPhy]
$mac basicMode_ Mode5_5Mb
$mac dataMode_ Mode5_5Mb
$mac per $per_b

$phy set CSTresh_ 7.7eâ`18
$phy set freq_ 2.437e+9

set nodes_pp($id) [new PowerProfile]
$mac powerProfile $nodes_pp($id)
$phy powerProfile $nodes_pp($id)

# Add modules
$nodes($id) addModule 2 $nodes_ll($id,$nodes_ll_count($id)) 3 "n${nodes_ll_count(0)}_LL"
$nodes($id) addModule 1 $nodes_phy($id) 3 "n0_PHY"

# Connect modules
$nodes($id) setConnection $nodes_ipif($id)
$nodes_ll($id,$nodes_ll_count($id)) 1
$nodes($id) setConnection $nodes_ll($id,$nodes_ll_count($id)) $nodes_phy($id)
1

# Add to channel
$nodes($id) addToChannel $channel $nodes_phy($id) 1

$nodes_aodvuu($id) add-if $nodes_ipif($id) $nodes_ll($id,$nodes_ll_count($id))
$nodes_aodvuu($id) if-queue [$nodes_ll($id,$nodes_ll_count($id)) getQueue]

incr nodes_ll_count($id)
}

proc create_initial_nodes_with_types_and_positions {} {
global opt ns node_type node_type_count nodes_pos_x nodes_pos_y node_tx_rx_paired

for {set i 0} {$i < 3} {incr i} {
set node_type_count($i) 0
}

# Node 0
set nodes_pos_x(0) [expr 1500 - $opt(distance)]
set nodes_pos_y(0) 1500
create_nodes 0 $nodes_pos_x(0) $nodes_pos_y(0) 0
attach_mac80211a_interface_to_node 0
attach_mac80211b_interface_to_node 0
set node_type(0) 2

```

```

incr node_type_count(2)

# Node 1
set nodes_pos_x(1) 1500
set nodes_pos_y(1) 1500
create_nodes 1 $nodes_pos_x(0) $nodes_pos_y(0) 0
attach_mac80211a_interface_to_node 1
attach_mac80211b_interface_to_node 1
set node_type(1) 2
incr node_type_count(2)

# Node 2
set nodes_pos_x(2) [expr 1500 + $opt(distance)]
set nodes_pos_y(2) 1500
create_nodes 2 $nodes_pos_x(0) $nodes_pos_y(0) 0
attach_mac80211a_interface_to_node 2
attach_mac80211b_interface_to_node 2
set node_type(2) 2
incr node_type_count(2)

for {set i 0} {$i < $opt(nn)} {incr i} {
    set node_tx_rx_paired($i) 0
}

}

proc generate_types_for_other_nodes {} {
    global opt ns node_type type_

    for {set id 3} {$id < $opt(nn)} {incr id} {
        set type [expr round([$type_ value])]
        set node_type($id) $type
    }
}

proc generate_positions_for_other_nodes {} {
    global opt ns node_type origin_ neighbour_ distance_ direction_ nodes_pos_x nodes_pos_y

    for {set id 3} {$id < $opt(nn)} {incr id} {

        $neighbour_ set min_ 0
        $neighbour_ set max_ [expr $id - 1]

        set neighbour [expr int([$neighbour_ value])]
        while {($node_type($neighbour) != 2) && ($node_type($neighbour) != $node_type($id))} {
            set neighbour [expr int([$neighbour_ value])]
        }

        set distance_x [expr int([$distance_ value])]
        set distance_y [expr int([$distance_ value])]
        set direction_x [expr round([$direction_ value])]
        set direction_y [expr round([$direction_ value])]

        if {$direction_x == 1} {
            set nodes_pos_x($id) [expr $nodes_pos_x($neighbour) + $distance_x]
        } else {
            if {$nodes_pos_x($neighbour) > $distance_x} {
                set nodes_pos_x($id) [expr $nodes_pos_x($neighbour) - $distance_x]
            } else {
                set nodes_pos_x($id) 0; #Or select neighbour's position i.e.
                $nodes_pos_x($neighbour)
            }
        }

        if {$direction_y == 1} {
            set nodes_pos_y($id) [expr $nodes_pos_y($neighbour) + $distance_y]
        } else {
            if {$nodes_pos_y($neighbour) > $distance_y} {
                set nodes_pos_y($id) [expr $nodes_pos_y($neighbour) - $distance_y]
            } else {
                set nodes_pos_y($id) 0; #Or select neighbour's position i.e.
                $nodes_pos_y($neighbour)
            }
        }
    }
}

```

```

    }
}

proc attach_interfaces_to_other_nodes {} {
    global opt ns node_type node_type_count

    for {set id 3} {$id < $opt(nn)} {incr id} {
        if {$node_type($id) == 0} {
            attach_mac80211a_interface_to_node $id
            incr node_type_count(0)
        } elseif {$node_type($id) == 1} {
            attach_mac80211b_interface_to_node $id
            incr node_type_count(1)
        } else {
            attach_mac80211a_interface_to_node $id
            attach_mac80211b_interface_to_node $id
            incr node_type_count(2)
        }
    }
}

proc generate_traffic_for_other_nodes {} {
    global opt ns node_type node_type_count tx_type_ start_
    set max_nodes [expr int($node_type_count(0) / 2)]
    set max_type 0
    set min_type 1
    if {$node_type_count(1) < $node_type_count(0)} {
        set max_nodes [expr int($node_type_count(1) / 2)]
        set max_type 1
        set min_type 0
    }

    if {$max_nodes >= $opt(ns)} {
        set max_nodes $opt(ns)
    }

    $tx_type_ set min_ 1
    $tx_type_ set max_ $max_nodes
    set num_($max_type) [expr int([$tx_type_ value])]
    set num_($min_type) [expr $opt(ns) - $num_($max_type)]

    if {$num_($min_type) > [expr int($node_type_count($min_type) / 2)]} {
        set num_($min_type) [expr int($node_type_count($min_type) / 2)]
    }

    set num_a $num_(0)
    set num_b $num_(1)

    puts "A: $num_a B: $num_b Total A: $node_type_count(0) Total B: $node_type_count(1)"

    for {set i 0} {$i < $num_a} {incr i} {
        set source_cbr_start [$start_ value]
        generate_tx_rx_pair_for_type 0 $source_cbr_start
    }
    for {set i 0} {$i < $num_b} {incr i} {
        set source_cbr_start [$start_ value]
        generate_tx_rx_pair_for_type 1 $source_cbr_start
    }
}

proc generate_tx_rx_pair_for_type {type source_cbr_start} {
    global opt ns node_type tx_pair_ node_tx_rx_paired node_type_count

    $tx_pair_ set min_ 0
    $tx_pair_ set max_ $node_type_count($type)

    # SOURCE
    set source_tx_id [expr int([$tx_pair_ value])]
    set source_id [get_node_id_from_node_tx_id $type $source_tx_id]
    while {$node_tx_rx_paired($source_id) == 1} {

```

```

        set source_tx_id [expr int([$tx_pair_value])]
        set source_id [get_node_id_from_node_tx_id $type $source_tx_id]
    }
    set node_tx_rx_paired($source_id) 1

    # SINK
    set sink_tx_id [expr int([$tx_pair_value])]
    set sink_id [get_node_id_from_node_tx_id $type $sink_tx_id]
    while {($sink_id == $source_id) || ($node_tx_rx_paired($sink_id) == 1)} {
        puts "$type Randomly selected: $sink_id -- INVALID $source_id
$node_tx_rx_paired($sink_id)"

        set sink_tx_id [expr int([$tx_pair_value])]
        set sink_id [get_node_id_from_node_tx_id $type $sink_tx_id]
    }
    set node_tx_rx_paired($sink_id) 1

    puts "source: $source_id, destination: $sink_id"

    attach_cbr_source_to_node $source_id
    attach_cbr_sink_to_node $sink_id
    connect_source_and_sink $source_id $sink_id $source_cbr_start
}

proc get_node_id_from_node_tx_id {node_tx_type node_tx_id} {
    global opt ns node_type

    set node_id -100
    set node_tx_count 0

    for {set id 3} {$id < $opt(nn)} {incr id} {
        if {($node_type($id) == $node_tx_type) && ($node_tx_id == $node_tx_count)} {
            set node_id $node_tx_count
            break
        } elseif {$node_type($id) == $node_tx_type} {
            incr node_tx_count
        }
    }

    return $node_id
}

proc record_stats {} {
    global opt ns hf pf ff nodes_cbr line_counter
}

proc finish_simulation {} {
    global ns tf opt meshTcpAgent
    puts "done!"
    $ns flush-trace
    close $tf

    puts ""
    puts "Tracefile: $opt(tracefname)"
    puts " Thrfile: $opt(thrfname)"
    puts " Perfile: $opt(perfname)"
    puts " Ftffile: $opt(ftffname)"
}

proc load_per_table {per} {
    $per add ModelMb 128 -1.000 0.994100
    $per add ModelMb 128 0.000 0.097336
    $per add ModelMb 128 1.000 0.012213
    $per add ModelMb 128 2.000 0.001023
    $per add ModelMb 128 3.000 0.000061
    $per add ModelMb 128 4.000 0.000007
    $per add ModelMb 128 5.000 0.000000
    $per add ModelMb 128 6.000 0.000000
    $per add ModelMb 128 7.000 0.000000
    $per add ModelMb 128 8.000 0.000000
}

```

\$per add	Mode1Mb	128	9.000	0.000000
\$per add	Mode1Mb	128	10.000	0.000000
\$per add	Mode1Mb	128	11.000	0.000000
\$per add	Mode1Mb	128	12.000	0.000000
\$per add	Mode1Mb	128	13.000	0.000000
\$per add	Mode1Mb	128	14.000	0.000000
\$per add	Mode1Mb	128	15.000	0.000000
\$per add	Mode1Mb	128	16.000	0.000000
\$per add	Mode1Mb	128	17.000	0.000000
\$per add	Mode1Mb	128	18.000	0.000000
\$per add	Mode1Mb	128	19.000	0.000000
\$per add	Mode2Mb	128	-1.000	0.994100
\$per add	Mode2Mb	128	0.000	0.994100
\$per add	Mode2Mb	128	1.000	0.994100
\$per add	Mode2Mb	128	2.000	0.707572
\$per add	Mode2Mb	128	3.000	0.193509
\$per add	Mode2Mb	128	4.000	0.030253
\$per add	Mode2Mb	128	5.000	0.002148
\$per add	Mode2Mb	128	6.000	0.000154
\$per add	Mode2Mb	128	7.000	0.000010
\$per add	Mode2Mb	128	8.000	0.000001
\$per add	Mode2Mb	128	9.000	0.000001
\$per add	Mode2Mb	128	10.000	0.000001
\$per add	Mode2Mb	128	11.000	0.000001
\$per add	Mode2Mb	128	12.000	0.000001
\$per add	Mode2Mb	128	13.000	0.000001
\$per add	Mode2Mb	128	14.000	0.000001
\$per add	Mode2Mb	128	15.000	0.000001
\$per add	Mode2Mb	128	16.000	0.000001
\$per add	Mode2Mb	128	17.000	0.000001
\$per add	Mode2Mb	128	18.000	0.000001
\$per add	Mode2Mb	128	19.000	0.000001
\$per add	Mode5_5Mb	128	-1.000	1.000000
\$per add	Mode5_5Mb	128	0.000	1.000000
\$per add	Mode5_5Mb	128	1.000	1.000000
\$per add	Mode5_5Mb	128	2.000	1.000000
\$per add	Mode5_5Mb	128	3.000	1.000000
\$per add	Mode5_5Mb	128	4.000	0.999248
\$per add	Mode5_5Mb	128	5.000	0.707572
\$per add	Mode5_5Mb	128	6.000	0.264530
\$per add	Mode5_5Mb	128	7.000	0.059592
\$per add	Mode5_5Mb	128	8.000	0.013224
\$per add	Mode5_5Mb	128	9.000	0.002761
\$per add	Mode5_5Mb	128	10.000	0.000512
\$per add	Mode5_5Mb	128	11.000	0.000072
\$per add	Mode5_5Mb	128	12.000	0.000012
\$per add	Mode5_5Mb	128	13.000	0.000002
\$per add	Mode5_5Mb	128	14.000	0.000002
\$per add	Mode5_5Mb	128	15.000	0.000002
\$per add	Mode5_5Mb	128	16.000	0.000002
\$per add	Mode5_5Mb	128	17.000	0.000002
\$per add	Mode5_5Mb	128	18.000	0.000002
\$per add	Mode5_5Mb	128	19.000	0.000002
\$per add	Mode11Mb	128	-1.000	1.000000
\$per add	Mode11Mb	128	0.000	1.000000
\$per add	Mode11Mb	128	1.000	1.000000
\$per add	Mode11Mb	128	2.000	1.000000
\$per add	Mode11Mb	128	3.000	1.000000
\$per add	Mode11Mb	128	4.000	1.000000
\$per add	Mode11Mb	128	5.000	0.999998
\$per add	Mode11Mb	128	6.000	0.995198
\$per add	Mode11Mb	128	7.000	0.871272
\$per add	Mode11Mb	128	8.000	0.511810
\$per add	Mode11Mb	128	9.000	0.193509
\$per add	Mode11Mb	128	10.000	0.059592
\$per add	Mode11Mb	128	11.000	0.021275
\$per add	Mode11Mb	128	12.000	0.007142
\$per add	Mode11Mb	128	13.000	0.001739
\$per add	Mode11Mb	128	14.000	0.000512
\$per add	Mode11Mb	128	15.000	0.000205
\$per add	Mode11Mb	128	16.000	0.000052

\$per add	Mode11Mb	128	17.000	0.000016
\$per add	Mode11Mb	128	18.000	0.000006
\$per add	Mode11Mb	128	19.000	0.000002
\$per add	Mode1Mb	256	-1.000	0.999965
\$per add	Mode1Mb	256	0.000	0.185198
\$per add	Mode1Mb	256	1.000	0.024277
\$per add	Mode1Mb	256	2.000	0.002046
\$per add	Mode1Mb	256	3.000	0.000123
\$per add	Mode1Mb	256	4.000	0.000014
\$per add	Mode1Mb	256	5.000	0.000000
\$per add	Mode1Mb	256	6.000	0.000000
\$per add	Mode1Mb	256	7.000	0.000000
\$per add	Mode1Mb	256	8.000	0.000000
\$per add	Mode1Mb	256	9.000	0.000000
\$per add	Mode1Mb	256	10.000	0.000000
\$per add	Mode1Mb	256	11.000	0.000000
\$per add	Mode1Mb	256	12.000	0.000000
\$per add	Mode1Mb	256	13.000	0.000000
\$per add	Mode1Mb	256	14.000	0.000000
\$per add	Mode1Mb	256	15.000	0.000000
\$per add	Mode1Mb	256	16.000	0.000000
\$per add	Mode1Mb	256	17.000	0.000000
\$per add	Mode1Mb	256	18.000	0.000000
\$per add	Mode1Mb	256	19.000	0.000000
\$per add	Mode2Mb	256	-1.000	0.999965
\$per add	Mode2Mb	256	0.000	0.999965
\$per add	Mode2Mb	256	1.000	0.999965
\$per add	Mode2Mb	256	2.000	0.914486
\$per add	Mode2Mb	256	3.000	0.349572
\$per add	Mode2Mb	256	4.000	0.059591
\$per add	Mode2Mb	256	5.000	0.004292
\$per add	Mode2Mb	256	6.000	0.000307
\$per add	Mode2Mb	256	7.000	0.000020
\$per add	Mode2Mb	256	8.000	0.000002
\$per add	Mode2Mb	256	9.000	0.000002
\$per add	Mode2Mb	256	10.000	0.000002
\$per add	Mode2Mb	256	11.000	0.000002
\$per add	Mode2Mb	256	12.000	0.000002
\$per add	Mode2Mb	256	13.000	0.000002
\$per add	Mode2Mb	256	14.000	0.000002
\$per add	Mode2Mb	256	15.000	0.000002
\$per add	Mode2Mb	256	16.000	0.000002
\$per add	Mode2Mb	256	17.000	0.000002
\$per add	Mode2Mb	256	18.000	0.000002
\$per add	Mode2Mb	256	19.000	0.000002
\$per add	Mode5_5Mb	256	-1.000	1.000000
\$per add	Mode5_5Mb	256	0.000	1.000000
\$per add	Mode5_5Mb	256	1.000	1.000000
\$per add	Mode5_5Mb	256	2.000	1.000000
\$per add	Mode5_5Mb	256	3.000	1.000000
\$per add	Mode5_5Mb	256	4.000	0.999999
\$per add	Mode5_5Mb	256	5.000	0.914486
\$per add	Mode5_5Mb	256	6.000	0.459084
\$per add	Mode5_5Mb	256	7.000	0.115633
\$per add	Mode5_5Mb	256	8.000	0.026273
\$per add	Mode5_5Mb	256	9.000	0.005514
\$per add	Mode5_5Mb	256	10.000	0.001023
\$per add	Mode5_5Mb	256	11.000	0.000143
\$per add	Mode5_5Mb	256	12.000	0.000025
\$per add	Mode5_5Mb	256	13.000	0.000003
\$per add	Mode5_5Mb	256	14.000	0.000003
\$per add	Mode5_5Mb	256	15.000	0.000003
\$per add	Mode5_5Mb	256	16.000	0.000003
\$per add	Mode5_5Mb	256	17.000	0.000003
\$per add	Mode5_5Mb	256	18.000	0.000003
\$per add	Mode5_5Mb	256	19.000	0.000003
\$per add	Mode11Mb	256	-1.000	1.000000
\$per add	Mode11Mb	256	0.000	1.000000
\$per add	Mode11Mb	256	1.000	1.000000
\$per add	Mode11Mb	256	2.000	1.000000
\$per add	Mode11Mb	256	3.000	1.000000

\$per add	Mode11Mb	256	4.000	1.000000
\$per add	Mode11Mb	256	5.000	1.000000
\$per add	Mode11Mb	256	6.000	0.999977
\$per add	Mode11Mb	256	7.000	0.983429
\$per add	Mode11Mb	256	8.000	0.761671
\$per add	Mode11Mb	256	9.000	0.349572
\$per add	Mode11Mb	256	10.000	0.115633
\$per add	Mode11Mb	256	11.000	0.042097
\$per add	Mode11Mb	256	12.000	0.014234
\$per add	Mode11Mb	256	13.000	0.003476
\$per add	Mode11Mb	256	14.000	0.001023
\$per add	Mode11Mb	256	15.000	0.000410
\$per add	Mode11Mb	256	16.000	0.000104
\$per add	Mode11Mb	256	17.000	0.000033
\$per add	Mode11Mb	256	18.000	0.000012
\$per add	Mode11Mb	256	19.000	0.000004
\$per add	Mode1Mb	512	-1.000	1.000000
\$per add	Mode1Mb	512	0.000	0.336098
\$per add	Mode1Mb	512	1.000	0.047964
\$per add	Mode1Mb	512	2.000	0.004088
\$per add	Mode1Mb	512	3.000	0.000246
\$per add	Mode1Mb	512	4.000	0.000029
\$per add	Mode1Mb	512	5.000	0.000001
\$per add	Mode1Mb	512	6.000	0.000001
\$per add	Mode1Mb	512	7.000	0.000001
\$per add	Mode1Mb	512	8.000	0.000001
\$per add	Mode1Mb	512	9.000	0.000001
\$per add	Mode1Mb	512	10.000	0.000001
\$per add	Mode1Mb	512	11.000	0.000001
\$per add	Mode1Mb	512	12.000	0.000001
\$per add	Mode1Mb	512	13.000	0.000001
\$per add	Mode1Mb	512	14.000	0.000001
\$per add	Mode1Mb	512	15.000	0.000001
\$per add	Mode1Mb	512	16.000	0.000001
\$per add	Mode1Mb	512	17.000	0.000001
\$per add	Mode1Mb	512	18.000	0.000001
\$per add	Mode1Mb	512	19.000	0.000001
\$per add	Mode2Mb	512	-1.000	1.000000
\$per add	Mode2Mb	512	0.000	1.000000
\$per add	Mode2Mb	512	1.000	1.000000
\$per add	Mode2Mb	512	2.000	0.992687
\$per add	Mode2Mb	512	3.000	0.576944
\$per add	Mode2Mb	512	4.000	0.115632
\$per add	Mode2Mb	512	5.000	0.008565
\$per add	Mode2Mb	512	6.000	0.000614
\$per add	Mode2Mb	512	7.000	0.000041
\$per add	Mode2Mb	512	8.000	0.000005
\$per add	Mode2Mb	512	9.000	0.000005
\$per add	Mode2Mb	512	10.000	0.000005
\$per add	Mode2Mb	512	11.000	0.000005
\$per add	Mode2Mb	512	12.000	0.000005
\$per add	Mode2Mb	512	13.000	0.000005
\$per add	Mode2Mb	512	14.000	0.000005
\$per add	Mode2Mb	512	15.000	0.000005
\$per add	Mode2Mb	512	16.000	0.000005
\$per add	Mode2Mb	512	17.000	0.000005
\$per add	Mode2Mb	512	18.000	0.000005
\$per add	Mode2Mb	512	19.000	0.000005
\$per add	Mode5_5Mb	512	-1.000	1.000000
\$per add	Mode5_5Mb	512	0.000	1.000000
\$per add	Mode5_5Mb	512	1.000	1.000000
\$per add	Mode5_5Mb	512	2.000	1.000000
\$per add	Mode5_5Mb	512	3.000	1.000000
\$per add	Mode5_5Mb	512	4.000	1.000000
\$per add	Mode5_5Mb	512	5.000	0.992687
\$per add	Mode5_5Mb	512	6.000	0.707410
\$per add	Mode5_5Mb	512	7.000	0.217896
\$per add	Mode5_5Mb	512	8.000	0.051855
\$per add	Mode5_5Mb	512	9.000	0.010998
\$per add	Mode5_5Mb	512	10.000	0.002046
\$per add	Mode5_5Mb	512	11.000	0.000287

\$per add	Mode5_5Mb	512	12.000	0.000049
\$per add	Mode5_5Mb	512	13.000	0.000007
\$per add	Mode5_5Mb	512	14.000	0.000007
\$per add	Mode5_5Mb	512	15.000	0.000007
\$per add	Mode5_5Mb	512	16.000	0.000007
\$per add	Mode5_5Mb	512	17.000	0.000007
\$per add	Mode5_5Mb	512	18.000	0.000007
\$per add	Mode5_5Mb	512	19.000	0.000007
\$per add	Mode11Mb	512	-1.000	1.000000
\$per add	Mode11Mb	512	0.000	1.000000
\$per add	Mode11Mb	512	1.000	1.000000
\$per add	Mode11Mb	512	2.000	1.000000
\$per add	Mode11Mb	512	3.000	1.000000
\$per add	Mode11Mb	512	4.000	1.000000
\$per add	Mode11Mb	512	5.000	1.000000
\$per add	Mode11Mb	512	6.000	1.000000
\$per add	Mode11Mb	512	7.000	0.999725
\$per add	Mode11Mb	512	8.000	0.943199
\$per add	Mode11Mb	512	9.000	0.576944
\$per add	Mode11Mb	512	10.000	0.217896
\$per add	Mode11Mb	512	11.000	0.082421
\$per add	Mode11Mb	512	12.000	0.028265
\$per add	Mode11Mb	512	13.000	0.006939
\$per add	Mode11Mb	512	14.000	0.002046
\$per add	Mode11Mb	512	15.000	0.000819
\$per add	Mode11Mb	512	16.000	0.000209
\$per add	Mode11Mb	512	17.000	0.000066
\$per add	Mode11Mb	512	18.000	0.000025
\$per add	Mode11Mb	512	19.000	0.000008
\$per add	Mode1Mb	1024	-1.000	1.000000
\$per add	Mode1Mb	1024	0.000	0.559234
\$per add	Mode1Mb	1024	1.000	0.093627
\$per add	Mode1Mb	1024	2.000	0.008159
\$per add	Mode1Mb	1024	3.000	0.000491
\$per add	Mode1Mb	1024	4.000	0.000057
\$per add	Mode1Mb	1024	5.000	0.000002
\$per add	Mode1Mb	1024	6.000	0.000002
\$per add	Mode1Mb	1024	7.000	0.000002
\$per add	Mode1Mb	1024	8.000	0.000002
\$per add	Mode1Mb	1024	9.000	0.000002
\$per add	Mode1Mb	1024	10.000	0.000002
\$per add	Mode1Mb	1024	11.000	0.000002
\$per add	Mode1Mb	1024	12.000	0.000002
\$per add	Mode1Mb	1024	13.000	0.000002
\$per add	Mode1Mb	1024	14.000	0.000002
\$per add	Mode1Mb	1024	15.000	0.000002
\$per add	Mode1Mb	1024	16.000	0.000002
\$per add	Mode1Mb	1024	17.000	0.000002
\$per add	Mode1Mb	1024	18.000	0.000002
\$per add	Mode1Mb	1024	19.000	0.000002
\$per add	Mode2Mb	1024	-1.000	1.000000
\$per add	Mode2Mb	1024	0.000	1.000000
\$per add	Mode2Mb	1024	1.000	1.000000
\$per add	Mode2Mb	1024	2.000	0.999947
\$per add	Mode2Mb	1024	3.000	0.821023
\$per add	Mode2Mb	1024	4.000	0.217893
\$per add	Mode2Mb	1024	5.000	0.017056
\$per add	Mode2Mb	1024	6.000	0.001228
\$per add	Mode2Mb	1024	7.000	0.000082
\$per add	Mode2Mb	1024	8.000	0.000010
\$per add	Mode2Mb	1024	9.000	0.000010
\$per add	Mode2Mb	1024	10.000	0.000010
\$per add	Mode2Mb	1024	11.000	0.000010
\$per add	Mode2Mb	1024	12.000	0.000010
\$per add	Mode2Mb	1024	13.000	0.000010
\$per add	Mode2Mb	1024	14.000	0.000010
\$per add	Mode2Mb	1024	15.000	0.000010
\$per add	Mode2Mb	1024	16.000	0.000010
\$per add	Mode2Mb	1024	17.000	0.000010
\$per add	Mode2Mb	1024	18.000	0.000010
\$per add	Mode2Mb	1024	19.000	0.000010

\$per add	Mode5_5Mb	1024	-1.000	1.000000
\$per add	Mode5_5Mb	1024	0.000	1.000000
\$per add	Mode5_5Mb	1024	1.000	1.000000
\$per add	Mode5_5Mb	1024	2.000	1.000000
\$per add	Mode5_5Mb	1024	3.000	1.000000
\$per add	Mode5_5Mb	1024	4.000	1.000000
\$per add	Mode5_5Mb	1024	5.000	0.999947
\$per add	Mode5_5Mb	1024	6.000	0.914391
\$per add	Mode5_5Mb	1024	7.000	0.388313
\$per add	Mode5_5Mb	1024	8.000	0.101022
\$per add	Mode5_5Mb	1024	9.000	0.021876
\$per add	Mode5_5Mb	1024	10.000	0.004088
\$per add	Mode5_5Mb	1024	11.000	0.000573
\$per add	Mode5_5Mb	1024	12.000	0.000098
\$per add	Mode5_5Mb	1024	13.000	0.000014
\$per add	Mode5_5Mb	1024	14.000	0.000014
\$per add	Mode5_5Mb	1024	15.000	0.000014
\$per add	Mode5_5Mb	1024	16.000	0.000014
\$per add	Mode5_5Mb	1024	17.000	0.000014
\$per add	Mode5_5Mb	1024	18.000	0.000014
\$per add	Mode5_5Mb	1024	19.000	0.000014
\$per add	Mode11Mb	1024	-1.000	1.000000
\$per add	Mode11Mb	1024	0.000	1.000000
\$per add	Mode11Mb	1024	1.000	1.000000
\$per add	Mode11Mb	1024	2.000	1.000000
\$per add	Mode11Mb	1024	3.000	1.000000
\$per add	Mode11Mb	1024	4.000	1.000000
\$per add	Mode11Mb	1024	5.000	1.000000
\$per add	Mode11Mb	1024	6.000	1.000000
\$per add	Mode11Mb	1024	7.000	1.000000
\$per add	Mode11Mb	1024	8.000	0.996774
\$per add	Mode11Mb	1024	9.000	0.821023
\$per add	Mode11Mb	1024	10.000	0.388313
\$per add	Mode11Mb	1024	11.000	0.158049
\$per add	Mode11Mb	1024	12.000	0.055731
\$per add	Mode11Mb	1024	13.000	0.013830
\$per add	Mode11Mb	1024	14.000	0.004088
\$per add	Mode11Mb	1024	15.000	0.001637
\$per add	Mode11Mb	1024	16.000	0.000418
\$per add	Mode11Mb	1024	17.000	0.000131
\$per add	Mode11Mb	1024	18.000	0.000049
\$per add	Mode11Mb	1024	19.000	0.000016
\$per add	Mode1Mb	1500	-1.000	1.000000
\$per add	Mode1Mb	1500	0.000	0.698824
\$per add	Mode1Mb	1500	1.000	0.134113
\$per add	Mode1Mb	1500	2.000	0.011928
\$per add	Mode1Mb	1500	3.000	0.000720
\$per add	Mode1Mb	1500	4.000	0.000084
\$per add	Mode1Mb	1500	5.000	0.000003
\$per add	Mode1Mb	1500	6.000	0.000003
\$per add	Mode1Mb	1500	7.000	0.000003
\$per add	Mode1Mb	1500	8.000	0.000003
\$per add	Mode1Mb	1500	9.000	0.000003
\$per add	Mode1Mb	1500	10.000	0.000003
\$per add	Mode1Mb	1500	11.000	0.000003
\$per add	Mode1Mb	1500	12.000	0.000003
\$per add	Mode1Mb	1500	13.000	0.000003
\$per add	Mode1Mb	1500	14.000	0.000003
\$per add	Mode1Mb	1500	15.000	0.000003
\$per add	Mode1Mb	1500	16.000	0.000003
\$per add	Mode1Mb	1500	17.000	0.000003
\$per add	Mode1Mb	1500	18.000	0.000003
\$per add	Mode1Mb	1500	19.000	0.000003
\$per add	Mode2Mb	1500	-1.000	1.000000
\$per add	Mode2Mb	1500	0.000	1.000000
\$per add	Mode2Mb	1500	1.000	1.000000
\$per add	Mode2Mb	1500	2.000	0.999999
\$per add	Mode2Mb	1500	3.000	0.919562
\$per add	Mode2Mb	1500	4.000	0.302327
\$per add	Mode2Mb	1500	5.000	0.024885
\$per add	Mode2Mb	1500	6.000	0.001798

```

$per add Mode2Mb 1500 7.000 0.000120
$per add Mode2Mb 1500 8.000 0.000014
$per add Mode2Mb 1500 9.000 0.000014
$per add Mode2Mb 1500 10.000 0.000014
$per add Mode2Mb 1500 11.000 0.000014
$per add Mode2Mb 1500 12.000 0.000014
$per add Mode2Mb 1500 13.000 0.000014
$per add Mode2Mb 1500 14.000 0.000014
$per add Mode2Mb 1500 15.000 0.000014
$per add Mode2Mb 1500 16.000 0.000014
$per add Mode2Mb 1500 17.000 0.000014
$per add Mode2Mb 1500 18.000 0.000014
$per add Mode2Mb 1500 19.000 0.000014
$per add Mode5_5Mb 1500 -1.000 1.000000
$per add Mode5_5Mb 1500 0.000 1.000000
$per add Mode5_5Mb 1500 1.000 1.000000
$per add Mode5_5Mb 1500 2.000 1.000000
$per add Mode5_5Mb 1500 3.000 1.000000
$per add Mode5_5Mb 1500 4.000 1.000000
$per add Mode5_5Mb 1500 5.000 0.999999
$per add Mode5_5Mb 1500 6.000 0.972691
$per add Mode5_5Mb 1500 7.000 0.513258
$per add Mode5_5Mb 1500 8.000 0.144442
$per add Mode5_5Mb 1500 9.000 0.031881
$per add Mode5_5Mb 1500 10.000 0.005982
$per add Mode5_5Mb 1500 11.000 0.000840
$per add Mode5_5Mb 1500 12.000 0.000144
$per add Mode5_5Mb 1500 13.000 0.000020
$per add Mode5_5Mb 1500 14.000 0.000020
$per add Mode5_5Mb 1500 15.000 0.000020
$per add Mode5_5Mb 1500 16.000 0.000020
$per add Mode5_5Mb 1500 17.000 0.000020
$per add Mode5_5Mb 1500 18.000 0.000020
$per add Mode5_5Mb 1500 19.000 0.000020
$per add Mode11Mb 1500 -1.000 1.000000
$per add Mode11Mb 1500 0.000 1.000000
$per add Mode11Mb 1500 1.000 1.000000
$per add Mode11Mb 1500 2.000 1.000000
$per add Mode11Mb 1500 3.000 1.000000
$per add Mode11Mb 1500 4.000 1.000000
$per add Mode11Mb 1500 5.000 1.000000
$per add Mode11Mb 1500 6.000 1.000000
$per add Mode11Mb 1500 7.000 1.000000
$per add Mode11Mb 1500 8.000 0.999776
$per add Mode11Mb 1500 9.000 0.919562
$per add Mode11Mb 1500 10.000 0.513258
$per add Mode11Mb 1500 11.000 0.222757
$per add Mode11Mb 1500 12.000 0.080569
$per add Mode11Mb 1500 13.000 0.020193
$per add Mode11Mb 1500 14.000 0.005982
$per add Mode11Mb 1500 15.000 0.002397
$per add Mode11Mb 1500 16.000 0.000612
$per add Mode11Mb 1500 17.000 0.000192
$per add Mode11Mb 1500 18.000 0.000072
$per add Mode11Mb 1500 19.000 0.000024
}

proc loadPERTable80211aPaper {per} {
    $per add Mode1Mb 128 -1 0.98
    $per add Mode1Mb 128 0 0.97
    $per add Mode1Mb 128 1 0.95
    $per add Mode1Mb 128 2 0.90
    $per add Mode1Mb 128 3 0.84
    $per add Mode1Mb 128 4 0.77
    $per add Mode1Mb 128 5 0.69
    $per add Mode1Mb 128 6 0.59
    $per add Mode1Mb 128 7 0.49
    $per add Mode1Mb 128 8 0.39
    $per add Mode1Mb 128 9 0.30
    $per add Mode1Mb 128 10 0.21
}

```

```
$per add Mode1Mb 128 11 0.16
$per add Mode1Mb 128 12 0.11
$per add Mode1Mb 128 13 0.07
$per add Mode1Mb 128 14 0.05
$per add Mode1Mb 128 15 0.03
$per add Mode1Mb 128 16 0.02
$per add Mode1Mb 128 17 0.015
$per add Mode1Mb 128 18 0.01
$per add Mode1Mb 128 19 0.005
```

```
$per add Mode6Mb 1500 -1 0.98
$per add Mode6Mb 1500 0 0.97
$per add Mode6Mb 1500 1 0.95
$per add Mode6Mb 1500 2 0.90
$per add Mode6Mb 1500 3 0.84
$per add Mode6Mb 1500 4 0.77
$per add Mode6Mb 1500 5 0.69
$per add Mode6Mb 1500 6 0.59
$per add Mode6Mb 1500 7 0.49
$per add Mode6Mb 1500 8 0.39
$per add Mode6Mb 1500 9 0.30
$per add Mode6Mb 1500 10 0.21
$per add Mode6Mb 1500 11 0.16
$per add Mode6Mb 1500 12 0.11
$per add Mode6Mb 1500 13 0.07
$per add Mode6Mb 1500 14 0.05
$per add Mode6Mb 1500 15 0.03
$per add Mode6Mb 1500 16 0.02
$per add Mode6Mb 1500 17 0.015
$per add Mode6Mb 1500 18 0.01
$per add Mode6Mb 1500 19 0.005
$per add Mode9Mb 1500 -1 1.000
$per add Mode9Mb 1500 0 1.000
$per add Mode9Mb 1500 1 0.990
$per add Mode9Mb 1500 2 0.985
$per add Mode9Mb 1500 3 0.970
$per add Mode9Mb 1500 4 0.960
$per add Mode9Mb 1500 5 0.935
$per add Mode9Mb 1500 6 0.900
$per add Mode9Mb 1500 7 0.850
$per add Mode9Mb 1500 8 0.800
$per add Mode9Mb 1500 9 0.730
$per add Mode9Mb 1500 10 0.650
$per add Mode9Mb 1500 11 0.590
$per add Mode9Mb 1500 12 0.500
$per add Mode9Mb 1500 13 0.400
$per add Mode9Mb 1500 14 0.330
$per add Mode9Mb 1500 15 0.260
$per add Mode9Mb 1500 16 0.200
$per add Mode9Mb 1500 17 0.160
$per add Mode9Mb 1500 18 0.125
$per add Mode9Mb 1500 19 0.090
```

```
}
```

```
#####
# Override Default Module Configuration
#####
```

```
PER set debug_ 0
Module/CBR set packetSize_ 180
Agent/UDP set packetSize_ 1500

Mac/802_11 set RTSThreshold_ 2346
Mac/802_11 set ShortRetryLimit_ 7
Mac/802_11 set LongRetryLimit_ 4
Mac/802_11/Multirate set useShortPreamble_ true
Mac/802_11/Multirate set gSyncInterval_ 0.000005
Mac/802_11/Multirate set bSyncInterval_ 0.00001

Phy/WirelessPhy set Pt_ 0.001
```

```

Phy/WirelessPhy set L_ 1.0
Queue/DropTail/PriQueue set Prefer_Routing_Protocols 1
Queue/DropTail/PriQueue set size_ 1000

ConnectorTrace/Bin set depth 5

#####
# Global declarations
#####

set channel [new Module/DumbWirelessCh]
$channel setTag "MCHA "

set pmodel [new Propagation/MrclFreeSpace]
create-god [expr $opt(nn) + 1]

set per_a [new PER]
$per_a set noise_ 2.512e-13 ;#-96 dBm for 10MHz bandwidth
#$per_a loadPERTable80211gTrivellato
loadPERTable80211aPaper $per_a
#$per_a loadPERTable80211aPaper

set per_b [new PER]
#$per_b set noise_ $noisePower
#load_per_table $per_b
$per_b loadPERTable80211bIntersilHFA3861B

set peerstats [new PeerStatsDB/Static]
$peerstats numpeers [expr $opt(nn) + 1]

set line_counter 1

#####
# Simulation configuration
#####

# Initialize nodes
create_initial_nodes_with_types_and_positions

# Generate nodes types
generate_types_for_other_nodes

# Generate nodes positions
generate_positions_for_other_nodes

# Create mesh nodes
for {set id 3} {$id < $opt(nn)} {incr id} {
    set posX $nodes_pos_x($id)
    set posY $nodes_pos_y($id)
    set posZ 0.00

    create_nodes $id $posX $posY $posZ
}
# Attach Interfaces to other nodes
attach_interfaces_to_other_nodes

# Create source and sink pairs
generate_traffic_for_other_nodes

# Run simulations
for {set id 0} {$id < $opt(nn)} {incr id} {
    $ns at 0.0 "$nodes_aodvuu($id) start"
}
$ns at 0.0 "record_stats"
$ns at [expr $opt(start_max) + $opt(duration) + 5] "finish_simulation; $ns halt"

puts -nonewline "Simulating..."
$ns run

```

G.2 AODV-UU-HP tcl script

```
#####
# Command-line parameters
#####
if {$argc == 0} {
    set opt(run) 1
    set opt(nn) 60
    set opt(ns) 4
    set opt(duration) 450
    set opt(sampling) 1.0
    set opt(distance) 150
    set opt(txpower) 0.01
} elseif {$argc == 6 || $argc == 7} {
    set opt(run) [lindex $argv 0]
    set opt(nn) [lindex $argv 1]
    set opt(ns) [lindex $argv 2]
    set opt(duration) [lindex $argv 3]
    set opt(sampling) [lindex $argv 4]
    set opt(distance) [lindex $argv 5]

    if {$argc == 7} {
        set opt(txpower) [lindex $argv 6]
    } else {
        set opt(txpower) 0.01
    }
} else {
    puts "invalid args"
}
#####
# Scenario Configuration
#####
set opt(xmax) 1500
set opt(xmin) 0
set opt(node_density) [expr $opt(nn) / ($opt(xmax) * $opt(xmax))]

# starting time of each transmission
set opt(start_min) 0
set opt(start_max) 0.05

set opt(resultfname) "$argv0-$opt(nn)-$opt(ns)-$opt(duration)-$opt(distance)-$opt(txpower).log"
set opt(tracefname) "$argv0-$opt(nn)-$opt(ns)-$opt(duration)-$opt(distance)-$opt(txpower).tr"
set opt(thrfname) "$argv0-$opt(nn)-$opt(ns)-$opt(duration)-$opt(distance)-$opt(txpower).thr"
set opt(perfname) "$argv0-$opt(nn)-$opt(ns)-$opt(duration)-$opt(distance)-$opt(txpower).per"
set opt(fttfname) "$argv0-$opt(nn)-$opt(ns)-$opt(duration)-$opt(distance)-$opt(txpower).ftt"
#####
# Module Libraries
#####
# The following lines must be before loading libraries and before instantiating the ns Simulator
#remove-all-packet-headers

source dynlibutils.tcl
dynlibload ns_tools_extensions
dynlibload Miracle
dynlibload miracleport
dynlibload miraclecbr
dynlibload cbrtracer
dynlibload miraclelink
dynlibload MiracleBasicMovement
dynlibload MiracleWirelessCh
dynlibload MiraclePhy802_11
dynlibload dei80211mr /home/oladayo/Dev/ns2/ns-allinone-2.34/dei80211mr-1.1.4/src/.libs
dynlibload MiracleMac802_11
dynlibload aodvu
#####
# Tracers
#####
dynlibload Trace
dynlibload cbrtracer
```

```

dynlibload aodvuuc1tracer
dynlibload phytracer
#####
# NS-2 Instance & Trace Files
#####
set ns [new Simulator]
$ns use-Miracle

set tf [open $opt(tracefname) w]
$ns trace-all $tf

set hf [open $opt(thrfname) w]
set pf [open $opt(perfname) w]
set ff [open $opt(fttfname) w]
#####
# Random Number Generators
#####
# seed the default RNG
global defaultRNG
$defaultRNG seed 9999

set startRNG [new RNG]
set typeRNG [new RNG]
set neighbourRNG [new RNG]
set positionRNG [new RNG]
set tx_pairRNG [new RNG]

# Create the RNGs and set them to the correct substream
for {set j 1} {$j < $opt(run)} {incr j} {
    $defaultRNG next-substream
    $startRNG next-substream
    $typeRNG next-substream
    $neighbourRNG next-substream
    $positionRNG next-substream
    $tx_pairRNG next-substream
}

set start_ [new RandomVariable/Uniform]
$start_ set min_ $opt(start_min)
$start_ set max_ $opt(start_max)
$start_ use-rng $startRNG

set type_ [new RandomVariable/Uniform]
$type_ set min_ 0
$type_ set max_ 1
$type_ use-rng $typeRNG

set neighbour_ [new RandomVariable/Uniform]
$neighbour_ set min_ 0
$neighbour_ set max_ $opt(nn)
$neighbour_ use-rng $neighbourRNG

set distance_ [new RandomVariable/Poisson]
$distance_ set avg_ $opt(distance)
$distance_ use-rng $positionRNG

set direction_ [new RandomVariable/Uniform]
$direction_ set min_ 0
$direction_ set max_ 1
$direction_ use-rng $positionRNG

set tx_type_ [new RandomVariable/Uniform]
$tx_type_ use-rng $typeRNG

set tx_pair_ [new RandomVariable/Uniform]
$tx_pair_ use-rng $tx_pairRNG
#####
# Functions
#####
# Create nodes
proc create_nodes {id posX posY posZ} {

```

```

puts "Creating node $id at $posX, $posY"
# +-----+
# |                                     4. AODVUU                               |
# +-----+
# |                                     3. IP/AODVUU Interface                       |
# +-----+

global ns nodes nodes_aodvuu nodes_ipif nodes_ll nodes_ll_count nodes_pos

set nodes($id)          [$ns create-M_Node]

set nodes_aodvuu($id)   [new Module/AODVUU]
set nodes_ipif($id)     [new Module/IP/AODVInterface]

set nodes_ll_count($id) 0

# Use default IP addressing i.e. 0, 1, 2, 3 etc

# Add modules
$nodes($id) addModule 4 $nodes_aodvuu($id)      3 "n0_AODV"
$nodes($id) addModule 3 $nodes_ipif($id)        3 "n0_IP"

# Connect modules
$nodes($id) setConnection $nodes_aodvuu($id)   $nodes_ipif($id) 1

# Set position
set nodes_pos($id) [new "Position/BM"]
$nodes($id) addPosition $nodes_pos($id)
$nodes_pos($id) setX_ $posX
$nodes_pos($id) setY_ $posY

puts [format "\tMesh Node \t$id : X = %.2f, Y = %.2f" \
          $posX $posY]
}
proc attach_cbr_source_to_node {id} {
puts "Attaching CBR source to node $id"
# +-----+
# |                                     6. CBR                               |
# +-----+
# |                                     5. Port                             |
# +-----+

global ns nodes nodes_port nodes_cbr nodes_cbr_port nodes_aodvuu

set nodes_cbr($id)      [new Module/CBR]
set nodes_port($id)     [new Module/Port/Map]

# Set CBR rate
$nodes_cbr($id) set period_ 0.05

# Add modules
$nodes($id) addModule 6 $nodes_cbr($id)          3 "n0_CBR"
$nodes($id) addModule 5 $nodes_port($id)         3 "n0_PORT"

# Connect modules
$nodes($id) setConnection $nodes_cbr($id)       $nodes_port($id) 1
$nodes($id) setConnection $nodes_port($id)      $nodes_aodvuu($id) 1

set nodes_cbr_port($id) [$nodes_port($id) assignPort $nodes_cbr($id)]
}
proc attach_cbr_sink_to_node {id} {
global ns nodes nodes_cbr nodes_port nodes_cbr_port nodes_aodvuu

set nodes_cbr($id)      [new Module/CBR]
set nodes_port($id)     [new Module/Port/Map]

# Set CBR rate
$nodes_cbr($id) set period_ 0.05

# Add modules
$nodes($id) addModule 6 $nodes_cbr($id)          3 "n0_CBR"

```

```

$nodes($id) addModule 5 $nodes_port($id) 3 "n0_PORT"

# Connect modules
$nodes($id) setConnection $nodes_cbr($id) $nodes_port($id) 1
$nodes($id) setConnection $nodes_port($id) $nodes_aodvuu($id) 1

set nodes_cbr_port($id) [$nodes_port($id) assignPort $nodes_cbr($id)]
}

proc connect_source_and_sink {sourceId sinkId source_cbr_start} {
    global ns opt nodes nodes_cbr nodes_port nodes_cbr_port nodes_aodvuu nodes_ipif

    $nodes_cbr($sourceId) set destAddr_ [$nodes_ipif($sinkId) addr]
    $nodes_cbr($sourceId) set destPort_ $nodes_cbr_port($sinkId)

    $nodes_cbr($sinkId) set destAddr_ [$nodes_ipif($sourceId) addr]
    $nodes_cbr($sinkId) set destPort_ $nodes_cbr_port($sourceId)

    set source_cbr_stop [expr $source_cbr_start + $opt(duration)]

    $ns at $source_cbr_start "$nodes_cbr($sourceId) start"
    $ns at $source_cbr_stop "$nodes_cbr($sourceId) stop"
}

proc attach_mac80211a_interface_to_node {id} {
    puts "Attaching IEEE 802.11a interface to node $id"
    # +-----+
    # |                2.n LL                |
    # +-----+
    # |                1 PHY                |
    # +-----+

    global ns nodes nodes_aodvuu nodes_ipif nodes_ll nodes_ll_count nodes_phy nodes_pp channel
    pmodel per_a

    set nodes_ll($id,$nodes_ll_count($id)) [create802_11MacModule "LL/Mrc1"
"Queue/DropTail/PriQueue" "Mac/802_11/Multirate" [$nodes_ipif($id) addr] "" 100]
    set nodes_phy($id) [createPhyModule "Phy/WirelessPhy/PowerAware" $pmodel
"Antenna/OmniAntenna" $nodes_ll($id,$nodes_ll_count($id)) ""]

    set mac [$nodes_ll($id,$nodes_ll_count($id)) getMac]
    set phy [$nodes_phy($id) getPhy]
    $mac basicMode_ Mode6Mb
    $mac dataMode_ Mode6Mb
    $mac per $per_a

    $phy set CStresh_ 6.31e-12
    $phy set freq_ 5.18e+9

    set nodes_pp($id) [new PowerProfile]
    $mac powerProfile $nodes_pp($id)
    $phy powerProfile $nodes_pp($id)

    # Add modules
    $nodes($id) addModule 2 $nodes_ll($id,$nodes_ll_count($id)) 3 "n${nodes_ll_count(0)}_LL"
    $nodes($id) addModule 1 $nodes_phy($id) 3 "n0_PHY"

    # Connect modules
    $nodes($id) setConnection $nodes_ipif($id)
$nodes_ll($id,$nodes_ll_count($id)) 1
$nodes($id) setConnection $nodes_ll($id,$nodes_ll_count($id)) $nodes_phy($id) 1

    # Add to channel
    $nodes($id) addToChannel $channel $nodes_phy($id) 1

    $nodes_aodvuu($id) add-if $nodes_ipif($id)
    $nodes_aodvuu($id) if-queue [$nodes_ll($id,$nodes_ll_count($id)) getQueue]

    incr nodes_ll_count($id)
}

```

```

proc attach_mac80211b_interface_to_node {id} {
    puts "Attaching IEEE 802.11b interface to node $id"
    # +-----+
    # |                2.n LL                |
    # +-----+
    # |                1 PHY                |
    # +-----+

    global ns nodes nodes_aodvuu nodes_ipif nodes_ll nodes_ll_count nodes_phy nodes_pp channel
    pmodel per_b

    set nodes_ll($id,$nodes_ll_count($id)) [create802_11MacModule "LL/Mrc1"
"Queue/DropTail/PriQueue" "Mac/802_11/Multirate" [$nodes_ipif($id) addr] "" 100]
    set nodes_phy($id) [createPhyModule "Phy/WirelessPhy/PowerAware" $pmodel
"Antenna/OmniAntenna" $nodes_ll($id,$nodes_ll_count($id)) ""]

    set mac [[$nodes_ll($id,$nodes_ll_count($id)) getMac]
    set phy [[$nodes_phy($id) getPhy]
    $mac basicMode_ Mode5_5Mb
    $mac dataMode_ Mode5_5Mb
    $mac per $per_b

    $phy set CSTresh_ 7.7eâ´18
    $phy set freq_ 2.437e+9

    set nodes_pp($id) [new PowerProfile]
    $mac powerProfile $nodes_pp($id)
    $phy powerProfile $nodes_pp($id)

    # Add modules
    $nodes($id) addModule 2 $nodes_ll($id,$nodes_ll_count($id)) 3 "n${nodes_ll_count(0)}_LL"
    $nodes($id) addModule 1 $nodes_phy($id) 3 "n0_PHY"

    # Connect modules
    $nodes($id) setConnection $nodes_ipif($id)
    $nodes_ll($id,$nodes_ll_count($id)) 1
    $nodes($id) setConnection $nodes_ll($id,$nodes_ll_count($id)) $nodes_phy($id) 1

    # Add to channel
    $nodes($id) addToChannel $channel $nodes_phy($id) 1

    $nodes_aodvuu($id) add-if $nodes_ipif($id)
    $nodes_aodvuu($id) if-queue [[$nodes_ll($id,$nodes_ll_count($id)) getQueue]

    incr nodes_ll_count($id)
}

proc create_initial_nodes_with_types_and_positions {} {
    global opt ns node_type node_type_count nodes_pos_x nodes_pos_y node_tx_rx_paired

    for {set i 0} {$i < 3} {incr i} {
        set node_type_count($i) 0
    }

    # Node 0
    set nodes_pos_x(0) [expr 1500 - $opt(distance)]
    set nodes_pos_y(0) 1500
    create_nodes 0 $nodes_pos_x(0) $nodes_pos_y(0) 0
    attach_mac80211a_interface_to_node 0
    attach_mac80211b_interface_to_node 0
    set node_type(0) 2
    incr node_type_count(2)

    # Node 1
    set nodes_pos_x(1) 1500
    set nodes_pos_y(1) 1500
    create_nodes 1 $nodes_pos_x(0) $nodes_pos_y(0) 0
    attach_mac80211a_interface_to_node 1
    attach_mac80211b_interface_to_node 1
    set node_type(1) 2
    incr node_type_count(2)
}

```

```

# Node 2
set nodes_pos_x(2) [expr 1500 + $opt(distance)]
set nodes_pos_y(2) 1500
create_nodes 2 $nodes_pos_x(0) $nodes_pos_y(0) 0
attach_mac80211a_interface_to_node 2
attach_mac80211b_interface_to_node 2
set node_type(2) 2
incr node_type_count(2)

for {set i 0} {$i < $opt(nn)} {incr i} {
    set node_tx_rx_paired($i) 0
}

}

proc generate_types_for_other_nodes {} {
    global opt ns node_type type_

    for {set id 3} {$id < $opt(nn)} {incr id} {
        set type [expr round([$type_ value])]
        set node_type($id) $type
    }
}

proc generate_positions_for_other_nodes {} {
    global opt ns node_type origin_ neighbour_ distance_ direction_ nodes_pos_x nodes_pos_y

    for {set id 3} {$id < $opt(nn)} {incr id} {

        $neighbour_ set min_ 0
        $neighbour_ set max_ [expr $id - 1]

        set neighbour [expr int([$neighbour_ value])]
        while {($node_type($neighbour) != 2) && ($node_type($neighbour) != $node_type($id))} {
            set neighbour [expr int([$neighbour_ value])]
        }

        set distance_x [expr int([$distance_ value])]
        set distance_y [expr int([$distance_ value])]
        set direction_x [expr round([$direction_ value])]
        set direction_y [expr round([$direction_ value])]

        if {$direction_x == 1} {
            set nodes_pos_x($id) [expr $nodes_pos_x($neighbour) + $distance_x]
        } else {
            if {$nodes_pos_x($neighbour) > $distance_x} {
                set nodes_pos_x($id) [expr $nodes_pos_x($neighbour) - $distance_x]
            } else {
                set nodes_pos_x($id) 0; #Or select neighbour's position i.e.
                $nodes_pos_x($neighbour)
            }
        }

        if {$direction_y == 1} {
            set nodes_pos_y($id) [expr $nodes_pos_y($neighbour) + $distance_y]
        } else {
            if {$nodes_pos_y($neighbour) > $distance_y} {
                set nodes_pos_y($id) [expr $nodes_pos_y($neighbour) - $distance_y]
            } else {
                set nodes_pos_y($id) 0; #Or select neighbour's position i.e.
                $nodes_pos_y($neighbour)
            }
        }
    }
}

}

proc attach_interfaces_to_other_nodes {} {
    global opt ns node_type node_type_count

    for {set id 3} {$id < $opt(nn)} {incr id} {
        if {$node_type($id) == 0} {
            attach_mac80211a_interface_to_node $id
        }
    }
}

```

```

        incr node_type_count(0)
    } elseif {$node_type($id) == 1} {
        attach_mac80211b_interface_to_node $id
        incr node_type_count(1)
    } else {
        attach_mac80211a_interface_to_node $id
        attach_mac80211b_interface_to_node $id
        incr node_type_count(2)
    }
}
}

proc generate_traffic_for_other_nodes {} {
    global opt ns node_type node_type_count tx_type_ start_
    set max_nodes [expr int($node_type_count(0) / 2)]
    set max_type 0
    set min_type 1
    if {$node_type_count(1) < $node_type_count(0)} {
        set max_nodes [expr int($node_type_count(1) / 2)]
        set max_type 1
        set min_type 0
    }

    if {$max_nodes >= $opt(ns)} {
        set max_nodes $opt(ns)
    }

    $tx_type_ set min_ 1
    $tx_type_ set max_ $max_nodes
    set num_($max_type) [expr int([$tx_type_ value])]
    set num_($min_type) [expr $opt(ns) - $num_($max_type)]

    if {$num_($min_type) > [expr int($node_type_count($min_type) / 2)]} {
        set num_($min_type) [expr int($node_type_count($min_type) / 2)]
    }

    set num_a $num_(0)
    set num_b $num_(1)

    puts "A: $num_a B: $num_b Total A: $node_type_count(0) Total B: $node_type_count(1)"

    for {set i 0} {$i < $num_a} {incr i} {
        set source_cbr_start [$start_ value]
        generate_tx_rx_pair_for_type 0 $source_cbr_start
    }
    for {set i 0} {$i < $num_b} {incr i} {
        set source_cbr_start [$start_ value]
        generate_tx_rx_pair_for_type 1 $source_cbr_start
    }
}

proc generate_tx_rx_pair_for_type {type source_cbr_start} {
    global opt ns node_type tx_pair_ node_tx_rx_paired node_type_count

    $tx_pair_ set min_ 0
    $tx_pair_ set max_ $node_type_count($type)

    # SOURCE
    set source_tx_id [expr int([$tx_pair_ value])]
    set source_id [get_node_id_from_node_tx_id $type $source_tx_id]
    while {$node_tx_rx_paired($source_id) == 1} {
        set source_tx_id [expr int([$tx_pair_ value])]
        set source_id [get_node_id_from_node_tx_id $type $source_tx_id]
    }
    set node_tx_rx_paired($source_id) 1

    # SINK
    set sink_tx_id [expr int([$tx_pair_ value])]
    set sink_id [get_node_id_from_node_tx_id $type $sink_tx_id]
    while {($sink_id == $source_id) || ($node_tx_rx_paired($sink_id) == 1)} {

```

```

    puts "$type Randomly selected: $sink_id -- INVALID $source_id
$node_tx_rx_paired($sink_id)"

    set sink_tx_id [expr int([$tx_pair_value])]
    set sink_id [get_node_id_from_node_tx_id $type $sink_tx_id]
}
set node_tx_rx_paired($sink_id) 1

puts "source: $source_id, destination: $sink_id"

attach_cbr_source_to_node $source_id
attach_cbr_sink_to_node $sink_id
connect_source_and_sink $source_id $sink_id $source_cbr_start
}

proc get_node_id_from_node_tx_id {node_tx_type node_tx_id} {
    global opt ns node_type

    set node_id -100
    set node_tx_count 0

    for {set id 3} {$id < $opt(nm)} {incr id} {
        if {($node_type($id) == $node_tx_type) && ($node_tx_id == $node_tx_count)} {
            set node_id $node_tx_count
            break
        } elseif {$node_type($id) == $node_tx_type} {
            incr node_tx_count
        }
    }

    return $node_id
}

proc record_stats {} {
    global opt ns hf pf ff nodes_cbr line_counter
}

proc finish_simulation {} {
    global ns tf opt meshTcpAgent
    puts "done!"
    $ns flush-trace
    close $tf

    puts ""
    puts "Tracefile: $opt(tracefname)"
    puts " Thrfile: $opt(thrfname)"
    puts "  Perfile: $opt(perfname)"
    puts "  Fttfile: $opt(fttfname)"
}

proc load_per_table {per} {
    $per add ModelMb 128 -1.000 0.994100
    $per add ModelMb 128 0.000 0.097336
    $per add ModelMb 128 1.000 0.012213
    $per add ModelMb 128 2.000 0.001023
    $per add ModelMb 128 3.000 0.000061
    $per add ModelMb 128 4.000 0.000007
    $per add ModelMb 128 5.000 0.000000
    $per add ModelMb 128 6.000 0.000000
    $per add ModelMb 128 7.000 0.000000
    $per add ModelMb 128 8.000 0.000000
    $per add ModelMb 128 9.000 0.000000
    $per add ModelMb 128 10.000 0.000000
    $per add ModelMb 128 11.000 0.000000
    $per add ModelMb 128 12.000 0.000000
    $per add ModelMb 128 13.000 0.000000
    $per add ModelMb 128 14.000 0.000000
    $per add ModelMb 128 15.000 0.000000
    $per add ModelMb 128 16.000 0.000000
    $per add ModelMb 128 17.000 0.000000
    $per add ModelMb 128 18.000 0.000000
}

```

\$per add	Mode1Mb	128	19.000	0.000000
\$per add	Mode2Mb	128	-1.000	0.994100
\$per add	Mode2Mb	128	0.000	0.994100
\$per add	Mode2Mb	128	1.000	0.994100
\$per add	Mode2Mb	128	2.000	0.707572
\$per add	Mode2Mb	128	3.000	0.193509
\$per add	Mode2Mb	128	4.000	0.030253
\$per add	Mode2Mb	128	5.000	0.002148
\$per add	Mode2Mb	128	6.000	0.000154
\$per add	Mode2Mb	128	7.000	0.000010
\$per add	Mode2Mb	128	8.000	0.000001
\$per add	Mode2Mb	128	9.000	0.000001
\$per add	Mode2Mb	128	10.000	0.000001
\$per add	Mode2Mb	128	11.000	0.000001
\$per add	Mode2Mb	128	12.000	0.000001
\$per add	Mode2Mb	128	13.000	0.000001
\$per add	Mode2Mb	128	14.000	0.000001
\$per add	Mode2Mb	128	15.000	0.000001
\$per add	Mode2Mb	128	16.000	0.000001
\$per add	Mode2Mb	128	17.000	0.000001
\$per add	Mode2Mb	128	18.000	0.000001
\$per add	Mode2Mb	128	19.000	0.000001
\$per add	Mode5_5Mb	128	-1.000	1.000000
\$per add	Mode5_5Mb	128	0.000	1.000000
\$per add	Mode5_5Mb	128	1.000	1.000000
\$per add	Mode5_5Mb	128	2.000	1.000000
\$per add	Mode5_5Mb	128	3.000	1.000000
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\$per add	Mode5_5Mb	128	7.000	0.059592
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\$per add	Mode5_5Mb	128	16.000	0.000002
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\$per add	Mode5_5Mb	128	18.000	0.000002
\$per add	Mode5_5Mb	128	19.000	0.000002
\$per add	Mode11Mb	128	-1.000	1.000000
\$per add	Mode11Mb	128	0.000	1.000000
\$per add	Mode11Mb	128	1.000	1.000000
\$per add	Mode11Mb	128	2.000	1.000000
\$per add	Mode11Mb	128	3.000	1.000000
\$per add	Mode11Mb	128	4.000	1.000000
\$per add	Mode11Mb	128	5.000	0.999998
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\$per add	Mode11Mb	128	12.000	0.007142
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\$per add	Mode11Mb	128	18.000	0.000006
\$per add	Mode11Mb	128	19.000	0.000002
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\$per add	Mode1Mb	256	2.000	0.002046
\$per add	Mode1Mb	256	3.000	0.000123
\$per add	Mode1Mb	256	4.000	0.000014
\$per add	Mode1Mb	256	5.000	0.000000

\$per add	Mode1Mb	256	6.000	0.000000
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\$per add	Mode1Mb	256	9.000	0.000000
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\$per add	Mode1Mb	256	11.000	0.000000
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\$per add	Mode1Mb	256	19.000	0.000000
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\$per add	Mode2Mb	256	16.000	0.000002
\$per add	Mode2Mb	256	17.000	0.000002
\$per add	Mode2Mb	256	18.000	0.000002
\$per add	Mode2Mb	256	19.000	0.000002
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\$per add	Mode5_5Mb	256	19.000	0.000003
\$per add	Mode11Mb	256	-1.000	1.000000
\$per add	Mode11Mb	256	0.000	1.000000
\$per add	Mode11Mb	256	1.000	1.000000
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\$per add	Mode11Mb	256	12.000	0.014234
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\$per add	Mode11Mb	256	16.000	0.000104
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\$per add	Mode1Mb	512	3.000	0.000246
\$per add	Mode1Mb	512	4.000	0.000029
\$per add	Mode1Mb	512	5.000	0.000001
\$per add	Mode1Mb	512	6.000	0.000001
\$per add	Mode1Mb	512	7.000	0.000001
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\$per add	Mode2Mb	512	10.000	0.000005
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\$per add	Mode5_5Mb	512	1.000	1.000000
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\$per add	Mode5_5Mb	512	18.000	0.000007
\$per add	Mode5_5Mb	512	19.000	0.000007
\$per add	Mode11Mb	512	-1.000	1.000000
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\$per add	Mode1Mb	1024	11.000	0.000002
\$per add	Mode1Mb	1024	12.000	0.000002
\$per add	Mode1Mb	1024	13.000	0.000002
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\$per add	Mode2Mb	1024	10.000	0.000010
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\$per add	Mode2Mb	1024	14.000	0.000010
\$per add	Mode2Mb	1024	15.000	0.000010
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\$per add	Mode2Mb	1024	17.000	0.000010
\$per add	Mode2Mb	1024	18.000	0.000010
\$per add	Mode2Mb	1024	19.000	0.000010
\$per add	Mode5_5Mb	1024	-1.000	1.000000
\$per add	Mode5_5Mb	1024	0.000	1.000000
\$per add	Mode5_5Mb	1024	1.000	1.000000
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\$per add	Mode11Mb	1024	-1.000	1.000000
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\$per add	Mode2Mb	1500	1.000	1.000000
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\$per add	Mode2Mb	1500	13.000	0.000014
\$per add	Mode2Mb	1500	14.000	0.000014
\$per add	Mode2Mb	1500	15.000	0.000014
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$per add Mode2Mb 1500 17.000 0.000014
$per add Mode2Mb 1500 18.000 0.000014
$per add Mode2Mb 1500 19.000 0.000014
$per add Mode5_5Mb 1500 -1.000 1.000000
$per add Mode5_5Mb 1500 0.000 1.000000
$per add Mode5_5Mb 1500 1.000 1.000000
$per add Mode5_5Mb 1500 2.000 1.000000
$per add Mode5_5Mb 1500 3.000 1.000000
$per add Mode5_5Mb 1500 4.000 1.000000
$per add Mode5_5Mb 1500 5.000 0.999999
$per add Mode5_5Mb 1500 6.000 0.972691
$per add Mode5_5Mb 1500 7.000 0.513258
$per add Mode5_5Mb 1500 8.000 0.144442
$per add Mode5_5Mb 1500 9.000 0.031881
$per add Mode5_5Mb 1500 10.000 0.005982
$per add Mode5_5Mb 1500 11.000 0.000840
$per add Mode5_5Mb 1500 12.000 0.000144
$per add Mode5_5Mb 1500 13.000 0.000020
$per add Mode5_5Mb 1500 14.000 0.000020
$per add Mode5_5Mb 1500 15.000 0.000020
$per add Mode5_5Mb 1500 16.000 0.000020
$per add Mode5_5Mb 1500 17.000 0.000020
$per add Mode5_5Mb 1500 18.000 0.000020
$per add Mode5_5Mb 1500 19.000 0.000020
$per add Mode11Mb 1500 -1.000 1.000000
$per add Mode11Mb 1500 0.000 1.000000
$per add Mode11Mb 1500 1.000 1.000000
$per add Mode11Mb 1500 2.000 1.000000
$per add Mode11Mb 1500 3.000 1.000000
$per add Mode11Mb 1500 4.000 1.000000
$per add Mode11Mb 1500 5.000 1.000000
$per add Mode11Mb 1500 6.000 1.000000
$per add Mode11Mb 1500 7.000 1.000000
$per add Mode11Mb 1500 8.000 0.999776
$per add Mode11Mb 1500 9.000 0.919562
$per add Mode11Mb 1500 10.000 0.513258
$per add Mode11Mb 1500 11.000 0.222757
$per add Mode11Mb 1500 12.000 0.080569
$per add Mode11Mb 1500 13.000 0.020193
$per add Mode11Mb 1500 14.000 0.005982
$per add Mode11Mb 1500 15.000 0.002397
$per add Mode11Mb 1500 16.000 0.000612
$per add Mode11Mb 1500 17.000 0.000192
$per add Mode11Mb 1500 18.000 0.000072
$per add Mode11Mb 1500 19.000 0.000024
}
proc loadPERTable80211aPaper {per} {
$per add Mode1Mb 128 -1 0.98
$per add Mode1Mb 128 0 0.97
$per add Mode1Mb 128 1 0.95
$per add Mode1Mb 128 2 0.90
$per add Mode1Mb 128 3 0.84
$per add Mode1Mb 128 4 0.77
$per add Mode1Mb 128 5 0.69
$per add Mode1Mb 128 6 0.59
$per add Mode1Mb 128 7 0.49
$per add Mode1Mb 128 8 0.39
$per add Mode1Mb 128 9 0.30
$per add Mode1Mb 128 10 0.21
$per add Mode1Mb 128 11 0.16
$per add Mode1Mb 128 12 0.11
$per add Mode1Mb 128 13 0.07
$per add Mode1Mb 128 14 0.05
$per add Mode1Mb 128 15 0.03
$per add Mode1Mb 128 16 0.02
$per add Mode1Mb 128 17 0.015
$per add Mode1Mb 128 18 0.01
$per add Mode1Mb 128 19 0.005

$per add Mode6Mb 1500 -1 0.98
$per add Mode6Mb 1500 0 0.97

```

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$per add Mode6Mb 1500 1 0.95
$per add Mode6Mb 1500 2 0.90
$per add Mode6Mb 1500 3 0.84
$per add Mode6Mb 1500 4 0.77
$per add Mode6Mb 1500 5 0.69
$per add Mode6Mb 1500 6 0.59
$per add Mode6Mb 1500 7 0.49
$per add Mode6Mb 1500 8 0.39
$per add Mode6Mb 1500 9 0.30
$per add Mode6Mb 1500 10 0.21
$per add Mode6Mb 1500 11 0.16
$per add Mode6Mb 1500 12 0.11
$per add Mode6Mb 1500 13 0.07
$per add Mode6Mb 1500 14 0.05
$per add Mode6Mb 1500 15 0.03
$per add Mode6Mb 1500 16 0.02
$per add Mode6Mb 1500 17 0.015
$per add Mode6Mb 1500 18 0.01
$per add Mode6Mb 1500 19 0.005
$per add Mode9Mb 1500 -1 1.000
$per add Mode9Mb 1500 0 1.000
$per add Mode9Mb 1500 1 0.990
$per add Mode9Mb 1500 2 0.985
$per add Mode9Mb 1500 3 0.970
$per add Mode9Mb 1500 4 0.960
$per add Mode9Mb 1500 5 0.935
$per add Mode9Mb 1500 6 0.900
$per add Mode9Mb 1500 7 0.850
$per add Mode9Mb 1500 8 0.800
$per add Mode9Mb 1500 9 0.730
$per add Mode9Mb 1500 10 0.650
$per add Mode9Mb 1500 11 0.590
$per add Mode9Mb 1500 12 0.500
$per add Mode9Mb 1500 13 0.400
$per add Mode9Mb 1500 14 0.330
$per add Mode9Mb 1500 15 0.260
$per add Mode9Mb 1500 16 0.200
$per add Mode9Mb 1500 17 0.160
$per add Mode9Mb 1500 18 0.125
$per add Mode9Mb 1500 19 0.090
}
#####
# Override Default Module Configuration
#####
PER set debug_ 0
Module/CBR set packetSize_ 180
Agent/UDP set packetSize_ 1500

Mac/802_11 set RTSThreshold_ 2346
Mac/802_11 set ShortRetryLimit_ 7
Mac/802_11 set LongRetryLimit_ 4
Mac/802_11/Multirate set useShortPreamble_ true
Mac/802_11/Multirate set gSyncInterval_ 0.000005
Mac/802_11/Multirate set bSyncInterval_ 0.00001

Phy/WirelessPhy set Pt_ 0.001
Phy/WirelessPhy set L_ 1.0
Queue/DropTail/PriQueue set Prefer_Routing_Protocols 1
Queue/DropTail/PriQueue set size_ 1000

ConnectorTrace/Bin set depth 5
#####
# Global declarations
#####

set channel [new Module/DumbWirelessCh]
$channel setTag "MCHA "

set pmodel [new Propagation/MrclFreeSpace]
create-god [expr $opt(nn) + 1]

```

```

set per_a [new PER]
$per_a set noise_ 2.512e-13 ;#-96 dBm for 10MHz bandwidth
#$per_a loadPERTable80211gTrivellato
loadPERTable80211aPaper $per_a
#$per_a loadPERTable80211aPaper

set per_b [new PER]
#$per_b set noise_ $noisePower
#load_per_table $per_b
$per_b loadPERTable80211bIntersilHFA3861B

set peerstats [new PeerStatsDB/Static]
$peerstats numpeers [expr $opt(nn) + 1]

set line_counter 1
#####
# Simulation configuration
#####
# Initialize nodes
create_initial_nodes_with_types_and_positions

# Generate nodes types
generate_types_for_other_nodes

# Generate nodes positions
generate_positions_for_other_nodes

# Create mesh nodes
for {set id 3} {$id < $opt(nn)} {incr id} {
    set posX $nodes_pos_x($id)
    set posY $nodes_pos_y($id)
    set posZ 0.00

    create_nodes $id $posX $posY $posZ
}
# Attach Interfaces to other nodes
attach_interfaces_to_other_nodes

# Create source and sink pairs
generate_traffic_for_other_nodes

# Run simulations
for {set id 0} {$id < $opt(nn)} {incr id} {
    $ns at 0.0 "$nodes_aodvuu($id) start"
}

$ns at 0.0 "record_stats"
$ns at [expr $opt(start_max) + $opt(duration) + 5] "finish_simulation; $ns halt"

puts -nonewline "Simulating..."
$ns run

```