

# Throughput Optimisation in Multi-Channel Wireless Mesh Networks

Thesis submitted for the degree of  
Doctor of Philosophy  
at the University of Leicester

by

AISHA MOUSA MASHRAQI

DEPARTMENT OF INFORMATICS

UNIVERSITY OF LEICESTER

DECEMBER 2017

# Throughput Optimisation in Multi-Channel Wireless Mesh Networks

Aisha Mousa Mashraqi

## *Abstract*

Wireless Mesh Networks (WMNs) are becoming common due to the features provided, especially the low cost and self-configuration ability. In WMNs, the data traffic is transmitted through intermediate nodes. With the nature of wireless networks, forwarding (routing) the data from the senders to the destinations and managing the network resources efficiently are challenging. There are various reasons that affect the network performance especially the throughput reduction such as signal interference, mobility and congestion. The focus of this research is to improve the throughput in the multi-channel wireless mesh networks from two perspectives. The first issue considered in this work is selecting a path with the maximum available bandwidth and low signal interference to transmit data from the source to the destination. Thus, we design two routing metrics, the Expected Transmission Time with Queueing (ETTQ) and the Delay and Interference Aware Metric (DIAM), that consider the intra-flow interference, inter-flow interference and delay. The simulation results of these routing metrics by the Network Simulator (NS2) demonstrate that the DIAM metric can estimate the intra-flow interference, inter-flow interference and delay of a link and then select the path efficiently. The second problem that has been addressed to improve the network throughput is controlling the network congestion. In this work, we address the issue of packet drops in the Interface Queue (IFQ) due to the node congestion. We solve this issue by reducing the number of dropped packets at IFQ by allocating the flow rate from the solution of a linear program (LP). The simulations using NS2 have shown that the LP-based flow rate improves the network throughput in chain networks. In addition, with the complex networks, traffic rate adjustments alone are not sufficient and we propose a simple forwarding delay scheme for the Ad Hoc On-Demand Distance Vector protocol with Forwarding delay (AODV-F) with DIAM routing metric that reduces node congestion and improves throughput. The forwarding delay scheme has also been evaluated using NS2. Moreover, the LP adjusted flow rate and the forwarding delay address the issue of maximising the flow fairness as the results have demonstrated.

# *Acknowledgements*

*My greatest thanks go to Allah for his blessing and help throughout my life.*

*All glory and praise is due to Allah.*

I would like to express my sincere gratitude to my advisor Prof. Thomas Erlebach for endless support throughout this project: patience, guidance, suggestions and availability. I will never forget his encouragement, which motivated me to accomplish my set targets. Special thanks to Prof. Thomas Erlebach for support and standing with me during hardship times in the third year, without his assistance it could have been challenging. I am very grateful to Prof. Erlebach for giving me the opportunity and assistance to work under his supervision and publish most of the results obtained in this thesis, and working with him is a memorable experience.

I would like to thank the annual committee, Dr. Fer-Jan de Vries and Dr. Emilio Tuosto for their questions and comments.

I would like to express my thanks to all staff members in the department for their respectfulness and friendship, and I am grateful to my colleagues for the lovely and enjoyable time that we spent together in the department.

I would also like to deeply express my gratitude to my father (Mousa), my mother (Layla) and my parents-in-law, for their continuous love, encouragement and prayers and for looking after my children sometimes whilst I was studying. I am also indebted to my husband Dr. Mutaib for his love, help, support and encouragement. To my children AbdulAziz, Jana and Jenan: I love you. I would like to thank my siblings for supporting me through my research.

Finally, I thank Najran University for giving me a great opportunity in providing a scholarship so that I could undertake my postgraduate study.

# Contents

Abstract	i
Acknowledgements	ii
List of Figures	vii
List of Tables	xii
Abbreviations	xiii
<b>1 Introduction</b>	<b>1</b>
1.1 Contributions . . . . .	4
1.2 Simulation Environment . . . . .	6
1.3 Thesis Outline . . . . .	6
<b>2 Background and Related Work</b>	<b>8</b>
2.1 Single-Channel . . . . .	8
2.2 Multi-radio Multi-channel . . . . .	9
2.3 Bandwidth . . . . .	9
2.4 Bit Rate . . . . .	10
2.5 Interference in Wireless Networks . . . . .	10

2.5.1	Intra-flow Interference . . . . .	10
2.5.2	Inter-flow Interference . . . . .	11
2.6	Physical Interference Model . . . . .	13
2.7	Network Performance Evaluation . . . . .	13
2.8	Mobility Model . . . . .	15
2.9	Ad hoc On-Demand Distance Vector (AODV) Routing Protocol . . .	16
2.9.1	Route Discovery . . . . .	16
2.10	Work Related to Routing Metrics . . . . .	19
2.11	Work Related to Congestion Control . . . . .	28
2.12	Summary . . . . .	31
<b>3</b>	<b>Routing Metric in Static Wireless Networks</b>	<b>32</b>
3.1	Introduction . . . . .	32
3.2	Related Work . . . . .	34
3.2.1	Single-Channel Routing Metrics . . . . .	34
3.2.1.1	Expected Transmission Count . . . . .	34
3.2.1.2	Expected Transmission Time . . . . .	35
3.2.1.3	End-to-End Delay . . . . .	35
3.2.2	Multi-Channel Routing Metrics . . . . .	36
3.2.2.1	Weighed Cumulative ETT . . . . .	36
3.2.2.2	Multi-Radio Achievable Bandwidth . . . . .	37
3.2.2.3	Weighted End-to-End Delay . . . . .	41
3.3	Proposed Metrics . . . . .	41
3.3.1	Expected Transmission Time with Queuing Delay . . . . .	41
3.3.2	Delay and Interference Aware Metric . . . . .	42
3.4	Routing Protocol Design . . . . .	44
3.5	Performance Evaluation . . . . .	47

3.5.1	Simulation Model . . . . .	47
3.5.2	ETTQ Performance Evaluation in a Single-Channel Network . . . . .	48
3.5.2.1	Impact of Traffic Load . . . . .	48
3.5.2.2	Impact of Network Density . . . . .	50
3.5.2.3	Impact of Number of Flows . . . . .	53
3.5.3	DIAM Performance Evaluation in a Multi-Channel Network . . . . .	55
3.5.3.1	Impact of Traffic Load . . . . .	55
3.5.3.2	Impact of Network Density . . . . .	56
3.5.3.3	Impact of Number of Flows . . . . .	58
3.6	Summary . . . . .	61
<b>4</b>	<b>Routing Metric in Mobile Wireless Networks</b>	<b>62</b>
4.1	Introduction . . . . .	62
4.2	Reactive and Proactive Routing Protocols . . . . .	64
4.3	Destination Sequenced Distance Vector (DSDV) . . . . .	64
4.4	Adapting the Delay and Interference Aware Metric (DIAM) to Mobility . . . . .	67
4.5	Performance Evaluation . . . . .	68
4.5.1	Simulation Model . . . . .	69
4.5.2	Impact of Traffic Load . . . . .	70
4.5.3	Impact of Mobility . . . . .	73
4.5.4	Impact of Network Density . . . . .	75
4.5.5	Impact of Number of Flows . . . . .	77
4.6	Summary . . . . .	80
<b>5</b>	<b>Congestion Control in Interface Queue (IFQ)</b>	<b>81</b>
5.1	Introduction . . . . .	81

5.2	Transmission Control Protocol (TCP)	84
5.3	Linear Programming	85
5.3.1	Linear Programming Model	85
5.4	Forwarding Delay Scheme	87
5.5	Performance Evaluation	89
5.5.1	Simulation Model	89
5.5.2	Maximise Total Throughput	90
5.5.2.1	Scenario A	91
5.5.2.2	Scenario B	95
5.5.2.3	Scenario C	102
5.5.2.4	Scenario D	105
5.5.3	Maximise Flow Fairness	108
5.5.3.1	Scenario E	108
5.5.3.2	Scenario F	112
5.5.3.3	Scenario G	118
5.6	Summary	120
<b>6</b>	<b>Conclusion</b>	<b>121</b>
6.1	Thesis Summary	121
6.2	Future Work	123
	<b>Bibliography</b>	<b>125</b>

# List of Figures

1.1	Example of wireless mesh network. . . . .	1
1.2	Example of broadband home networking . . . . .	2
2.1	Example of single-radio single-channel . . . . .	9
2.2	Example of multi-radio multi-channel . . . . .	9
2.3	Example of intra-flow interference. . . . .	11
2.4	Example of inter-flow interference. . . . .	12
2.5	Example of reducing the inter-flow interference. . . . .	12
2.6	A RREQ message initiated by source node S in the path discovery process. . . . .	18
2.7	A RREP message is sent back to the source node. . . . .	18
2.8	AODV protocol messaging. . . . .	19
2.9	Routing metric classification. . . . .	20
3.1	MRAB flow chart. . . . .	40
3.2	Example of DIAM explanation. . . . .	44
3.3	Flow chart of route discovery process. . . . .	46
3.4	Grid network $5 \times 5$ . . . . .	49
3.5	Total throughput in single-channel under the impact of traffic load . .	50
3.6	Packet delivery ratio in single-channel under the impact of traffic load	51
3.7	Total throughput in single-channel under the impact of network size .	52

3.8	Packet delivery ratio in single-channel under the impact of network size . . . . .	53
3.9	Total throughput in single-channel under the impact of number of flows . . . . .	54
3.10	Packet delivery ratio in single-channel under the impact of number of flows . . . . .	55
3.11	Total throughput in multi-channel under the impact of traffic load . . . . .	57
3.12	Packet delivery ratio in multi-channel under the impact of traffic load . . . . .	57
3.13	Total throughput in multi-channel under the impact of network size . . . . .	58
3.14	Packet delivery ratio in multi-channel under the impact of network size . . . . .	59
3.15	Total throughput in multi-channel under the impact of number of flows . . . . .	60
3.16	Packet delivery ratio in multi-channel under the impact of number of flows . . . . .	61
4.1	Mobile network example . . . . .	63
4.2	DSDV network example. . . . .	65
4.3	DSDV network example with mobile nodes. . . . .	66
4.4	A simple network to illustrate the change in the interference nodes with a mobile node. . . . .	67
4.5	Total throughput in mobile network under the impact of traffic load. . . . .	71
4.6	Packet delivery ratio in mobile network under the impact of traffic load. . . . .	72
4.7	Routing overhead mobile network under the impact of traffic load . . . . .	72
4.8	Total throughput in multi-channel mobile under the impact of increasing the mobility. . . . .	74

4.9	Packet delivery ratio in multi-channel mobile network under the impact of increasing the mobility . . . . .	74
4.10	Routing overhead in multi-channel mobile network under the impact of increasing the mobility . . . . .	75
4.11	Total throughput in multi-channel mobile network under the impact of increasing number of network nodes . . . . .	76
4.12	Packet delivery ratio in multi-channel mobile network under the impact of increasing number of network nodes . . . . .	77
4.13	Routing overhead in multi-channel mobile network under the impact of increasing number of network nodes. . . . .	77
4.14	Total throughput in multi-channel mobile network under the impact of increasing number of flows. . . . .	79
4.15	Packet delivery ratio in multi-channel mobile network under the impact of increasing number of flows. . . . .	79
4.16	Routing overhead multi-channel mobile network under the impact of increasing number of flows. . . . .	80
5.1	Congestion scenario. . . . .	82
5.2	TCP in wireless network protocol stack . . . . .	84
5.3	Wireless network protocol stack . . . . .	88
5.4	Chain network with 5 nodes. . . . .	91
5.5	Throughput of flows 1-3 and 0-4 . . . . .	92
5.6	Number of dropped packets of flows 1-3 and 0-4 . . . . .	92
5.7	Throughput of flows 1-3 and 4-0 . . . . .	94
5.8	Number of dropped packets of flows 1-3 and 4-0 . . . . .	94
5.9	Network topology. . . . .	95
5.10	Finding optimum delay for 0-3 and 1-3 flows . . . . .	97
5.11	Finding optimum congestion threshold for 0-3 and 1-3 flows . . . . .	97

5.12	Throughput of flows 1-3 and 0-3 . . . . .	98
5.13	Number of dropped packets of flows 1-3 and 0-3 . . . . .	98
5.14	Finding optimum delay for 0-2 and 0-3 flows . . . . .	100
5.15	Finding optimum congestion threshold for 0-2 and 0-3 flows . . . . .	100
5.16	Throughput of flows 0-2 and 0-3 . . . . .	101
5.17	Number of dropped packets of flows 0-2 and 0-3 . . . . .	101
5.18	Finding optimum delay for 2-0, 3-1 and 3-5 flows . . . . .	103
5.19	Finding optimum congestion threshold for 2-0, 3-1 and 3-5 flows . . . . .	103
5.20	Throughput of flows 2-0, 3-1 and 3-5 . . . . .	104
5.21	Number of dropped packets of flows 2-0, 3-1 and 3-5 . . . . .	104
5.22	Finding optimum delay for 20-node random network . . . . .	106
5.23	Finding optimum congestion threshold for 20-node random network . . . . .	106
5.24	Throughput of 20-node random network . . . . .	107
5.25	Number of dropped packets in 20-node random network . . . . .	107
5.26	Throughput of flows 1-3 and 0-4 with fairness . . . . .	109
5.27	Number of dropped packets of flows 1-3 and 0-4 with fairness . . . . .	110
5.28	Throughput of flows 1-3 and 4-0 with fairness . . . . .	111
5.29	Number of dropped packets of flows 1-3 and 4-0 with fairness . . . . .	111
5.30	Finding optimum delay for 0-3 and 1-3 flows with fairness. . . . .	113
5.31	Finding optimum congestion threshold for 0-3 and 1-3 flows with fairness . . . . .	113
5.32	Throughput of flows 1-3 and 0-3 with fairness. . . . .	114
5.33	Number of dropped packets of flows 1-3 and 0-3 with fairness. . . . .	114
5.34	Finding optimum delay for 0-2 and 0-3 flows with fairness . . . . .	115
5.35	Finding optimum congestion threshold for 0-2 and 0-3 flows with fairness . . . . .	116
5.36	Throughput of flows 0-2 and 0-3 with fairness . . . . .	116

*List of Figures*

---

5.37	Number of dropped packets of flows 0-2 and 0-3 with fairness . . . . .	117
5.38	Finding optimum delay for 2-0, 3-1 and 3-5 flows with fairness . . . . .	117
5.39	Throughput of flows 2-0, 3-1 and 3-5 with fairness . . . . .	119
5.40	Number of dropped packets of flows 2-0, 3-1 and 3-5 with fairness . . . . .	119

# List of Tables

2.1	Summery of Routing Metrics Characteristics. . . . .	26
2.2	Summery of Routing Metrics Limitations. . . . .	27
3.1	Explanation of MRAB notation . . . . .	37
3.2	Simulation parameters for static networks. . . . .	48
4.1	Node 3 routing table . . . . .	66
4.2	Node 3 updated routing table . . . . .	66
4.3	Simulation parameters for mobile networks. . . . .	70
5.1	Explanation of notation . . . . .	87
5.2	Simulation parameters for congestion control in IFQ . . . . .	90

# Abbreviations

<b>ABR</b>	<b>A</b> vailable <b>B</b> it <b>R</b> ate
<b>AIMD</b>	<b>A</b> dditive <b>I</b> ncrease and <b>M</b> ultiplicative <b>D</b> ecrease
<b>AODV</b>	<b>A</b> d <b>H</b> oc <b>O</b> n- <b>D</b> emand <b>D</b> istance <b>V</b> ector
<b>AODV-F</b>	<b>A</b> d <b>H</b> oc <b>O</b> n- <b>D</b> emand <b>D</b> istance <b>V</b> ector with <b>F</b> orwarding delay
<b>ARC</b>	<b>A</b> daptive <b>R</b> ate <b>C</b> ontrol
<b>CAR</b>	<b>C</b> ongestion <b>A</b> ware <b>R</b> outing
<b>CBR</b>	<b>C</b> onstant <b>B</b> it <b>R</b> ate
<b>CL-ILD</b>	<b>C</b> ross <b>L</b> ayer <b>I</b> nterference <b>L</b> oad and <b>D</b> elay aware
<b>CODA</b>	<b>C</b> ongestion <b>D</b> etection and <b>A</b> voidance
<b>CRP</b>	<b>C</b> ongestion adaptive <b>R</b> outing <b>P</b> rotocol
<b>CSC</b>	<b>C</b> hannel <b>S</b> witching <b>C</b> ost
<b>DIAM</b>	<b>D</b> elay and <b>I</b> nterference <b>A</b> ware <b>M</b> etric
<b>DSDV</b>	<b>D</b> estination <b>S</b> equenced <b>D</b> istance <b>V</b> ector
<b>ETT</b>	<b>E</b> xpected <b>T</b> ransmission <b>T</b> ime
<b>EED</b>	<b>E</b> nd-to- <b>E</b> nd <b>D</b> elay
<b>ETTQ</b>	<b>ETT</b> with <b>Q</b> ueuing delay
<b>ETX</b>	<b>E</b> xpected <b>T</b> ransmission <b>C</b> ount
<b>GSPN</b>	<b>G</b> eneralized <b>S</b> tochastic <b>P</b> etri <b>N</b> et
<b>HTAP</b>	<b>H</b> ierarchical <b>T</b> ree <b>A</b> lternative <b>P</b> ath
<b>iAware</b>	<b>i</b> nterference <b>A</b> ware

<b>IFQ</b>	<b>I</b> nter <b>f</b> ace <b>Q</b> ueue
<b>ILA</b>	<b>I</b> nterference <b>L</b> oad <b>A</b> ware
<b>INX</b>	<b>I</b> nterferer <b>N</b> eighbours <b>C</b> ount
<b>IR</b>	<b>I</b> nterference <b>R</b> atio
<b>IRU</b>	<b>I</b> nterference <b>R</b> esource <b>U</b> sage
<b>LAETT</b>	<b>L</b> oad <b>A</b> ware <b>E</b> TT
<b>LAN</b>	<b>L</b> ocal <b>A</b> rea <b>N</b> etwork
<b>LP</b>	<b>L</b> inear <b>P</b> rogramming
<b>MIC</b>	<b>M</b> etric of <b>I</b> nterference and <b>C</b> hannel switching
<b>MRAB</b>	<b>M</b> ulti- <b>R</b> adio <b>A</b> chievable <b>B</b> andwidth
<b>MTI</b>	<b>M</b> etric of <b>T</b> raffic <b>I</b> nterference
<b>N</b>	<b>B</b> ackground <b>N</b> oise
<b>NAIA</b>	<b>N</b> etwork <b>A</b> daptive <b>I</b> nterference <b>A</b> ware
<b>NS</b>	<b>N</b> etwork <b>S</b> imulator
<b>PN</b>	<b>P</b> etri <b>N</b> et
<b>QNM</b>	<b>Q</b> ueuing <b>N</b> etwork <b>M</b> odel
<b>UDP</b>	<b>U</b> ser <b>D</b> atagram <b>P</b> rotocol
<b>RREP</b>	<b>R</b> oute <b>R</b> eply
<b>RREQ</b>	<b>R</b> oute <b>R</b> equest
<b>SINR</b>	<b>S</b> ignal to <b>I</b> nterference plus <b>N</b> oise <b>R</b> atio
<b>SPN</b>	<b>S</b> tochastic <b>P</b> etri <b>N</b> et
<b>TADR</b>	<b>T</b> raffic <b>A</b> ware <b>D</b> ynamic <b>R</b> outing
<b>TCP</b>	<b>T</b> ransmission <b>C</b> ontrol <b>P</b> rotocol
<b>WCETT</b>	<b>W</b> eighed <b>C</b> umulative <b>E</b> TT
<b>WCETT-LB</b>	<b>W</b> CETT - <b>L</b> oad <b>B</b> alancing
<b>WEED</b>	<b>W</b> eighed <b>E</b> nd-to- <b>E</b> nd <b>D</b> elay
<b>WMN</b>	<b>W</b> ireless <b>M</b> esh <b>N</b> etwork

*Dedicated to my lovely parents... Layla and Mousa and  
my lovely family ... Muatib, AbdulAziz, Jana and  
Jenan...*

# Chapter 1

## Introduction

Wireless technology is the medium for transferring information between two or more points that are not connected by wire. The most common wireless use radio technology [63]. Wireless technology can be found in different applications such as cellular telephones, wireless networking, mobile networks, and wireless keyboards and headphones. In recent years, wireless mesh networks (WMNs) have gained popularity, especially in the Local Area Network (LAN), due to features such as their dynamic self-configuration, easy access to the network, and low cost [41].

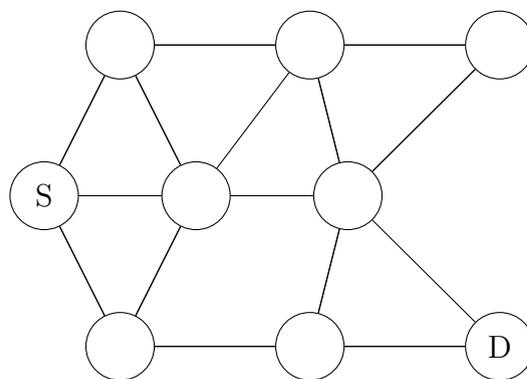


FIGURE 1.1: Example of wireless mesh network.

A WMN is a network of nodes (computers or devices) connected by wireless communication (radio links). WMNs are also known as multi-hop networks; because of the limitations of radio links, many pairs of nodes cannot communicate directly. As a result, the data should be forwarded via one or more intermediate nodes; thus, each node acts as host and router. Figure 1.1 shows an example of a wireless mesh network and how pairs of nodes (source and destination) can communicate with each other via intermediate nodes [5]. In addition, nodes in WMNs can act as router or client (or both) and communicate via radio. There are several applications utilising WMNs such as broadband home networking, metropolitan area networks, and enterprise networking [4, 41]. IEEE 802.11 is one of the wireless communication technologies that are commonly used in wireless broadband services. This popularity is due to easy deployment and the cheapness of the equipment; thus, it is widely used by home applications. Figure 1.2 shows an example of broadband home networking which contains laptops, smart TV, tablets, smart phones and a WiFi printer.

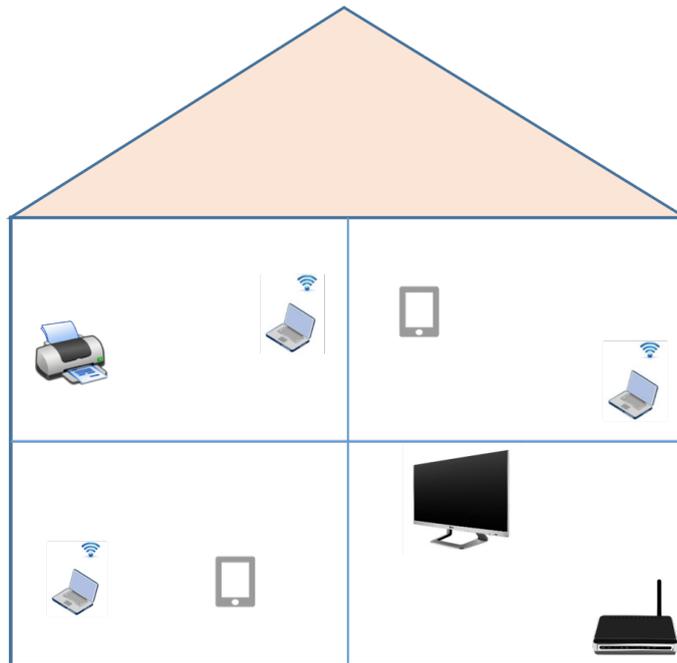


FIGURE 1.2: Example of broadband home networking.

However, despite the notable features of WMNs, many challenges contribute to throughput reduction, especially with the increase in the number of nodes [41]. In wireless networks, many nodes share the same wireless medium, so these nodes might transmit simultaneously. Therefore, a Medium Accesses Control (MAC) protocol manages the accesses to the shared link [21]. In addition, network performance is affected by radio communication as signals interfere with each other. This interference leads to collisions, and then the packets will be dropped. This issue can be addressed by a multi-channel approach [49], which results in a reduction in interference, which will further improve the network's capacity. The multi-channel network gives nodes an opportunity to transmit data simultaneously through each radio channel. We use the term link to describe the connection between the nodes while term channel means that a specific medium uses for transmitting data.

In addition, routing in wireless mesh networks is used for transmitting data between two nodes. Routing is one of the most challenging matters in WMNs [25]. One of the significant issues is that packets are dropped, which may be due to many factors such as the network topology, mobility, link interference and network congestion. For example, with a mobile network, the node may move, which leads to broken links and the network topology will change [43]; as a result, some packets might be dropped. Moreover, transmitting data through intermediate nodes may produce signal interference, and this can also lead to packets being dropped. The signal could interfere with other links on the same path or from other transmitting paths [20]. In addition, some packets might be lost during the forwarding of the data to the destination node because of congestion in the network. During data transmission, the node will queue the packets until they can be serviced by the medium, which may cause an overflow in the queue. Therefore, it is necessary to control the congestion to prevent it from occurring in the network and then improve the network's performance.

Performance optimisation in WMNs is a challenge and has resulted in extensive research. There are various issues that affect the network performance. A serious issue is packet loss due to interference or congestion [55] and there is some research that focuses on the throughput optimisation in WMNs. Therefore, the aim of this thesis is to improve the network throughput by reducing the number of packets dropped due to link interference and node congestion.

## 1.1 Contributions

The main contributions are as follows: the first contribution comes in Chapter 3, where we design the Expected Transmission Time with Queuing delay (ETTQ) metric for a single-channel network. The ETTQ metric improves the Expected Transmission Time (ETT) metric [16] for a single-channel network which estimates the total amount of time taken to transmit the packet over the path. The ETT metric considers the packet loss ratio and the transmission rate but it ignores the queuing delay; as a result, the ETT metric may select a path with a heavy load. Therefore, the path selected by ETT may affect the network's performance due to the fact that queuing the packet consumes more time in transmitting it over the path. Consequently, we have addressed this issue by considering the queuing delays in the ETTQ. The performance of the ETTQ has been measured through simulation and the results compared with some previous work. Some of the results have been published in [39].

In relation to considering the multi-channel network and link interference, the ETTQ has been combined with the Multi-Radio Achievable Bandwidth (MRAB), which is an algorithm to calculate achievable bandwidth under the impact of inter-flow and intra-flow interference [35], to design the Delay and Interference Aware Metric

(DIAM) in Chapter 3. DIAM improves the network's performance because it selects a path with a high data rate and low signal interference. We show the evaluation of DIAM through network simulation and the results are compared with some previous work. Some of the results have been published in [39].

In Chapter 4, we adapt the Delay and Interference Aware (DIAM) routing metric for mobile networks. With the mobile networks, the node may move, which can lead to links being broken and then the network topology will change. Therefore, we adapt the Delay and Interference Aware (DIAM) routing metric for mobile networks in order to calculate an accurate estimation of the interference degree from the interference nodes. The performance of the adapted DIAM routing metric has been evaluated by simulation and the results have been compared with DSDV in mobile multi-channel wireless networks. Some of the results have been published in [39].

In Chapter 5, we address the node congestion level in multi-channel WMNs and reduce the dropped packets at Interface Queue (IFQ) by adjusting the traffic rate based on the solution of a linear program (LP). The problem of maximising the network throughput and flow fairness is formulated as LP and then the solution is used to adjust the network flow rate in the Network Simulator (NS2). In addition, we propose a simple forwarding delay scheme in order to reduce the number of dropped packets at IFQ for the Ad Hoc On-Demand Distance Vector protocol with Forwarding delay (AODV-F) with DIAM routing metric. The combination of LP-based flow rate and forwarding delay scheme reduces node congestion and improves total throughput and flow fairness. The advantage of LP-based flow rate and forwarding delay scheme is demonstrated in simulations in different network scenarios. Some of the results have been published in [40].

## 1.2 Simulation Environment

This section presents the tools employed to perform the simulation evaluations described in different sections of this thesis.

The simulation approach in particular selected because is flexible and it also has the ability to design different experiments. There are various network simulator tools for the purposes of research into wireless networks with the most commonly used one being NS2 [27], which is an open source event-driven simulator designed for research into networks. In order to investigate network performance, the researcher can use a simple script language to configure the network and then run the simulation and observe the results using NS2. There are many versions of NS2, such as ns-2.33, ns-2.34 and ns-2.35. The patch by Calvo and Campo [9] was used to extend ns-2 and support multi-interface and multi-channel communication. The modifications were tested in ns-2.35, ns-2.34 and ns-2.33. ns-2.33 was found to be the one that can be used to implement the multi-radio multi-channel network.

## 1.3 Thesis Outline

This thesis is organised as follows: Chapter 2 presents the basic information and terminology and also a description of the AODV routing protocol mechanism and the literature review. In Chapter 3, we design two routing metrics, the Expected Transmission Time with Queuing delay (ETTQ) for single-channel WMNs and the Delay and Interference Aware Metric (DIAM) for multi-channel WMNs. In addition, the performance of the two metrics has been measured by conducting simulation in NS2, comparing the results with other routing metrics in single-channel and multi-channel WMNs. In Chapter 4, we adapt the DIAM to consider the mobile networks

and then the performance of the adapted DIAM is measured by using the NS2 simulator. Also, the results are compared with the DSDV routing protocol. In Chapter 5, the problem of maximising the network throughput and flow fairness is formulated as LP for a given scenario and then the solution is used to adjust the network flow rate in the NS2 simulator. In addition, we propose a simple forwarding delay scheme in order to reduce the number of dropped packets at IFQ, which leads to an increase in the total throughput and flow fairness. Finally, Chapter 6 presents the conclusion and future work.

# Chapter 2

## Background and Related Work

This chapter presents some basic terminologies that will utilise throughout this thesis. First, we explain some terminologies such as single-channel and multi-channel and describe two types of interference. Then, we will introduce the interference model. In addition, we discuss the related work and explain the basic AODV routing protocol because the evaluation of our work is measured by extending the basic AODV.

### 2.1 Single-Channel

A channel is a physical transmission medium such as radio communication. The channel is used to transmit data from senders to receivers. A single-radio mesh node is a node that uses a single network interface and a single-channel at a time to communicate with the other mesh nodes [37, 50], as shown in Figure 2.1.



FIGURE 2.1: Example of single-radio single-channel

## 2.2 Multi-radio Multi-channel

In a wireless environment, if links are close to each other and operate on the same channel, the signals will interfere with each other. This phenomenon is called co-channel interference, and is considered to be a significant factor for limiting throughput in multi-hop wireless networks. In order to improve network capacity, multi-radio multi-channel technology can be utilised, which allows simultaneous transmission in one node. In multi-radio technology, nodes are equipped with two or more wireless radio interfaces that are tuned to different channels [37, 49], as Figure 2.2 illustrates.

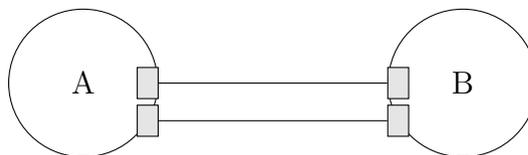


FIGURE 2.2: Example of multi-radio multi-channel

## 2.3 Bandwidth

The bandwidth of a link is the amount of data that can be transmitted from one point to another in a period of time (usually a second) and is measured in bits per second (bit/s) [47].

## 2.4 Bit Rate

Bit rate is the amount of data that will be transmitted in a second. There are different types of bitrate such as Constant Bit Rate (CBR) and Available Bit Rate (ABR). In the CBR the data rate is fixed while in the ABR the data rate is adjusted based on available bandwidth [59].

## 2.5 Interference in Wireless Networks

One of the main factors that reduce network performance is signal interference. There are two types of interference: intra-flow interference and inter-flow interference [20].

### 2.5.1 Intra-flow Interference

Intra-flow interference occurs between two or more links working on the same channel in the same path of a flow. Figure 2.3 illustrates the intra-flow interference happening between nodes A, B and C. Assume that the link between node A and node B and the link from node A to C operate on the same channel. Thus, the intra-flow interference will occur between Links BA and AC. In order to eliminate the intra-flow interference, different channels are assigned between consecutive links [53]. In addition, the intra-flow interference can happen over multiple hops due to the fact that the interference range may be larger than one hop [36]

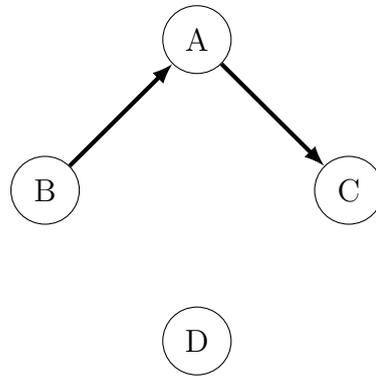


FIGURE 2.3: Example of intra-flow interference.

### 2.5.2 Inter-flow Interference

Inter-flow interference occurs among the nodes in the network if different flows transmit their data simultaneously. Figure 2.4 shows that when node B sends data to node D and at the same time node E transmits data to node F, the signals will interfere with each other because node E is at the interference range of node D. This type of interference is called inter-flow interference. This problem can be solved by transmitting the data in a different path [53], as shown in Figure 2.5. The Figure 2.5 illustrates that when node B transmits data to node A and at the same time node E sends data to node F, both transmissions will success because of that the node E is out of the interference range of node A.

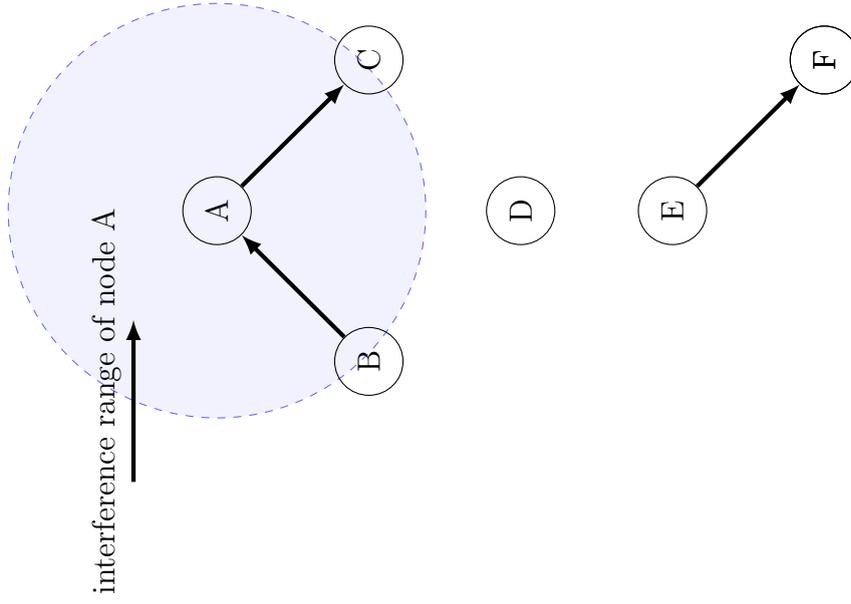


FIGURE 2.5: Example of reducing the inter-flow interference.

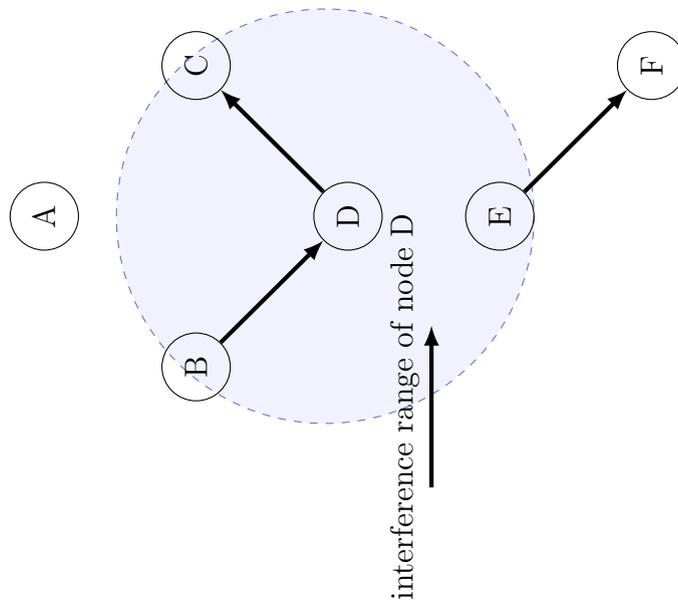


FIGURE 2.4: Example of inter-flow interference.

## 2.6 Physical Interference Model

In this section, we present the interference model that applies throughout this thesis. The physical interference model is also known as the signal-to-interference-and-noise-ratio (SINR) model. In the physical model, a node  $d$  successfully receives a message from a sender  $s$  if and only if the SINR at node  $d$  is above its predetermined threshold  $\gamma$  [34], as shown in Equation (2.1).

$$\frac{P_d(s)}{N + \sum_{k \in D'} P_d(k)} \geq \gamma \quad (2.1)$$

Here  $P_d(s)$  refers to the received power at node  $d$  from node  $s$ ,  $D'$  is a set of interference nodes with  $d$ ,  $N$  the background noise and  $P_d(k)$  the interference power from a different transmitting node  $k$ .

## 2.7 Network Performance Evaluation

This section provides a description of network performance evaluation. The network performance measures the quality of service provided by the network. Performance evaluation is needed at several network stages (design, implementation and building). There are three main approaches for performance evaluation techniques, which are measurement instrumentation, analytic modelling and simulation [18, 23].

Modelling is a framework for gathering, organising, evaluating and understanding the network system such as Queuing Network Model (QNM), Petri Net (PN), Stochastic Petri Net (SPN), Generalised Stochastic Petri Net (GSPN) [19] and Process algebra [24]. Modelling approach helps view the network system and defines the important elements in the system and the relation between them. The modelling provides an

abstraction for real world networks that simplify the complexity of the networks. In addition, in order to provide an accurate and useful model, the modellers have to understand the network and its important features. A modelling approach can be used as a platform to study systems before they exist or even without having an effect on actual implementation. However, the modelling method has some drawbacks, for example, it is difficult to describe the interaction between the network elements [18].

Simulation is the imitation of the real system according to the system described in the model [18]. The modelling represents the network itself, while the simulation represents the operation of the network [19]. The estimation of results gained by simulation will provide a better understanding of the elements in a real network and the interaction between them. In order to have an efficient simulation, the system has to be constructed precisely and correctly translated into a computer program [18]. The network simulator is a software that simulates the network behaviour such as NS2 [27], NS3 [1] and OMNeT++ [2]. The simulation has a significant feature, which is its flexibility, which helps to study problems that were challenging in other techniques (e.g. modelling and measurement instrumentation) [18]. Although the simulation needs a long time to perform the network evaluation, it has been chosen as the performance evaluation approach of this work. This is because it enables the researcher to design a wide range of experiments to study the network performance [18].

The measurement instrumentation approach uses a real network system (testbed network) that requires real equipment, monitoring of the network and then extraction of the data [18]. The testbed provides a realistic system that helps to understand the network behaviour and functionality. In addition, when the measurement results support the results obtained by modelling and simulation, the model will be valid. However, implementing a testbed network is expensive, in addition to the cost of the modification and developing the testbed network [18].

## 2.8 Mobility Model

In the performance evaluation of new protocols and algorithms the network should be in a realistic condition. Mobility has a significant impact on the performance of the network. The movement pattern of a mobile node and its changing location and speed can be described by mobility modelling. Mobility models are utilised to simulate and evaluate the performance of mobile wireless networks. There are different types of mobility models in mobile networks such as Random Walk Mobility Model, Random Waypoint Mobility Model and Random Direction Mobility Model [10].

In the Random Walk Mobility Model [62], the mobile node moves from its location to a new destination by randomly choosing direction and speed. Nevertheless, one disadvantage of this model is that the selection of the new direction and speed is independent from the previous movement, which leads to unrealistic movement for example sharp turns and sudden stops. In the Random Waypoint Mobility Model [31], the mobile node chooses a random speed and direction and introduces a pause time between the movements. It is also flexible and the movement configuration is realistic [10]. Therefore, this model was considered in this work. In the Random Direction Mobility Model [51], the mobile node selects a random direction and then the node travels to the border of the simulation area in the same direction. The node then stops when it reaches the boundary of the simulation area for a period of time before choosing another direction and continuing the process. However, this movement model does not reflect mobility in the real world because the mobile node has to reach the simulation edge and also pauses only at the edge of the simulation area.

## 2.9 Ad hoc On-Demand Distance Vector (AODV) Routing Protocol

This section explains of the basics of the Ad hoc On Demand Distance Vector (AODV) routing protocol which was extended to evaluate the new approaches presented in the thesis.

The Ad hoc On-Demand Distance Vector Routing (AODV) Protocol [11, 45, 46] is a reactive routing protocol, where the route is constructed only when needed. The AODV maintains a routing table for storing the active path information. The AODV uses control messages such as Hello messages, Route Request (RREQ) and Route Reply (RREP). The source and forwarding nodes maintain a routing table, which contains a destination, next hop, metric and a sequence number for the destination. The sequence number is used to ensure the route is loop-free and has the recent route information. The basic AODV applies the shortest path routing metric.

Hello message is used to detect the neighbouring node and the link information. The Hello message is broadcasted periodically to all neighbours. If a node does not receive a Hello message from a neighbour, the break in the link is detected. The AODV has a Route Discovery mechanism for constructing a route, which employs the control messages RREQ and RREP. The sub-section below describe the basic operations of the AODV routing protocol.

### 2.9.1 Route Discovery

When the source needs to send data to the destination, first the source node searches for a route to the destination in its routing table. If there is a valid route to reach

the destination, it will start sending data packets. Otherwise, the source node will initiate route discovery by broadcasting a Route Request (RREQ) packet that contains a unique *broadcast id* and *sequence number* as well as information about source and destination nodes. To distinguish the most recent route information, every node has to check two counters: *broadcast id* and *sequence number*. The *broadcast id* identifies each RREQ packet, which is increased by one each time the source node sends a new RREQ packet, while *sequence number* is for checking the validation of the route and is updated by the destination node when it receives a RREQ packet. In addition, each node maintains and updates the *sequence number* for the destination in the routing table [52].

The RREQ packet propagates through the network until it reaches its destination, as shown in Figure 2.6. When an intermediate node receives the RREQ packet, one of two cases occurs: if the RREQ packet has already been received, which can be detected by checking *broadcast id* and *sequence number*, i.e. it is a copy of the previous RREQ, then it will discard the packet. If the intermediate node receives the first copy of the RREQ, it will record the address of the previous neighbour in order to calculate the reverse route and then broadcast the RREQ packet. The reverse route is used to forward the RREP packet. For example, the node *S* will broadcast a RREQ packet to its neighbour nodes (1, 2 and 3), and then the neighbour nodes will check the *broadcast id* and record the previous node. After that, the nodes 1, 2 and 3 will forward the RREQ packet to their neighbour nodes. The node 1 will receive other copies of the RREQ packet from node 2 and 3. Consequently, the node 1 will discard the RREQ packets that have been received from node 2 and 3.

When the RREQ broadcast reaches its destination or an intermediate node to the destination that has a *sequence number* that is greater or equal than the one contained in the RREQ packet, the node will create a unicast RREP packet and then

the RREP packet will be sent back to the previous node and then it will be forwarded through the reverse route, which was built whilst the RREQ packet was being broadcast, as shown in Figure 2.7. Figure 2.8 illustrates the AODV protocol messaging.

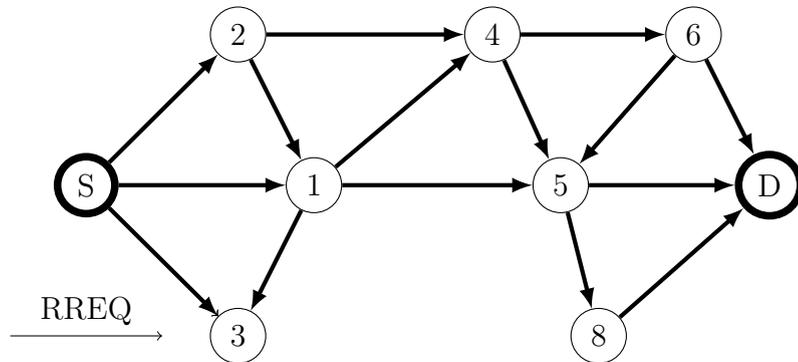


FIGURE 2.6: A RREQ message initiated by source node S in the path discovery process.

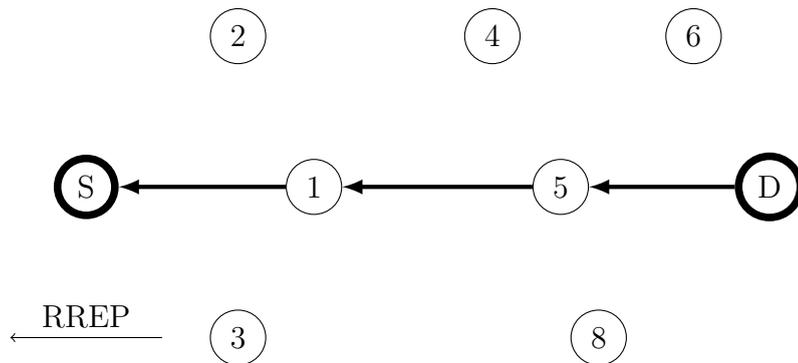


FIGURE 2.7: A RREP message is sent back to the source node.

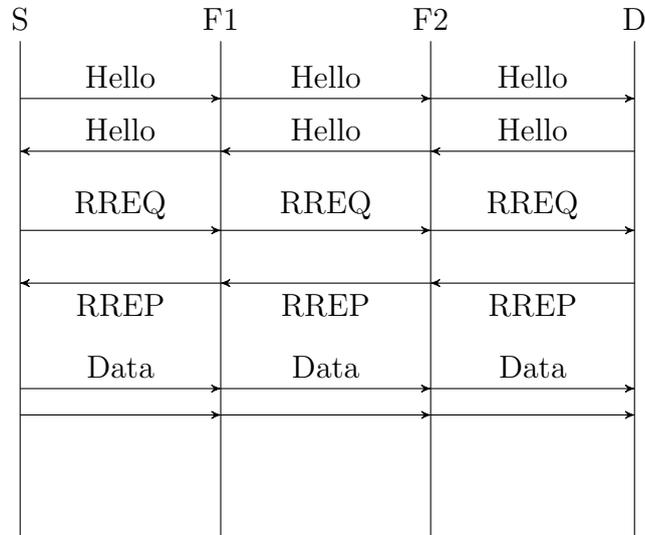


FIGURE 2.8: AODV protocol messaging.

## 2.10 Work Related to Routing Metrics

Applications such as multimedia and video streaming need high throughput. There are studies and techniques to improve the throughput in WMNs, such as scheduling algorithms and routing protocols including routing metrics and channel assignment in multi-channel networks. The majority of these approaches are utilised to address certain factors that affect the network's performance such as packet loss, transmission rate, interference and network load.

Routing metrics in WMNs have been studied in the literature. A routing metric is a mathematical calculation that gives the path a real number, also, it is designed to make the decision for selecting a path. Therefore, it is better if the routing metric considers certain aspects, such as packet loss, transmission rate, interference and traffic load. This will improve the network's performance because the data will be transmitted through a good quality path. Figure 2.9 illustrates the basic

classification of routing metrics. In addition, Table 2.1 gives a summary of routing metrics characteristics and Table 2.2 provides routing metrics limitations.

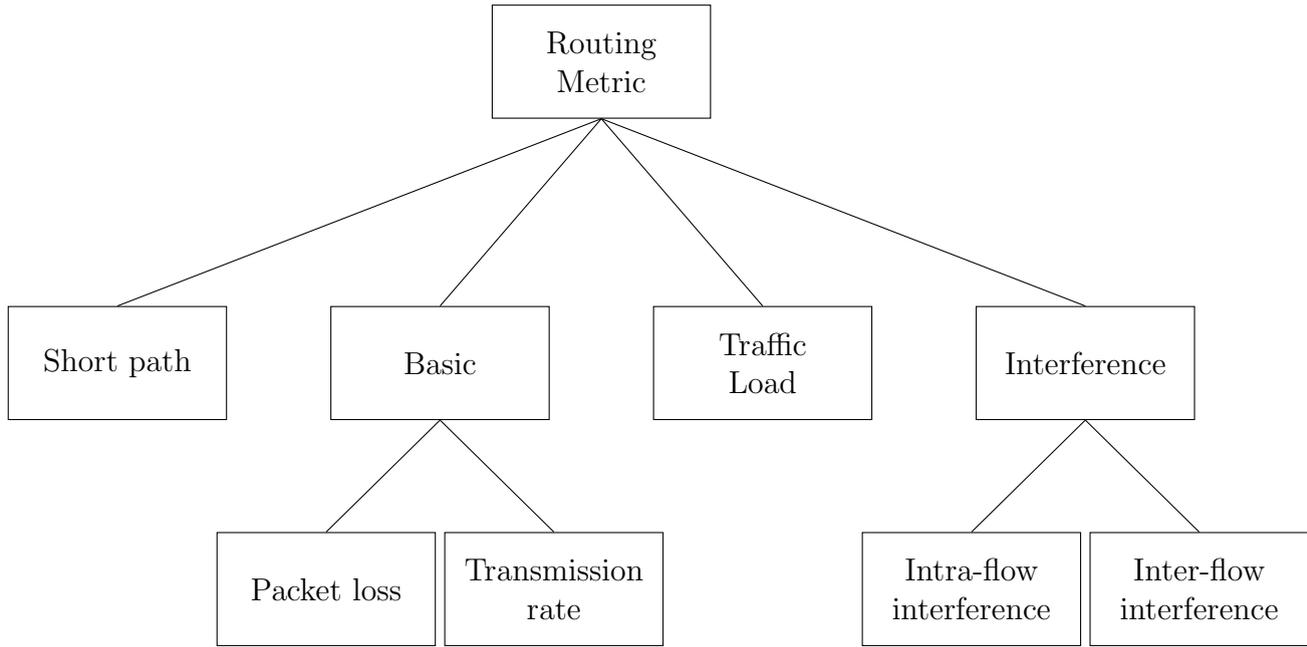


FIGURE 2.9: Routing metric classification.

Several routing metrics have been proposed for WMNs. A popular one utilised in the existing routing protocols is hop count. In a simple way, this metric provides the path with the minimum hop count. However, one of its significant disadvantages is that hop count does not take link quality, such as transmission rate and packet loss, into account. For example, a path consisting of two hops with good quality links could give a better performance or be more reliable than a one-hop path that will be selected by the hop count metric [13].

In relation to link quality metrics, we discuss some routing metrics that measure the quality of link and path. The most common routing metric in a single-channel is the Expected Transmission Count (ETX) [13]. The ETX is defined as a measurement of the expected number of transmissions and retransmissions that are required to transmit a packet over a link  $i$ . The ETX captures the effect of the packet loss ratio.

However, one of the significant drawbacks of the ETX metric is that it does not consider the differences in transmission rate between links [16]. A link with a heavy load may have a very low loss rate, yet, the ETX might assign the same loss rate for links with different data rates [14] [20].

Draves *et al* [16] have proposed a routing metric that considers the issue of different link rates. This metric is called the Expected Transmission Time (ETT) [16]. The ETT metric estimates the total amount of time required to transmit a packet over a path.

The ETT metric is able to address the issues of different transmission rates and the packet loss ratio because it is an extended metric of the ETX [13]. However, the ETT does not take the queuing delay into account, so it is more likely to select a path with a heavy load, which will affect the network throughput.

Load Aware ETT (LAETT) [3] is an extended routing metric of ETT that takes the traffic load into account. The LAETT uses the Hello message to measure traffic load. This parameter changes dynamically so it is better to obtain the information of traffic load locally through the node. In addition, the LAETT still has the ETX and ETT drawbacks: it does not take advantage of multi-channel technology, and it also does not consider the interference.

The Interferer Neighbours Count (INX) [33] improves the ETX metric by considering the interference. The INX is the product of the ETX metric and the number of all the interference nodes. The INX measures the interference in a static way and does not include the physical interference model. Moreover, the INX does not take the traffic load into consideration so it might select a congested path, which would lead to poor throughput.

The End-to-End Delay (EED) metric has two components: the queuing delay and the transmission delay. The queuing delay is calculated by the number of buffering packets in the queue. In addition, Li *et al* [34] tried to address the transmission delay along a path by calculating the back-off time. According to Draves *et al* [16], they attempted to examine the impact of back-off time in the ETT in tested experiments and their conclusion was that the ETT metric has better throughput without the back-off time. Therefore, the performance of the EED metric will be affected by the back-off time parameter.

In [16], they proposed Weighted Cumulative ETT (WCETT), which is the extension of the ETT routing metric in order to consider the multi-channel. The WCETT has two components: the first component is the ETT metric, which considers the packet loss ratio and transmission rate. The second component provides a path with less intra-flow interference, which selects the path with the greater channel diversity. However, the WCETT has significant drawbacks. It does not take the inter-flow interference into account; also, it does not consider the traffic load, which leads to transmitting data through a congested path. In addition, the WCETT assumes all links on a path operating on the same channel interfere with each other, even if they are out of their interference range.

Weighted Cumulative ETT Load Balancing (WCETT-LB) [38] improves the WCETT [16] routing metric by taking the traffic load into account to avoid congested paths. However, the WCETT-LB is based on the WCETT metric, so it still suffers from the WCETT limitations. A significant limitation is that it assumes that all links on a path operating on the same channel will interfere with each other. In addition, the WCETT does not capture the inter-flow interference.

The metric of interference and channel switching (MIC) [69] has two components: Interference Resource Usage (IRU) and Channel Switching Cost (CSC). The first

component is a multiplication of ETT by all interference nodes and the second component assumes a high value when consecutive links have the same operating channel. The MIC attempts to capture the intra-flow and inter-flow interference on a path. In fact, the MIC measures the number of interference nodes instead of the interference amount; as a result, the estimation of the intra-flow interference and inter-flow interference is not accurate. In addition, the MIC does not consider the traffic load, so the selected path might be a high load path; as a result, the network's performance will be affected.

The Interference-Load Aware (ILA) routing metric was proposed to consider interference and traffic load [58]. The ILA has two components: Metric of Traffic Interference (MTI) and Channel Switching Cost (CSC). The ILA metric addresses the intra-flow and inter-flow interference, which measures the interference level depending on the traffic load of the interfering nodes. However, the measurement of the interference does not employ the physical model.

The interference Aware routing metric (iAware) [60] has been designed for multi-radio wireless networks. This metric uses the physical model to calculate the inter-flow interference. The authors introduced the Interference Ratio (IR) to measure the interference. However, the iAware metric gives more weight to the ETT component than to the interference. As a result, the iAware metric might select a link with low ETT and high interference. In addition, the iAware does not consider the traffic load, so it might provide a highly congested path.

The Cross Layer Interference-Load and Delay aware (CL-ILD) [42] routing metric considers three parameters: interference, delay and load estimation by channel utilisation. The CL-ILD is a combination of two components: the first component captures the inter-flow interference, load and delay. The second component is channel diversity, which captures the intra-flow interference by giving a high value when

the consecutive links are operating on the same channel. The inter-flow interference is estimated by using the Interference Ratio (IR) proposed in [60] and the estimation of delay calculated by ETT [16]. However, the CL-ILD does not consider the queuing buffer which may cause it to provide a congested path.

The Network Adaptive Interference Aware routing metric (NAIA) [66] has two components: inter-flow interference and intra-flow interference. However, the NAIA uses the queuing buffer to dynamically determine the tunable parameter to assign the weights between the interference and channel diversity. Therefore, the NAIA does not take the traffic load into account, which may cause it to provide a congested path. In addition, the NAIA metric captures the intra-flow interference by using the second component in the WCETT [16], so it still has the same problem: assuming that all links on a path operating on the same channel will interfere with each other.

Ji *et al* [30], worked out that the Interference Ratio (IR) introduced in [60] gives more weight to the background noise  $N$ , so the value of IR will be high with larger  $N$ . As a result, with high signal interference coming from interference nodes, the value of IR might be low with low  $N$ . Consequently, the interference estimation is unreliable. In addition, some studies such as [42] and [66] used the IR to calculate the interference ratio in order to measure the link quality, so their metric will suffer from the same issue. Moreover, Ji *et al* [30] redefine signal to interference and noise ratio (SINR) to estimate the interference in their metric. The iAware+ also employs the node load and the neighbour load. The iAware+ is the weighted combination of two components: the quotient of the previous value of ETT of a link on SINR and the quotient of the current value of ETT of a link on SINR. However, one of the iAware+ limitations is that the collecting of the node load happens at the Hello message; however, as the value of the node load changes dynamically, it is better to obtain this parameter locally at the node.

The Multi Radio Achievable Bandwidth (MRAB) metric measures the effect of intra-flow and inter-flow interference on path capacity [34] by using the physical interference model. However, the MRAB does not consider the traffic load, so the path selected by the MRAB could affect the network's performance.

Hongkun *et al* [35] proposed a multi-channel routing metric that considers the interference and delay. The WEED is a combination of two metrics, EED [34] and MRAB [35]. However, the EED metric is a part of the WEED metric and, as mentioned above, the EED metric has the limitation that it considers the back-off. As a result, the performance of the WEED will be negatively affected by the potentially reduced performance of EED.

TABLE 2.1: Summary of Routing Metrics Characteristics.

Metric	Channel Diversity	Packet loss	Transmission rate	Traffic load	Intra-flow	inter-flow
ETX	No	Yes	No	No	No	No
ETT	No	Yes	Yes	No	No	No
LAETT	No	Yes	Yes	Yes	No	No
INX	No	Yes	No	No	Yes	Yes
EED	No	Yes	Yes	Yes	No	No
WCETT	Yes	Yes	Yes	No	Yes	No
WCETT-LB	Yes	Yes	Yes	Yes	Yes	No
MIC	Yes	Yes	Yes	No	Yes	Yes
ILA	Yes	Yes	Yes	No	Yes	Yes
iAware	Yes	Yes	Yes	No	Yes	Yes
CL-ILD	Yes	Yes	Yes	Yes	Yes	Yes
NAIA	Yes	Yes	Yes	No	Yes	Yes
iAware+	Yes	Yes	Yes	Yes	Yes	Yes
MRAB	Yes	Yes	Yes	No	Yes	Yes
WEED	Yes	Yes	Yes	Yes	Yes	Yes

TABLE 2.2: Summary of Routing Metrics Limitations.

<b>Metric</b>	<b>Limitation</b>
ETX	Gives same loss ratio for all links even with different data rate.
ETT	Does not consider the effect of queuing delay.
LAETT	Traffic load measurement happens at the Hello message and this value changes dynamically, so it is better to obtain this parameter locally at the node.
INX	The interference estimation is not accurate and also the traffic load is not considered.
EED	Back-off time affects the estimation of link quality.
WCETT	All links on a path operation on the same channel interfere with each other even if they are out of their interference range, and also ignores the inter-flow interference and the traffic load.
WCETT-LB	All links on a path operation on the same channel interfere with each other even if they are out of their interference range and also ignores the inter-flow interference.
MIC	The interference estimation is not accurate and ignores the traffic load.
ILA	The measurement of the interference is not accurate.
iAware	Gives more weight to ETT rather than interference.
CL-ILD	Ignores the effect of queuing delay.
NAIA	All links on a path operation on the same channel interfere with each other even if they are out of their interference range.
iAware+	Traffic load measurement happens at the Hello message and this value changes dynamically, so it is better to obtain this parameter locally at the node.
MRAB	Does not consider the effect of traffic load.
WEED	Negatively affected by the performance of EED.

## 2.11 Work Related to Congestion Control

Controlling congestion in wireless networks is a big challenge. In congested networks, a source and destination often cannot communicate properly. There are different approaches for controlling congestion in wireless networks. Some of the existing work aims to control the congestion of the links in the network by finding alternative paths or using multipath mechanisms or traffic rate adaptations [55]. In this section, we briefly discuss some of the previous work.

Chiu and Jain [12] analysed additive increase and multiplicative decrease (AIMD) which is a congestion avoidance technique. The AIMD approach uses the increases and decreases in the traffic load to avoid the congestion. When the congestion is detected by losing packets, the AIMD will reduce the sending rate. In addition, a number of studies on controlling network congestion are based on the AIMD mechanism [12], such as [48, 67, 68]. One of the drawbacks of the AIMD technique is that it detects the congestion by packet loss; however, there are different reasons that lead to dropped packets, such as the signal interference and node mobility. As a result, the AIMD leads to the selection of an inappropriate traffic rate, which affects the network's performance.

One of the prime congestion control approaches is the Transmission Control Protocol (TCP) [48]. The TCP applies a mechanism for minimising network congestion by controlling the flow rate. It provides a method by which to manage the amount of sending data based on the AIMD [12] to prevent buffer overflow. The TCP approach detects the congestion by the loss of packets.

Woo and Culler proposed the Adaptive Rate Control (ARC) scheme [68] that applies the AIMD traffic control scheme to control congestion. In the ARC technique,

the intermediate node increases its sending rate if the previously sent packet is successfully forwarded by the next node. Otherwise, the intermediate node reduces its sending rate. However, the ARC does not detect the congestion; also, it controls the traffic rate based on the packet loss.

Congestion Detection and Avoidance algorithm (CODA) [67] attempts to address the congestion issue using three mechanisms: Congestion detection, open-loop hop-by-hop backpressure notification, and closed-loop multi-source regulation. The congestion detection mechanism is used to activate the rest of the congestion controlling mechanisms. Congestion detection is by channel utilisation and queue buffer. When the congestion is detected, the node broadcasts the congestion notification via backpressure that propagates through the network. Any node that receives the backpressure must make a decision to reduce the traffic rate and forward the backpressure depending on its congestion condition. Finally, CODA implements a closed-loop, multi-source regulation mechanism in order to control congestion which is based on the AIMD [12] traffic control mechanism.

Hull *et al* [26] designed Fusion as a congestion control method which detects congestion by queue buffer. Fusion uses certain techniques in order to control congestion, which are hop-by-hop flow control, rate limiting and prioritised MAC. When the node detects the congestion by the queue size, a hop by hop flow control stops transmitting packets and limits the rate of transmission. Prioritising the MAC mechanism gives the congested node the priority for channel access. However, Fusion applies the reduction in traffic rate when congestion is detected which might assign an inappropriate value that affects the network's performance.

Congestion Aware Routing (CAR) was proposed by Raju *et al* [32]. In CAR, the data separates into two categories: high priority and low priority; also, the network

is divided into two zones: the congested zone and the uncongested zone. The high priority data is routed through the congested zone while the low priority data forwarded via the uncongested zone. However, the CAR method applies multipath routing, which leads to increasing the probability of link collision.

Tran and Raghavendra proposed a routing protocol called Congestion Adaptive Routing Protocol (CRP) using the bypass concept to prevent congestion from occurring [65]. A bypass is a subpath connecting a node with a non-congested node. If a node detects congestion, then the CRP distributes the incoming traffic over the bypass and the primary routes.

Another algorithm called Traffic-Aware Dynamic Routing (TADR), proposed by He *et al* [22], employs two fields, the depth field and the queue length field. The depth field provides a shortest path mechanism while the queue length field is used by the TADR mechanism. Using the queue length field, if congestion appears, the packets are distributed along multipaths to idle or underloaded nodes. However, because the use of multipaths increases the probability of link collision, the performance of CRP [65] and TADR [22] routing protocols might be affected.

On the other hand, other studies have applied alternative techniques. For example, Sergiou and Vassiliou [56] proposed a congestion avoidance and control algorithm (DAIPaS). DAIPaS employs two stages (soft stage and hard stage). Every node enters the soft stage when it receives packets from more than one flow, attempting to reach a situation where each node receives data from only one flow. In the case of high traffic volume, this is not achievable, and therefore the node enters the hard stage, which forces the selection of an alternative path. The alternative path selection is based on path cost, remaining node energy and buffer threshold.

Another algorithm for controlling congestion, which was proposed by Sergiou *et al* [57], is the Hierarchical Tree Alternative Path (HTAP). When congestion arises, an alternative path selection is created based on local information.

## 2.12 Summary

In this chapter, we have explained some terminologies and given an overview of the AODV routing protocol. In addition, related work has been provided to show how different techniques address the issue of dropping packets in wireless networks. From reviewing the literature, we focus on designing a routing metric in order to select a good quality path; also, we propose a simple forwarding delay scheme to control the congestion at the forwarding nodes in multi-channel wireless mesh networks.

# Chapter 3

## Routing Metric in Static Wireless Networks

### 3.1 Introduction

Routing protocols, especially link metrics, play a key role in ensuring good network performance. Packets sent by wireless links are more likely to be lost due to collision (interference between neighbouring nodes), which affects network throughput. One of the most widely used metrics in WMNs is hop count. It provides a path that has a minimum number of hops but does not take into account the link quality, such as transmission rate and packet loss [15]. Therefore, one way to improve network capacity is to select a path that has high data rate and low signal interference. The principle for selecting a path depends on a mathematical calculation that gives the path a real number, based on the designed routing metric. Consequently, designing a routing metric that estimates the link quality in a multi-channel network is more challenging compared to designing one for a single-channel network.

In this chapter, we propose the two routing metrics Expected Transmission Time with Queuing delay (ETTQ) and Delay and Interference Aware Metric (DIAM), which selects a path with high data rate and low signal interference to achieve high performance. The DIAM metric estimates the intra-flow interference, inter-flow interference and delay of a link for multi-channel WMNs. We have implemented the DIAM in the AODV routing protocol using the Network Simulator (NS2). The performance of the DIAM metric is measured by conducting simulation experiments in static wireless networks which are presented in this chapter and mobile wireless networks that are illustrated in the Chapter 4.

The remainder of the chapter is organised as follows: in Sections 3.2, we explain some of the preliminaries related to our work in this chapter. Section 3.3 presents our proposed routing metric Delay and Interference Aware Metric (DIAM). Section 3.4 provides the design of a routing protocol with DIAM routing metric. Section 3.5 provides the simulation results and the performance evaluation of the proposed work. Section 3.6 concludes the chapter.

## 3.2 Related Work

This section provides a description of the previous work that is relevant to our topic in this chapter in both single-channel and multi-channel routing metrics.

### 3.2.1 Single-Channel Routing Metrics

This section will provide a description of some routing metrics in the single-channel networks and their mathematical equations.

#### 3.2.1.1 Expected Transmission Count

As explained in Chapter 2, the ETX (Expected Transmission Count) is one of the popular routing metrics in WMN [13]. The ETX is defined as a measurement of the expected number of transmissions and retransmissions needed to transmit a packet over a link. Therefore, the ETX metric was designed to evaluate a link in both the forward and reverse directions. The ETX metric in Equation (3.1) captures the effect of the packet loss ratio of a link  $i$ , where  $d_f$  and  $d_r$  are the probability of successful packet in both the forward and reverse direction respectively. The path metric is the sum of the ETX values for each link in the path. The selection of the path  $p$  contains  $H$  hops, is based on the minimum sum of ETX values over all  $H$  hops of the path (3.2). The performance of ETX was evaluated through a testbed [13].

$$ETX_i = \frac{1}{d_r * d_f} \quad (3.1)$$

$$ETX_p = \sum_{i=1}^H ETX_i \quad (3.2)$$

### 3.2.1.2 Expected Transmission Time

The ETT (Expected Transmission Time) [16] is a metric designed to address the limitation of ETX [13]. ETT takes different link rates into account as defined in Equation (3.3), where  $S$  represents the packet size and  $B_i$  is the link bandwidth [16]. ETT is simply the expected time to successfully transmit a packet over a link. The ETT of a path  $p$  is obtained by adding up all ETT values of the links along the  $H$  hops of the path (3.4). The ETT has been evaluated in a testbed [16].

$$ETT_i = ETX_i \frac{S}{B_i} \quad (3.3)$$

$$ETT_p = \sum_{i=1}^H ETT_i \quad (3.4)$$

### 3.2.1.3 End-to-End Delay

The End-to-End Delay (EED) is a routing metric that takes the delay over a path into account [34]. The EED is a combination of two parameters, queuing delay and transmission delay, as shown in Equation (3.5). In order to measure the EED metric over a link, each node has to monitor the waiting packets in the buffer and the transmission failure probability [34]. The performance of EED metric was tested using the network simulator (NS2) [34].

$$EED_i = \text{queuing delay} + \text{transmission delay}. \quad (3.5)$$

### 3.2.2 Multi-Channel Routing Metrics

The previous metrics described above are designed for a single-channel, and so do not support the multi-channel environment. In a wireless multi-channel network, the node is equipped with one or more radio interfaces. These radio interfaces are assigned to different channels, which can transmit data simultaneously. Therefore, the network throughput will be improved significantly compared to using a single-channel [49].

#### 3.2.2.1 Weighed Cumulative ETT

The Weighed Cumulative ETT (WCETT) [16] has been designed to improve the ETT metric by considering the multi-channel environment and the WCETT has been evaluated in testbed. Darves *et al* [16] compute the expected transmission time over channel  $j$  via Equation (3.6). Within the  $h$  hops of the path  $p$ , they assume  $k$  channels in the system, where  $X_j$  is the transmission time for hops on channel  $j$ . The path metric under the impact of channel diversity is computed by Equation (3.7) as the largest of the  $X_j$  [16].

$$X_j = \sum_{\text{Hop } h \text{ is on channel } j} ETT_h, \quad 1 \leq j \leq k \quad (3.6)$$

$$WCETT1 = \max X_j \quad (3.7)$$

The WCETT metric of a path defined in Equation (3.8) is a combination of the two metrics in Equations (3.4) and (3.7), where  $\beta$  is a tunable parameter subject to  $0 \leq \beta \leq 1$  [16]:

$$WCETT = (1 - \beta) * \sum_{i=1}^n ETT_i + \beta * WCETT1 \quad (3.8)$$

### 3.2.2.2 Multi-Radio Achievable Bandwidth

The Multi-Radio Achievable Bandwidth (MRAB) is an algorithm to calculate achievable bandwidth under the impact of inter-flow and intra-flow interference [35]. First of all, the calculation of achievable bandwidth under the impact of inter-flow interference will be explained and then how to compute the achievable bandwidth under the impact of intra-flow interference. Finally, the MRAB algorithm will be provided. Table 3.1 shows the main notations.

TABLE 3.1: Explanation of MRAB notation.

Value	Explanation
$B_{ITi}$	achievable bandwidth under the impact of inter-flow interference over a link
$B_{IR}(ij)$	achievable bandwidth under the impact of intra-flow interference over a link
$R_i$	interference degree ratio
$B_{sub}$	achievable bandwidth over subpath
$P_v(u)$	received signal power from node $u$ to node $v$
$P_v(k)$	interference power from different transmission nodes $k$
$P_v^I(u)$	Maximum tolerable interference power at node $v$ to receive the signal from node $u$
$\gamma$	SINR threshold for a successful transmission
N	background noise

In order to calculate MRAB, we first compute the achievable bandwidth under the impact of inter-flow interference over the link  $i$  denoted by  $B_{ITi}$  and calculated by Equation (3.9), where  $B_i$  refers to the channel bandwidth of link  $i$  and  $ETX_i$  is the expected number of transmission attempts to achieve successful transmission over link  $i$ . The notation  $R_i$  is the interference degree ratio for link  $i$  between the sender  $u$  and receiver  $v$ . Equation (3.10) describes how to calculate  $R_i$ , where  $P_v^I(u)$  is the maximum tolerable interference power at node  $v$  to receive the signal from node  $u$ , as shown in Equation (3.11) [29] and the  $P_v(k)$  is the interference power from different transmission nodes  $k \in v'$  where  $v'$  is the set of nodes located in the interference range of node  $v$  [35].

$$B_{ITi} = \frac{(1 - R_i)B_i}{ETX_i} \quad (3.9)$$

$$R_i = \frac{\sum_{k \in v': k \neq v} P_v(k)}{P_v^I(u)} \quad (3.10)$$

$$P_v^I(u) = \frac{P_v(u)}{\gamma} - N \quad (3.11)$$

In relation to calculating the bandwidth achievable under the impact of intra-flow interference over link  $i$ , for a successful transmission the sender and receiver should be outside the interference range of other active transmitters and receivers, assuming that the transmission range is one hop and the interference range is  $r$  ( $\geq 1$ ) hops. Li *et al* [35] define a subpath concept. The subpath contains all consecutive links that will interfere with each other if they operate on the same channel. The subpath length is  $r + 2$  hops. Then, the achievable bandwidth is iteratively computed over two interfering links in order to compute the bandwidth achievable over the subpath. For example, if there are two consecutive links  $i$  and  $j$  within a subpath and which operate on the same channel so the two links can not be active simultaneously, the achievable bandwidth under the impact of intra-flow interference is as follows :

$$B_{IR}(ij) = \frac{B_i B_j}{B_i + B_j} \quad (3.12)$$

There are two types of links in a subpath: co-channel links and multi-channel links. In the co-channel links in a subpath, the bandwidth achievable over the subpath under the impact of intra-flow interference ( $B_{IR}(ij)$ ) is calculated by equation (3.12). However, in the multi-channel links in a subpath, the achievable bandwidth under the impact of intra-flow interference ( $B_{IR}(ij)$ ) is computed by equation (3.13) over two links,  $i$  and  $j$ , operating in different channels [35].

$$B_{IR}(ij) = \min(B_i, B_j) \quad (3.13)$$

The available bandwidth for a subpath ( $B_{sub}$ ) is computed by following the iterative steps below, and Figure 3.1 illustrates the algorithm for the MRAB.

- Step 1: The first link in the subpath sets

$$B_{sub} = B_{IT,i} \quad (3.14)$$

- Step 2: In order to calculate achievable bandwidth of link  $i$  in this subpath, first the channel of the link  $i$  has to be checked if it is used by any of the previous links in the subpath; if yes it goes to step 3, otherwise it goes to step 4.

- Step 3: set

$$B_{sub} = \frac{B_{sub}B_{IT,i}}{B_{sub} + B_{IT,i}} \quad (3.15)$$

then go to step 5.

- Step 4: set

$$B_{sub} = \min(B_{sub}, B_{IT,i}) \quad (3.16)$$

- Step 5: check the link of the subpath; if it is the last link terminate the iteration, otherwise go to step 2.

The multi-radio achievable bandwidth (MRAB) for a H-hop path consisting of several subpaths is calculated by equation (3.17) [35], where  $B_{(sub,j)}$  refers to the  $j^{th}$  subpath of the path.

$$MRAB = \min_j(B_{sub,j}) \quad (3.17)$$

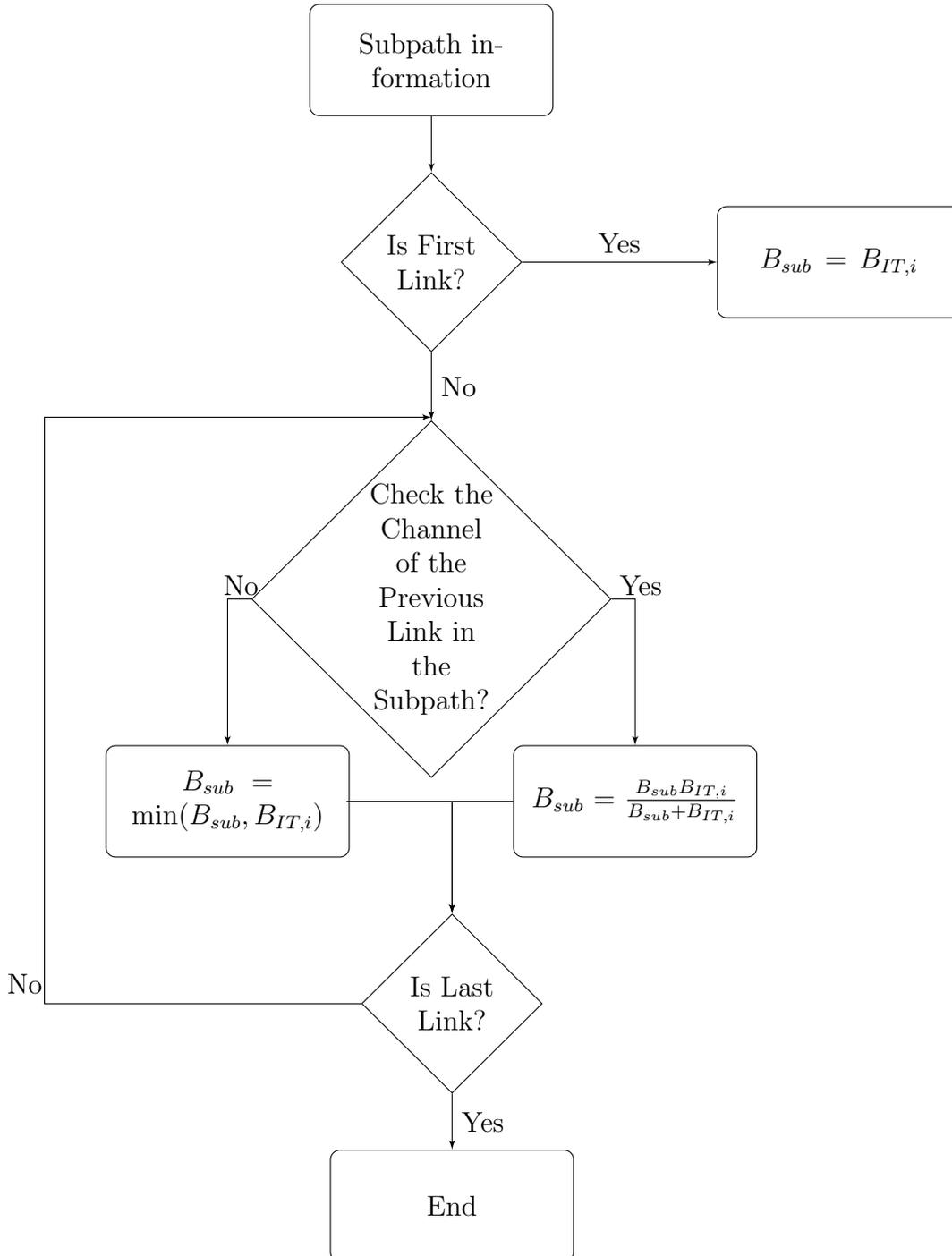


FIGURE 3.1: MRAB flow chart.

### 3.2.2.3 Weighted End-to-End Delay

Li *et al* [35] proposed the WEED (weighted end-to-end delay) metric for minimising the path delay, which is a combination of the MRAB metric in Section 3.2.2.2 and the EED metric in Section 3.2.1.3. The total number of packets queued in the buffer along a path is indicated by  $N_p$  and  $L$  refers to packet size [35]. The WEED was evaluated on NS2 simulation.

$$WEED = \alpha * \sum_{i=1}^H EED_i + (1 - \alpha) * \frac{N_p * L}{MRAB} \quad (3.18)$$

## 3.3 Proposed Metrics

When using a radio connection in the wireless network, certain factors affect the link quality, such as delay, interference and buffering. Therefore, because of intra-flow interference and inter-flow interference, it is crucial to look for a path with the maximum available bandwidth to transmit data from the source to the destination. In order to achieve high performance, it is vital to select a path with high data rate and low signal interference especially in a multi-channel network. Therefore, this section presents the two routing metrics Expected Transmission Time with Queuing delay (ETTQ) for single-channel and Delay and Interference Aware Metric (DIAM) for a multi-channel wireless mesh network.

### 3.3.1 Expected Transmission Time with Queuing Delay

As explained earlier, the ETT metric is a link metric capturing the expected time to successfully transmit a packet over a link. First, we have improved the expected transmission time (ETT) by considering queuing delay to select a lightly loaded

path. The calculation of queuing delay is straightforward: by counting the number of packets in the buffer. Therefore, ETTQ is the expected time with queuing delay to successfully transmit a packet over a link. Equation (3.19) shows the calculation of ETTQ, where  $P_i$  indicates the number of packets in the buffer of a link  $i$  and  $P_i + 1$  is the number of buffering packets plus the newly arriving packet.

$$ETTQ_i = (P + 1)ETT_i \quad (3.19)$$

The following section will explain how to extend the ETTQ by considering the channel interference.

### 3.3.2 Delay and Interference Aware Metric

In order to improve ETTQ to take the interference into account, we propose a routing metric, Delay and Interference Aware Metric (DIAM), which selects a path with high data rate and low signal interference to achieve high performance. The DIAM metric estimates the intra-flow interference, inter-flow interference and delay of path links for multi-channel WMNs. The DIAM is the quotient of the ETTQ of a path and the MRAB as shown in Equation (3.20). The ETTQ represents expected transmission time with delay and the MRAB calculates the impact of inter-flow and intra-flow interference along a path. The DIAM looks for a path with low loss ratio, high data rate and low level of interference.

$$DIAM = \frac{\sum_{i=1}^H ETTQ_i}{MRAB} \quad (3.20)$$

Consider the network in Figure 3.2 as an example to illustrate the impact of queuing delay and interference on routing. The dashed circle drawn around the link indicates that the link is transmitting data (active) by using a specific channel. Suppose that the link from node 2 to node 3, the link from node 8 to node 10 and the link from node 1 to node 6 operate in channel 1, while the link from node 3 to node 8 operates in channel 2. Figure 3.2 shows that the link from node 2 to node 3, the link from node 8 to node 10 and the link from node 1 to node 6 are active (transmitting data) and they are operating on the same channel. As a result, the link from node 1 to node 6 will interfere with the links from node 2 to node 3 and from node 8 to node 10 because these links operate on the same channel. The dashed lines represent link queuing packets which means the link is heavy loaded.

Selecting a path to transmit the data from the source node ( $S$ ) to the destination node ( $D$ ) is critical, especially with a multi-channel network. Consider the network in Figure 3.2, the basic hop routing metric would prefer the path ( $S$ -1-6- $D$ ) without taking the link quality into account and then the shortest path will affect the network performance because the link from node 1 to node 6 has heavy load, as shown in Figure 3.2. On the other hand, the DIAM routing metric will prefer the path ( $S$ -5-7-9-4- $D$ ) over other paths due to the fact that the DIAM takes the signal interference and queuing delay into account during selecting path from the source  $S$  to the destination  $D$ . Therefore, the path ( $S$ -5-7-9-4- $D$ ) has less interference and lightly loaded links. Consequently, the network performance will be improved.

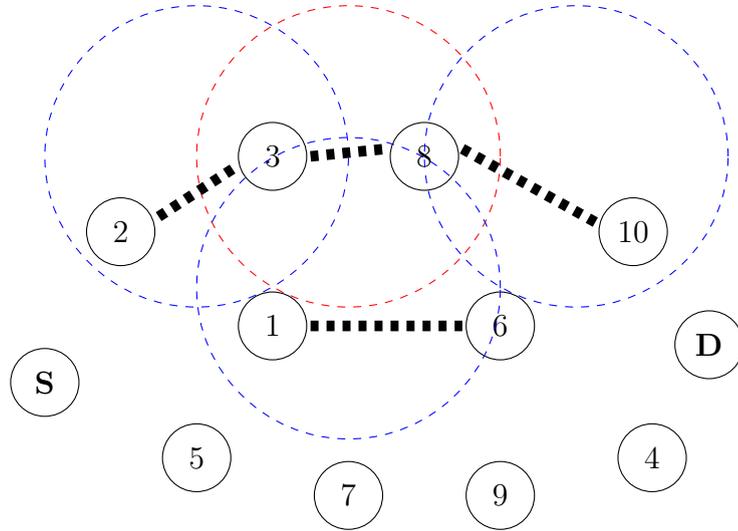


FIGURE 3.2: Example of DIAM explanation.

### 3.4 Routing Protocol Design

We also have extended the basic AODV routing protocol for implementing the DIAM routing metric in order to select a high quality path.

Each node needs to add an additional entry named DIAM in its routing table for every destination named  $rt - DIAM$ . The  $rt - DIAM$  records the quality of the path to the destination. In addition, when a node receives an RREQ or RREP message, it needs to recalculate the DIAM and update the routing table  $rt - DIAM$  if the new  $DIAM \leq rt - DIAM$ . The HELLO message is used to estimate the Expected Transmission Count (ETX) and interference degree ratio (R) of each link. In relation to designing the multi-channel model, each interface of a node is assigned as value in order to identify a node when it is working on a specific channel.

The source node determines the destination node and broadcasts the RREQ message. Each forwarding node inserts the information about the ETX, ETTQ, interference degree ratio (R) and the operating channel into the RREQ message in order to compute the path metric. The interference degree ratio (R) is the sum of all received

power from all interference nodes and the calculation of received power is the quotient of transmitting power and the distance between the receiver and the interfering node. When the intermediate node receives a RREQ, the node will compute the DIAM metric based on the information in RREQ. If the new path is better, it will update the reverse route, attach the related information in RREQ, and forward it on each of its interfaces. When the destination node receives the RREQ message, it will generate an RREP message.

The RREP message is unicast to reach through the reverse route recorded during transmission of the RREQ message. Through transmission of the RREP message, the intermediate nodes record the forwarding route to the destination node. The source node receives the RREP message and then will start sending the data packets via the route. Figure 3.3 demonstrates the flow chart for the route discovery process.

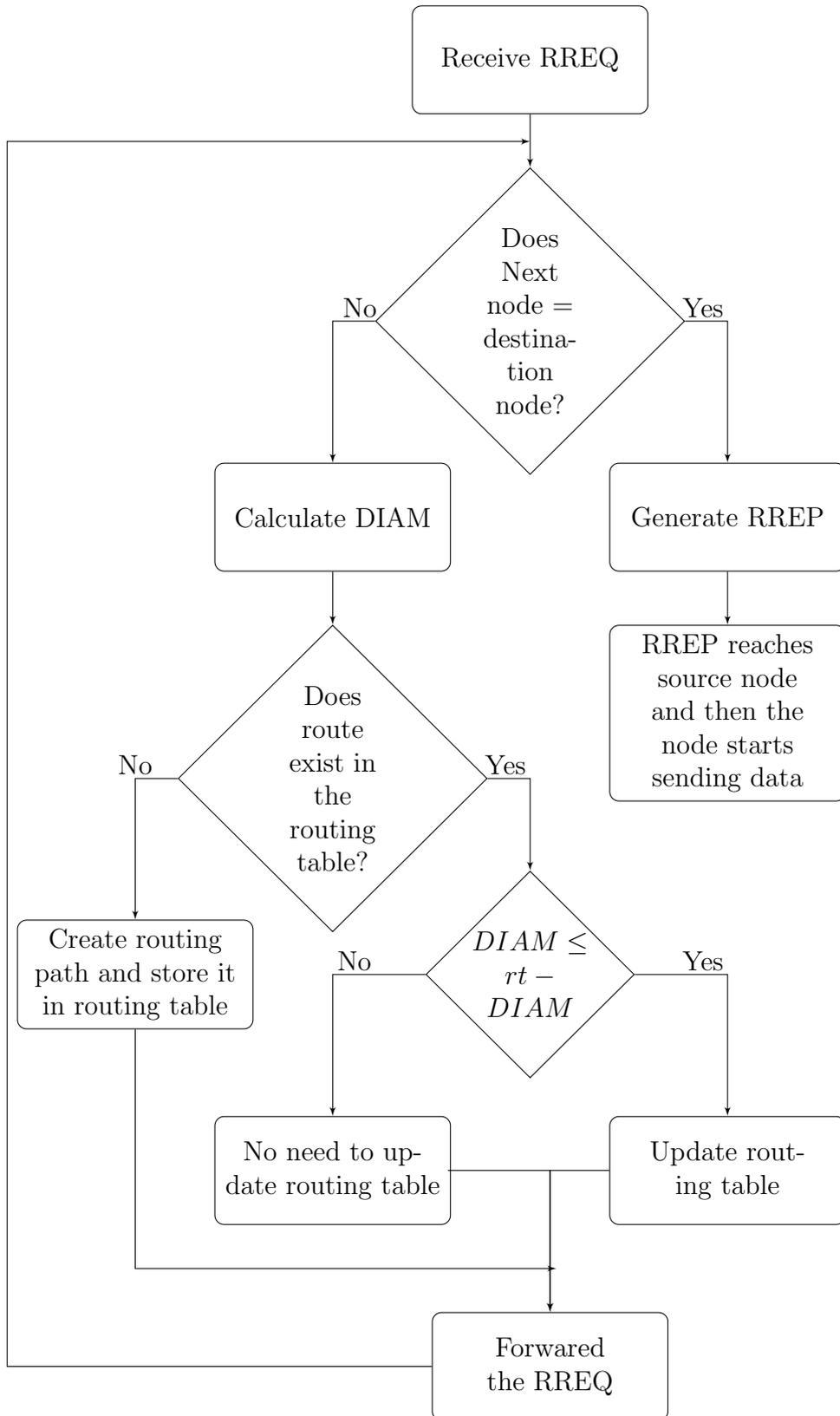


FIGURE 3.3: Flow chart of route discovery process.

## 3.5 Performance Evaluation

In this section, we evaluate the performance of the ETTQ and DIAM routing metric in both the single-channel and multi-channel environments. We have applied the routing metrics in the AODV protocol. To obtain more accurate results, the simulations have been repeated 15 times and then the average was taken, as shown in the figures. In addition, the error bars in Figures indicate the minimum and maximum throughput and the packet delivery ratio.

### 3.5.1 Simulation Model

The popular tool NS2 [27] has been used to conduct our simulations. Wireless mesh networks are static and the IEEE 802.11 radios have been used for simulation; every node has been equipped with one radio interface with one channel in the single-channel scenario and two radio interfaces with two channels in the multi-channel scenario. The transmission power is set to give a transmission range of 250m and an interference range of 550m. Each channel has 11 Mbps and the packet size is 1000 bytes. To collect network information such as the neighbours, interference nodes and the packet loss ratio, a HELLO message is broadcast every five seconds. Table 5.2 displays the simulation parameters. After trying a range of different simulation times, the 150s simulation time is selected because the results are consistent in this simulation time. The evaluation of the proposed metric ETTQ is examined in a single-channel grid network. In addition, the performance of the DIAM metric is examined in multi-channel static wireless mesh networks. The performance measurement metrics are the throughput and packet delivery ratio.

- Throughput: data successfully transmitted from source to destination per second.

- Packet delivery ratio: the ratio of received packets to total packets sent.

TABLE 3.2: Simulation parameters for static networks.

Simulation Parameters	Value
Mac type	IEEE 802.11b
Routing protocol	AODV
Transmission range	250m
Interference range	550m
Traffic type	CBR(UDP)
Packet size	1000 byte
Channel bandwidth	11 Mbps
Simulation time	150s

### 3.5.2 ETTQ Performance Evaluation in a Single-Channel Network

The performance of ETTQ has been compared with hop count metric, the ETX [13] (see page 33), ETT [16] (see page 34) and EED [34] (see page 34) in the single-channel scenario. The performance of the ETTQ was evaluated in a grid network in Section 3.5.2.1 and random network in Section 3.5.2.2 and Section 3.5.2.3 and each node has been equipped with one radio interface and one channel.

#### 3.5.2.1 Impact of Traffic Load

In this section, we study the performance of the ETTQ metric under the impact of increasing the traffic load. Figure 3.4 shows the simulation network  $5 \times 5$  grid topology and the distance between two nodes is 250m. The selection of  $5 \times 5$  is to increase the number of available paths and help routing metric to select the best path. We run two flows over the network, the first flow (F1) from node 10 to node 14 with varying flow rate, and the second flow (F2) from node 12 to node 13 with

fixed data rate 2 Mbps. In this scenario, flow F2 has a higher rate to demonstrate the impact of queuing delay on the network performance.

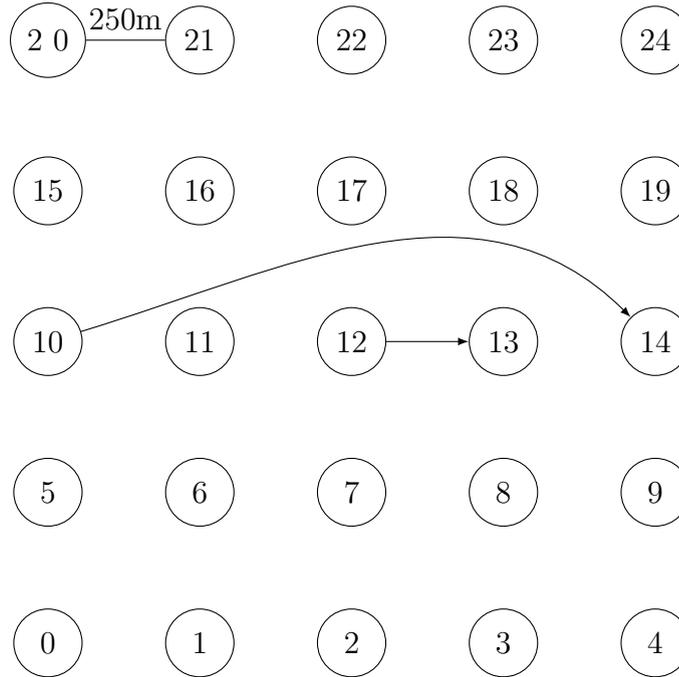


FIGURE 3.4: Grid network  $5 \times 5$ .

The total throughput of all metrics has increased with an increase in the data flow rate, as shown in Figure 3.5: also, with the small flow rate most of the routing metrics perform in a similar manner. In addition, Figure 3.5 shows that the total throughput of the ETTQ has a better performance compared to that of ETT, ETX and EED. It can be observed that from 1.6 Mbps to 2.2 Mbps the ETTQ metric outperforms the others, and this is because it selects the path efficiently by considering the queuing delay. Additionally, we observe that the hop count metric gives the lowest throughput when compared to others, as shown in Figure 3.5. In fact, the hop count metric is designed to find the shortest path from the source node to the destination node, regardless of the link quality. Moreover, it can be observed that at 0.9 Mbps the hop count has low throughput because it selects the path with minimum hops without considering the path quality. Thus, if the data is transmitted through a good quality path, the network throughput will be improved.

Figure 3.6 illustrates the comparison of packet delivery ratios with respect to flow data rate. Generally, we observed that when increasing the flow rate the packet delivery ratio decreased, due to the fact that the data packets will be dropped. This is because the link becomes congested with a high input rate. The ETTQ has better performance than the others in terms of packet delivery ratio with a flow rate 1.6 Mbps and 2Mbps. This is because the ETTQ selects a lightly loaded path from the source to the destination, then fewer packets will be lost. In addition, the paths selected by hop count metric reduces the packet delivery ratio, as shown in Figure 3.6 and this because the hop count selects bad quality path. Therefore, transmitting data through a good quality path will improve the network performance.

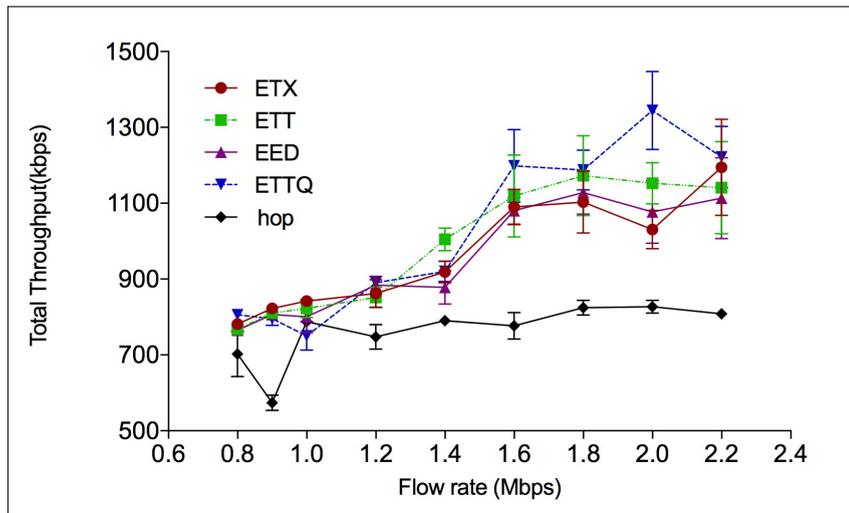


FIGURE 3.5: Total throughput in single-channel under the impact of traffic load.

### 3.5.2.2 Impact of Network Density

The aim of this scenario is to evaluate the performance of the ETTQ metric under the impact of different network sizes. In this scenario, the performance of the ETTQ is compared only with the ETT and EED metrics due to the bad performance of ETX and hop count discussed in Section 3.5.2.1. The network nodes are generated

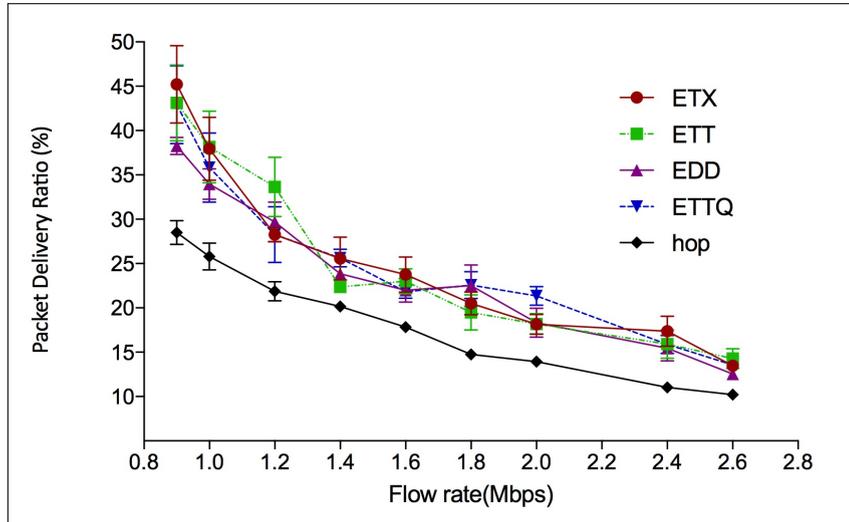


FIGURE 3.6: Packet delivery ratio in single-channel under the impact of traffic load.

randomly in an area of  $1000\text{ m} \times 1000\text{ m}$  considering that the network is also connected. We have run two flows with a fixed flow rate of 3.25 Mbps and the flows are generated between random sources and destinations.

Figure 3.7 shows that the total throughput of all metrics has decreased gradually, especially from 20 nodes until 40 nodes. The ETTQ shows a better performance from 40 nodes to 60 nodes in comparison with the ETT and EED, as shown in Figure 3.7. In fact, the ETTQ metric selects the path efficiently, which leads to improving the network performance. In addition, the Figure 3.7 illustrates that a network with 40 nodes has lower throughput in comparison to the network with 30 nodes. This perhaps is because of the growth in the control message due to the increase of the network size. As a result, the interference will grow and then more packets will be dropped, as shown in Figure 3.8. On the other hand, the growth in the network size increases the number of available paths between the source and destination that led to routing metric to select the best path, and hence, improve the network performance. In conclusion, selecting a good quality path develops the network performance.

Figure 3.8 illustrates the comparison of packet delivery ratio with respect to network size. Generally, the performance of all metrics decreases when increasing the network size and this is probably because the growing of network size results in the increase of control message which can lead to interference. In addition, Figure 3.8 shows that the ETTQ has a better performance compared to ETT and EED due to that the ETTQ metric selects the lightly loaded path. Moreover, Figure 3.8 shows slight increase of the packet delivery ratio of networks with 50 and 60 nodes. This is because of the increase in the network size, which results in the growth of the number of available paths and hence, the routing metrics will select the best quality path. It can be concluded that such a path will develop the network performance.

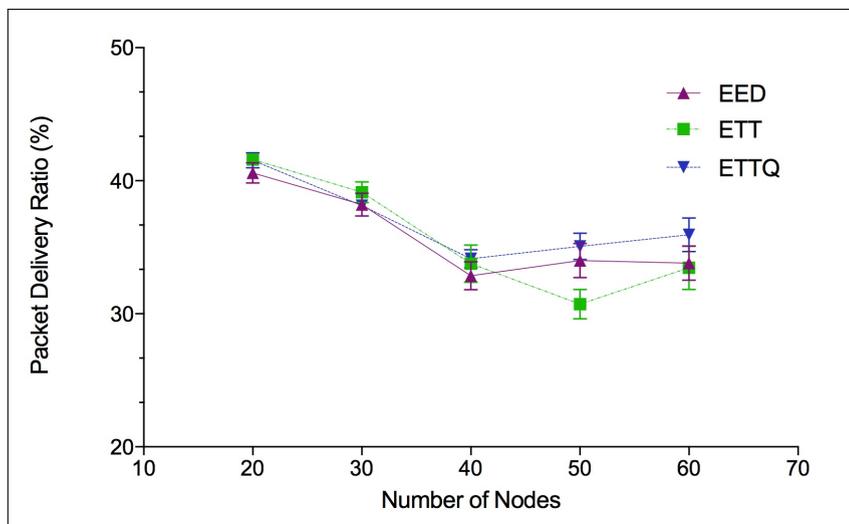


FIGURE 3.7: Total throughput in single-channel under the impact of network size.

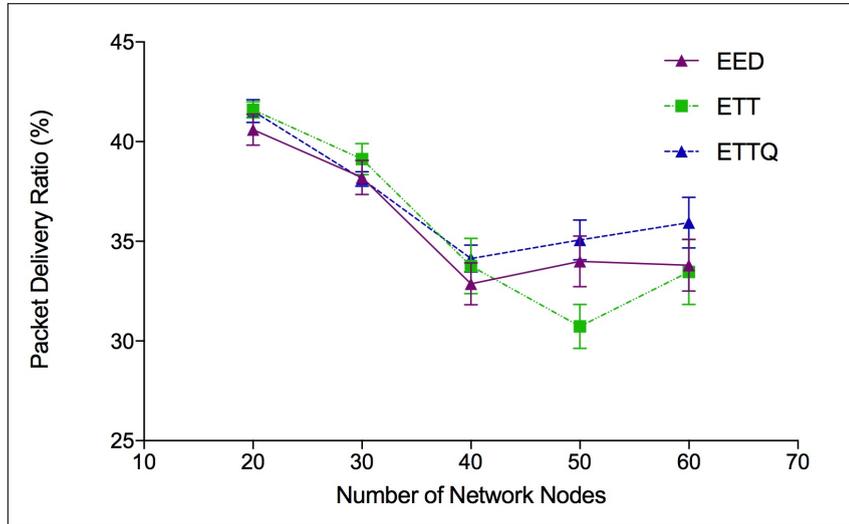


FIGURE 3.8: Packet delivery ratio in single-channel under the impact of network size.

### 3.5.2.3 Impact of Number of Flows

In this scenario, we study the effect of the number of flows on the performance of routing metrics. In addition, again the performance of ETTQ has been compared only with the ETT and EED metrics due to the bad performance of ETX and hop count described in Section 3.5.2.1. The connected network has 50 nodes generated randomly in  $1000\ m \times 1000\ m$ . We have run different numbers of flows generated randomly between sources and destinations with a fixed flow rate of 1.2 Mbps.

The total throughput of all metrics has increased gradually due to the fact that the number of sent packets increased which led to an increase in the total network throughput. The ETTQ shows a better performance compared to ETT and EED, as shown in Figure 3.9. In addition, Figure 3.9 illustrates that the ETTQ metric, with 8 flows, outperform others and this because the ETTQ selects the lightly loaded paths. In fact, the ETTQ metric selects the path efficiently, which leads to an improvement in the network performance. Therefore, selecting a good quality path improves the network performance.

In relation to the packet delivery ratio, Figure 3.10 illustrates the comparison of packet delivery ratios with respect to an increase in the number of flows. We observed that, when increasing the number of flows, the packet delivery ratio decreased, due to the fact that data packets were dropped. This is because of an increase in the number of flows, which results in an increase in the interference. The ETTQ selects lightly loaded path, and therefore, it has a better performance than the others. Figure 3.10 shows a high packet delivery ratio with two and four flows due to less interference and the network congestion.

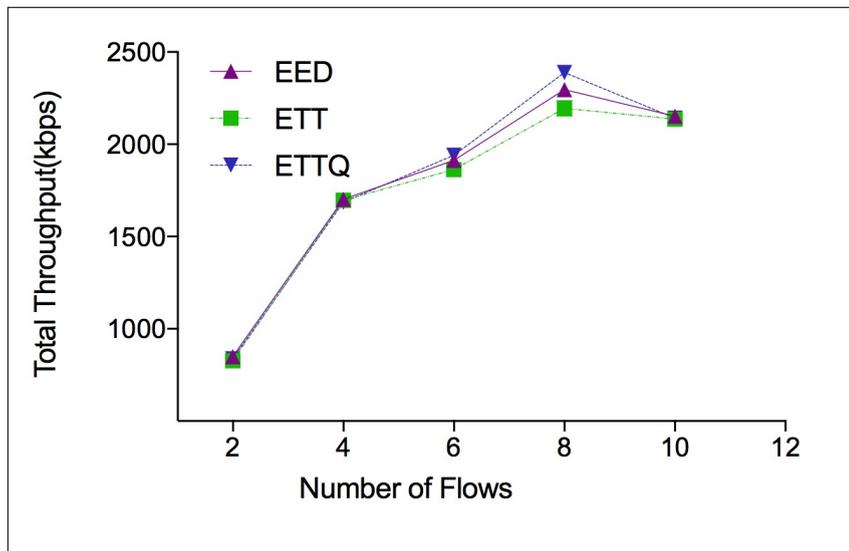


FIGURE 3.9: Total throughput in single-channel under the impact of number of flows.

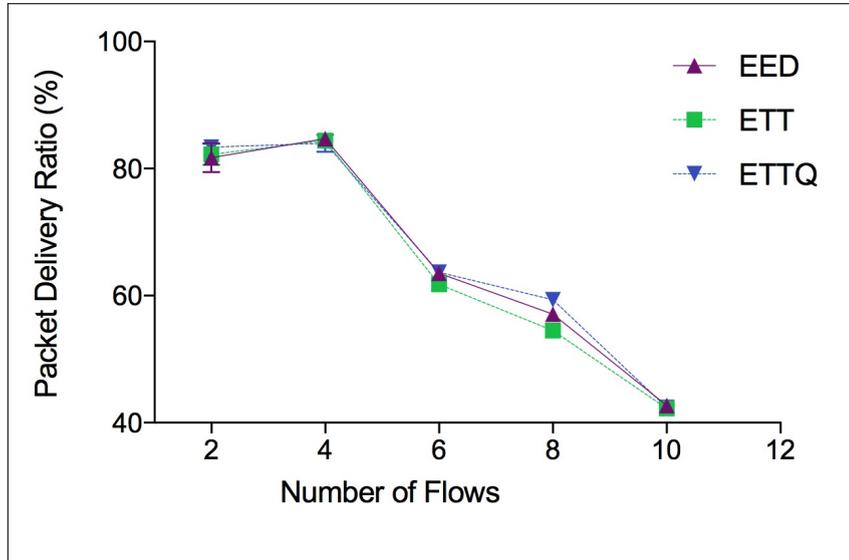


FIGURE 3.10: Packet delivery ratio in single-channel under the impact of number of flows.

### 3.5.3 DIAM Performance Evaluation in a Multi-Channel Network

The performance of the DIAM has been compared with the WCETT [16], MRAB [35] and WEED [35] in a multi-channel wireless mesh network. The network area is  $1000\text{ m} \times 1000\text{ m}$  and each node has been equipped with two radio interfaces and two channels.

#### 3.5.3.1 Impact of Traffic Load

The aim of this study is to measure the performance of DIAM under the impact of network congestion. The simulation network has 40 connected nodes and placed randomly. We run four flows over the network that generated randomly between sources and destinations. We have varied the flow data rate to study the performance of the routing metric over a congested network.

The total throughput of all metrics has increased with an increase in the data flow rate, as shown in Figure 3.11. Figure 3.11 shows that the DIAM has better throughput on most of data flow rates than the WCETT, MRAB and WEED. The DIAM metric selects the path efficiently by considering the queuing delay and inter-flow and intra-flow interference. Therefore, it sends the data packets through a lightly loaded path with less interference. In conclusion, the results show that estimating the link quality by taking into account the impact of queuing delay and signal interference will improve the network throughput.

Figure 3.12 shows the comparison of packet delivery ratio with respect to flow data rate. Figure 3.12 illustrates that with low flow rate such as 0.8Mbps and 0.9Mbps, packet delivery ratio will be high. This is because of that there are a few number of sending packets so the network will be uncongested. Moreover, we observed that the packet delivery ratio decreased when increasing the flow rate. One reason for this is that, with high input rate, links become congested; as a result, a lot of packets will be dropped. The DIAM has a better performance than the others in terms of packet delivery ratio for most flow rates; this is due to the fact that the DIAM chooses the path efficiently by using the delay and interference parameters. However, the DIAM metric show a slightly reduction in the packet delivery ratio at 1.8 Mbps, as shown in Figure 3.12 and this is because there are some of simulation results that have low packet delivery ratio which affect the average.

### **3.5.3.2 Impact of Network Density**

In this section, we study the performance of the DIAM metric under the impact of network size. The network nodes are connected and generated randomly in  $1000\ m \times 1000\ m$ . We have run two flows that generated randomly between the sources and destinations with a fixed flow rate of 3.25 Mbps.

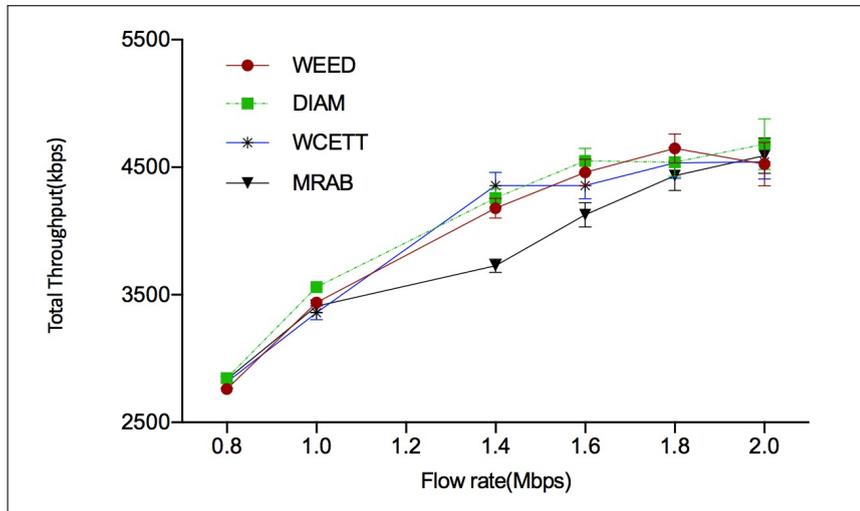


FIGURE 3.11: Total throughput in multi-channel under the impact of traffic load.

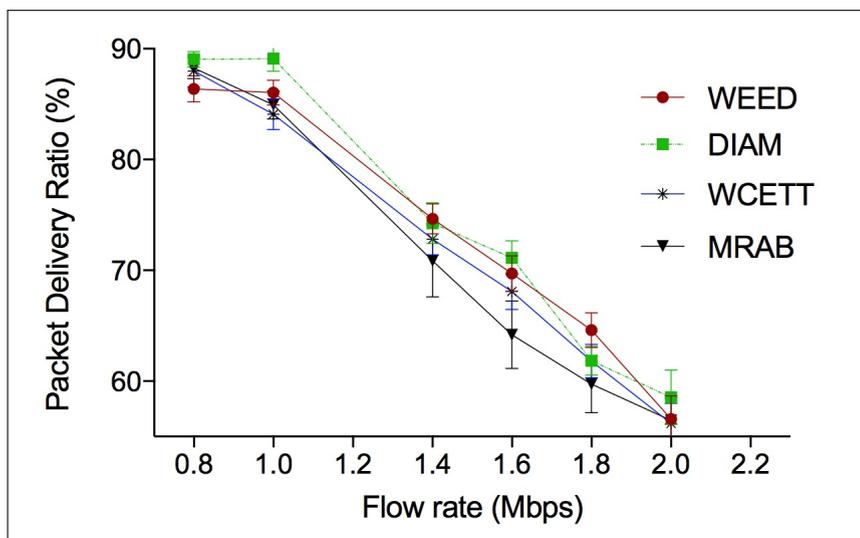


FIGURE 3.12: Packet delivery ratio in multi-channel under the impact of traffic load.

The total throughput of all metrics has decreased gradually with an increase in the network size, as shown in Figure 3.13. In addition, it can be seen that the DIAM has a better throughput than the others, and this is because the DIAM metric selects the path efficiently by considering the delay and interference. Thus, DIAM chooses the path with a high data rate and low signal interference. Moreover, Figure 3.13 illustrates that at 20 nodes network the DIAM and WEED have better performance

than WCETT and MRAB. This may be because the DIAM and WEED metrics select the path efficiently considering the queuing delay during selecting the routing path. Hence, selecting an efficient path will improve the network throughput.

Figure 3.14 illustrates the comparison of packet delivery ratio with respect to network size. Generally, the packet delivery ratio decreases with the increase in network size, as shown in Figure 3.14. The DIAM has a better performance compared to WCETT, MRAB and WEED. This is due to the fact that the DIAM chooses the path efficiently by taking the interference and delay into account. Interestingly, with 20 nodes network, the performance of DIAM and WEED have high packet delivery ratio than WCETT and MRAB, as shown in Figure 3.14. This is perhaps due to that the DIAM and WEED select lightly loaded path. Thus, an efficient path will improve the packet delivery ratio.

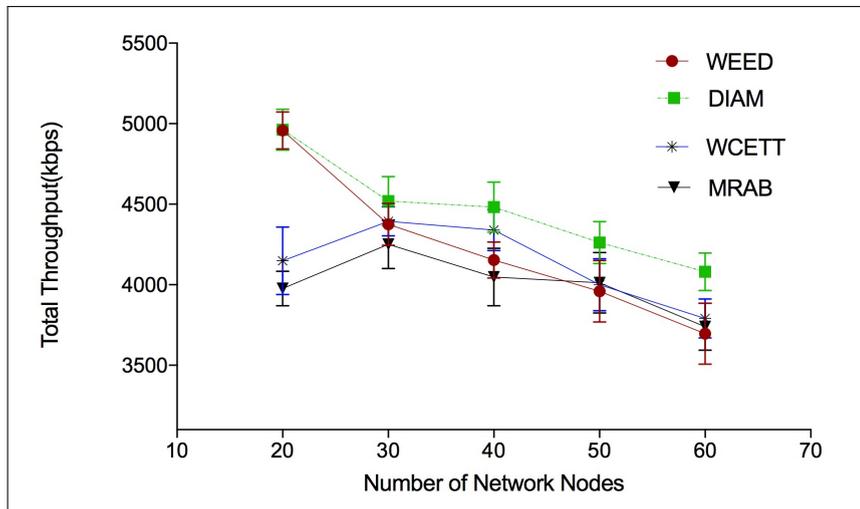


FIGURE 3.13: Total throughput in multi-channel under the impact of network size.

### 3.5.3.3 Impact of Number of Flows

In this scenario, we study the effect of number of flows in the performance of routing metrics. The network has 50 connected nodes generated randomly in  $1000 m \times$

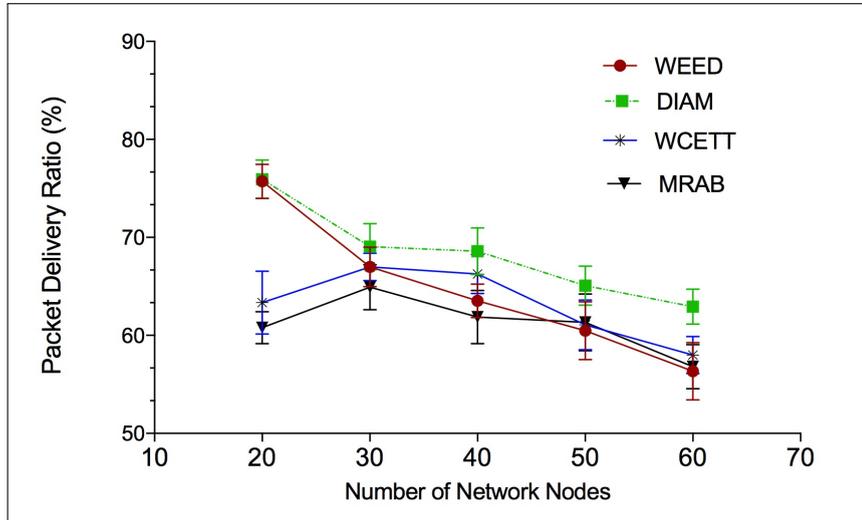


FIGURE 3.14: Packet delivery ratio in multi-channel under the impact of network size.

1000  $m$ . We have run different numbers of flows that generated randomly between the sources and destinations with a fixed flow rate of 1.5 Mbps.

The total throughput of all metrics has increased gradually due to the fact that the number of sent packets increased, which led to an increase in the total network throughput. The DIAM shows a better performance in comparison with others, as shown in Figure 3.15. In fact, the DIAM metric selects the path efficiently by considering the delay and interference; as a result, the network performance will be improved. Interestingly, the network with 4 flows has the highest throughput among the others, as shown in Figure 3.15. This may be because these metrics select a good quality path in terms of the interference and time needed to transmit data. In addition, Figure 3.15 illustrates that from 6 flows to 10 flows, the total throughput gradually reduces and this is perhaps due to the increase in the interference and congestion. Therefore, selecting a good quality path improves the network performance.

Figure 3.16 shows the comparison of packet delivery ratios with the number of flows. When increasing the number of flows the packet delivery ratio decreases, due to that

the interference increases and the network becomes congested. Consequently, a lot of packets will be dropped. The DIAM has a better performance than the others because it selects the path efficiently in terms of delay and interference. In addition, the packet delivery ratio with 4 flows has the highest value, as shown in Figure 3.16, and this is because the routing metrics select paths with low interference and high data rate. In conclusion, transmitting data through a good quality path will improve the network performance.

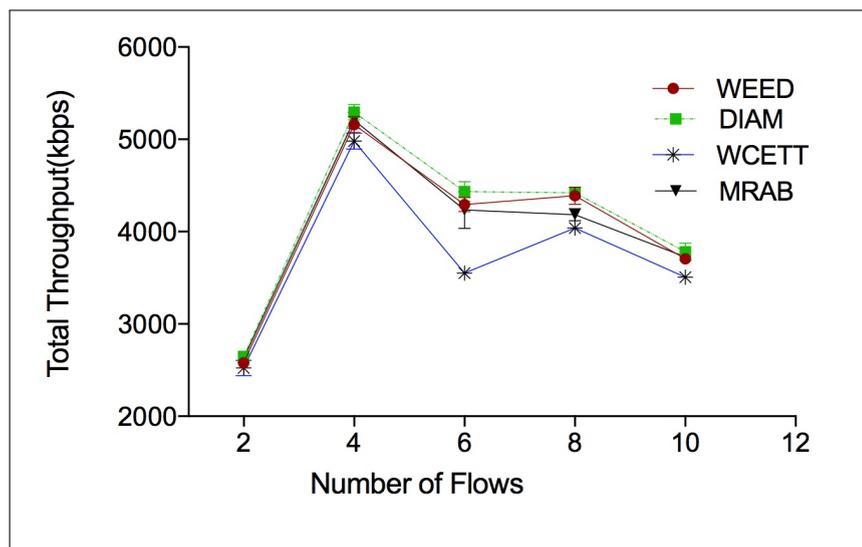


FIGURE 3.15: Total throughput in multi-channel under the impact of number of flows.

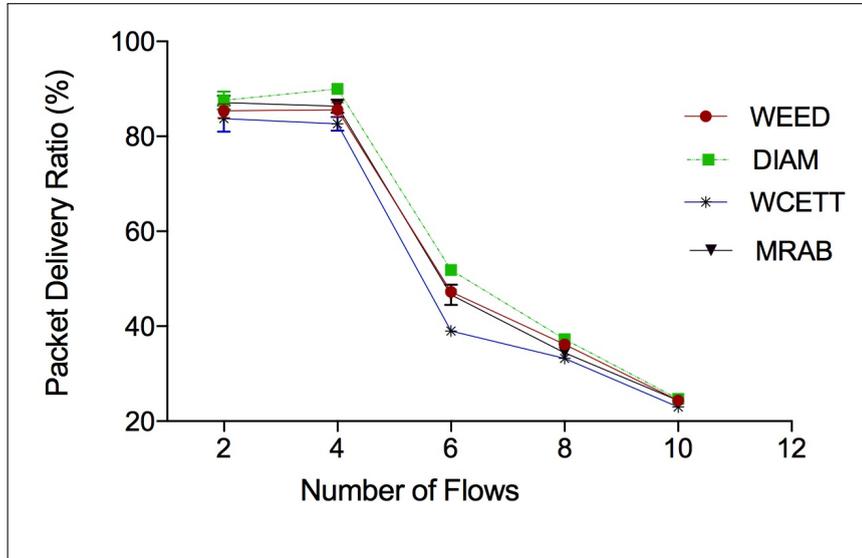


FIGURE 3.16: Packet delivery ratio in multi-channel under the impact of number of flows.

### 3.6 Summary

In this chapter we have designed a routing metric that aims to select a path with high data rate and low (inter and intra) flow interference. Moreover, we have made two contributions: firstly, we have proposed the ETTQ metric for single-channel networks by taking the queuing delay into account. Secondly, we have designed the DIAM by considering the multi-channel network and the interference with the ETTQ metric. We have implemented these metrics in the AODV routing protocol using the NS2 simulator. The performance was analysed in static wireless networks in different scenarios. The results point out that the ETTQ and DIAM routing metrics have shown a good performance in both single and multi-channel static wireless mesh networks.

The next chapter describes the evaluation of the DIAM in a mobile wireless network.

# Chapter 4

## Routing Metric in Mobile Wireless Networks

### 4.1 Introduction

A mobile network is one kind of multi-hop network in which the nodes can change their location at any time; thus, the network topology may change dynamically. This feature is why mobile networks are becoming very attractive. In addition, any node can act as a router that transmits data to other nodes. Figure 4.1 shows an example of a mobile network. Nowadays, many applications use mobile networks, such as the emergency services, military applications and home networks [54].

In relation to mobility, the network topology changes dynamically, which leads to frequent broken links; as a result, the route through the mobile node will not be valid. Therefore, the nodes need to collect the connectivity information periodically. Consequently, the mobility issue adds more complexity when designing the routing protocol. As a result, designing a routing metric for a mobile multi-channel network is more challenging than for static networks.

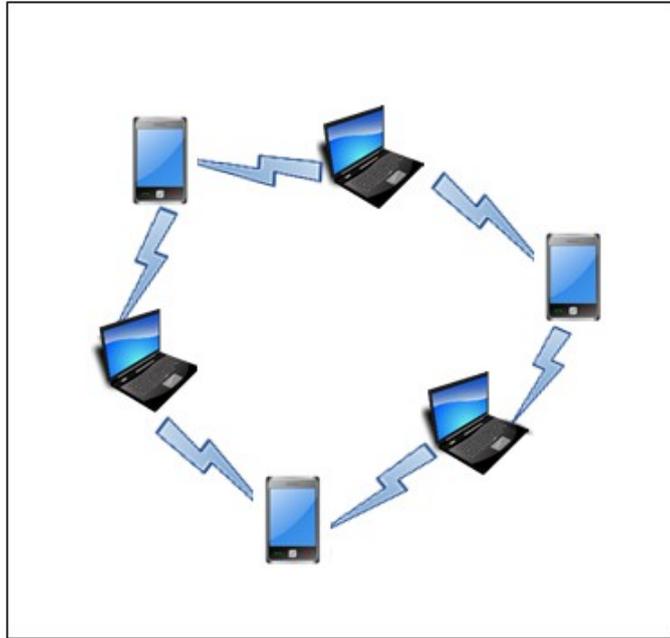


FIGURE 4.1: Mobile network example.

In the previous chapter, our simulation results showed that considering the link quality when selecting the path improves network performance. Therefore, in this chapter, we adapt the Delay and Interference Aware (DIAM) routing metric to mobile networks. The DIAM metric has been implemented in the basic Ad-hoc On-demand Distance Vector (AODV) routing protocol, which is a reactive routing protocol. The performance of the DIAM metric is measured by conducting simulation experiments in the mobile wireless network. Then, the results are compared with the Destination Sequenced Distance Vector (DSDV) protocol, which is a proactive protocol. The DSDV routing protocol has been selected because in the DSDV each node transmits an updated routing table periodically also due to mobility the node dynamically updated the routing table and advertised when the network topology changes.

The remainder of the chapter is structured as follows: Section 4.2 presents a brief description of the reactive and proactive routing protocols. Section 4.3 provides an explanation of the DSDV routing protocol mechanism. In Section 4.4, we present the adapted DIAM routing protocol with mobility. Section 4.5 presents the performance evaluation of the DIAM in mobile wireless networks. Finally, Section 4.6 concludes the chapter.

## 4.2 Reactive and Proactive Routing Protocols

There are different criteria for classifying routing protocols for wireless networks such as when and how to compute routes and how routes are maintained [70]. In this section, we will provide a brief description of reactive and proactive routing protocols based on how routes maintained.

Proactive routing protocols maintain routing information in a routing table at each node in the network. As a result, a route is available to every node in the network, whether it is needed or not. When the network topology changes, the updated routes will propagate throughout the entire network. On the other hand, the reactive routing is also known as (on-demand) routing protocols that create routes only when needed by the source node. The source node will initiate a route discovery process to establish a route when it needs to send data to a destination node.

## 4.3 Destination Sequenced Distance Vector (DSDV)

The Destination Sequenced Distance Vector (DSDV) [44] is a proactive routing protocol. In the DSDV routing protocol, each node in the network has to maintain a routing table for all destinations, the number of hops to reach the destination and

the next hop. In order to provide consistency in the mobile network, the routing table is periodically transmitted to all neighbour nodes.

Consider the network topology in Figure 4.2, which has 9 nodes. Initially, all the nodes advertise their routing information to all the nodes in the network; for example, Table 4.1 shows a possible routing table for node 3. Suppose that node 2 and node 8 are mobile nodes; if they move away from their location, the links between node 8 and 4 and node 2 and 0 are broken and the network topology will change, as shown in Figure 4.3. Consequently, when the broken links are detected at node 4 and 0, the nodes will update their routing tables and advertise the new routing tables. In addition, new links are detected between node 0 and 8 and also from node 2 to node 1, so the nodes will update their routing tables and then propagate the new routing tables. Table 4.2 shows the updated routing table for node 3.

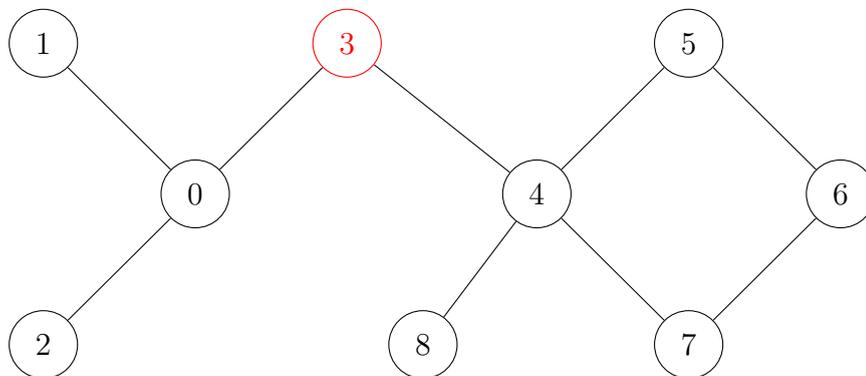


FIGURE 4.2: DSDV network example.

TABLE 4.1: Node 3 routing table.

Destination	Next hop	Hops
0	0	1
1	0	2
2	0	2
4	4	1
5	4	2
6	4	3
7	4	2
8	4	2

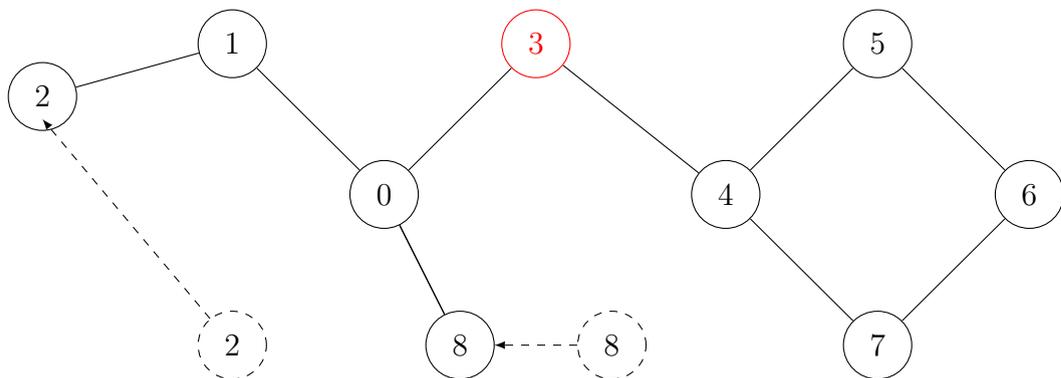


FIGURE 4.3: DSDV network example with mobile nodes.

TABLE 4.2: Node 3 updated routing table.

Destination	Next hop	Hops
0	0	1
1	0	2
2	0	3
4	4	1
5	4	2
6	4	3
7	4	2
8	0	2

## 4.4 Adapting the Delay and Interference Aware Metric (DIAM) to Mobility

In this section, we will explain how the DIAM routing metric was adapted to mobile networks. First of all, the limitation of the Hello message will be presented and then how the DIAM routing metric can tackle this issue. The Hello message can only detect the mobility of neighbour nodes and so does not detect the mobility of the interference nodes. Consequently, the estimation of link quality will be affected due to the fact that the mobile interference nodes might change the link interference degree ratio (R).

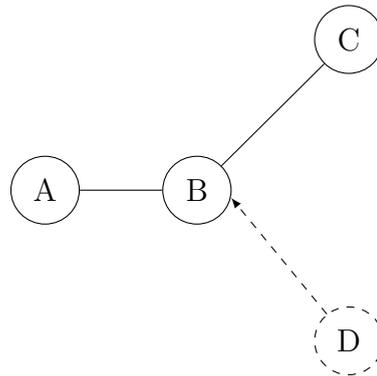


FIGURE 4.4: A simple network to illustrate the change in the interference nodes with a mobile node.

With regard to calculating the interference degree ratio in a mobile network, the DIAM routing metric has been adapted to mobility to efficiently select the routing path in order to achieve high performance throughput. For the estimation of the interference degree ratio in the mobile network, through broadcasting the Hello messages, every node has to update its interference nodes periodically via the collection of the two-hop neighbours. Consider the network in Figure 4.4, the node D is a mobile node and has just joined the network, so the node D is a new neighbour for the node B. In addition, the node D is two hops away from the node A (the interference

range of node A) and considered as an interference node with the node A. Consequently, the interference degree ratio of link from A to B will change. Therefore, the adapted DIAM metric addresses this issue by the updated information received from the node B. The benefit of this approach is that the adapted DIAM is more likely to estimate an accurate interference degree ratio due to the fact that the interference nodes are updated periodically. Consequently, the established routing path will be efficient and then the network performance will improve.

## 4.5 Performance Evaluation

In this section, we evaluate the performance of the DIAM routing metric, which is an extension of the AODV routing protocol for mobile multi-channel networks. To obtain more accurate results, the simulations have been repeated 15 times and then the average was taken, as shown in the figures. In addition, the error bars in Figures indicate the minimum and maximum throughput.

The performance measurement metrics are the throughput, packet delivery ratio and routing overhead.

- Throughput: Data successfully transmitted from source to destination per second.
- Packet delivery ratio: It is the ratio of received packets to total packets sent.
- Routing overhead: The total number of routing packets transmitted during the simulation. Every packet sent or received over one hop is counted as one transmission and this is because with the nature of the wireless networks the packet is sent but may be lost for different reasons.

### 4.5.1 Simulation Model

The popular tool NS2 [27] has been used to conduct our simulations. The wireless mesh networks are mobile and IEEE 802.11 radios have been used for simulation; every node has been equipped with two radio interfaces with two channels in the multi-channel scenario. The transmission power is set to give a transmission range of 250 m and the interference range is 550 m. To collect network information such as the neighbours, interference nodes and the packet loss ratio, the Hello message is broadcast every 5 seconds.

The node movement model is the random waypoint mobility model [8] and it is one of the most popular mobility models [10]. In this movement model, a mobile node moves towards a random destination. In addition, the random waypoint mobility model is flexible and the movement pattern is realistic as previously explain in Section 2.8 in Chapter 2. Table 5.2 displays the simulation parameters. The performance of the DIAM metric has been measured in a random multi-channel mobile wireless networks. We have studied the performance of the DIAM routing metric under the impact of flow congestion in Section 4.5.2 and increasing the number of mobile nodes in Section 4.5.3. In addition, the impact of network size has been studied in Section 4.5.4 and the impact of the number of flows in Section 4.5.5.

TABLE 4.3: Simulation parameters for mobile networks.

<b>Simulation Parameter</b>	<b>Value</b>
Mac type	IEEE 802.11b
Routing protocol	AODV
Transmission range	250m
Interference range	550m
Traffic type	CBR(UDP)
Mobility	random waypoint
Packet size	1000 byte
Channel bandwidth	11 Mbps
Simulation time	80s

### 4.5.2 Impact of Traffic Load

In this simulation scenario, the wireless network topology has 40 nodes set in a random position; 5 of them are mobile nodes with a maximum speed of 5 m/s and the rest are static and have 4 CBR traffic flows; the sources and destination nodes are static. Every node has been equipped with two radio interfaces and two channels. The performance of the DIAM protocol with DIAM metric is compared with the DSDV protocol. The goal of this section is to study the routing protocol efficiency in a congested network by varying the flow rate for all four flows.

One interesting finding is that the DSDV routing protocol has lower throughput in comparison with DIAM routing in the AODV routing protocol. Although, with low mobility, the expectation was that DSDV would have good throughput due to the fact that the proactive routing protocol has smaller control message overhead than a reactive routing protocol such as AODV, as shown in Figure 4.7. Therefore, the routing overhead will consume less link capacity and then the network might have good throughput. However, we observe that DIAM has better throughput compared to DSDV, and this is because the DIAM selects the path efficiently and detects the impact of mobility, as shown in Figure 4.5. In addition, it can be seen that the total

network throughput increases with the increase of the data flow rate in both routing protocols and this is because the increasing in the number of sending packets, the AODV with the DIAM metric and the DSDV protocol, as Figure 4.5 shows. Hence, consuming some of the link capacity with routing messages, rather than reducing the control messages, leads to a more reliable route. In addition, the most significant reason for the low throughput with the DSDV protocol might be that with mobile nodes, links may be broken and the routing table does not update and as a result many packets are dropped. Moreover, Figure 4.6 shows the measurement of the packet delivery ratio with a variety of data flow rates. It can be noticed that the performance of both protocols decreases, because with the increasing of flow rate, the links become more congested, and then a lot of packets will be dropped. Overall, selecting an efficient path considering the signal interference, detecting mobility and lightly loaded path will improve the network performance.

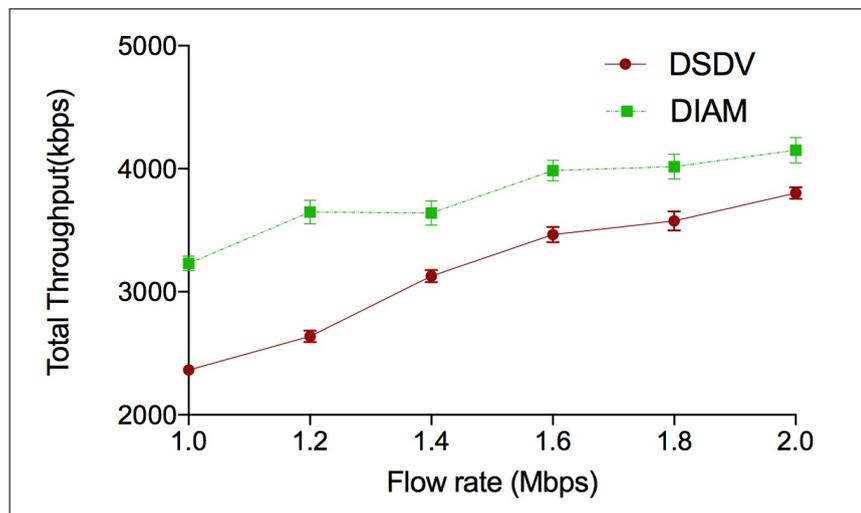


FIGURE 4.5: Total throughput in multi-channel mobile network under the impact of traffic load.

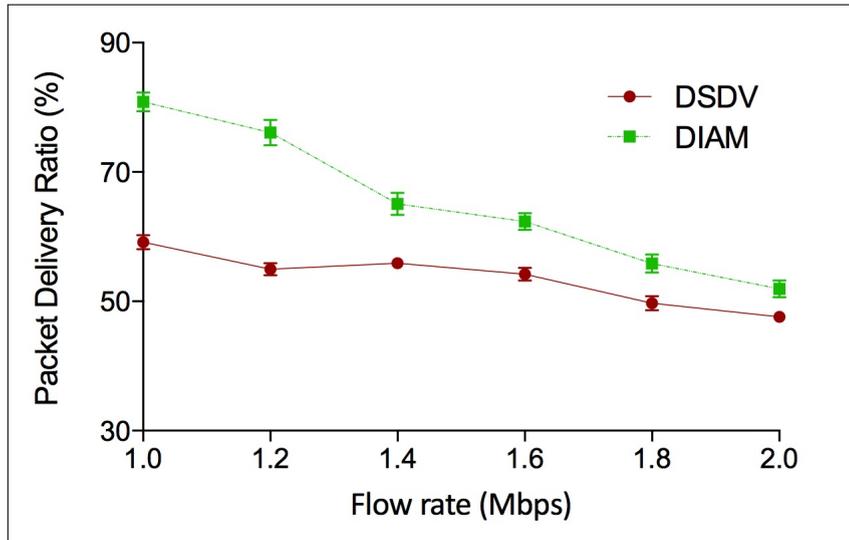


FIGURE 4.6: Packet delivery ratio in multi-channel mobile network under the impact of traffic load.

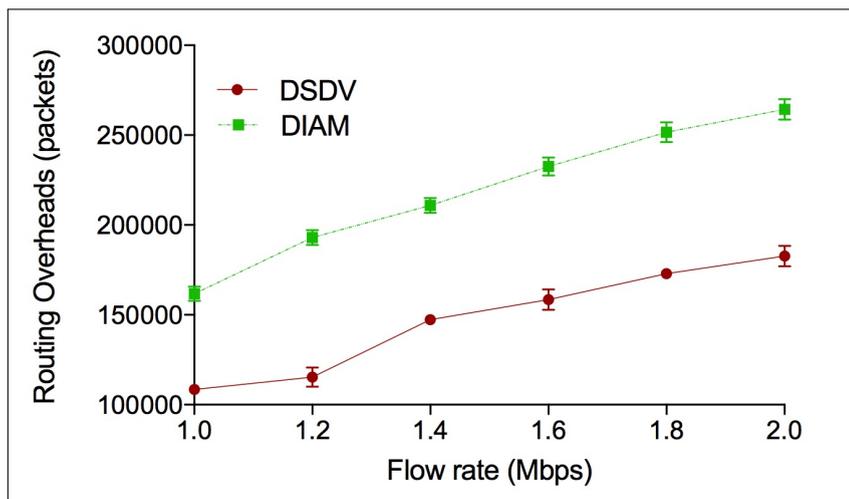


FIGURE 4.7: Routing overhead in multi-channel mobile network under the impact of traffic load.

### 4.5.3 Impact of Mobility

In this section, we study the effects of varying the number of mobile nodes in the wireless mesh network. The wireless network topology has 40 nodes set in a random position; the number of mobile nodes varies, and each mobile node has a maximum speed of 5 m/s while the rest of the nodes are static. We run 4 CBR traffic flows over the network with a fixed flow rate of 1.2 Mbps and the sources and destination nodes are static. Every node has been equipped with two radio interfaces and two channels. The performance of the AODV protocol with the DIAM metric is then compared with the DSDV protocol.

Regarding total network throughput, we find that DIAM has a better performance than DSDV. It can be seen that, with 5 mobile nodes, the throughput of the AODV protocol with the DIAM metric is significantly better than the DSDV protocol, as shown in Figure 4.8. Thus, in a low mobility scenario, both protocols have a good throughput in comparison with the high mobility network, as shown in Figure 4.8. In addition, after 10 mobile nodes, both protocols have shown a dramatic throughput reduction; this result may be explained by the fact that, with the increase in mobile nodes, there is an increase of broken links. Interestingly, Figure 4.8 illustrates that as the number of mobile nodes increases, the performance of the DSDV protocol continues to decrease while the DIAM is more likely to become steady. A possible explanation for these results may be that the adapted DIAM routing metric addressed the issue of detecting the mobility in the network especially with interference nodes, which results in the selection of an efficient routing path. In addition, detecting broken links and updating routing tables and then propagate the new routing table will consume a lot of time which can lead to increase in the number of dropped packets.

Figure 4.9 shows the packet delivery ratio with an increasing number of mobile nodes, leading to an increase in the broken links, which decreased the packet delivery ratio. However, the network routing overhead is not affected by increasing the number of mobile nodes, as shown in Figure 4.10. It can be concluded that the efficient selection of a routing path, taking the signal interference and mobility into account, improves the network performance.

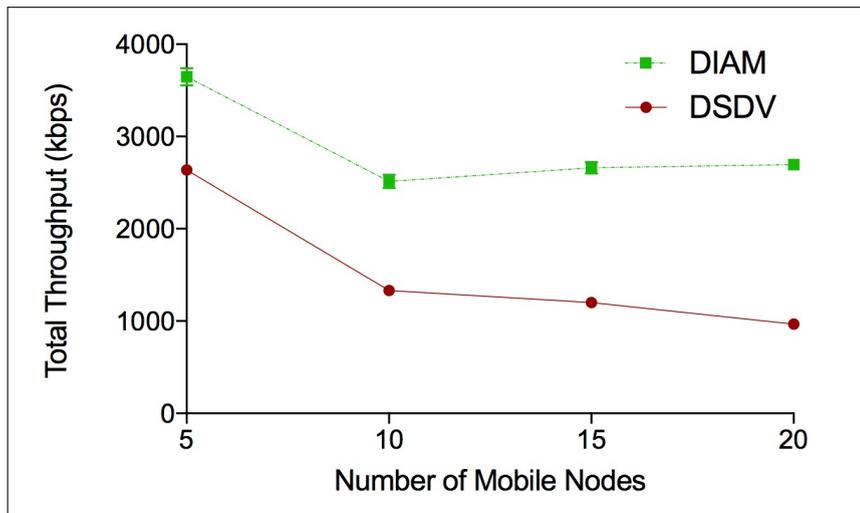


FIGURE 4.8: Total throughput in multi-channel mobile network under the impact of increasing the mobility.

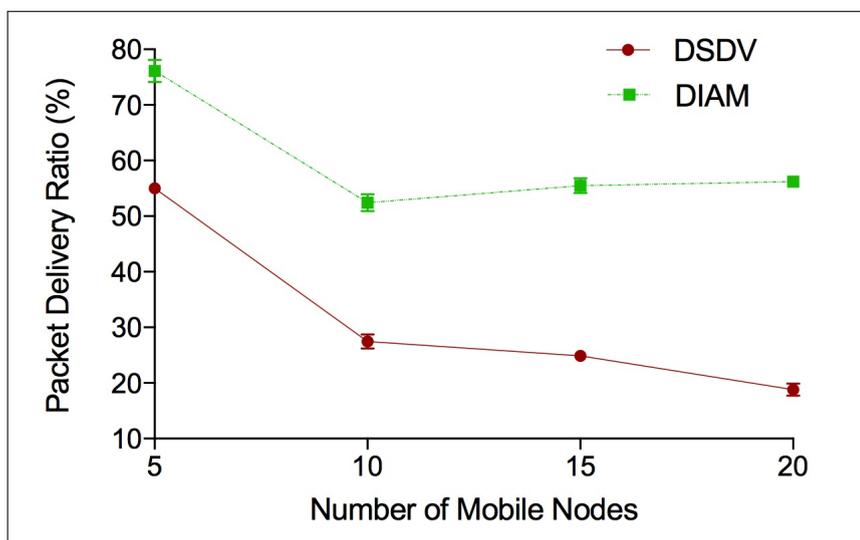


FIGURE 4.9: Packet delivery ratio in multi-channel mobile network under the impact of increasing the mobility.

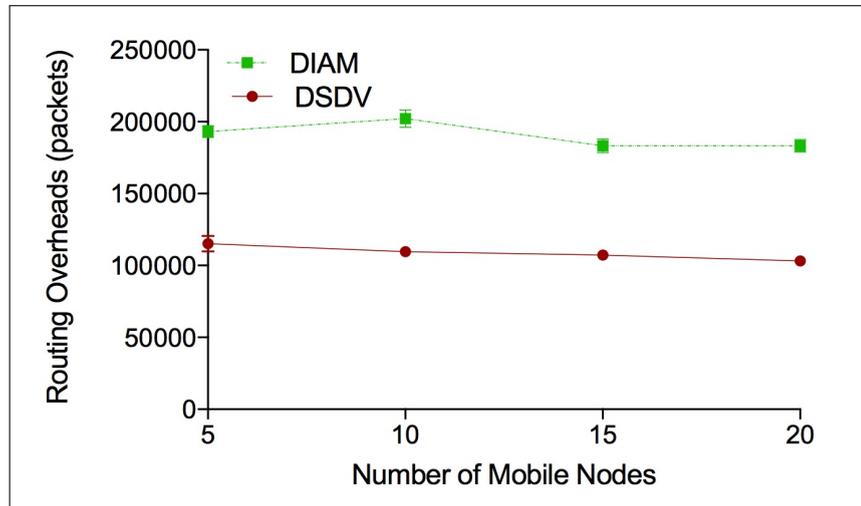


FIGURE 4.10: Routing overhead in multi-channel mobile network under the impact of increasing the mobility.

#### 4.5.4 Impact of Network Density

In this section, we study the performance of the DIAM metric under the impact of network size. The network nodes are generated randomly in  $1000\text{ m} \times 1000\text{ m}$ . We have run two flows with a fixed flow rate of 3.25 Mbps. In addition, the source and destination nodes are mobile with a maximum speed of 5 m/s, while the rest of the nodes are static. Every node has been equipped with two radio interfaces and two channels. The performance of the AODV protocol with the DIAM metric is then compared with the DSDV protocol.

In terms of total network throughput, generally, the performance of the AODV with the DIAM is better than the performance of DSDV. Figure 4.11 shows that, when the network size increases, the throughput of the DIAM decreases gradually. This is perhaps because the control messages overhead is more likely to be high when the number of network nodes increase, as shown in Figure 4.13. As a result, interference will occur and then more packets will be lost. Moreover, Figure 4.13 shows a decrease in the routing overhead with 60 nodes and this is perhaps because of

the increasing of the interference which lead to loss of more packets of controlling messages. In addition, the mobility of the source and destination nodes contributes to the throughput reduction; this result may be explained by the fact that, with mobile nodes, there is an increase in broken links. Interestingly, Figure 4.11 illustrates that the throughput of the DSDV protocol increases with networks with a size of 40 and 50 nodes; a possible explanation for these results may be that in this scenario the increase in network size might increase the number of routes. Consequently, the DSDV might select a good path with the 40 and 50 nodes. However, it can be seen that the DSDV shows a dramatic decrease with a network containing 60 nodes, and this is perhaps because, with a large scale network, updating the routing table and distributing the routes through the network consume a lot of time. Moreover, Figure 4.12 shows the measurement of the packet delivery ratio with an increase in network size. It can be noticed that the performance of DIAM is better than that of the DSDV. In addition, with the increase in network size, the interference becomes higher, and then a lot of packets will be dropped.

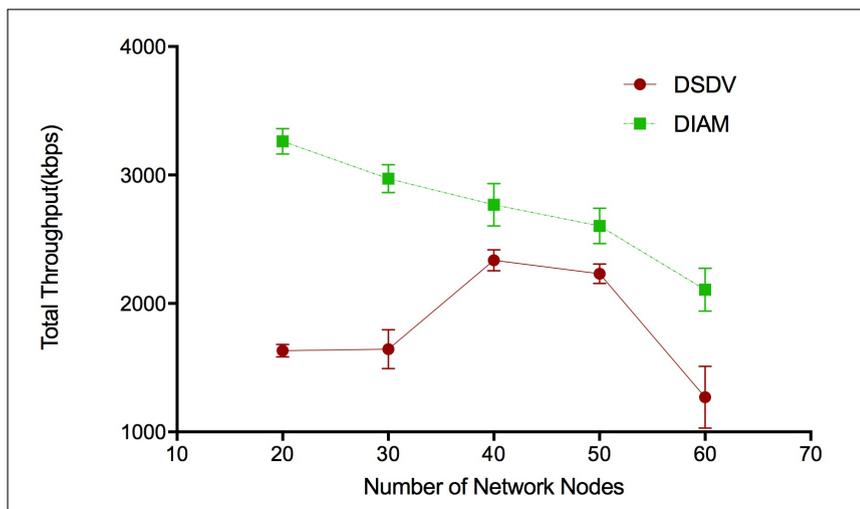


FIGURE 4.11: Total throughput in multi-channel mobile network under the impact of increasing number of network nodes.

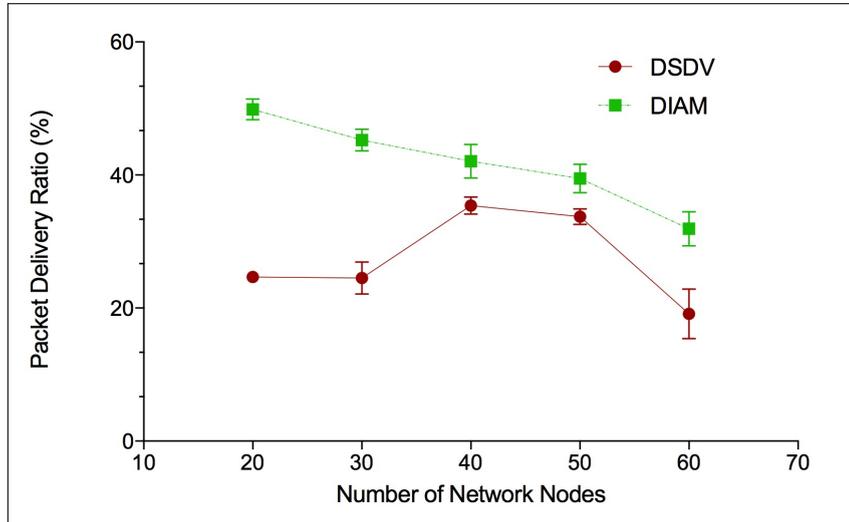


FIGURE 4.12: Packet delivery ratio in multi-channel mobile network under the impact of increasing number of network nodes.

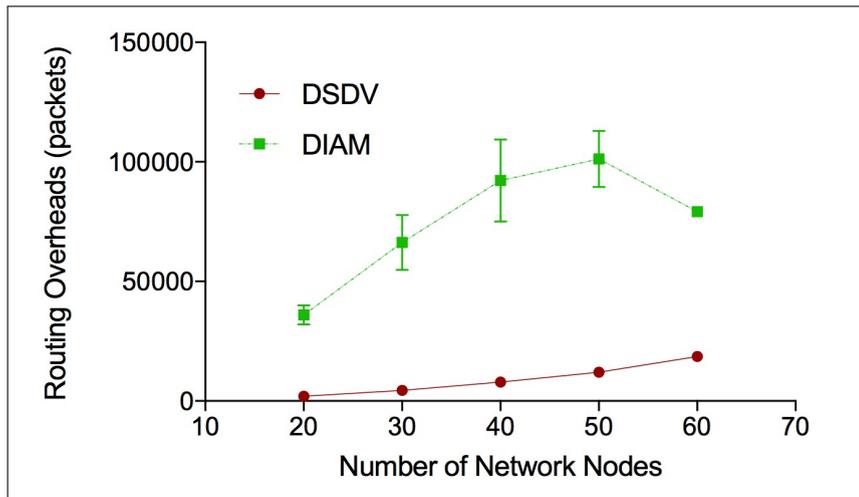


FIGURE 4.13: Routing overhead in multi-channel mobile network under the impact of increasing number of network nodes.

### 4.5.5 Impact of Number of Flows

In this scenario, we study the effect of number of flows on the performance of routing metrics. The network has 50 nodes generated randomly in  $1000\ m \times 1000\ m$ , with five mobile nodes having a maximum speed of 5 m/s while the rest of the nodes

are static. We have varied the number of flows with a fixed flow rate of 1.5 Mbps. Every node has been equipped with two radio interfaces and two channels. The performance of the AODV protocol with the DIAM metric is then compared with the DSDV protocol.

Generally, the total throughput of both protocols has increased due to the fact that the number of packets sent increased, which led to an increase in the total network throughput. The DIAM shows a better performance compared to the DSDV, as shown in Figure 4.14. In fact, the DIAM metric selects the path efficiently by considering the mobility, delay and interference; as a result, the network performance will be improved. Therefore, selecting a good quality path improves the network performance. In addition, Figure 4.14 illustrates that with 6 flows the throughput decreases and this is may be because of the increasing of interference and then more packets will be lost.

Figure 4.15 shows the comparison of packet delivery ratios with respect to the increase in the number of flows. When increasing the number of flows, the packet delivery ratio decreases, due to the fact that the interference will increase. Consequently, a lot of packets will be dropped. The DIAM shows a better performance than DSDV because the DIAM selects the path efficiently and detects the impact of mobility. In addition, Figure 4.16 illustrates the routing overheads. The DIAM shows a dramatic increase of routing overheads and this is because, with the increase in the number of flows, there is an increase in the number of the request and reply messages. Interestingly, the DSDV routing overheads are more likely to be steady. This is perhaps because the number of nodes is fixed, and as a result, the amount of routing overhead is not affected by the number of flows.

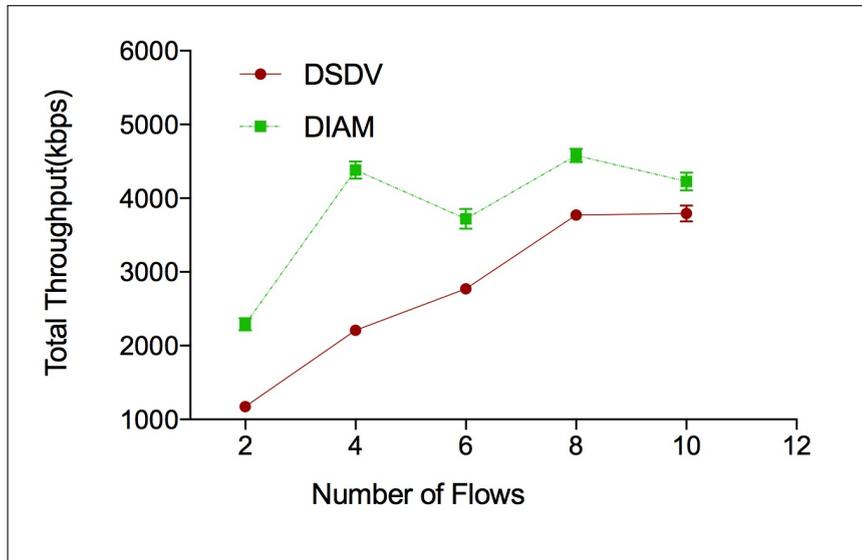


FIGURE 4.14: Total throughput in multi-channel mobile network under the impact of increasing number of flows.

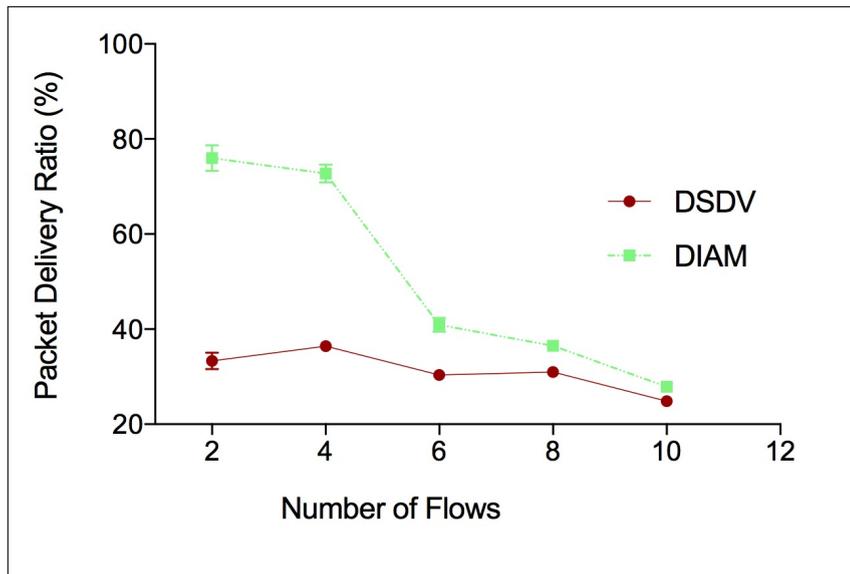


FIGURE 4.15: Packet delivery ratio in multi-channel mobile network under the impact of increasing number of flows.

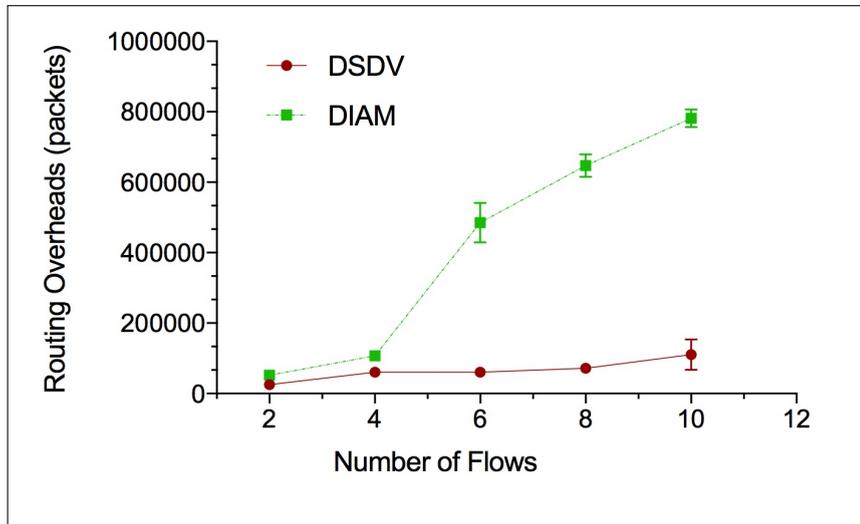


FIGURE 4.16: Routing overhead in multi-channel mobile network under the impact of increasing number of flows.

## 4.6 Summary

In this chapter we have adapted the DIAM routing metric in order to detect the node mobility from an interference node perspective. Consequently, the DIAM will select a path with high data rate and low (inter and intra) flow interference. The adapted DIAM routing metric was implemented in the AODV routing protocol using the NS2 simulator. The performance was analysed in mobile multi-channel scenarios. The results show that the adapted DIAM routing metric, compared to the DSDV routing protocol, has a good performance in congested networks, high mobility networks, and also with different network size and different number of flows.

# Chapter 5

## Congestion Control in Interface Queue (IFQ)

### 5.1 Introduction

Watching streaming video in wireless networks requires huge bandwidth and buffer sizes. Therefore, the network bandwidth and buffer sizes are the main resources that need to be managed effectively to improve the network performance. There are various issues that affect the network performance. A serious issue is packet loss due to interference or congestion [55]. One of the reasons for network congestion is high traffic load. Congestion causes a lot of packet drops due to buffer overflow, especially at forwarding nodes. In this work, we consider the node congestion occurring under high traffic load leading to buffer overflow as shown in Figure 5.1. Figure 5.1 illustrates the occurrence of congestion due to buffer overflow at the Interface Queue (IFQ) level at node 2. The IFQ explanation will follow in Section 5.4. The node receives packets at a higher rate than it can transmit, and hence becomes a bottleneck node. In this case, a huge number of packets will be dropped at the IFQ buffer,

leading to a throughput reduction. To address this problem, a congestion control mechanism is required. Reducing the congestion in wireless networks, several studies have been conducted. It is essential to adjust the flow rate to reduce the excess packets and control the network congestion in order to reduce the packet losses and improve network performance.

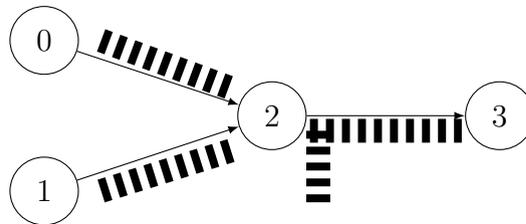


FIGURE 5.1: Congestion scenario.

In this chapter, we address the node congestion level in multi-channel WMNs and reduce the dropped packets at IFQ by adjusting the traffic rate based on the solution of a linear program (LP). Our contributions are as follows: First, we use a linear programming (LP) approach to determine the maximum total throughput or maximum flow fairness and corresponding traffic flow rates for a given scenario. After solving the LP, we use the flow rates provided by the LP to adjust the actual traffic flow rates in NS2 simulations. For simple networks, this flow rate adjustment reduces the number of dropped packets at the IFQ. Second, for more complex networks, we show that such traffic rate adjustments alone are not sufficient, so we propose a new combination of a forwarding delay scheme with flow rate adjustment for tackling packet losses at the IFQ buffer. We measure the performance of the flow rate adjustment and forwarding delay scheme by conducting simulation experiments in Ad Hoc On-Demand Distance Vector with Forwarding delay (AODV-F) with DIAM routing metric in order to select a good quality path. In addition, the results are compared with the performance of AODV with DIAM routing metric and the TCP congestion control technique in multi-channel WMNs.

The remainder of the chapter is organised as follows. First of all, a description of the Transmission Control Protocol (TCP) will be presented because that is one of the previous congestion control approaches. In addition, the performance of our approach will be compared to TCP because TCP utilises a congestion control mechanism for adjusting the sending rate for data packets when congestion is detected. Then, we explain the linear programming model and flow rate adjustment in Section 5.3. In Section 5.4, we present the idea of the forwarding delay scheme. The performance evaluation of flow rate adjustment and the forwarding delay scheme is presented in Section 5.5. Section 5.6 gives the chapter conclusion.

## 5.2 Transmission Control Protocol (TCP)

One of the primary congestion control approaches is the Transmission Control Protocol (TCP) [48]. The TCP applies a mechanism for minimising network congestion by employing the AIMD [12] mechanism for controlling the network congestion. In this section, we provide an explanation of the TCP mechanism.

The TCP uses the stream of bytes service, which sends and receives a stream of bytes. The functionality of TCP is provided at the Transport Layer in the protocol stack, as shown in Figure 5.2. TCP provides a method to manage the amount of sending data to prevent buffer overflow. TCP uses the sliding window technique for controlling the flow rate, which indicates the number of packets that the network can safely handle. TCP increases the window size after every new acknowledgement until it detects a packet loss and then TCP reduces the window size to half.

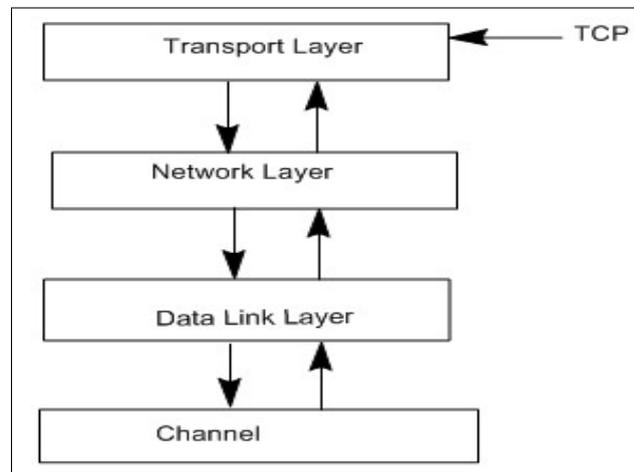


FIGURE 5.2: TCP in wireless network protocol stack.

One of the limitations with the TCP approach is that TCP assumes that the packet loss is due to the network congestion (queue buffer). As a result, TCP forces senders to respond to all kinds of losses in the same way, which leads to throughput reduction [64].

## 5.3 Linear Programming

Linear programming (LP) is a mathematical technique, which is used in optimisation applications. Basically, linear programming is to find the best solution (maximisation or minimisation) under linear constraints [6]. The objective function is a linear function, which is the value to be optimised in solving the problem and the constraints are a set of linear equalities and/or inequalities.

### 5.3.1 Linear Programming Model

The reduction of network throughput in multi-hop wireless mesh networks is a significant drawback due to the increase of dropped packets. Many studies have formulated the problem of finding the maximum achievable throughput as a linear programming (LP) problem in order to determine the optimal wireless network throughput.

In this work we use the following LP formulation that is similar to the one proposed by Jain *et al* [28]. The notation is illustrated in Table 5.1.

The objective function is to maximise total throughput. Constraint (5.2) states that the total flow from  $s_k$  to  $d_k$  is the sum of the flow amounts of flow  $k$  on the neighbouring links leaving the source  $s_k$  of flow  $k$ . The second constraint expresses flow conservation, i.e., the incoming amount of flow  $k$  must equal the outgoing amount of flow  $k$  at every node except  $s_k, d_k$ . Constraint (5.4) ensures that there is no incoming flow  $k$  in source  $s_k$ , and constraint (5.5) ensures that there is no outgoing flow  $k$  from destination  $d_k$  to the neighbouring links. The set  $I$  represents a feasible set of links, i.e., a set of links that can transmit at the same time without interference. The physical interference model is used to determine the feasible link

sets  $I$  for a given scenario. The SINR at all receivers of the links in  $I$  must be above threshold for  $I$  to be feasible.

$\mathcal{I}$  contains all feasible link sets. The amount of flow on a link cannot exceed the usable capacity of the link as stated by constraint (5.6). The usable capacity is the full capacity  $C_{ij}$  of the link multiplied with the fraction of time during which it is used. Constraint (5.7) ensures that the sum of  $\lambda_I$  over all feasible link sets  $I$  does not exceed one.

$$\max \sum_{k=1}^K f_k \quad (5.1)$$

subject to

$$f_k = \sum_{l_{s_k i}} f_{s_k i}^k, \text{ for all } k \quad (5.2)$$

$$\sum_{l_{ij}} f_{ij}^k = \sum_{l_{ji}} f_{ji}^k, \text{ for all } k \text{ and } i \neq s_k, d_k \quad (5.3)$$

$$\sum_{l_{i s_k}} f_{i s_k}^k = 0, \text{ for all } k = 1, \dots, K \quad (5.4)$$

$$\sum_{l_{d_k i}} f_{d_k i}^k = 0, \text{ for all } k = 1, \dots, K \quad (5.5)$$

$$\sum_k f_{ij}^k \leq \sum_{I: l_{ij} \in I} \lambda_I C_{ij}, \text{ for all } l_{ij} \quad (5.6)$$

$$\sum_I \lambda_I \leq 1 \quad (5.7)$$

$$\lambda_I \geq 0, \text{ for all } I \in \mathcal{I} \quad (5.8)$$

$$f_k \geq 0, \text{ for all } k = 1, \dots, K \quad (5.9)$$

$$f_{ij}^k \geq 0, \text{ for all } k = 1, \dots, K \text{ and all } l_{ij} \quad (5.10)$$

We have implemented a simple tool for generating some types of wireless network configurations by producing node positions and transmission powers. Furthermore,

a second tool was also implemented that reads such a network configuration and generates the corresponding LP. Then, the LP solver `lp_solve` [7] was used to solve the LP, assuming all flows are fixed. The flow rates  $f_k$  provided by solving the LP have then been used to adjust the flow rates in an NS2 simulation of the same network configuration, in order to study the effect on the network throughput.

TABLE 5.1: Explanation of notation.

Notation	Explanation
$K$	Number of flows
$s_k$	Source of flow $k$
$d_k$	Destination of flow $k$
$f_k$	Total amount of flow $k$
$f_{ij}^k$	Amount of flow $k$ through $l_{ij}$
$l_{ij}$	Link from node $i$ to node $j$
$C_{ij}$	Capacity of link $l_{ij}$
$I$	Feasible link set
$\lambda_I$	Fraction of time when link set $I$ is active
$\mathcal{I}$	all feasible link sets
SINR	Signal-to-Interference-plus-Noise Ratio

## 5.4 Forwarding Delay Scheme

First of all, a brief description of the data link layer in the wireless network protocol stack will be given and then the idea of the forwarding delay scheme will follow. The data link layer has two sub-layers, the Link Layer (LL) and the Medium Access Layer (MAC). Figure 5.3 shows that an outgoing packet from LL must wait at the IFQ before being sent out onto the channel via the MAC layer. In addition, before transmitting the packet, the MAC layer senses the channel; if the channel is idle then the packet will be transmitted. Otherwise, the packet will be queued until it can be sent. Moreover, if the queue is full the incoming packet will be dropped and then the node will retransmit the dropped packets. Therefore, this retransmission

of the dropped packets results in an increase in the number of dropped packets due to collision.

Our idea is now to introduce a small delay at forwarding nodes in multi-hop networks for each received packet when the forwarding node detects link congestion. The congested intermediate node adds a small delay to a data packet at the Network layer instead of immediately passing it down to the link layer. This delay increases the chance for the IFQ buffer between LL and MAC to have space for a new packet to be forwarded. Therefore, this delay reduces the number of packets that get dropped because of a full queue. For example, assume the introduced delay at a forwarding node is  $d$  seconds and two packets arrive at the network layer at time  $t_1$  and  $t_2$ , respectively. Consequently, the forwarding node will delay the two packets until time  $t_1 + d$  and  $t_2 + d$ , respectively. As a result, this delay will increase the chance to have space in the IFQ buffer between LL and MAC, also minimising the queuing time before sending the packet via the channel. Moreover, the forwarding delay reduces the number of dropped packets resulting from the full queue. As a result, the number of packet collisions is more likely to reduce because of the reduction in the number of retransmitted packets. Therefore, the network throughput will improve. The forwarding delay scheme pseudo code is shown in Algorithm 1.

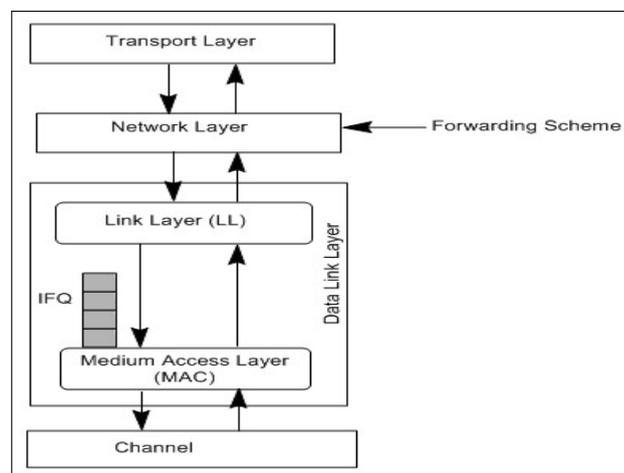


FIGURE 5.3: Wireless network protocol stack.

---

**Algorithm 1** Forwarding delay scheme

---

```
 $NQ_i$  = Number of queuing packets in the  $link_i$   
 $C_i$  = Congestion threshold // Detecting link congestion  
if  $NQ_i \geq C_i$  then  
    Forwarding with Optimum Delay  
else  
    Immediate Forwarding  
end if
```

---

## 5.5 Performance Evaluation

The performance of LP-based flow rate adjustments and the forwarding delay scheme has been evaluated in the NS2 simulator. The LP solution provides the traffic flow rate that can be transmitted through one channel. In addition, to reduce the interference at consecutive links, a multi-channel setting with two channels was used. Essentially, this means that intermediate nodes receive a packet through one channel and then transmit the packet on the second channel. In addition, the optimum forwarding delay is the best delay that has been found among the values that have been tried.

### 5.5.1 Simulation Model

The simulation assumes a static wireless mesh network with nodes that have IEEE 802.11 radios. Every node is equipped with two radio interfaces and uses two channels. The AODV with DIAM routing metric has been used. Table 5.2 shows the simulation parameters and the selection of 150s simulation time is because of that after trying a range of different simulation times, we found that the results are consistent in simulation with 150s.

For total throughput maximisation, we consider four scenarios (Scenario A-D) in Section 5.5.2. In terms of fairness maximisation, it is investigated in three scenarios (Scenario E-G) in Section 5.5.3. In Scenario A and E, the simulation was run for a chain network in two different settings: one with AODV with 2.25 Mbps as flow rate for each flow, and one with AODV but with flow rates adjusted according to the LP solution. In Scenarios B-D and F-G, the simulation was run four times for a complex network: The first run used AODV with DIAM routing metric with 2.25 Mbps for each flow, and the second run used AODV with DIAM routing metric with flow rates adjusted according to the LP solution. The third and fourth simulations use AODV with forwarding delay scheme (AODV-F) for both 2.25 Mbps flow rate and flow rates adjusted according to the LP solution, respectively. In addition, the UDP Internet Protocol has been used with the LP-based flow rate, fixed 2.25 Mbps flow rate and forwarding delay and then the results have been compared with TCP.

TABLE 5.2: Simulation parameters for congestion control in IFQ.

Simulation Parameter	Value
MAC type	IEEE 802.11b
Routing protocol	AODV with DIAM
Transmission range	250m
Interference range	550m
Traffic type	CBR
Packet size	1000 bytes
Channel bandwidth	5.5 Mbps
Network layer queue size	64
Simulation time	150s

## 5.5.2 Maximise Total Throughput

The aim of this section is to study the performance of LP-based flow rate adjustments for maximising the total network throughput in Scenarios A–D. In addition, we added constraints to the LP ensuring that the flow rate of every flow is less than or equal to 2.25 Mbps.

### 5.5.2.1 Scenario A

We have examined the effect of flow rate adjustment for maximising the total network throughput in a basic chain network with 5 nodes, as shown in Figure 5.4. The examination was done for two cases: a) flows in the same direction. b) flows in different directions (bidirectional traffic).

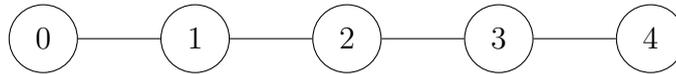


FIGURE 5.4: Chain network with 5 nodes.

#### Scenario A-1

In this scenario, the network has two flows, one from node 0 to node 4, and one from node 1 to node 3. The traffic rate after solving the LP is 0.33 Mbps for the flow from 0 to 4 and 2.25 Mbps for the flow from 1 to 3. This flow rate can be explained by the fact that flows with fewer hops will have higher data rate in order to maximise the total throughput.

As shown in Figure 5.5, the LP-based flow rate adjustment yields 20% better total throughput than TCP and using a 2.25 Mbps flow rate for each flow. The improvement of throughput in the LP-adjusted flow rate can be explained by the dramatic reduction of the number of dropped packet at the IFQ to 0 as Figure 5.6 illustrates. Although TCP showed a similar amount of dropped packet reduction at IFQ, the LP-based flow rate enables a much higher network throughput. The reduction of dropped packets at IFQ with the TCP mechanism is due to the fact that the TCP considers any lost packet as congestion so it reduce the sender's rate. As a result, the network may not suffer as much from the congestion at IFQ.

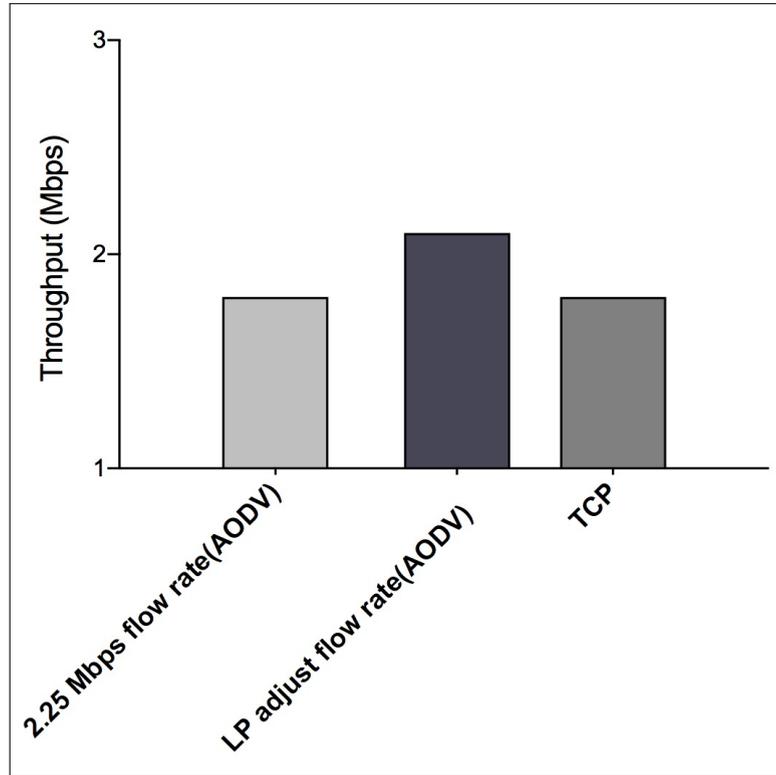


FIGURE 5.5: Throughput of flows 1-3 and 0-4.

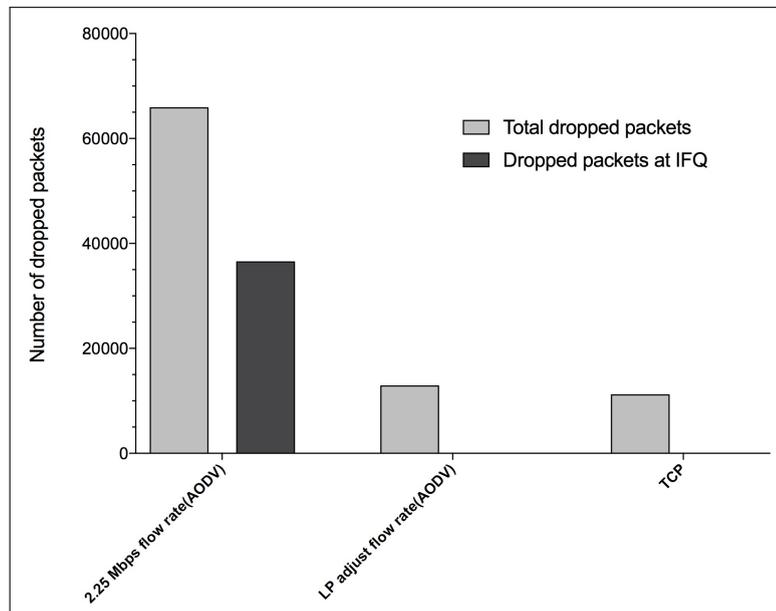


FIGURE 5.6: Number of dropped packets of flows 1-3 and 0-4.

### **Scenario A-2**

This section investigates the benefit of the LP-based flow rate adjustment for bidirectional traffic. The network has two flows: one from node 4 to node 0, and one from node 1 to node 3. The LP-adjusted flow rate is 0.5 Mbps for the flow from node 4 to node 0 and 2.25 Mbps from node 1 to node 3. As shown in Figure 5.7, the adjusted flow rates again led to better total throughput compared to that observed with flow rate 2.25 Mbps for each flow and TCP.

Figure 5.8 illustrates that although the LP-based flow rate adjustment revealed an immense reduction of the number of dropped packets at IFQ compared to that of 2.25 Mbps, the TCP showed the lowest amount of dropped packets at IFQ. The observed improvement in the LP-based flow rate adjustment in comparison to the TCP can perhaps be attributed to the fact that the TCP reduces the transmission rate when the packets are being lost.

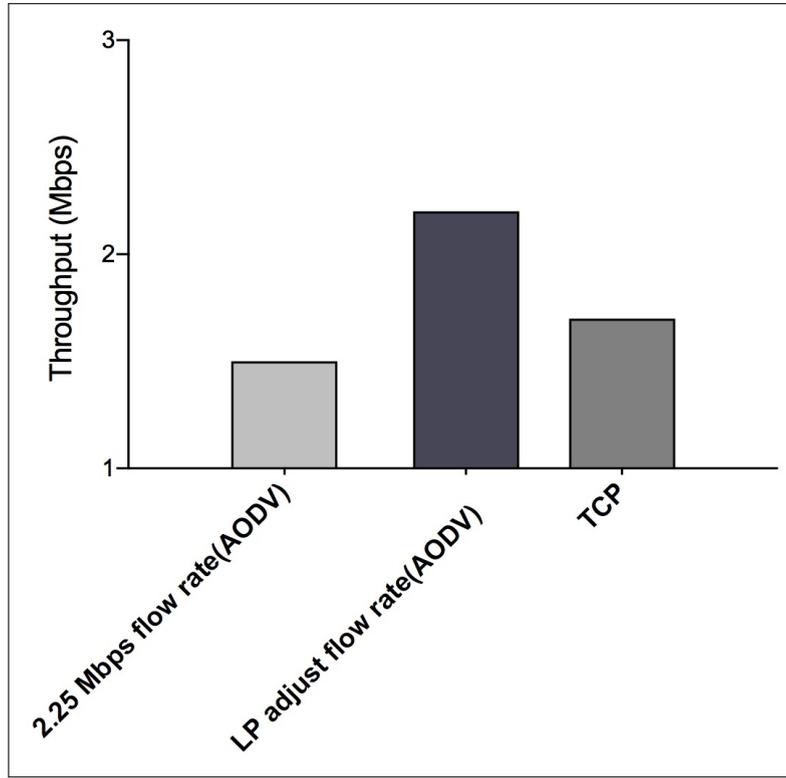


FIGURE 5.7: Throughput of flows 1-3 and 4-0.

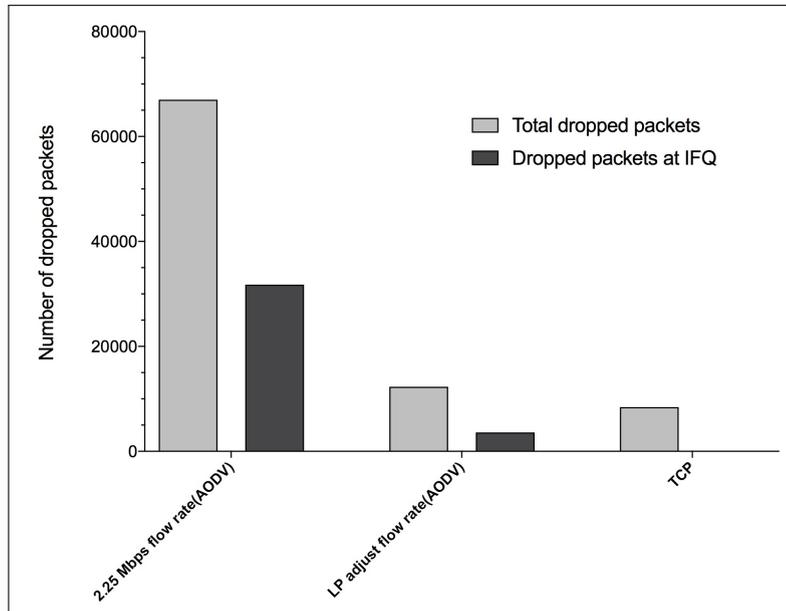


FIGURE 5.8: Number of dropped packets of flows 1-3 and 4-0.

### 5.5.2.2 Scenario B

We now consider a network with 7 nodes placed in a  $1100\text{ m} \times 1100\text{ m}$  square region and the distance between two nodes is 250m, as shown in Figure 5.9. The performance of LP-based flow rate adjustments and the forwarding delay scheme has been examined in two cases: a) Two flows with the same destination b) Two flows with the same source. The two scenarios are referred to as Scenario B-1 and Scenario B-2, respectively.

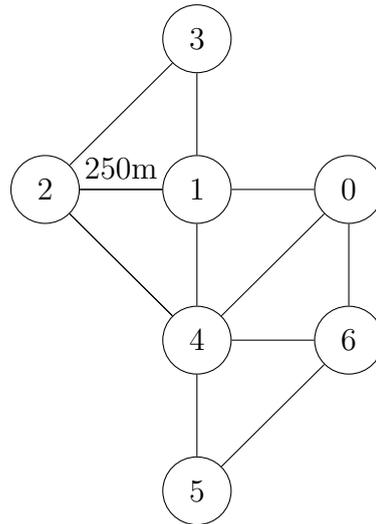


FIGURE 5.9: Network topology.

#### Scenario B-1

The network in Figure 5.9 is used with 2 flows: nodes 0 and 1 are the sources, and node 3 is the destination. The LP solution for this scenario achieves 3.87 Mbps total throughput with flow rate 1.62 Mbps for the flow from 0 to 3 and flow rate 2.25 Mbps for the flow from 1 to 3. In order to maximise the total throughput, the LP gives the flow from 1 to 3 a higher data rate because it has fewer hops.

We have tried out a range of delay values and congestion thresholds to find an optimal delay and congestion threshold for packet forwarding in LP-based flow rate adjustments and AODV-F. The results show that among the considered values the optimal delay in this scenario is 0.6s, yielding the maximum throughput in Figure 5.10. Moreover, Figure 5.11 shows that the optimum congestion threshold is 0 which achieves maximum throughput. In addition, this optimisation achieves almost twice the throughput of immediate forwarding. Then, we have applied the 0.6s forwarding delay and 0 congestion threshold to the different flow rate scenarios (flow rate 2.25 Mbps and LP-based flow rates). Figure 5.12 shows that the forwarding delay leads to a significant increase in the total throughput in both flow rate scenarios. The throughput is about 100% better than immediate forwarding. This significant improvement is perhaps due to the dramatic decrease in the number of dropped packets at IFQ as shown in Figure 5.13. In addition, the 0.6s forwarding delay reduces the link congestion, which leads to selecting a better path and then improves the network throughput. Although the TCP has the lowest number of dropped packets at IFQ, it has lower throughput in comparison to the forwarding delay scheme. The TCP throughput reduction may be because of the transmission rate decrease. It can be concluded that adjusting the flow rate in combination with an optimal forwarding delay will improve the network performance significantly.

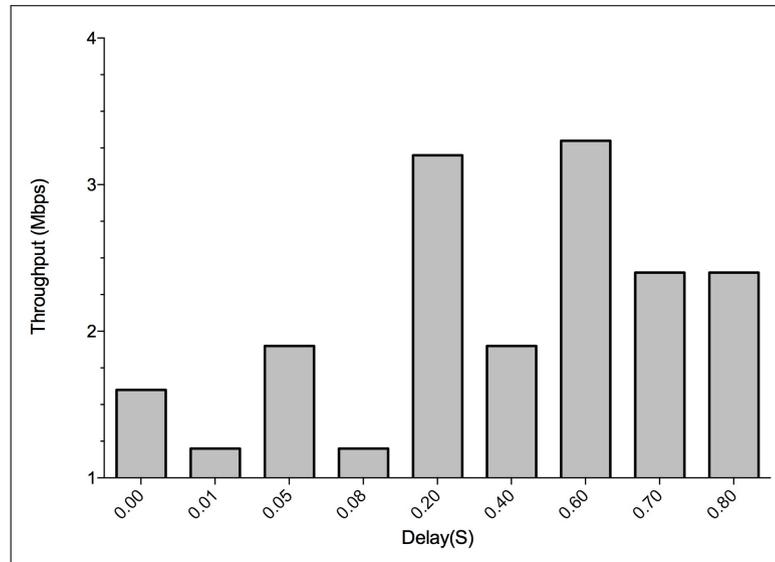


FIGURE 5.10: Finding optimum delay for 0-3 and 1-3 flows.

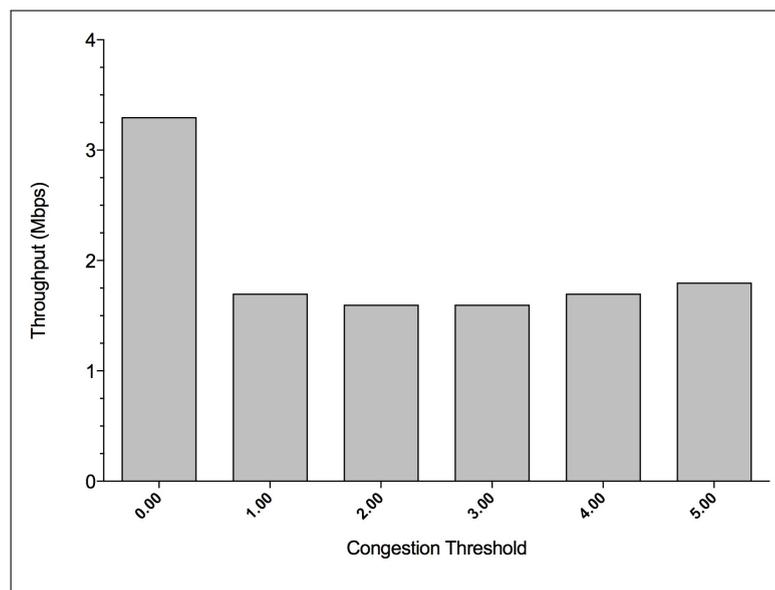


FIGURE 5.11: Finding optimum congestion threshold for 0-3 and 1-3 flows.

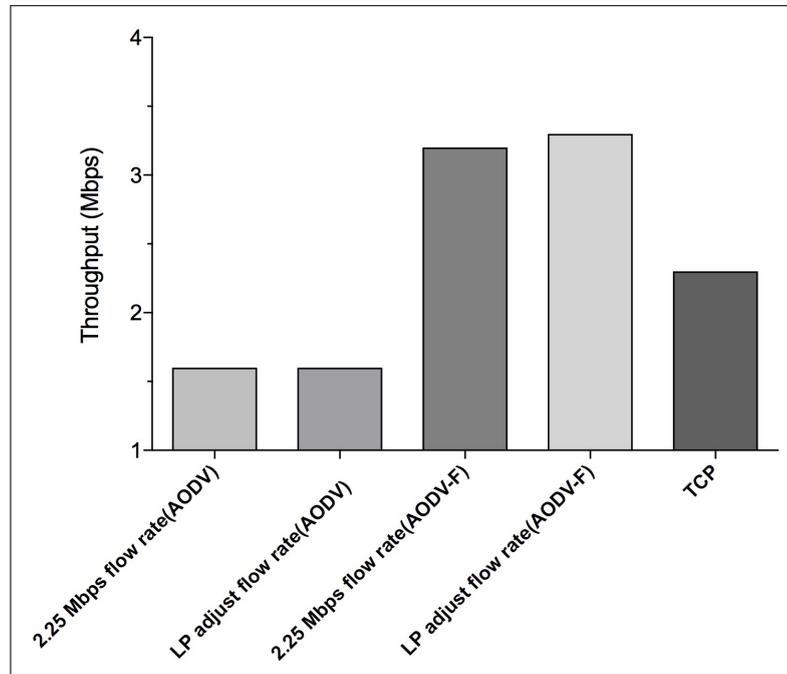


FIGURE 5.12: Throughput of flows 1-3 and 0-3.

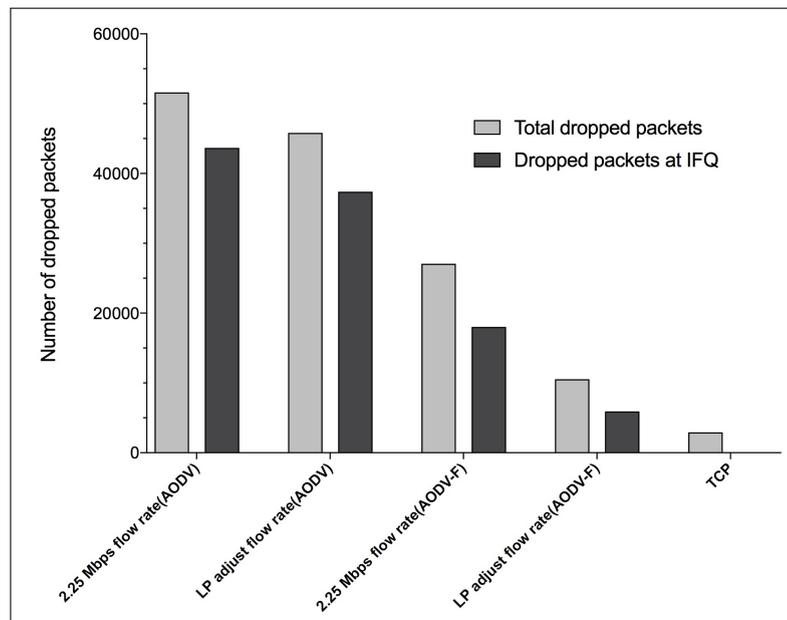


FIGURE 5.13: Number of dropped packets of flows 1-3 and 0-3.

**Scenario B-2**

The network in Figure 5.9 is simulated with 2 flows. Node 0 is the common source, and node 2 and 3 are the destinations. The LP solution for this scenario has 2.75 Mbps total throughput with a flow rate of 2.25 Mbps for the flow from 0 to 3 and a flow rate of 0.5 Mbps from 0 to 2 for maximising the total throughput.

First of all, we examined a range of forwarding delays and congestion thresholds in LP-based flow rate adjustments and AODV-F to find an optimal delay and congestion threshold for forwarding packets in LP-based flow rate adjustments and AODV-F in this scenario, as shown in Figure 5.14 and Figure 5.15. The optimum delay in this scenario is 0.09s and the congestion threshold is 0, which give almost twice the throughput of immediate forwarding. Then, we have applied this delay of 0.09s and the congestion threshold to the different cases of setting the flow rates (flow rate 2.25 Mbps and LP-adjusted flow rates). Figure 5.16 illustrates that forwarding delay 0.09s leads to better throughput than immediate forwarding. Moreover, the combination of LP-adjusted flow rate and forwarding delay could maximise the total network throughput because the number of dropped packets at the IFQ is 0, as shown in Figure 5.17. This leads to the selection of less congested paths.

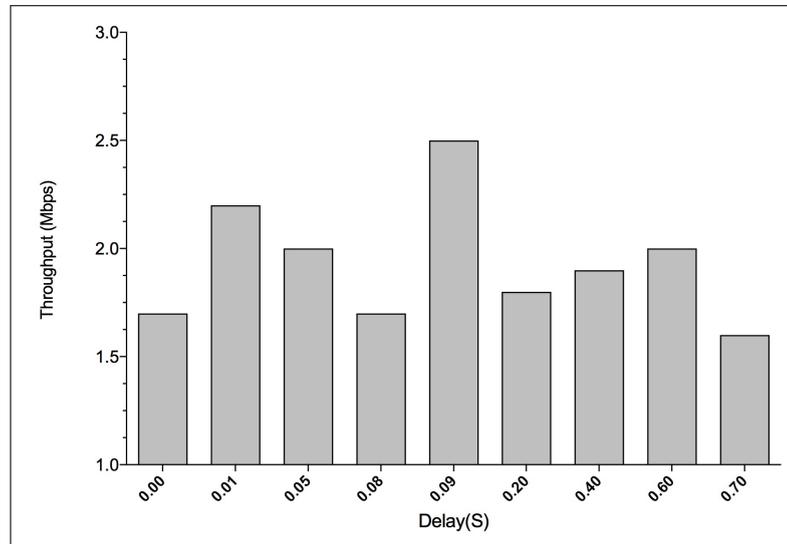


FIGURE 5.14: Finding optimum delay for 0-2 and 0-3 flows.

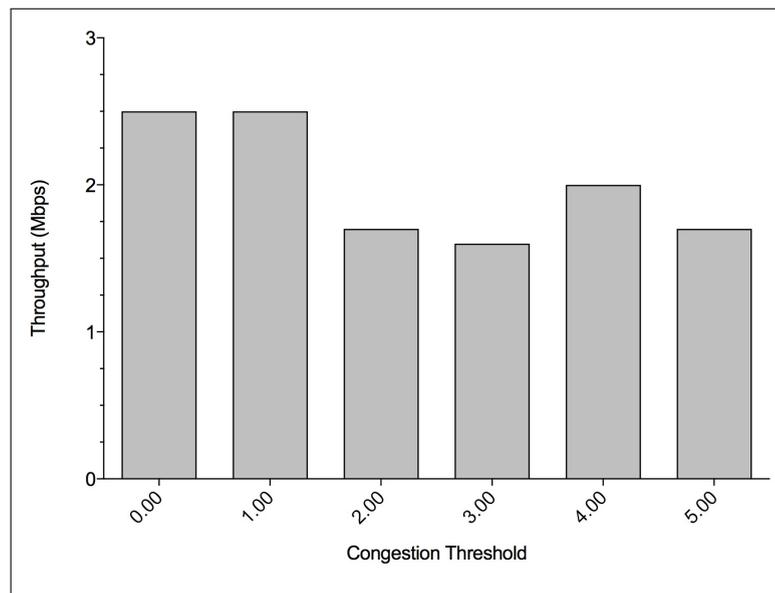


FIGURE 5.15: Finding optimum congestion threshold for 0-2 and 0-3 flows.

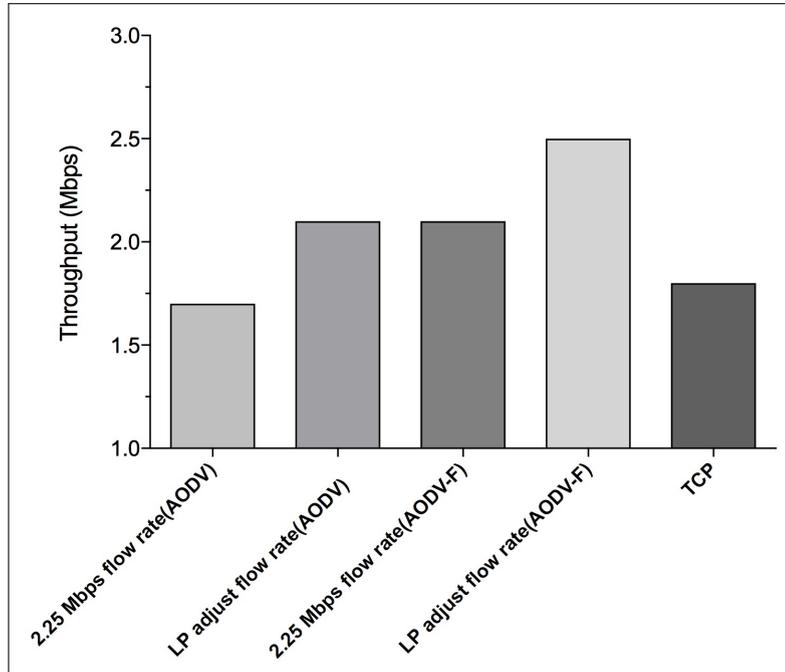


FIGURE 5.16: Throughput of flows 0-2 and 0-3.

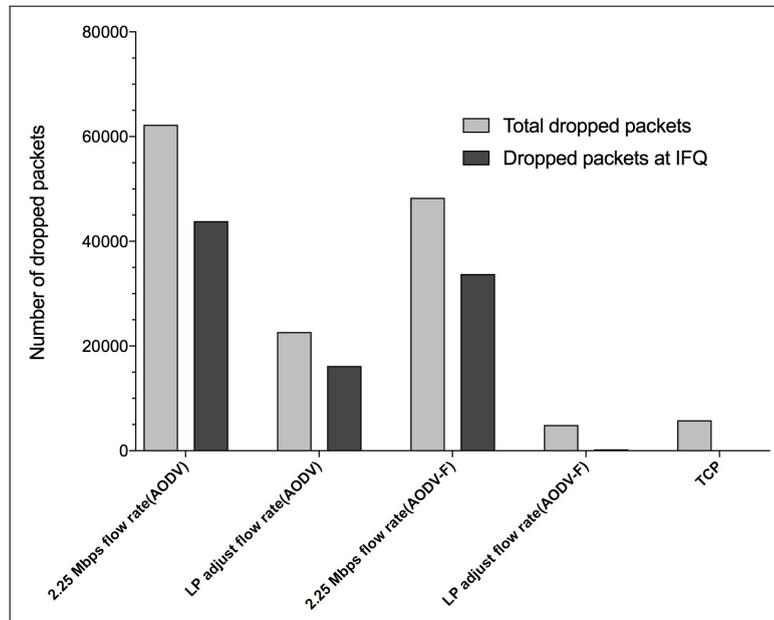


FIGURE 5.17: Number of dropped packets of flows 0-2 and 0-3.

### 5.5.2.3 Scenario C

The aim of studying this scenario is to evaluate the congestion control scheme in a network with high congestion. We have introduced 3 flows in the network shown in Figure 5.9. The first two flows are from node 3 to node 1 and to node 5, and the third flow is from node 2 to node 0. Solving the LP yields a flow rate of 0.815 Mbps for the flows from node 3 to 5 and from node 2 to 0, while the flow rate from 3 to 1 is 2.25 Mbps. This flow rate can be explained by the fact that flows with fewer hops will have higher data rate in order to maximise the total throughput.

Figure 5.20 shows that controlling the network congestion by adjusting the flow rate according to the LP achieves better throughput than using a fixed flow rate of 2.25 Mbps. In addition, the optimum forwarding delay is 0.6s for this scenario in LP-based flow rate adjustments and AODV-F, as Figure 5.18 illustrates. Moreover, the optimum congestion threshold is 4 with LP-based flow rate adjustments and AODV-F, as shown in Figure 5.19. Figure 5.21 shows that TCP has the lowest amount of dropped packets at IFQ. The observed improvement of throughput in the combination of the LP-based flow rate adjustment and forwarding delay in comparison to the TCP is perhaps due to the fact that the TCP reduces the transmission rate when the packets are being lost. As a result, the combination of LP-based flow rates and forwarding delay reduces the number of dropped packets at IFQ, as shown in Figure 5.21. Therefore, a good quality path with less congestion will be selected and then the network throughput will improve.

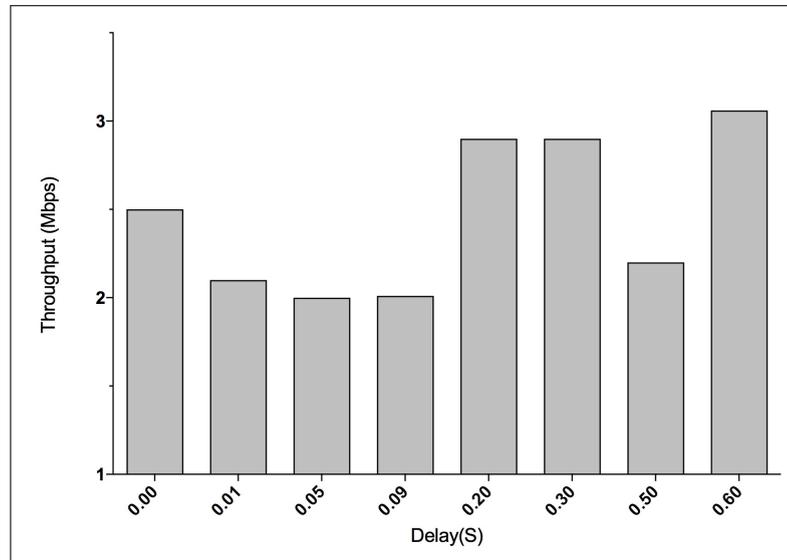


FIGURE 5.18: Finding optimum delay for 2-0, 3-1 and 3-5 flows.

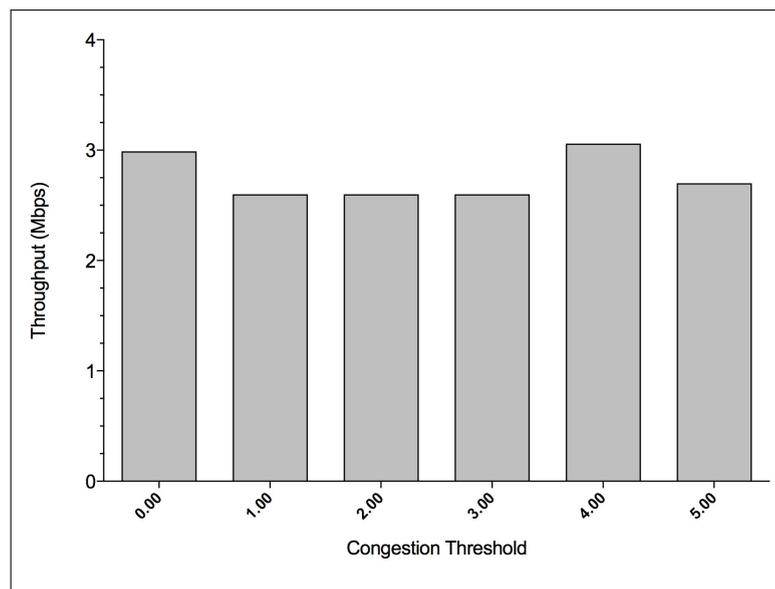


FIGURE 5.19: Finding optimum congestion threshold for 2-0, 3-1 and 3-5 flows.

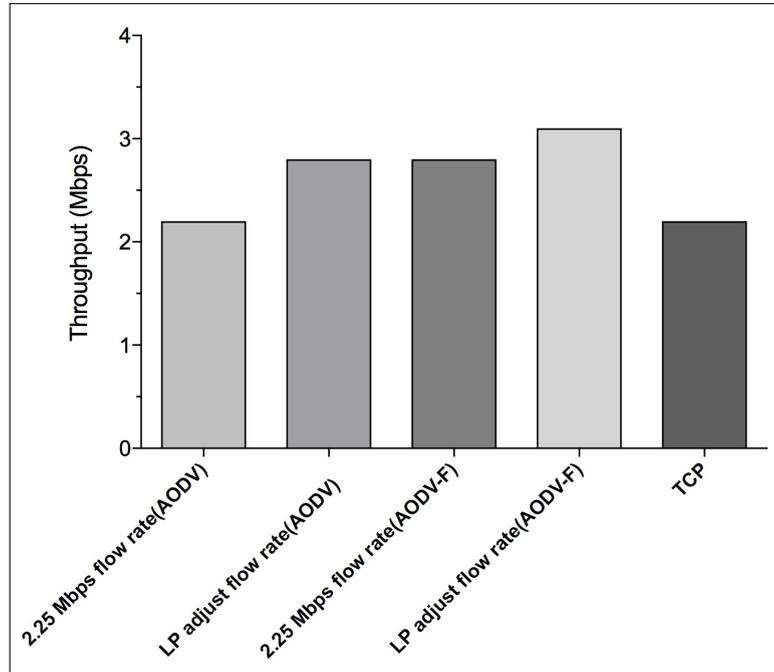


FIGURE 5.20: Throughput of flows 2-0, 3-1 and 3-5 .

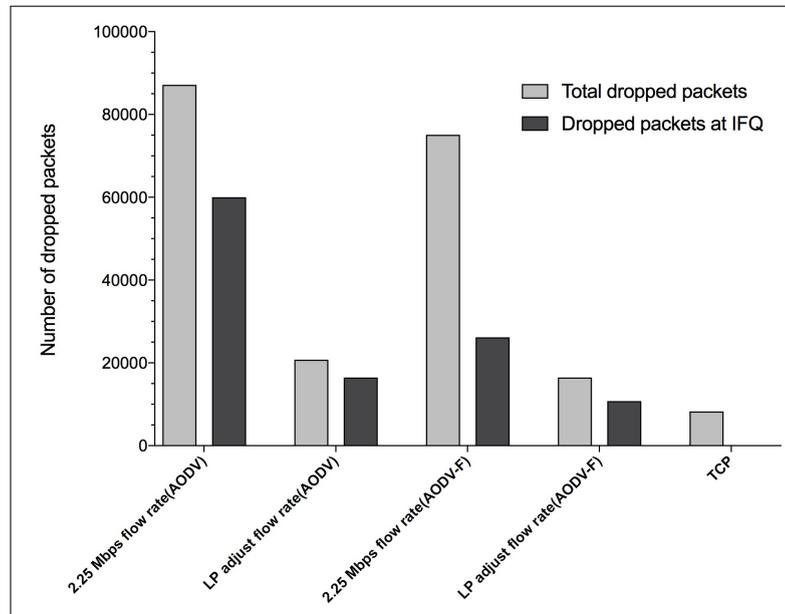


FIGURE 5.21: Number of dropped packets of flows 2-0, 3-1 and 3-5.

#### 5.5.2.4 Scenario D

In order to solve the LP using an LP solver, as the number of feasible link sets, the network needs to have a relatively small number of links. Otherwise, the size of the LP can be exponential in the number of links, if the network size is big. Consequently, solving the LP for large network by the LP solver will need very long time. In this section we consider a larger network and study the effect of using only the forwarding delay scheme, but not the LP-adjusted flow rates.

The network consists of 20 nodes with randomly generated positions and the network area is  $1100\text{ m} \times 1100\text{ m}$ . There are four traffic flows with random sources and destinations. Each flow has a flow rate of 2.25 Mbps. Figure 5.22 illustrates that the introduction of forwarding delay yields better total throughput than immediate forwarding, especially with the delay value of 0.01s. The optimum forwarding delay reduces the network congestion, which leads to selecting a better path and improves the network performance. In addition, Figure 5.23 shows that the optimum congestion thresholds are 0 and 5, which yield better total throughput.

Figure 5.24 shows that fixed 2.25 Mbps flow rate with forwarding delay 0.01s and congestion threshold 5 achieves better throughput in comparison to TCP and fixed 2.25 Mbps flow rate with immediate forwarding. While TCP has the lowest amount of dropped packets at IFQ as shown in Figure 5.25, it has additionally the lowest throughput in comparison to the forwarding delay and immediate forwarding. This effect is perhaps due to the fact that the TCP reduces the transmission rate when the packets are being lost. It can be concluded that an optimal forwarding delay will improve the network performance.

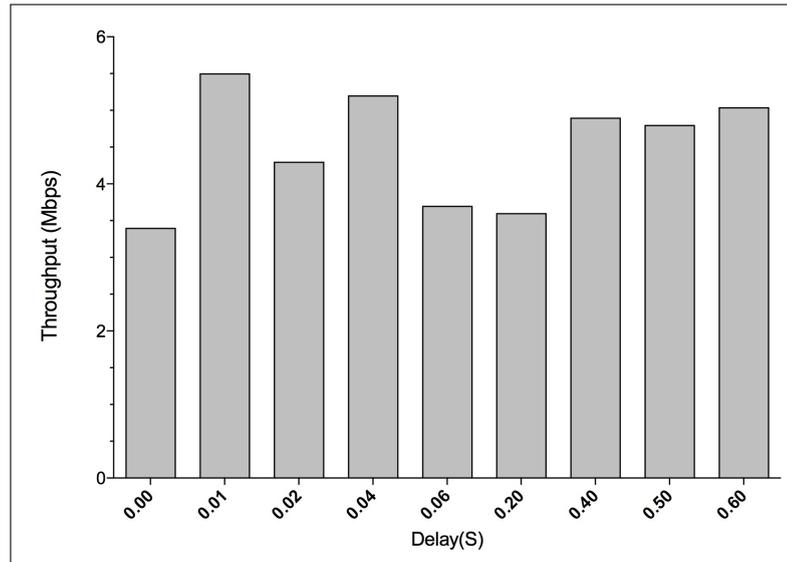


FIGURE 5.22: Finding optimum delay for 20-node random network.

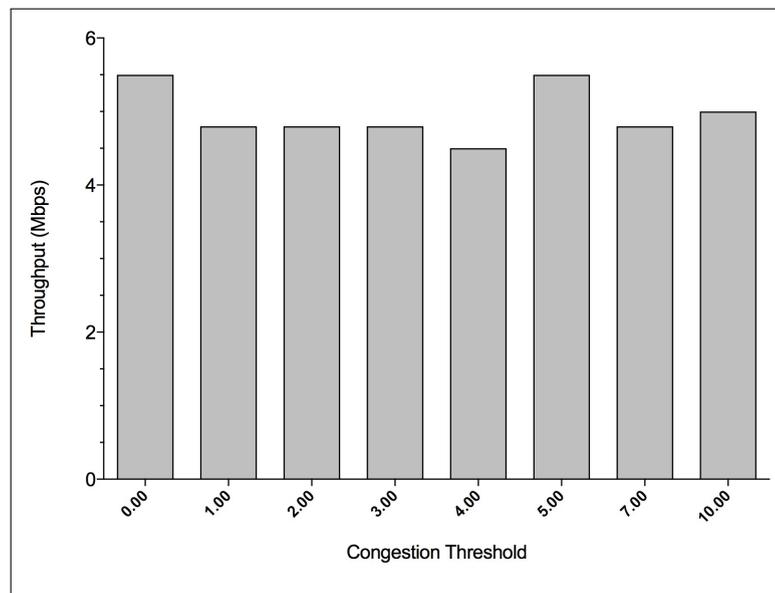


FIGURE 5.23: Finding optimum congestion threshold for 20-node random network.

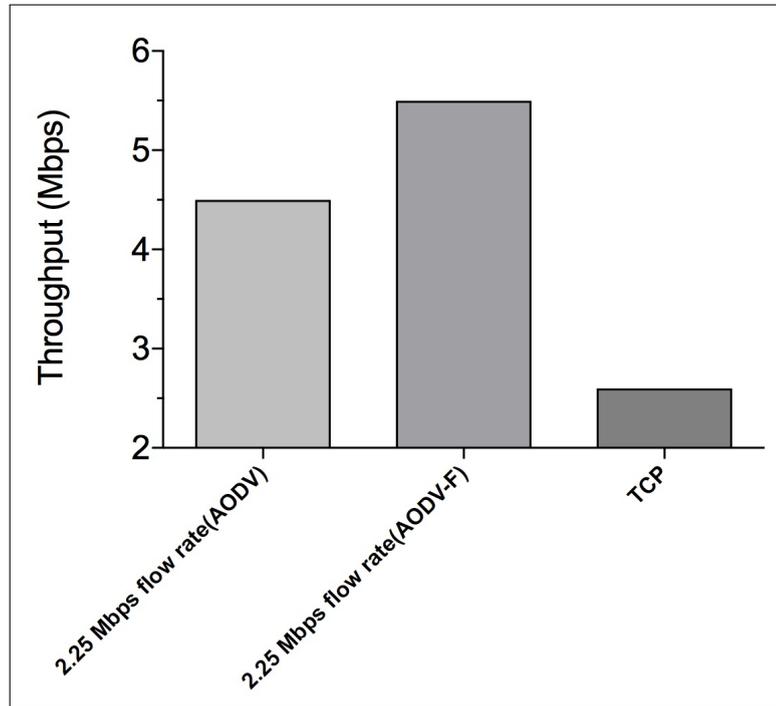


FIGURE 5.24: Throughput of 20-node random network.

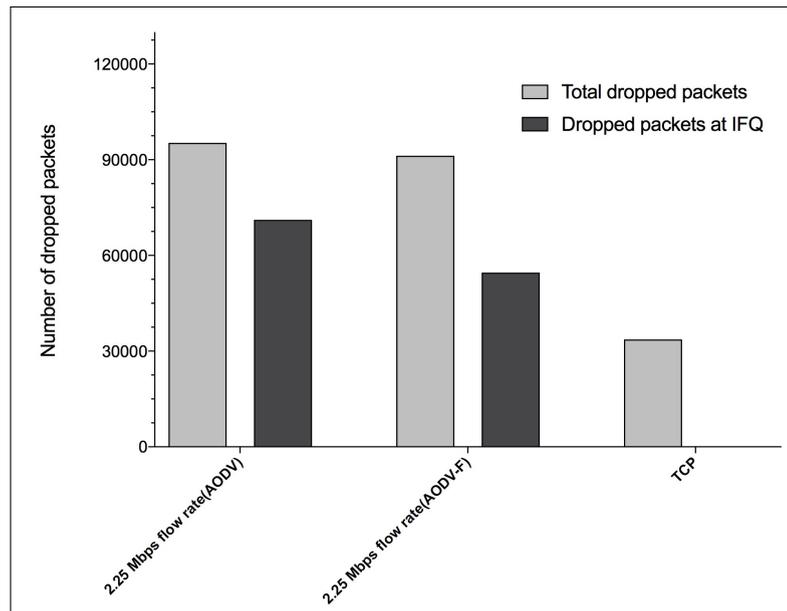


FIGURE 5.25: Number of dropped packets in 20-node random network.

### 5.5.3 Maximise Flow Fairness

The LP objective function for maximising the total network throughput leads to unfairness in the network flows. Essentially, the network bandwidth should be shared in a fair way used by all flows. Hence, the aim of this section is to study the performance of LP-based flow rate adjustments for maximising flow fairness. In order to maximise throughput of the flows, we modify the LP objective function in Scenarios E–G, as shown in Equation (5.11). In addition, we added constraints to the LP ensuring that the flow rate of every flow is greater than or equal to  $f$ , .

$$\max \quad f \tag{5.11}$$

#### 5.5.3.1 Scenario E

We have examined the effect of flow rate adjustment for maximum flow fairness in a basic chain network with 5 nodes, as shown in Figure 5.4. Two different cases were considered for the examination: a) flows in the same direction. b) flows in different directions (bidirectional traffic).

##### Scenario E-1

In this scenario, the network has two flows, one from node 0 to node 4, and one from node 1 to node 3. The traffic rate after solving the LP is 1.1 Mbps for each flow.

The LP-based flow rate adjustment provides better flow fairness than TCP and using a 2.25 Mbps flow rate for each flow, as shown in Figure 5.26. However, Figure 5.26 illustrates that the TCP and using a 2.25 Mbps flow rate have higher throughput for the flow from node 1 to node 3 and this is because the shortest path has higher

flow rate, which may cause unfairness. In addition, the LP-adjusted flow rate for providing flow fairness dramatically reduces the number of dropped packet at the IFQ as Figure 5.27 illustrates. Although TCP showed a dramatic reduction of dropped packets at IFQ to 0, the LP-based flow rate provides a much better flow fairness.

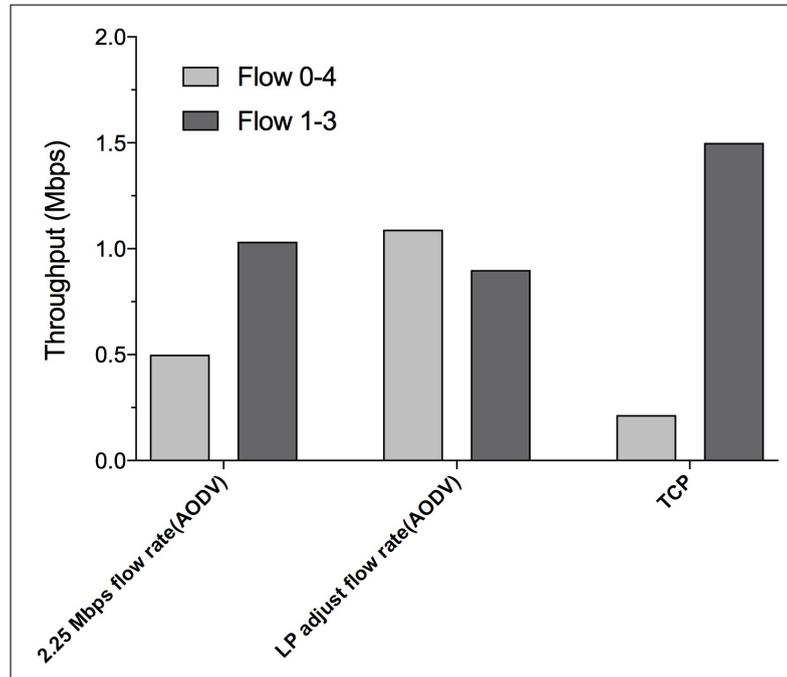


FIGURE 5.26: Throughput of flows 1-3 and 0-4 with fairness.

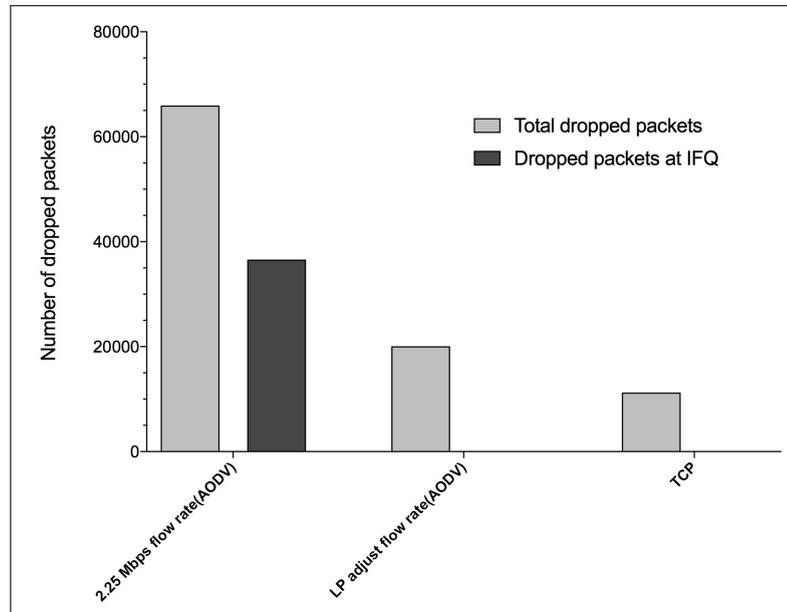


FIGURE 5.27: Number of dropped packets of flows 1-3 and 0-4 with fairness.

### Scenario E-2

This section studies the effect of the LP-based flow rate adjustment for flow fairness in bidirectional traffic. The network has two flows: one from node 4 to node 0, and one from node 1 to node 3. The traffic rate after solving the LP is 1.37 Mbps for each flow.

As shown in Figure 5.28, it can be observed that flow rate 2.25 Mbps for each flow and TCP provide most of the channel bandwidth for the flow from node 1 to node 3 which is unfair for utilising the network resource. However, the adjusted flow rates again led to better flow fairness compared to using flow rate 2.25 Mbps for each flow and TCP.

Figure 5.29 illustrates that although the LP-based flow rate adjustment decreases the number of dropped packets at IFQ compared to that of 2.25 Mbps, the TCP showed the lowest amount of dropped packets at IFQ.

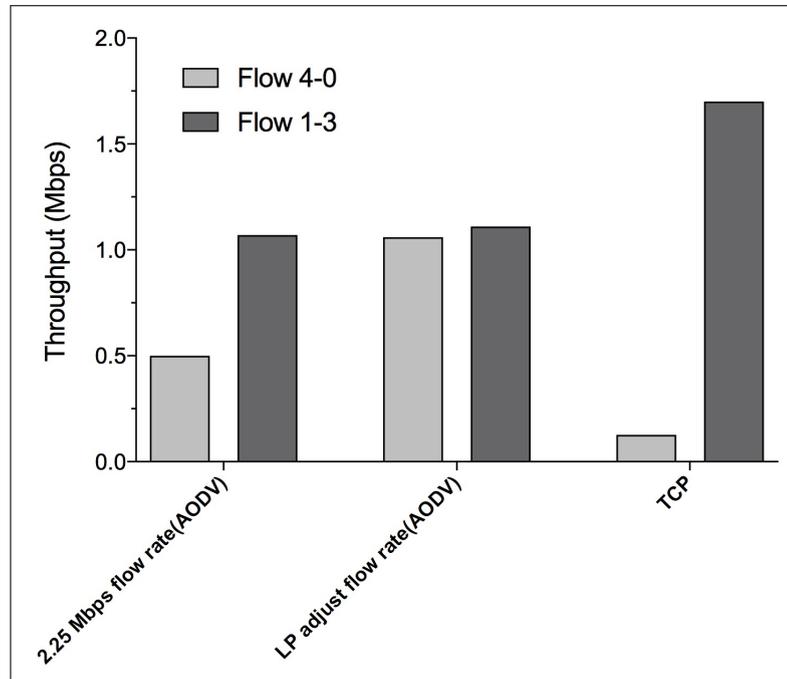


FIGURE 5.28: Throughput of flows 1-3 and 4-0 with fairness.

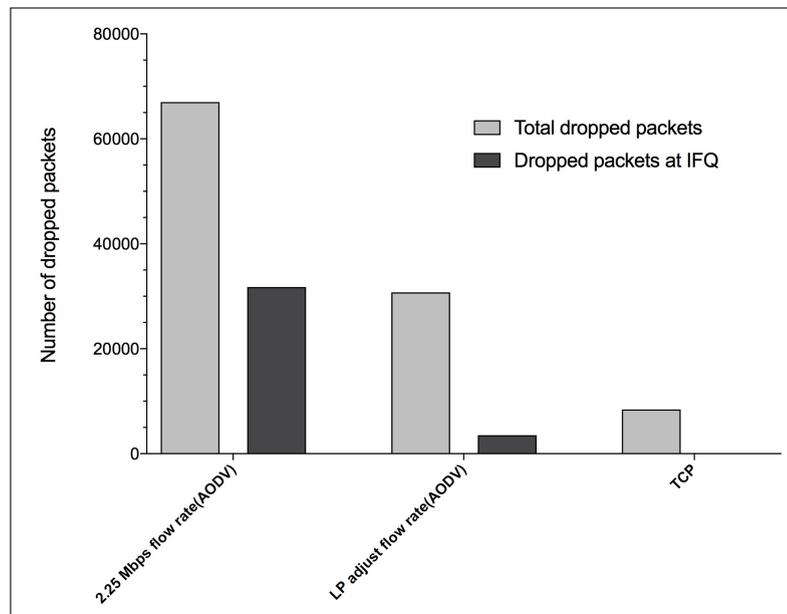


FIGURE 5.29: Number of dropped packets of flows 1-3 and 4-0 with fairness.

### 5.5.3.2 Scenario F

In this scenario, we consider a network with 7 nodes placed in a  $1100\ m \times 1100\ m$  square region, as shown in Figure 5.9. The performance of LP-based flow adjustments for maximising flow fairness and the forwarding delay scheme has been examined in two cases: a) Two flows with the same destination b) Two flows with the same source.

#### Scenario F-1

For this scenario 2 flows (from node 0 to node 3 and from node 1 to node 3) are present in the network as shown in Figure 5.9. The LP solution for this scenario gives flow rate 1.8 Mbps for each flow.

We have tried out a range of delay values and congestion thresholds to find an optimal delay and congestion threshold for packet forwarding with LP-based flow rate adjustments and AODV-F. The results show that the optimal delay in this scenario is 0.02s, giving the maximum flow throughput, as shown in Figure 5.30. Moreover, Figure 5.31 shows that the optimum congestion threshold is 0 which achieves maximum flow fairness. In addition, this optimisation achieves a better fairness than immediate forwarding. Then, we have applied the 0.02s forwarding delay and 0 congestion threshold to the different flow rate scenarios (flow rate 2.25 Mbps and LP-based flow rates). Figure 5.32 shows that the forwarding delay leads to an increase in the flow throughput in both flow rate scenarios. The LP-based flow rates provide better flow fairness than using 2.25 Mbps and TCP. In addition, the optimisation of LP-based flow rates and forwarding delay decreases the number of dropped packets at IFQ as shown in Figure 5.33. Hence the congestion at the network is reduced. Therefore, adjusting the flow rate in order to provide flow fairness and an optimal forwarding delay will improve the flow fairness.

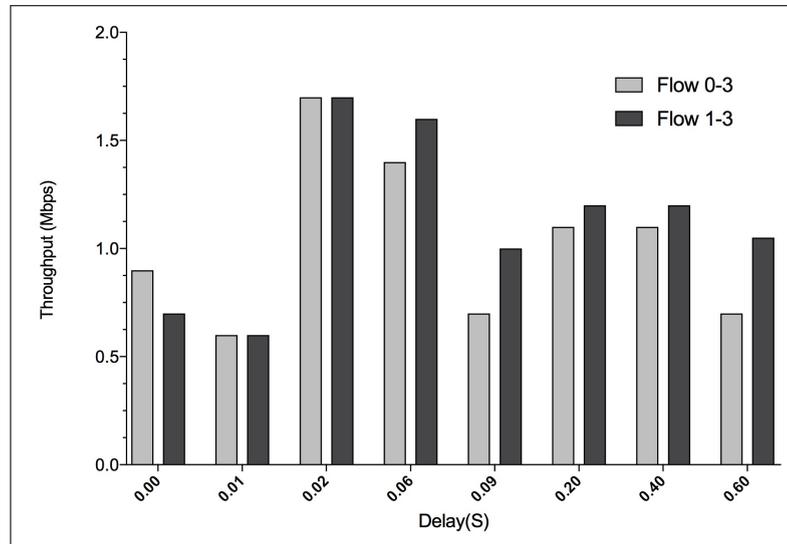


FIGURE 5.30: Finding optimum delay for 0-3 and 1-3 flows with fairness.

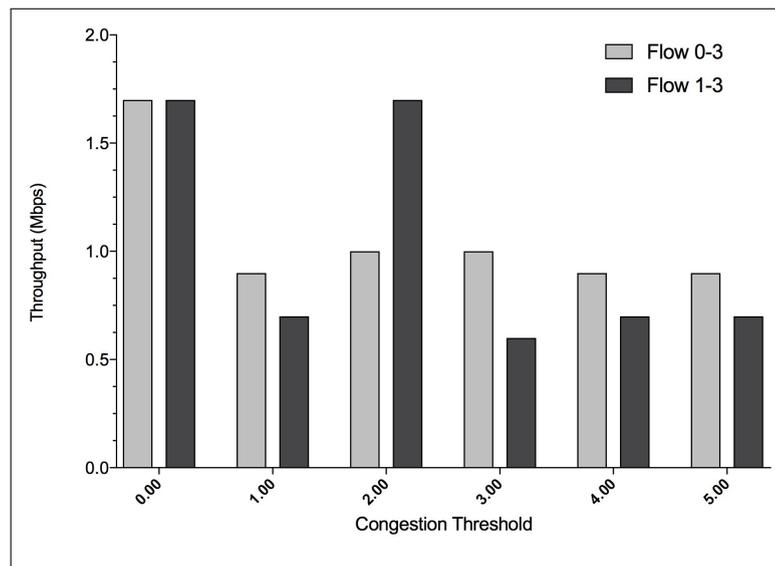


FIGURE 5.31: Finding optimum congestion threshold for 0-3 and 1-3 flows with fairness.

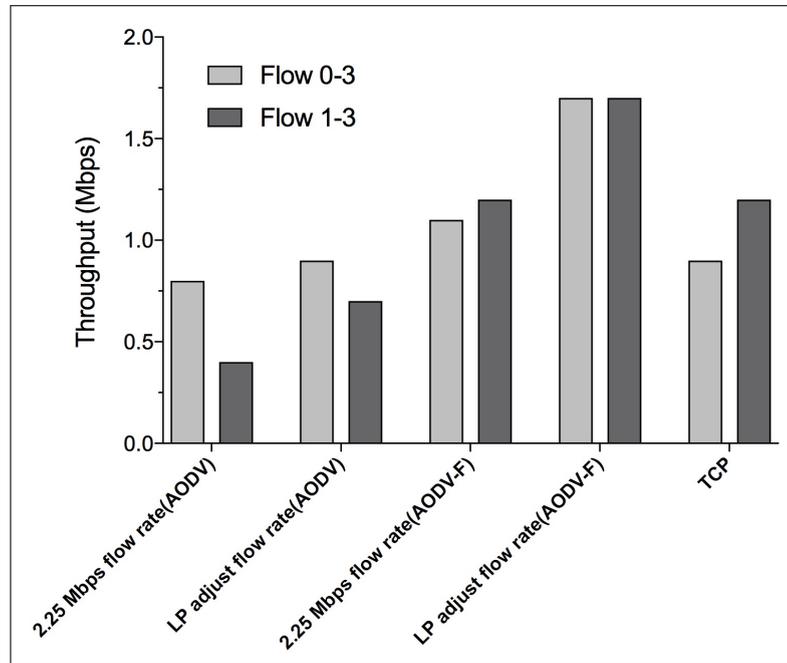


FIGURE 5.32: Throughput of flows 1-3 and 0-3 with fairness.

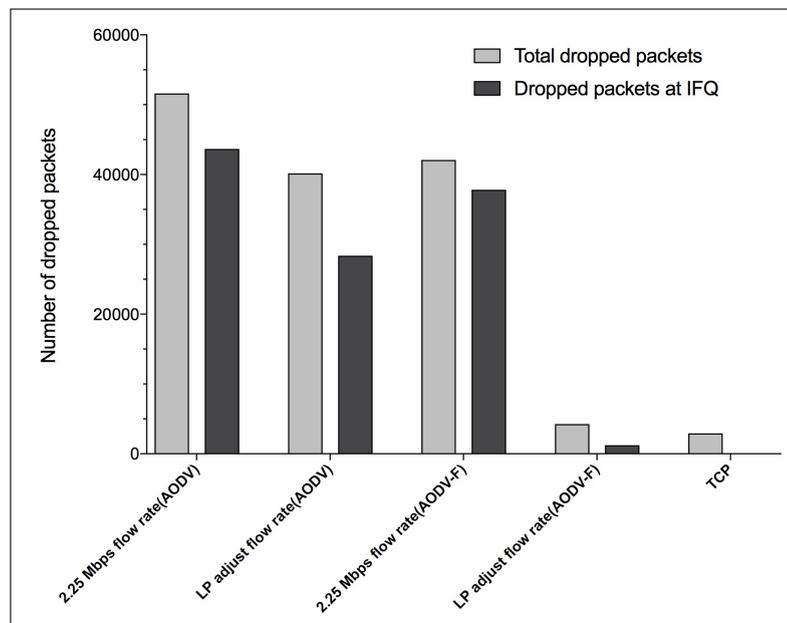


FIGURE 5.33: Number of dropped packets of flows 1-3 and 0-3 with fairness.

**Scenario F-2**

The network in Figure 5.9 is simulated with 2 flows. Node 0 is the common source, and node 2 and 3 are the destinations. The LP solution for this scenario has 1.375 Mbps flow rate for each flow.

First of all, in order to find an optimum forwarding delay and congestion threshold, we examined a range of delays and congestion thresholds in LP-based flow rate adjustments and AODV-F. For this scenario, as shown in Figure 5.34 and Figure 5.35, the optimum delay is 0.01s and the congestion threshold is 1, which give better flow throughput than immediate forwarding and more fairness. Then, we have applied this delay of 0.01s and the congestion threshold 1 to different cases of setting the flow rates (flow rate 2.25 Mbps and LP-adjusted flow rates). Figure 5.36 shows that the combination of LP-based flow rate and forwarding delay 0.01s leads to better fairness than using 2.25 Mbps and TCP. Moreover, the combination of LP-adjusted flow rate and forwarding delay reduces the number of dropped packets at the IFQ to 0, as shown in Figure 5.37.

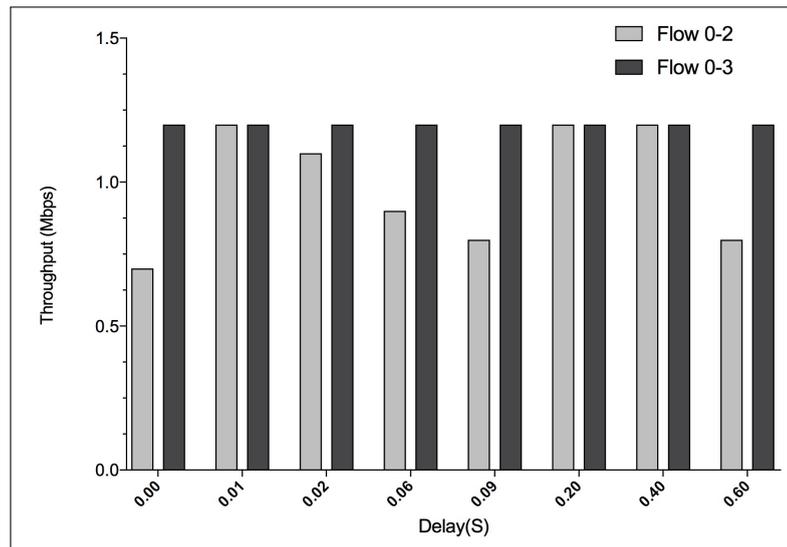


FIGURE 5.34: Finding optimum delay for 0-2 and 0-3 flows with fairness.

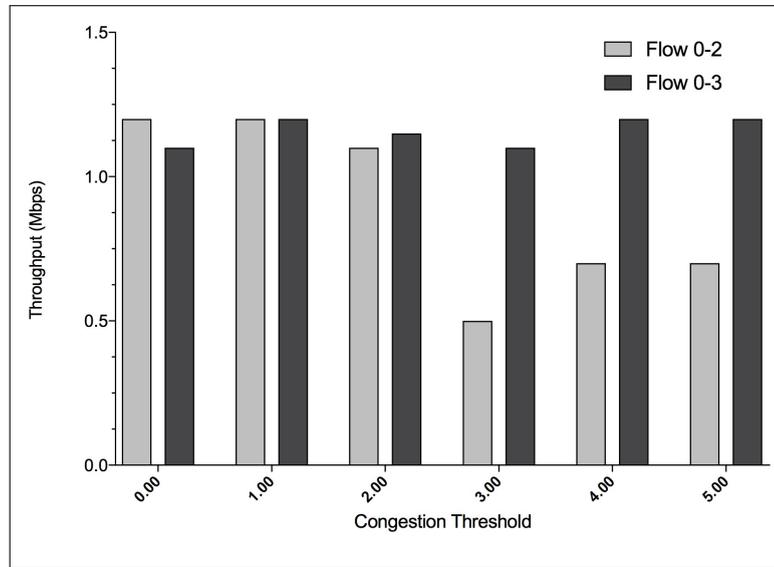


FIGURE 5.35: Finding optimum congestion threshold for 0-2 and 0-3 flows with fairness.

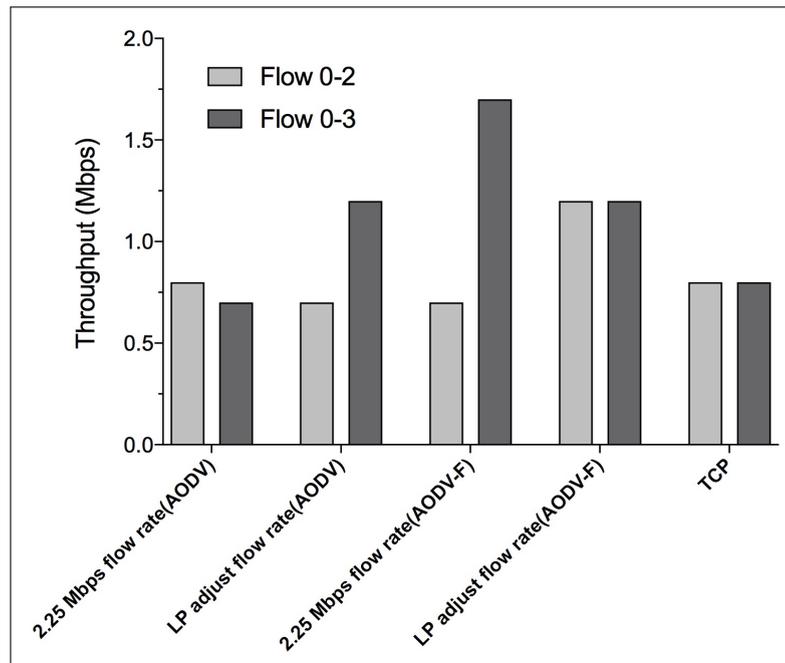


FIGURE 5.36: Throughput of flows 0-2 and 0-3 with fairness.

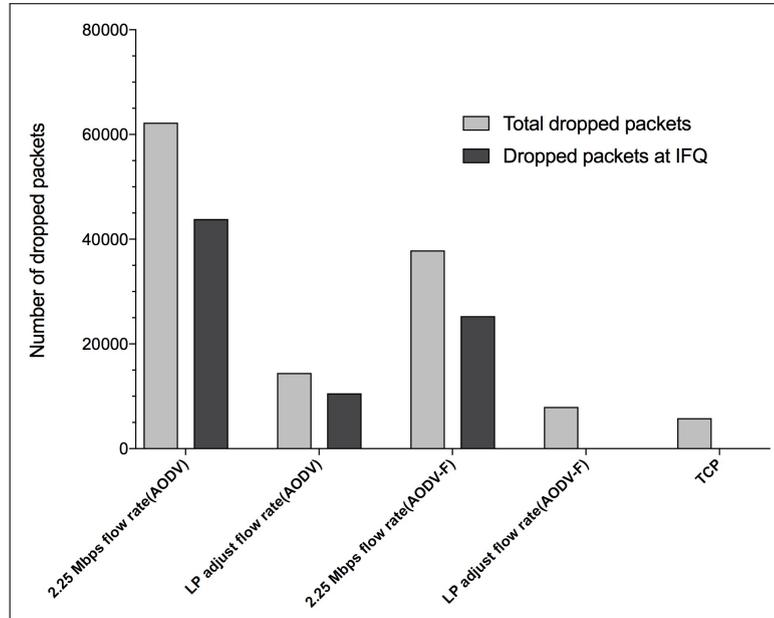


FIGURE 5.37: Number of dropped packets of flows 0-2 and 0-3 with fairness.

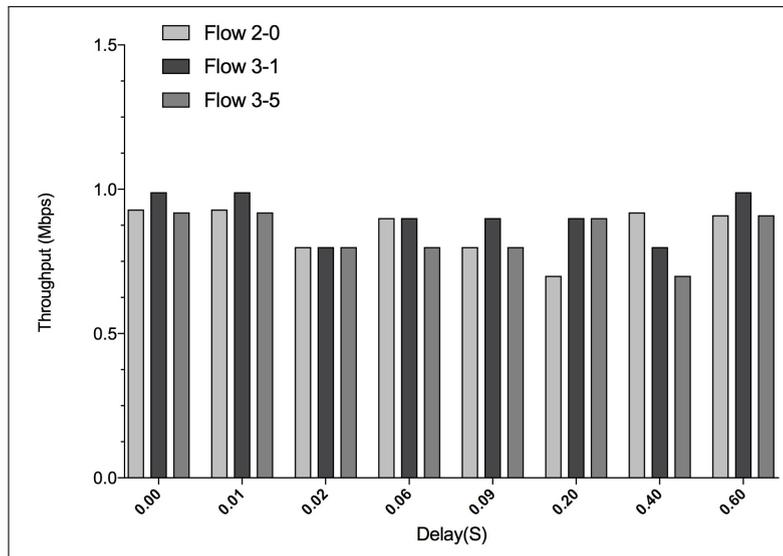


FIGURE 5.38: Finding optimum delay for 2-0, 3-1 and 3-5 flows with fairness.

### 5.5.3.3 Scenario G

In this scenario, we investigate flow throughput fairness in a network with high congestion. Three flows in the network shown in Figure 5.9 have been introduced. The first two flows are from node 3 to node 1 and to node 5, and the third flow is from node 2 to node 0. Solving the LP yields a flow rate of 1 Mbps for each flow.

Figure 5.39 shows that adjusting the flow rate according to the LP achieves better flow fairness than using a fixed flow rate of 2.25 Mbps and TCP. In addition, Figure 5.38 illustrates that the LP-based flow rate adjustment alone is sufficient in this scenario. This improvement can be explained by the observation that the LP-adjusted flow rate reduces the number of dropped packets at the IFQ to 0, as shown in Figure 5.40. Therefore, this reduction reduces the network congestion and then the AODV routing protocol will select a good quality path. Interestingly, the TCP gives a higher transmission rate for the flow from node 2 to node 0 than the flow from node 3 to node 1. This is perhaps because the node 3 is a common source for destinations nodes 1 and 5, so the node 3 is more likely to be a congested node. Therefore, the TCP reduces the transmission rate of node 3.

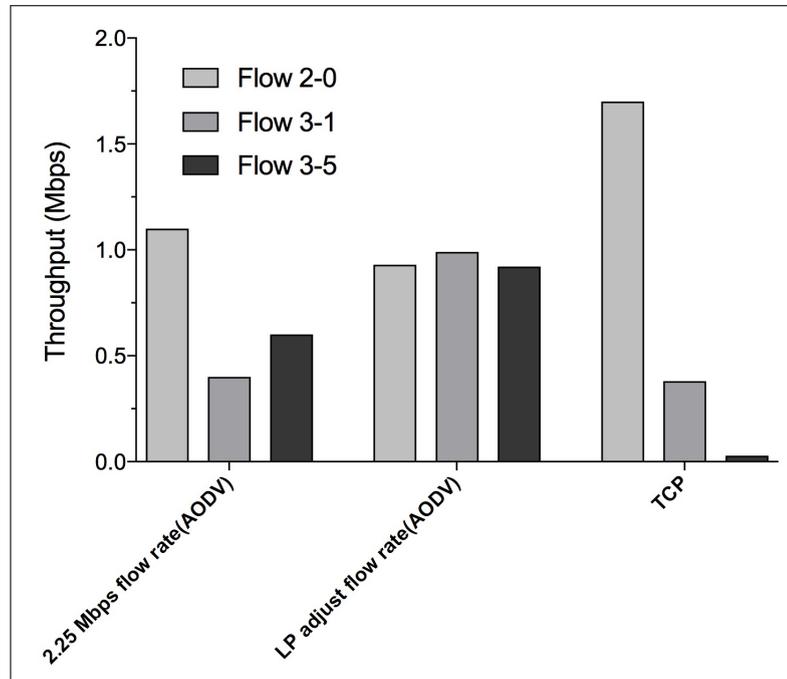


FIGURE 5.39: Throughput of flows 2-0, 3-1 and 3-5 with fairness.

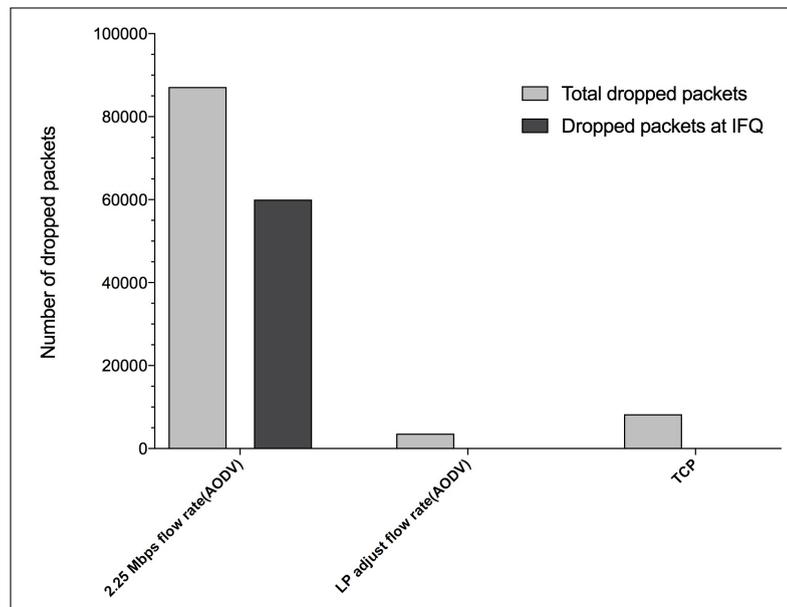


FIGURE 5.40: Number of dropped packets of flows 2-0, 3-1 and 3-5 with fairness.

## 5.6 Summary

In this chapter, we have addressed the problem of packet drops at the IFQ in two stages. Firstly, we have adjusted the traffic rates in order to avoid the congestion occurring due to heavy traffic load. As shown in the chain network, the adjusted flow rates improve the network throughput. Secondly, we have designed a simple forwarding delay scheme to address the congestion due to buffer overflow that arises in more complex network topologies. Moreover, we have examined the LP-based flow rate, optimal forwarding delay and congestion threshold in order to maximise the flow fairness. Combining an optimal forwarding delay, congestion threshold, adjusted flow rates and selecting a good quality path can improve the network performance. Our simulation has confirmed that there is a significant throughput improvement and a dramatic reduction of dropped packets at IFQ, and also there is an increase in the flow fairness. We think that the network topology and the traffic load affect the optimum forwarding delay and congestion threshold. For example, with high traffic load the optimum forwarding delay is more likely to be high while the congestion threshold tends to be small.

# Chapter 6

## Conclusion

This chapter summarises the research contribution and presents some directions for future research.

### 6.1 Thesis Summary

In the WMNs, the nodes share the network resources such as the medium and network bandwidth; also, the network nodes are one of the key elements for forwarding (routing) the data between a sender and a receiver. Therefore, managing the network resources is challenging due to the fact that there are a lot of packets being dropped in wireless networks. There are many reasons why the packets are dropped, such as signal interference, network congestion and mobility. One way to reduce the number of dropped packets in wireless networks is to employ a multi-channel technique [49]. Therefore, the aim of this work was to improve the network throughput by selecting a good quality path and reducing the number of dropped packets due to congestion. However, the routing has to be designed to consider the advantages of

multi-channel networks efficiently, and the routing metric is one of the key elements in this.

The first contribution in this thesis was to design a routing metric for a single-channel network; it is called Expected Transmission Time with Queueing (ETTQ). The ETTQ is an improved metric based on the ETT [16]. The ETT is the expected transmission time for a packet over a path considering the packet loss ratio and transmission rate. However, the ETT does not consider the time consumed by queuing the packet before it is transmitted over the link. The ETTQ does consider the queuing delay; it does this by multiplying the ETT metric by the number of queued packets. Therefore, the ETTQ will select a path with a light load. In addition, the ETTQ has been implemented in the basic AODV routing protocol. The performance evaluation of the ETTQ via the simulation in different scenarios demonstrated that it has a better performance in comparison with metrics discussed in previous work such as ETX [13], ETT [16] and EED [34].

In order to take advantage of the multi-channel network, the ETTQ has been combined with the MRAB [35] and a routing metric called the Delay and Interference Aware Metric (DIAM) has been proposed. The DIAM considers the inter-flow and intra-flow interference and the queueing delay over a path. It efficiently selects the path with a high data rate and low signal interference. The DIAM has been implemented in the basic AODV routing protocol. In addition, the performance evaluation in the simulation showed that the DIAM gives a good performance compared to WCETT [16], MRAB and WEED [35] as tested in Chapter 3 in different scenarios.

With mobility nodes may move, as a result, the network topology and interference degree will change. The mobile nodes may increase or decrease the interference

degree if they approach or move away from other nodes. The DIAM routing metric has been adapted to deal with the mobility issue by efficiently selecting the path by estimating the interference degree. The adapted DIAM has been implemented in the basic AODV routing protocol and evaluated by simulation in different scenarios. The simulation results show that the adapted DIAM has a better performance than the DSDV.

In order to improve the network throughput from a different perspective, another important factor for packet loss is network congestion, which may be caused by high traffic load. In this work, we considered congestion due the high traffic load at the forwarding nodes. To solve this issue, we adjusted the flow rate by solving a Linear Program (LP) in order to maximise the total network throughput and flow fairness. In addition, we proposed a simple forwarding delay scheme in order to reduce the dropped packets at IFQ and then improve the network performance.

## 6.2 Future Work

This section provides some interesting directions for further research into wireless mesh networks:

- In Chapter 3, we designed a routing metric for static wireless mesh networks to select an efficient path. One of the potential future directions for research is to adjust the transmitting power such as [61] and [17]. One of the possible ideas for control the transmitting power based on the distance between the sender and the next hop node, which would allow the transmitter to communicate with the next hop by using less power. Therefore, adjusting the transmitting power reduces the interference and also reduces power consumption, which is one of the hot topics in wireless mesh networks, especially with mobile nodes.

- The ETTQ routing metric provides simple load balancing by measuring the queue size. In order to improve the metric in relation to load balancing, it is better to equalise the utilisation of a channel by shared nodes. Hence, the load balancing could provide a fairly shared channel in wireless networks. This would be another interesting direction for future research.
- Routing overheads consume the link bandwidth and increase the interference, which affects the network performance. Therefore, it would be interesting to design an algorithm to reduce unnecessary broadcasting of control messages.
- In Chapter 5, we utilised the LP to adjust the flow rate in order to reduce the congestion at the forwarding nodes. For future work, it would be useful to find an alternative approach to constructing and solving the LP for larger networks (for example, using techniques such as column generation), in order to be able to apply the approach to networks with a larger number of links and flows. The effects of flow rate adjustments and forwarding delays can then be examined after solving the large LP in simulations or tested experiments.
- In Chapter 5, we used the CBR data rate that transmits the data in a constant bit per second. It would be interesting to examine the average bitrate that can transfer average amount of data per second. The average bitrate may contribute to the development of the network performance.
- In Chapter 5, we designed a simple forwarding delay algorithm. The algorithm has a congestion threshold and we set this value experimentally. Thus, it would be interesting to find an automated way to determine the congestion threshold and the optimal delay. For example, utilising machine learning approach could be a good way in order to predict the congestion threshold and the optimal delay.

# Bibliography

- [1] NS3 Home Page. <https://www.nsnam.org/>. [accessed on November-2017].
- [2] OMNeT++ Home Page. <https://omnetpp.org/>. [accessed on November-2017].
- [3] H. Aiache, V. Conan, L. Lebrun, and S. Rousseau. A load dependent metric for balancing internet traffic in wireless mesh networks. In *2008 5th IEEE International Conference on Mobile Ad Hoc and Sensor Systems*, pages 629–634, Sept 2008.
- [4] Ian F Akyildiz and Xudong Wang. A survey on wireless mesh networks. *IEEE Communications Magazine*, 43(9):S23–S30, 2005.
- [5] Ian Fuat Akyildiz. *Wireless mesh networks*. Wiley, Chichester, U.K., 2009.
- [6] Mokhtar S Bazaraa, John J Jarvis, and Hanif D Sherali. *Linear Programming and Network Flows*. John Wiley & Sons, 2011.
- [7] Eikland Kjell Berkelaar Michel and Notebaert Peter. lpsolve, version 5.5. *Eindhoven University of Technology*, <http://sourceforge.net/projects/lpsolve>, 2006.
- [8] Josh Broch, David A Maltz, David B Johnson, Yih-Chun Hu, and Jorjeta Jetcheva. A performance comparison of multi-hop wireless ad hoc network routing protocols. In *Proceedings of the 4th Annual ACM/IEEE International Conference on Mobile Computing and Networking*, pages 85–97. ACM, 1998.

- [9] Ramon Agüero Calvo and Jesús Pérez Campo. Adding multiple interface support in ns-2. *University of Cantabria*, 2007.
- [10] Tracy Camp, Jeff Boleng, and Vanessa Davies. A survey of mobility models for ad hoc network research. *Wireless Communications and Mobile Computing*, 2(5):483–502, 2002.
- [11] I. D. Chakeres and E. M. Belding-Royer. Aodv routing protocol implementation design. In *24th International Conference on Distributed Computing Systems Workshops, 2004. Proceedings.*, pages 698–703, March 2004.
- [12] Dah-Ming Chiu and Raj Jain. Analysis of the increase and decrease algorithms for congestion avoidance in computer networks. *Computer Networks and ISDN Systems*, 17(1):1–14, 1989.
- [13] Douglas SJ De Couto, Daniel Aguayo, John Bicket, and Robert Morris. A high-throughput path metric for multi-hop wireless routing. *Wireless Networks*, 11(4):419–434, 2005.
- [14] Richard Draves, Jitendra Padhye, and Brian Zill. Comparison of routing metrics for static multi-hop wireless networks. In *ACM SIGCOMM Computer Communication Review*, volume 34, pages 133–144. ACM, 2004.
- [15] Richard Draves, Jitendra Padhye, and Brian Zill. Comparison of routing metrics for static multi-hop wireless networks. *SIGCOMM Computer Communication Review*, 34(4):133–144, August 2004.
- [16] Richard Draves, Jitendra Padhye, and Brian Zill. Routing in multi-radio, multi-hop wireless mesh networks. In *Proceedings of the 10th Annual International Conference on Mobile Computing and Networking, MobiCom '04*, pages 114–128, New York, NY, USA, 2004. ACM.

- [17] H. Farhadi, C. Wang, and M. Skoglund. Distributed transceiver design and power control for wireless mimo interference networks. *IEEE Transactions on Wireless Communications*, 14(3):1199–1212, March 2015.
- [18] Paul Fortier and Howard Michel. *Computer Systems Performance Evaluation and Prediction*. Digital Press, 2003.
- [19] J. Suarez Francisco, Nuno Pelayo, C. Granda Juan, and F. Garcia Daniel. Chapter 7 - computer networks performance modeling and simulation. In Mohammad S. Obaidat, Petros Nicopolitidis, and Faouzi Zarai, editors, *Modeling and Simulation of Computer Networks and Systems*, pages 187–223. Morgan Kaufmann, Boston, 2015.
- [20] J. Guerin, M. Portmann, and A. Pirzada. Routing metrics for multi-radio wireless mesh networks. In *Australasian Telecommunication Networks and Applications Conference, 2007. ATNAC 2007*, pages 343–348, Dec 2007.
- [21] A. C. V. Gummalla and J. O. Limb. Wireless medium access control protocols. *IEEE Communications Surveys Tutorials*, 3(2):2–15, 2000.
- [22] T. He, F. Ren, C. Lin, and S. Das. Alleviating congestion using traffic-aware dynamic routing in wireless sensor networks. In *2008 5th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks*, pages 233–241, June 2008.
- [23] P. Heidelberger and S. S. Lavenberg. Computer performance evaluation methodology. *IEEE Transactions on Computers*, C-33(12):1195–1220, Dec 1984.
- [24] Holger Hermanns, Ulrich Herzog, and Joost-Pieter Katoen. Process algebra for performance evaluation. *Theoretical Computer Science*, 274(1):43 – 87, 2002. Ninth International Conference on Concurrency Theory 1998.

- [25] Xiaoyan Hong, Kaixin Xu, and Mario Gerla. Scalable routing protocols for mobile ad hoc networks. *IEEE Network*, 16(4):11–21, 2002.
- [26] Bret Hull, Kyle Jamieson, and Hari Balakrishnan. Mitigating congestion in wireless sensor networks. In *Proceedings of the 2nd International Conference on Embedded Networked Sensor Systems*, pages 134–147. ACM, 2004.
- [27] Teerawat Issariyakul and Ekram Hossain. *Introduction to network simulator NS2*. Springer Science & Business Media, 2011.
- [28] Kamal Jain, Jitendra Padhye, Venkata N. Padmanabhan, and Lili Qiu. Impact of interference on multi-hop wireless network performance. In *Proceedings of the 9th Annual International Conference on Mobile Computing and Networking, MobiCom '03*, pages 66–80, New York, NY, USA, 2003. ACM.
- [29] Kamal Jain, Jitendra Padhye, Venkata N Padmanabhan, and Lili Qiu. Impact of interference on multi-hop wireless network performance. *Wireless Networks*, 11(4):471–487, 2005.
- [30] J. W. Jiang, W. Yichuan, L. Yanxiao, Z. Lei, M. Weigang, and Y. Li. A new interference aware routing metric for multi-radio multi-channel wireless mesh networks. In *2016 International Conference on Networking and Network Applications (NaNA)*, pages 135–140, July 2016.
- [31] David B. Johnson and David A. Maltz. *Dynamic Source Routing in Ad Hoc Wireless Networks*, pages 153–181. Springer US, Boston, MA, 1996.
- [32] R. Kumar, R. Crepaldi, H. Rowaihy, A. F. Harris III, G. Cao, M. Zorzi, and T. F. La Porta. Mitigating performance degradation in congested sensor networks. *IEEE Transactions on Mobile Computing*, 7(6):682–697, June 2008.

- [33] Rami Langar, Nizar Bouabdallah, and Raouf Boutaba. Mobility-aware clustering algorithms with interference constraints in wireless mesh networks. *Computer Networks*, 53(1):25–44, 2009.
- [34] Hongkun Li, Yu Cheng, Chi Zhou, and Weihua Zhuang. Minimizing end-to-end delay: A novel routing metric for multi-radio wireless mesh networks. In *INFOCOM 2009, IEEE*, pages 46–54, April 2009.
- [35] Hongkun Li, Yu Cheng, Chi Zhou, and Weihua Zhuang. Routing metrics for minimizing end-to-end delay in multiradio multichannel wireless networks. *IEEE Transactions on Parallel and Distributed Systems*, 24(11):2293–2303, Nov 2013.
- [36] Jinyang Li, Charles Blake, Douglas S.J. De Couto, Hu Imm Lee, and Robert Morris. Capacity of ad hoc wireless networks. In *Proceedings of the 7th Annual International Conference on Mobile Computing and Networking, MobiCom '01*, pages 61–69, New York, NY, USA, 2001. ACM.
- [37] Wenjing Li, Ming Lou and Kai Zeng. *Multihop Wireless Networks*. Wiley, 2011.
- [38] L. Ma and M. K. Denko. A routing metric for load-balancing in wireless mesh networks. In *Advanced Information Networking and Applications Workshops, 2007, AINAW '07. 21st International Conference on*, volume 2, pages 409–414, May 2007.
- [39] A. M. Mashraqi and T. Erlebach. Delay and interference aware metric in multi-channel wireless mesh network. In *2016 Wireless Telecommunications Symposium (WTS)*, pages 1–7, April 2016.
- [40] Aisha Mousa Mashraqi and Thomas Erlebach. Throughput improvement by reducing dropped packets at interface queue (IFQ) in multi-channel wireless mesh networks. *2017 14th International Symposium on Pervasive Systems*,

- Algorithms and Networks & 2017 11th International Conference on Frontier of Computer Science and Technology & 2017 Third International Symposium of Creative Computing (ISPAN-FCST-ISCC)*, pages 140–147, 2017.
- [41] Sudip Misra, Subhas Chandra Misra, and Isaac Woungang. *Guide to wireless mesh networks*. Springer, 2009.
- [42] DG Narayan, M Uma, G Pavan, and S Suraj. CL-ILD: a cross layer interference-load and delay aware routing metric for multi-radio wireless mesh network. In *Advanced Computing, Networking and Security (ADCONS), 2013 2nd International Conference on*, pages 181–186. IEEE, 2013.
- [43] Georgios Parissidis, Merkourios Karaliopoulos, Rainer Baumann, Thrasyvoulos Spyropoulos, and Bernhard Plattner. Routing metrics for wireless mesh networks. In *Guide to wireless mesh networks*, pages 199–230. Springer, 2009.
- [44] Charles E. Perkins and Pravin Bhagwat. Highly dynamic destination-sequenced distance-vector routing (dsv) for mobile computers. *SIGCOMM Computer Communication Review*, 24(4):234–244, October 1994.
- [45] Charles E Perkins and Elizabeth M Royer. The ad hoc on-demand distance-vector protocol. In *Ad hoc Networking*, pages 173–219. Addison-Wesley Longman Publishing Co., Inc., 2001.
- [46] E. Perkins C., Belding-Royer and S. Das. Ad hoc on-demand distance vector (aodv) routing. *SIGCOMM Computer Communication Review*, 24(4), October 2003.
- [47] Larry L Peterson and Bruce S Davie. *Computer networks: a systems approach*. Elsevier, 2007.
- [48] Jon Postel. Transmission control protocol. *RFC 793, IETF*, 1981.

- [49] A. Raniwala and Tzi-cker Chiueh. Architecture and algorithms for an IEEE 802.11-based multi-channel wireless mesh network. In *Proceedings IEEE 24th Annual Joint Conference of the IEEE Computer and Communications Societies.*, volume 3, pages 2223–2234 vol. 3, March 2005.
- [50] T. S. Rappaport. Wireless personal communications: trends and challenges. *IEEE Antennas and Propagation Magazine*, 33(5):19–29, Oct 1991.
- [51] E. M. Royer, P. M. Melliar-Smith, and L. E. Moser. An analysis of the optimum node density for ad hoc mobile networks. In *ICC 2001. IEEE International Conference on Communications. Conference Record (Cat. No.01CH37240)*, volume 3, pages 857–861 vol.3, 2001.
- [52] E. M. Royer and Chai-Keong Toh. A review of current routing protocols for ad hoc mobile wireless networks. *IEEE Personal Communications*, 6(2):46–55, Apr 1999.
- [53] K. Sangeetha, R. Priyadharsini, A. Anbuelaveni, and R. Sivaranjani. Comparative study on different interference aware routing metrics in WMN: A survey. In *Advanced Computing (ICoAC), 2012 Fourth International Conference on*, pages 1–6, Dec 2012.
- [54] Subir Kumar Sarkar, TG Basavaraju, and C Puttamadappa. *Ad hoc mobile wireless networks: principles, protocols and applications*. CRC Press, 2007.
- [55] C. Sergiou, P. Antoniou, and V. Vassiliou. A comprehensive survey of congestion control protocols in wireless sensor networks. *IEEE Communications Surveys and Tutorials*, 16(4):1839–1859, Fourth quarter 2014.
- [56] C. Sergiou and V. Vassiliou. Dalpas: A performance aware congestion control algorithm in wireless sensor networks. In *2011 18th International Conference on Telecommunications*, pages 167–173, May 2011.

- [57] Charalambos Sergiou, Vasos Vassiliou, and Aristodemos Paphitis. Hierarchical tree alternative path (HTAP) algorithm for congestion control in wireless sensor networks. *Ad Hoc Networks*, 11(1):257 – 272, 2013.
- [58] Devu Manikantan Shila and Tricha Anjali. Load aware traffic engineering for mesh networks. *Computer Communications*, 31(7):1460–1469, 2008.
- [59] William Stallings and Moumita Mitra Manna. *Data and Computer Communications*, volume 6. Prentice Hall Englewood Cliffs, NJ, 1997.
- [60] A. P. Subramanian, M. M. Buddhikot, and O. Miller. Interference aware routing in multi-radio wireless mesh networks. In *2006 2nd IEEE Workshop on Wireless Mesh Networks*, pages 55–63, Sept 2006.
- [61] Chi Wan Sung and Kin-Kwong Leung. A generalized framework for distributed power control in wireless networks. *IEEE Transactions on Information Theory*, 51(7):2625–2635, July 2005.
- [62] Miguel SÁnchez and Pietro Manzoni. Anejos: a java based simulator for ad hoc networks. *Future Generation Computer Systems*, 17(5):573 – 583, 2001. I: Best of Websim99. II: Traffic Simulation.
- [63] Vahid Tarokh, Nambi Seshadri, and A Robert Calderbank. Space-time codes for high data rate wireless communication: Performance criterion and code construction. *IEEE Transactions on Information Theory*, 44(2):744–765, 1998.
- [64] Ye Tian, Kai Xu, and Nirwan Ansari. TCP in wireless environments: problems and solutions. *IEEE Communications Magazine*, 43(3):S27–S32, 2005.
- [65] D. A. Tran and H. Raghavendra. Congestion adaptive routing in mobile ad hoc networks. *IEEE Transactions on Parallel and Distributed Systems*, 17(11):1294–1305, Nov 2006.

- [66] U. Ullah, A. K. Kiani, R. F. Ali, and R. Ahmad. Network adaptive interference aware routing metric for hybrid wireless mesh networks. In *2016 International Wireless Communications and Mobile Computing Conference (IWCMC)*, pages 405–410, Sept 2016.
- [67] Chieh-Yih Wan, Shane B. Eisenman, and Andrew T. Campbell. Coda: Congestion detection and avoidance in sensor networks. In *Proceedings of the 1st International Conference on Embedded Networked Sensor Systems, SenSys '03*, pages 266–279, New York, NY, USA, 2003. ACM.
- [68] Alec Woo and David E Culler. A transmission control scheme for media access in sensor networks. In *Proceedings of the 7th Annual International Conference on Mobile Computing and Networking*, pages 221–235. ACM, 2001.
- [69] Yaling Yang, Jun Wang, and Robin Kravets. Load-balanced routing for mesh networks. *SIGMOBILE Mobile Computing and Communications Review*, 10(4):3–5, October 2006.
- [70] Xukai Zou, Byrav Ramamurthy, and Spyros Magliveras. Routing techniques in wireless ad hoc networks classification and comparison. In *Proceedings of the Sixth World Multiconference on Systemics, Cybernetics and Informatics, SCI*, pages 1–6, 2002.