DEVELOPMENT OF AN IMPROVED LINK METRIC FOR ROUTING PROTOCOLS IN WIRELESS AD-HOC NETWORKS

by

Kabiwa Tchokonte Maxime Stephane

Submitted in partial fulfilment of the requirements for the degree

MAGISTER TECHNOLOGIAE

in the

Department of Electrical Engineering / FSATI

FACULTY OF ENGINEERING AND THE BUILT ENVIRONMENT

TSHWANE UNIVERSITY OF TECHNOLOGY

Supervisor : Prof. K. Djouani
Co-Supervisor : Dr. A. Kurien

February 2014

Declaration

"I hereby declare that the thesis submitted for the degree M Tech: Electrical Engineering, at the Tshwane University of Technology, is my own original work and has not previously been submitted to any other institution of higher education. I further declare that all sources cited or quoted are indicated and acknowledged by means of a comprehensive list of references".

M.S. Kabiwa

Dedication

To God who strengthens me, be all the glory.

This work is dedicated to my beloved family; my mother, Yambou Julienne; my late father, Tchokonte David; and my brother-in-law, Mr Tiani Placide. I would not be who I am today without you. Thank you for all the support and prayers. I am forever grateful to you.

Acknowledgements

First and above all, I praise God the Almighty for providing me with this opportunity and granting me the capability to proceed successfully. This dissertation summarises two years worth of effort, frustration and achievement. However, there are several people to whom I am indebted for their contribution and support in various aspects of this research and in the writing of this dissertation.

First of all, I would like to express my sincere gratitude to my supervisor and co-supervisor, Prof Karim Djouani and Dr Anish Kurien for supporting me and giving me the freedom to explore this interesting research area these past years. Throughout the years, their advice, guidance, insights, patience and words of encouragement have often inspired me and renewed my hopes for completing this dissertation.

Most importantly, none of this would have been possible without the love, prayers and patience of my family. My family to whom this dissertation is dedicated, has been a constant source of love, concern, support and strength all these years.

Many friends have helped me stay sane throughout these difficult years. Their support and care helped me overcome setbacks and stay focused on my research study. I greatly value their friendship, and I deeply appreciate their belief in me.

I thank the Tshwane University of Technology and the French South African Institute of Technology (FSATI) for giving me the opportunity to further my career in a conducive environment.

Abstract

Wireless ad-hoc networks consist of wireless nodes. In these networks some nodes are not within transmission range of each other. Intermediate nodes act as routers to receive and send routing and data packets to the nodes in their transmission range. In these networks, messages are relayed or routed over multiple wireless hops to reach their destination through the utilisation of a routing protocol. The quality of the routing protocol depends on the efficiency of the routing metric operating in it. In wireless ad-hoc networks, all the nodes are broadcasting by nature and do not have a dedicated medium, as is the case in wired networks. Therefore, the nodes have to compete for the transmission opportunities with their neighbours, resulting in contention and bandwidth starvation for some nodes. This phenomenon is known as interference, and is the foremost factor that limits the capacity of the network.

This dissertation addresses the problem of interference in wireless ad-hoc networks. It is important for a routing metric to capture the potential interference experienced by the wireless links. In this study, an enhanced routing metric based on the Interference and Bandwidth adjusted Expected Transmission Count (IBETX) metric is proposed. As the original IBETX, this improved metric is a threefold metric. Firstly, it tackles the interference in wireless networks using a cross-layered approach by probing the physical layer. Using a physical interference model is less restrictive and more realistic. This model has the excellent advantage of depicting measures by using online data traffic in contrast with the original IBETX metric. Secondly, the nominal bit rate or transmission rate information is provided to all nodes in the same contention domain by considering the bandwidth-sharing mechanism of 802.11.Thirdly, as with the original IBETX and the Expected Transmission Count (ETX) metrics, the improved metric also calculates link delivery ratios that directly affect throughput and selects those routes or paths that bypass dense regions in the network.

Simulation results, using a discrete event simulator (NS-2), show that at a high traffic rate, the enhanced routing metric gives a 6% higher throughput than the original IBETX metric and an 11% higher than the ETX metric. It also succeeds to reduce the normalised routing load by 12% when compared with the original IBETX metric and by 11% when compared with the ETX metric. In terms of average packet end-to-end delay, it produces 6% less delay than the original IBETX metric and 8% less delay than the ETX metric.

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Acronyms and Abbreviations

ACK	Acknowledgement
AODV	Ad hoc On-demand Distance Vector
BPSK	Binary Phase Shift Keying
CBR	Constant Bit Rate
CBT	Channel Busy Time
CSMA-CA	Carrier Sensing Multiple Access with Collision Avoidance
CTS	Clear To Send
CSC	Channel Switching Cost
DCF	Distributed Coordinated Function
DSDV	Destination Sequenced Distance Vector
DSR	Dynamic Source Routing
DYMO	Dynamic Manets On-Demand
EDR	Expected Data Rate
ELB	Expected Link Bandwidth
ELD	Expected Link Delivery
ELI	Expected Link Interference
ELP	Expected Link Performance
ETP	Expected Throughput
ETT	Expected Transmission Time
ETX	Expected Transmission Count

FIFO	First In First Out
IBETX	Interference and Bandwidth adjusted ETX
iAWARE	Interference Aware
IF	Interference Factor
IR	Interference Ratio
IRU	Interference Resource Usage
MAC	Medium Access Control
MANETs	Mobile Ad-hoc Networks
MIC	Metric of Interference and channel switching
MIND	Metric for Interference and Channel Diversity
MCR	Multi-Channel Routing
MWNs	Multi-hop Wireless Networks
NAV	Network Allocation Vector
OLSR	Optimised Link State Routing
PDR	Packet Delivery Ratio
QPSK	Quadrature Phase Shift Keying
QAM	Quadrature Amplitude Modulation
RERR	Route Error
RREP	Route Reply
RREQ	Route Request
RTS	Clear To Send
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
TCD	Transmission Contention Degree
UDP	Unit Datagram Protocol
WCETT	Weighted Cumulative Expected Transmission Time
WMNs	Wireless Mesh Networks

CHAPTER 1. Introduction

1.1 Background and Motivation

Wireless ad-hoc networks consist of mobile battery-powered devices that attempt to communicate without exploiting any fixed infrastructure or pre-determined organisation of available links. Each node must discover which peers are available for direct connection and establish communication paths along the network. Messages are relayed or routed over multiple wireless hops to reach their destination. In order to have acceptable performance from underlying wireless ad-hoc networks, the routing protocol plays a key role in directing communication. The network routing process involves two steps. The first considers the assigning of cost metrics to links. The second provides the routing information in the network (Hossain E, 2007). Optimal paths are determined based on routing metrics; they play an important role in characterising the links since they obtain the information that will be used to make routing decisions.

For decades, most routing protocols used the strategy of finding the shortest path between the source and the destination in the network. This encouraged the use of the minimum hop-count for route selection in wireless ad-hoc routing protocols. There are other inherent reasons that support such a choice. The first is mobility; mobility has always been a major research area in Mobile Ad-hoc Networks (MANETs). The selection of the shortest path between a source-destination pair reduces the probability of route breakage due to the mobility of an intermediate node. The second reason is energy consumption in MANETs; the longer the route from the source to the destination, the more hops the data has to cross and this consequently impacts on the energy consumption. In static wireless ad-hoc or mesh networks in which nodes have low mobility or are stationary, energy consumption and mobility are not valid concerns. In fact, selecting the shortest path between a pair of nodes is a good choice if every wireless link in the network has the same characteristics. However, this is not the case in reality. There can be huge differences between wireless links (in terms of link latency; link interference; and link capacity or link loss ratio). Hence, using the minimum hop-count for quality-based applications such as Internet-based applications may not be a good choice (Douglas S. J. De Couto and Morris, 2002). These critical disadvantages of the minimum hop-count metric motivated the need for better performing link or cost metrics that can take into consideration the multiple factors influencing wireless networks. The pioneering metric in the research area of quality routing metrics was the Expected Transmission Count (ETX) (Couto, 2004). This estimates the number of transmissions and retransmissions needed to send a data packet successfully over a wireless link. It does not consider the fact that a node may use different transmission rates to different neighbours. In this case, the links with lower bit rates lower the performance of the faster links because they receive more time to transmit than the faster links. To overcome the limitations of the ETX metric, the Expected Transmission Time (ETT) metric (Draves *et al.*, 2004) was proposed. This is obtained by multiplying the ETX with the link bandwidth to obtain the expected link airtime for the successful transmission of a packet.Unlike wired networks, in wireless ad-hoc networks where all the nodes are broadcasting by nature and the links do not have the same characteristics, it is difficult or impossible to spatially partition the wireless medium into clear disjoints links. Therefore, the nodes must compete for the transmission opportunities with their neighbours resulting in contention and bandwidth starvation for some nodes. Consequently, interference is the foremost factor that limits capacity in wireless ad-hoc networks. Interference causes congestion and collisions that seriously affect the capacity of the network (Gupta and Kumar, 2000). Therefore, it is important for a routing metric to capture the potential interference experienced by the wireless links to find routes or paths that suffer less interference and improve the overall network capacity. Previous routing metrics do not take interference into account. In the literature, three main interference models have been proposed to pick up the inter-flow interference: the protocol (Gupta and Kumar, 2000); the physical (Padhye *et al.*, 2005); and the logical (U. Ashraf and Juanole, 2008) interference models. All these models of interference are influenced by the concept of transmission and interference ranges. In the protocol model, each node or radio has a transmission range and an interference range. A transmission from node X to node Y is successful if Y is in the transmission range of X and not in the interference range of nodes other than X. This model is very strict and restrictive. It is difficult to implement since it depends on the interference range, which changes quite often in wireless ad-hoc networks. The logical interference is based on the Carrier Sensing Multiple Access with Collision Avoidance (CSMA-CA) from Medium Access Control (MAC). This requires the station to wait until the channel is free before starting the transmission. The shared channel maybe occupied by transmissions from other nodes that are using the same channel within the interference range. This model is less restrictive than the protocol model. However, the logical interference model may not be suitable to meet the high-traffic demand of wireless ad-hoc networks. The reason is that CSMA-CA is a very conservative mechanism. Due to the combination of carrier-sensing and collision-avoidance techniques, several nodes in the network are silenced when a certain communication is ongoing. In (Javaid, 2010) and (U. Ashraf and Juanole, 2008), the authors proposed the Interference and Bandwidth adjusted Expected Transmission Count (IBETX) and the Expected Link Performance (ELP) routing metrics, respectively to tackle the issue of the inter-flow interference. These routing metrics take the interference into account by using the logical model but do not take into account or neglect the interference at the physical layer.

1.2 Problem Statement

The Interference and Bandwidth adjusted ETX routing metric uses a logical interference model that refers to the interference arising from the Carrier Sensing Multiple Access with Collision Avoidance (CSMA-CA) based Medium Access Control. This approach of capturing inter-flow is complex and more restrictive. In this dissertation, a more realistic and less restrictive approach based on the information available at the physical layer (signal strength) is used to capture the interference.In contrast to the logical interference model, this has the excellent advantage of measuring the parameters using online data traffic. The question is whether actual capacity improvements can be achieved by considering the physical interference model.

1.2.1 Sub-problem

To achieve the objectives of this research work, the following sub-problems are addressed:

- The network layer, which is responsible for choosing the wireless link to relay the packets to the destination and the physical layer where the relevant information for interference is available, are not adjacent. Therefore, there is a need to develop a cross layer to gather that information in a dynamic way and use it at the routing layer.
- The variations in links Signal to Interference Noise Ratio (SINR) and Signal to Noise Ratio (SNR) are very fast, in the order of microseconds for fast fading. Network topology changes more slowly, in the order of seconds, while variations

of user traffic based on their applications may change over tens to hundreds of seconds. These different time scales of the network variations suggest that each layer should attempt to compensate for variation at that layer first. There is a need to develop a method to obtain the SINR from the physical layer in an accurate way since these variations are so high.

1.3 Hypotheses

The following assumptions are subject to verification:

- Cross-layer approach is actually the collaboration across the borders, that is the sharing of information between the different layers such as, the network layer, the MAC layer and the physical layer. This concept is helpful in improving the overall network performance.
- The routing layer can give appreciable information in ad-hoc or multi-hop networks, if it takes the relevant information from the physical layer.
- Due to its very conservative nature, the logical interference can show poor performance when the offered load in the network is high.

1.4 Delimitation

Recent research indicates most of the quality link metrics perform best in low mobility or static networks because there is a need of time of initialisation in order to compute the cost metric of each wireless link before forwarding data packets. Therefore, this research focuses only on static networks. It only considers a single radio, single channel environment. All nodes have similar receiver characteristics: omni-directional antenna; the same transmit power and noise floor; and similar physical and MAC layer performance. Only software simulations are implemented in this dissertation.

1.5 Benefits of the Study

This research is of great importance since it addresses the problem of interference-aware routing in wireless networks, which is a central performance limiting factor. It considers the interference experienced by wireless links at the physical layer that use online data and their impact on routing decisions. A simple and efficient approach is proposed to capture the physical interference model.

1.6 Contributions

The contributions made in this research study are based on the information presented in the sub-problems. Listed below are the tangible research outputs made in this work:

- Kabiwa,M.S. Djouani, K. and Kurien, A. "Performance Evaluation of IBETX routing metric over DSDV Routing Protocol in Ad-hoc Wireless Networks", Accepted and presented at the 8th International Symposium on Intelligent Systems Techniques for Ad-hoc and Wireless Sensor Networks (IST-AWSN 2013), Halifax, Nova Scotia, Canada, June 25-28, 2013.
- Kabiwa, M.S. Djouani, K. and Kurien, A., "Performance Comparison of IBETX Routing Metric over AODV and DSDV Routing Protocols", Accepted and presented at the 10th International Wireless Communications and Mobile Computing Conference (IWCMC 2014), Nicosia, Cyprus, August 04-08, 2014.
- Kabiwa,M.S. Djouani, K. and Kurien, A., "Development of an Improved Routing Metric Based on IBETX Metric for Wireless Ad-hoc Networks", accepted and

presented at the 17th Southern African Telecommunication Networks and Applications Conference (SATNAC 2014), Port Elizabeth, South Africa, August 31-September 3 2014.

- Kabiwa, M.S. Djouani, K. and Kurien, A., “Improvement of a Link Metric in Wireless Ad-hoc Networks”, (POSTER presentation at the Faculty Research Day of the Faculty of Engineering and Built Environment, Tshwane University of Technology, Pretoria, South Africa, 7 September 2013)

1.7 Outline of the Dissertation

The remainder of this dissertation is structured as follows:

- Chapter 2 presents design considerations for routing metrics and a review of existing routing metrics for wireless networks along with their shortcomings.
- Chapter 3 presents a performance comparison of the recently proposed routing metric IBETX with two prominent routing protocols. The performance differentials are analysed using varying packet rate and size and number of sources.
- Chapter 4 presents the development of a proposed approach to capture interference at the physical layer.
- Chapter 5 covers the simulation results of the performance evaluation of the improved link quality metric.
- Chapter 6 concludes this dissertation. Based on the objectives set out, the achieved goals are highlighted. A number of recommendations for further work to be considered are also highlighted and followed by the final conclusions.

CHAPTER 2. Related Work On Routing Metrics in Wireless Mesh Networks

2.1 Introduction

Wireless Mesh Networks (WMNs) are composed of mesh routers that facilitate the connectivity and inter-communication of wireless clients through multi-hop wireless paths. In these networks, messages are relayed (routed) over multiple wireless hops to reach their destination. Yet, within these networks, routing metrics play a major role on the network efficiency and performance. In WMNs, the main goal is to achieve the best possible quality and efficiency of data transmission between the source and destination nodes.

Routing protocols are at the heart of WMNs, and the strength of the routing protocol depends on the efficiency of the routing metric operating in it. The routing metric first considers the quality routes and then selects the best end-to-end path. The routing metric plays an essential role in achieving the desired performance of the underlying network by making the routing protocol: fast enough to adapt to topological changes; light weight to minimally use the resources of nodes; and intelligent to select the fastest path from source to destination among the available paths. In this chapter, an extensive overview of existing routing metrics is given with their shortcomings highlighted.

2.2 Metric Components

Considering the demands of a wireless mesh network from its operating protocol and the factors influencing its performance, the main components that can be utilised to formulate a routing metric for multi-hop wireless networks are identified and discussed.

2.2.1 Link Capacity

The link capacity gives a view of the current throughput capability of a link. There are different ways in which this can be measured. These include actively probing the link to measure the transfer speeds, and relying on the current rate radio interface. Furthermore, because most interfaces have the ability to automatically lower their transmission speeds to deal with lossy links, finding links with higher capacity will lower medium access time and increase the performance of the network (B. Awerbuch and Rubens, 2003).

2.2.2 Channel Diversity

Using the same channel on multiple consecutive hops of a path results in significant co-channel interference and a reduction in the overall throughput. Ideally, all links of a path within interference range of each other should be operating on non-overlapping channels since this results in significant performance gains (Kumar, 2009). Channel diversity is only relevant for multi-radio networks, because in single radio networks, all interfaces are required to operate on the same channel to guarantee connectivity.

2.2.3 Link Quality

The determination of high-quality links could greatly improve the overall performance of a path through higher transfer speeds and lower error rates. Link quality can be evaluated in different ways. The most common metrics are Packet Delivery Ratio (PDR), which can be determined through active probing and Signal to Noise Ratio (SNR) which is typically available from the device driver of wireless interface.

2.3 Characteristics of a Routing Metric

Routing is a fundamental characteristic of Multi-hop Wireless Networks (MWNs). The routing protocol is responsible for controlling the formation, for configuration of the topology of the network and for selecting the best path with quality links from source to destination with low end-to-end delay and high throughput. To ensure good performance, Yang et al (Yang and Kravets, 2005) proposed four principle requirements that routing metrics must satisfy. Firstly, route stability: the routing metric should not vary greatly over time. Abrupt changes in the metric can trigger a protocol to send out route updates, and this may cause the protocols overhead to become extremely high. Secondly, minimum weight paths should be selected. Thirdly, efficient algorithms with polynomial complexity should be used to find minimum weight paths. Finally, the routing metric should be designed so that it does not cause loops. A good routing metric must accurately capture the quality of network links and aid in the computation of good quality paths. In the following section, the characteristics that must be taken into account while designing a routing metric are identified. It is worth stating that it is impossible to implement all mentioned characteristics in a single metric.

2.3.1 Interference

According to (Sudip Misra and Woungang, 2009), radio interference represents a superposition of signals or waves that changes the original (amplitude in particular) and causes bit alterations, which in turn, cause data and/or frame check sequence alterations. The result of these alterations is the link layer may drop packets causing a failed transmission. This is a serious issue in wireless multi-hop networks due to the shared nature of the wireless medium that results different flows competing for their share of the bandwidth. Interference can be classified in to three broad categories.

2.3.1.1 Intra-flow Interference

This form of interference occurs if more than one link on the same path within the radio range of a node uses the same channel (J. Guerin and Pirzada, 2007). Successive links in the path of a flow can interfere with each other and impact on the performance of the network. A simple solution to reduce the intra-flow interference is to increase the channel diversity by selecting different non-overlapping channels for adjacent hops of a path for a given flow. For example, in Figure 2.1, an interference aware metric should give a lower weight to the path $A \rightarrow D \rightarrow C$ than the path $A \rightarrow B \rightarrow C$ since the reuse of channel 1 (CH1) on the path $A \rightarrow B \rightarrow C$ creates more intra-flow interference than that in path $A \rightarrow D \rightarrow C$. The interference range of a node (area where a sending node can disturb the transmission from a third node) is typically bigger than a single hop. Hence, links on the same the channel in a multi-hop path can still interfere with each other and are not only restricted to immediate neighbours.

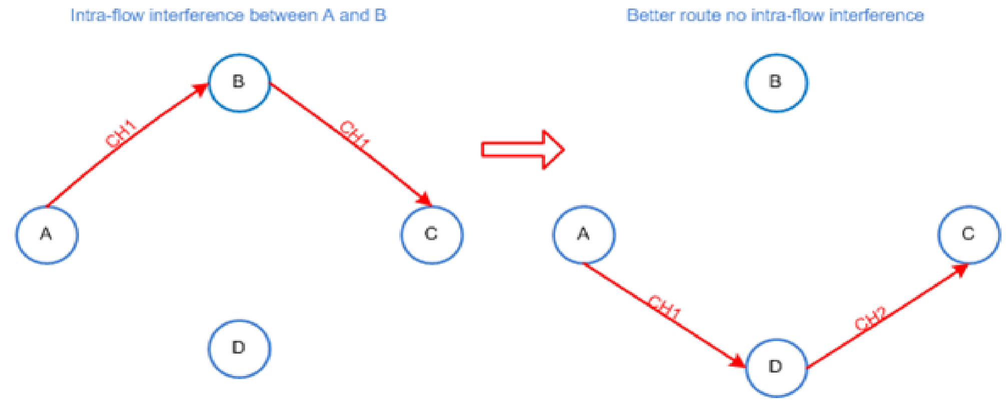

Figure 2.1: An example of intra-flow interference over a path

2.3.1.2 Inter-flow Interference

Inter-flow interference occurs when different flows operate on the same channel within the radio range (maximum range where a radio frequency signal can be correctly received) of each other, thereby competing for medium access. This may lead to bandwidth starvation because affected nodes might sense the channel to be busy. To avoid such starvation, the routing metric must help the routing protocol to choose paths that cannot only balance the traffic load along the path of a flow, but also reduce the inter-flow interference imposed in the entire neighbouring area. For example, in Figure 2.2, a good routing metric should give a lower weight to the path $A \rightarrow B \rightarrow C$ than the path $A \rightarrow D \rightarrow C$ since path $A \rightarrow B \rightarrow C$ is less affected by inter-flow interference than path $A \rightarrow D \rightarrow C$. It is difficult to predict the occurrence of the inter-flow interference. Hence, it is challenging to control it due to the involvement of multiple flows over different paths (Sudip Misra and Woungang, 2009).

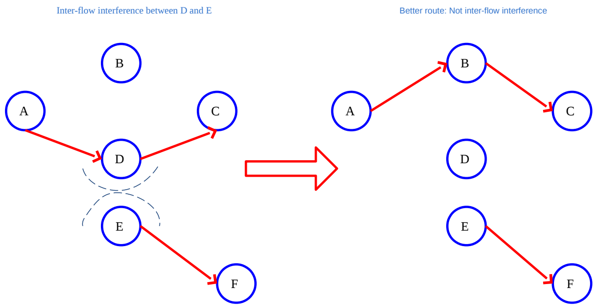

Figure 2.2: An example of inter-flow interference over a path

2.3.1.3 External interference

External interference occurs when a link experiences interference outside of the control of any node in the network. There are two types of external interferences: controlled interference, where other nodes external to the network use networking technologies that overlap with those used by the network; and uncontrolled interference, which is caused by any other source of radio signals emitted in the same frequency range but not participating in the same MAC protocol. In summary, to find minimum weight with good performance, a routing metric must capture both intra-flow and inter-flow interference.

2.3.2 Load Balancing

Load balancing is the ability of a routing link metric to balance the load and to provide fair usage of network resources. This is a very important consideration especially when there is a concentration of traffic at the Internet gateways in mesh networks. The routing metric should use real-time information on link capacity gathered from neighbouring nodes to make a choice, in order to avoid the highly loaded paths and thus minimise the impact on the neighbouring flows. This can be achieved by finding routes that are under-utilised (Liu and Liao, 2006).

2.3.3 Isotonicity

Isotonic property means that a routing link metric should ensure that the order of the weights of two paths is preserved if they are appended or prefixed by a common third path. If a routing metric does not account for the isotonic property, only algorithms with exponential complexity can calculate the minimum weight paths based on this routing link metric. Links might not be stable when routing algorithms use the isotonic property to calculate minimum weight paths. An example of isotonic property is given below, in which $w(a)$ refers to the weight or cost of a path a. Isotonicity is defined as follows: let $w(a)$ and $w(b)$ be the costs or weights of paths a and b respectively, if $w(a) \leq w(b)$ implies both $w(a \oplus c) \leq w(b \oplus c)$ and $w(c' \oplus a) \leq w(c' \oplus b)$, for all paths a, b, c, c' (Yang and Kravets, 2005). See (Figure 2.3)

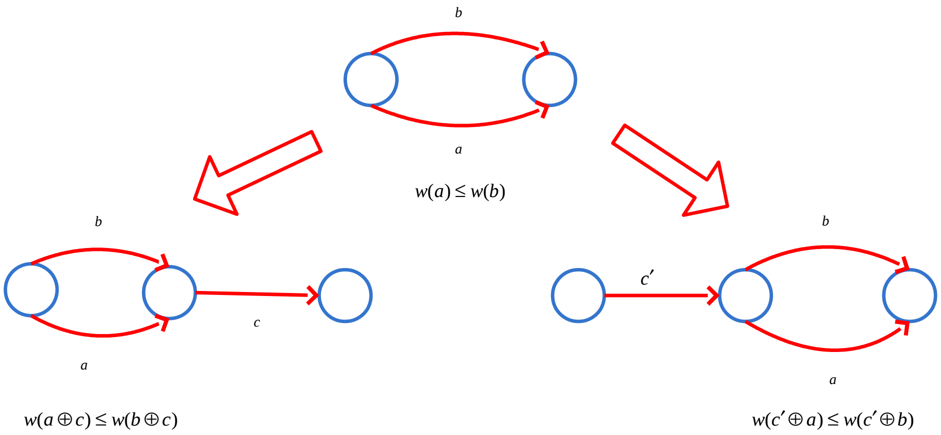

Figure 2.3: The isotonicity property

2.3.4 Agility

Agility refers to the ability of a routing link metric to respond quickly and efficiently to changes in the network in terms of load and topology. In order for a metric to be considered agile, the rate at which measurements are taken should be higher than the rate of change in the network.

2.4 Optimisation Goals of Routing Link Metrics

A routing link metric is essentially a value assigned to the link of a path or route and is used by the routing algorithm to select one or more routes from a subset of routes discovered by the routing protocol. These values usually reflect the cost of using a particular route with respect to some optimisation objective. More specifically, the objective of the routing algorithm, and thus the routing link metric, may be one of the following:

- to minimise hop-count or path length: Often a longer path increases the end-to-end delay and reduces the throughput of a path. Therefore, the respective metric must prefer a path with minimum length over it. Minimum hop count is the most widely used metric in MANET routing protocols (Perkins and Royer, 1997), because all of the RFC's prefer to use it as a routing metric for the sake of simplicity and least computational overhead;

- to minimise delay: The network route over which the data can be delivered with minimum delay is selected. If interference, queuing delays, and link capacity are not taken into account, then delay minimisation often results being equivalent to the minimum hop-count;

- to maximise network throughput: The objective maybe formulated as the maximisation of data flow in the entire network or, rather the minimisation of interference and retransmissions;

- to maximise probability of data delivery: For real-time applications, the main objective is to achieve a low data packet loss rate along the network path, even at the expense of increased delay. This is equivalent to minimising the probability of data packet loss between network end-points;

- to minimise energy consumption: Wireless nodes are characterised by having limited energy resources, which requires them to perform multi-hop communication in order to share information. This becomes a major issue in wireless multi-hop networks where the battery lifetime constrains the autonomy of network nodes. If a protocol chooses a path with an unreliable link, it would probably produce a longer delay due to the higher retransmission rates. This ultimately results in increased energy consumption along with computational processing overhead of aggressive control packets; and

- to balance traffic load: Balanced traffic load is a more general approach. The aim is to ensure that no link is disproportionately used, and this can be achieved, for example, by minimising the difference between the maximum and minimum traffic load over the network links. When a link becomes over-utilised and causes congestion, the link metric can choose to divert the traffic from the congested path or overloaded nodes to the idle nodes to ease the burden.

2.5 Metric Computation Methods

There are several ways in which network nodes acquire the information required for the computation of the routing metric:

- passive monitoring (R. Baumann and Weibel, 2007): Information for the metric is gathered by observing the traffic arriving and leaving a node. No active measurements are needed. This could be used to estimate the available bandwidth;

- node-related: Information for the metric is acquired from the node without high effort. Such information may include the number of node interfaces and number of neighbour nodes;

- piggy-back probing: Measurements are performed by including probing information in regular traffic or routing protocol packets without creating specific packets for metric measurements thus reducing the overhead for the network. This is a common measurement method to estimate the delay; and
- active probing: Special packets are generated to measure the properties of a link or path. This method incurs more overhead on the network, which directly depends on the frequency of measurements.

2.6 Review of Existing Routing Metrics for Wireless Mesh Networks

Due to the dynamic and asymmetric nature of wireless links, various routing link metrics have been proposed in literature to cope with the vagaries of the communication channel. In this section, a comprehensive discussion of the various existing routing link metrics proposed for wireless mesh networks is presented highlighting advantages, drawbacks and implementation details.

2.6.1 Hop Count

This is the default metric in many popular wireless network routing protocols, such as Ad hoc On-demand Distance Vector (AODV) (Perkins and Royer, 1997), Destination Sequenced Distance Vector (DSDV) (Perkins and Bhagwat, 1994) and Dynamic Source Routing (DSR) (Johnson and Maltz., 1996). The concept of the hop count metric is simple. Every link counts as one equal unit independent of the quality or other characteristics of the link. The hop count selects paths with least or shortest number of hops and thus avoids any computational burden on the routing protocol. It outperforms other load-dependent routing metrics in high mobility scenarios because of its agility. Since the hop count metric is isotonic, efficient algorithms can find loop free and minimum weight paths. However in wireless mesh networks where the mobility of nodes is not an issue, it may choose paths with low throughput and poor medium utilisation. It treats all links in the network alike, that is, it disregards the link quality (transmission rate, packet loss ratio, and interference experienced by links).

2.6.2 Expected Transmission Count (ETX)

Simple path selection based on hop count often leads to poor performance due to the fact that paths with a lower hop count often have higher packet loss rates. Better paths can be obtained by characterising the quality of the wireless link. De Couto (Couto, 2004) proposed a metric that is based on bidirectional loss ratios. Expected Transmission Count (ETX) predicts the number of transmissions including retransmissions, that are required to successfully deliver a packet over a wireless link. Minimising the number of transmissions does not only optimise the overall throughput, it also minimises the total consumed energy if constant transmission power levels are considered as well as the resulting interference in the network. It is calculated using the forward and the reverse delivery ratios of the link. The forward delivery ratio, d_f, is the measured probability that a data packet successfully arrives at the receiver; the reverse delivery ratio, d_r , is the probability that the acknowledgement (ACK) packet is successfully transmitted. De Couto assumed that each attempt to transmit a packet is statistically independent from the previous one and also independent of the packet size. Each transmission attempt can be considered as a Bernoulli trial and the probability that a packet arrives and is successfully acknowledged is $d_f \times d_r$. Therefore, according to (Couto, 2004), the expected number of transmissions is:

$$ETX = \frac{1}{d_f \times d_r} \tag{2.1}$$

The weight of a path is defined as the summation of the ETXs of all links along the path. Therefore, the ETX path metric for a path p becomes (Couto, 2004):

$$ETX(p) = \sum_{l \in p} ETX_l \tag{2.2}$$

The delivery ratios are measured using link-layer broadcast probes, which are not acknowledged at the 802.11 MAC layer. Each node broadcasts a probe packet every second and also remembers the number of probe packets received from each neighbouring node over the last 10 seconds. Once this information is obtained, the ETX metric for all the wireless links from that node to its neighbours is calculated. The main advantages of the ETX metric are its account for asymmetric links and for the effects of link loss ratios. In other words, ETX does not try to route around congested links. It is isotonic and, therefore, guarantees the efficient calculation of minimum weight and loop-free paths. However, ETX is not capable of describing the complex scenarios in wireless mesh networks. These normally involve intra-flow and inter-flow interference, which have a significant impact on the link quality and data rate at which packets are transmitted over each link. It does not consider differences in the transmission rates in the links. Because it does not consider the load of the link, it will route through heavily loaded nodes, leading to unbalanced resource usage. In a highly mobile environment, it shows poor agility due to the long time window over which it is obtained.

2.6.3 Modified ETX (mETX)

Packet loss can vary significantly over different orders of magnitude depending on the radio technology of a system. This can lead to poor performance when the average of the packet loss ratio is taken as the basis for ETX. To address this problem, the authors in (A. Miu and Koksal, 2007) proposed the modified ETX (mETX) metric, which is aware of probe size and therefore, the inclusion of the data rate is trivial. Along with the link quality average values, this metric considers the standard deviation to project physical layer variations. The mETX metric works at the bit level. It computes the bit error probability using the position of the corrupted bit in the probe and the dependence of these bit errors throughout successive transmissions. The variability of the link is modelled using the statistics of the stochastic process. The mean number of transmissions is then analytically computed, and the results show that it can be closely approximated with the statistics of the bit error probability summed over packet duration. For mETX, the critical time scale for the link variability is the transmission time of a single packet including all its transmissions. According to (A. Miu and Koksal, 2007) mETX can be defined as:

$$mETX = exp(\mu + \frac{\sigma^2}{2}) \tag{2.3}$$

where μ is the estimated average packet loss ratio of a link and σ^2 is the variance of this value. μ and σ^2 are estimated by considering the number of erred bits in each probe packet. The main disadvantage of the mETX is the complexity of channel estimation, because probe packets are processed at the bit level raising the energy consumption issue in wireless mesh networks. σ^2 increases with increased estimation error.

2.6.4 Expected Transmission Time (ETT)

The ETX metric assumes all radios have the same transmission rate which is not necessarily true. The ETX metric prefers heavily congested links to unloaded links if the link layer loss rates of congested links are smaller than those of the unloaded links. Draves et al (Draves *et al.*, 2004) proposed the ETT metric, which seeks to improve the ETX metric by counting the heterogeneous channel rate or different link rates. The ETT of a link is defined as the expected MAC layer duration for the successful transmission of a packet over the link. According to (Draves *et al.*, 2004) for a single link ETT defined as:

$$ETT_l = ETX_l \times \frac{S}{B_l} \tag{2.4}$$

where S represents the size of the probing packet, and B_l is the current transmission rate or bandwidth of the link l. By introducing B_l into the cost of a path, the ETT metric captures the impact of link capacity on the performance of the path. To measure the bandwidth, Draves et al used the packet pair technique (Keshav and Srinivasan, 1991). This technique unicasts two packets in sequence, a small one (137 bytes) followed by a larger one (1137 bytes), to estimate the link bandwidth to each neighbour reassuring the inter-arrival time period between the two packets and reporting it back to the sender. The computed bandwidth is the size of the largest packet of the sequence divided by the minimum delay received for that link. The cost of a path is the summation of the ETTs for all the links in that path and is represented as:

$$ETT(p) = \sum_{l \in p} ETT_l \tag{2.5}$$

The Expected Transmission Time can increase the throughput of a path by measuring the link capacities, and this would increase the overall performance of the network.In addition, it is isotonic. However, it retains many of the drawbacks of ETX meaning that it does not consider link load explicitly due to the fact it cannot avoid routing traffic through already heavily loaded nodes and links. Hence, it does not minimise intra-flow interference. For instance,the ETT may choose a path that only uses one channel even though a path with more diversified channels has less intra-flow interference, and hence, higher throughput. It is not designed for multi-radio networks.

2.6.5 Weighted Cumulative Expected Transmission Time (WCETT)

Draves et al (Draves *et al.*, 2004) noticed that the throughput of a path is lower if many links are on the same channel, this is due to intra-flow interference. They subsequently proposed the WCETT metric, which is an extension to the ETT metric. The main motivation behind WCETT was to specifically reduce the intra-flow interference by minimising the number of nodes on the same channel for the end-to-end path so that the channel diversity minimises the intra-flow interference. It supports multi-radio or multi-channel wireless networks. According to (Draves *et al.*, 2004) the WCETT metric of a path p is calculated as :

$$ETX(p) = (1-\beta)\sum_{l\in p} ETT_l + \beta max_{1\leq j\leq k} X_j \tag{2.6}$$

where β is a tunable parameter within the bound $0 \leq \beta \leq 1$, which allows a controlling preference over path lengths versus channel diversity and X_j represents the number of times a channel j is used on links in the end-to-end path. The term $max_{1\leq j\leq k} X_j$ in the equation can be interpreted since it explicitly captures the intra-flow interference. This is because the paths that have more channel diversity will have lower weights. Although it considers intra-flow interference, it does not explicitly capture the effect of inter-flow interference. Therefore, it may route flows to dense areas where congestion is more likely, and this may even result in starvation of some nodes. Moreover, there is no efficient algorithm that can calculate the minimum weight WCETT for a wireless multi-hop network because WCETT is not isotonic.

2.6.6 Metric of Interference and Channel Switching (MIC)

Although WCETT considers intra-flow interference, it avoids inter-flow interference, which may lead WCETT to select congested routes. To address this issue, (Yaling Yang and Kravets, 2005) proposed the Metric of Interference and Channel Switching (MIC) that incorporates both inter-flow and intra-flow interferences and also the cost of switching channels. According to (Yaling Yang and Kravets, 2005), the MIC metric for a path is calculated as :

$$MIC(p) = \frac{1}{N \times min(ETT)} \sum_{l\in p} IRU_l + \sum_{i\in p} CSC_i \tag{2.7}$$

where N is the total number of nodes in the network and $min(ETT)$ is the smallest ETT in the network that can be estimated based on the lowest transmission rate of wireless cards. The Interference Resource Usage (IRU) component is the aggregate channel time consumed (or amount of bandwidth resource consumed) on a link l. In other words, this component includes the Expected Transmission Time for an intended sender as well as the time neighbour nodes have to defer in Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) MAC protocols. The URI component favours a path that consumes less channel time at its neighbouring nodes and according to (Yaling Yang and Kravets, 2005) it is defined as :

$$IRU_l = ETT_l \times N_l \tag{2.8}$$

The Channel Switching Cost (CSC) refers to the cost for a node to switch from one channel to another. It represents the intra-flow interference, favouring paths with more diversified channel assignments and penalising paths with consecutive links using the same channel. It is defined as:

$$CSC_i = \begin{cases} \omega_1 & \text{if } CH(prev(i)) \neq CH(i), \\ \omega_2 & \text{if } CH(prev(i)) = CH(i), \end{cases} where 0 \leq \omega_1 \leq \omega_2 \tag{2.9}$$

The MIC demonstrates better performance because it considers intra and inter-flow interferences and channel diversity. It can be made isotonic if it is decomposed into virtual nodes while applying minimum weight path finding algorithms such as Dijkstra's algorithm. The disadvantage of the metric is the overhead required to maintain updated information of ETT for each link. This can significantly affect the network performance depending on traffic loads. Each node should be aware of the total number of nodes in the network, since in large networks this may become very expensive.

2.6.7 Multi-Channel Routing Metric (MCR)

(Kyasanur and Nitin, 2006) extended WCETT in a different direction to MIC; they considered the cost of changing channels. Let $InterfaceUsage(i)$ be the fraction of time that a switchable interface spends on transmitting on channel i and let $P_s(j)$ be the probability that the interface used is on a different channel when a packet is sent on channel j . assuming that the total current interface idle time can potentially be used on channel j and according to (Kyasanur and Nitin, 2006) $P_s(j)$ can be estimated as:

$$P_s(j) = \sum_{\forall i \neq j} InterfaceUsage(i) \tag{2.10}$$

where $SwitchingDelay$ denotes the switching latency of an interface. This value can be measured offline. As stated by (Kyasanur and Nitin, 2006), the cost of using channel j is measured as :

$$SC(c_i) = p_s \times SwitchingDelay \tag{2.11}$$

In order to prevent frequent channel switching of the chosen paths, a switching cost is included into the ETT metric, so that the resulting MCR metric (Kyasanur and Nitin, 2006) is:

$$MCR = (1-\beta) \times \sum_{i=1}^{n} (ETT_i + SC(c_i)) + \beta \times max_{1 \leq j \leq k} X_j \tag{2.12}$$

Simulation results evaluating the MCR metric have shown that the network capacity is improved by using multiple channels even if only two interfaces per node are available.

2.6.8 Interference Aware (iAWARE) Metric

The interference Aware Metric (Prabhu Subramanian and Miller, 2006) is the first routing metric for multi-radio to take into account both inter-flow and intra-flow interference and is characterised by the physical interference model. It also takes link quality variation into account. This metric uses the Signal to Noise Ratio (SNR) and Signal to Interference and Noise Ratio (SINR) to regularly reproduce the neighbouring interference variations. The iAWARE metric estimates the average time the medium is busy through transmissions from each interfering neighbour. The iAWARE metric for a path

p is defined by (Prabhu Subramanian and Miller, 2006) as:

$$iAWARE(p) = (1 - \beta) \times \sum_{i=1}^{n}(iAWARE_i) + \beta \times max_{1 \leq j \leq k} X_j \tag{2.13}$$

The X_j component is the same as in the WCETT metric, in which the iAWARE values are used instead of the ETT values. The iAWARE value of a link j is defined by (Prabhu Subramanian and Miller, 2006) as:

$$iAWARE_j = \frac{ETT_j}{IR_j} \tag{2.14}$$

where IR_j is the Interference Ratio for the link j between nodes n and m, and is defined by (Prabhu Subramanian and Miller, 2006) as:

$$IR_j = min(IR_j(n), IR_j(m)) \tag{2.15}$$

The interference ratio value at a single node n for a link i is defined by (Prabhu Subramanian and Miller, 2006) as:

$$IR_i(n) = \frac{SINR_i(n)}{SNR_i(n)} \tag{2.16}$$

where $SINR_i(n)$ is the Signal-to-Interference Noise Ratio and $SNR_i(n)$ is the Signal-to-Noise Ratio at node n for link i. These are defined by (Prabhu Subramanian and Miller, 2006) as:

$$SNR_i(n) = \frac{P_n(m)}{N} \tag{2.17}$$

$$SINR_i(n) = \frac{P_n(m)}{[N + \sum_{k \in \nu(n) - m} \tau(k) \times P_n(k)]} \tag{2.18}$$

where: $P_n(m)$ represents the signal power of the current packet coming from node n and received at node m; N is the noise; $\nu(n)$ denotes the set of nodes from which node n can sense (or hear) a packet; and $\tau(k)$ is the normalised rate at which node m generates traffic averaged over a period of time. $\tau(k)$ is 1 when node k sends out packets at the supported full data rate . Although the iAWARE metric captures both intra-flow and inter-flow interference, it does not capture the logical interference that occurs due to the

MAC protocol. The iAWARE metric also has a static view of channels since the second component counts the number of channels and not their relative positions. Moreover, it is a non-isotonic metric.

2.6.9 Metric for Interference and channel Diversity (MIND)

Despite the improvement of ETX to iAWARE metrics, all the metrics discussed employ an active probing that sends fixed size packet-pairs in order to estimate the link quality. (Borges *et al.*, 2009) argued that the active monitoring mechanism of using probes to measure link quality in existing metrics can cause excessive overhead on the network. They propose the Metric for Interference and channel Diversity (MIND), which uses passive measurements. The MIND metric has two components: INTER_LOAD, which includes both physical and logical interferences; and the channel switching cost (CSC). The MIND metric for a path p is given by (Borges *et al.*, 2009) as:

$$MIND(p) = \sum_{l \in p}^{n} INTER\_LOAD_l + \sum_{nodej \in p}^{m} CSC_j \tag{2.19}$$

The first component captures inter-flow interference. To express the INTER_LOAD component, (Borges *et al.*, 2009) estimate the physical interference and medium load as:

$$INTER\_LOAD_l = ((1 - IR_l) \times \tau) \times CBT_l where 0 \leq IR \leq 1 and 0 \leq CBT \leq 1 \tag{2.20}$$

$$where 0 \leq IR \leq 1 and 0 \leq CBT \leq 1 \tag{2.21}$$

The Interference Ratio IR_l represents the physical interference based on the ratio between SINR and SNR. It relies on a passive monitoring technique to capture the SINR and SNR values without additional traffic. The Channel Busy Time (CBT) represents the medium load. The authors (Borges *et al.*, 2009) argue that τ (a configurable parameter) is used to provide a higher weight to interference in the $INTER\_LOAD$ component. The CBT calculation is based on the time that packets spend in a wireless medium for a successful transmission. The CBT at a node i is defined by (Borges *et al.*, 2009) as:

$$CBT_l = \frac{TotalTime - IdleTime}{TotalTime} \tag{2.22}$$

$TotalTime$ is the duration that the channel is observed whereas Idle Time represents the back off times and i.e. the time that the medium is free of data). Finally, similar to existing metrics for capturing intra-flow interference, MIND uses Channel Switching Cost (CSC) (2.9) to express the channel diversity. Overall, the MIND metric provides an interesting approach of integrating physical and logical interference and attempts to capture both intra-flow and inter-flow interference components. Moreover, MIND is a non-isotonic metric although (Borges *et al.*, 2009) propose a virtual network-based scheme to resolve this problem.

2.6.10 Expected Throughput (ETP) Metric

Understanding that the nominal bit rate has a huge impact on the link quality, (V.P. Mhatre and Diot, 2007) propose the Expected Throughput (ETP) metric that focuses on improving the network throughput by capturing the bandwidth sharing mechanism of the 802.11 Distributed Coordinated Function (DCF). The DCF tries to provide fair sharing to all the contending links. The notion of fairness as per the 802.11 DCF is to allocate an equal number of transmission opportunities to all the contending links. This means that the slow links will have the same number of transmissions as the fast ones. Previous studies (Choi, 2005) and (M. Heusse and Duda, 2003) have shown that this results in the slow links (low nominal bit rate) occupying the wireless channel for a long duration, thereby leading to throughput reduction of the neighbouring fast links (high nominal bit rate). To state ETP, let l be the link that belongs to path P in the contention domain S_l. $S_l \cap P$ is the set links on path P that contend with link l. r_l is the nominal bit rate of link l. All links have an equal number of opportunities for transmission when saturated, as per the 802.11 DCF. The expected bandwidth received by each link l is given by (V.P. Mhatre and Diot, 2007) as:

$$b_l = \frac{1}{\sum_{j \in S_l \cap P} \frac{1}{r_j}} \tag{2.23}$$

However, the actual throughput is lower due to packet loss rates on that link. The ETP metric accounts for packet loss by introducing the forward (P_l^f) and reverse (P_l^r) packet loss probabilities of link l into the formula. The ETP of link l is given by:

$$ETP_l = \frac{P_l^r \times P_l^f}{b_j} \tag{2.24}$$

Unlike ETX and ETT, the ETP metric is a more accurate model for the impact of contention in 802.11 MAC. However, it does not consider inter-flow interference. The routing metric of the path, $f(P)$, is then defined by (V.P. Mhatre and Diot, 2007)as the throughput of the bottleneck link of the path:

$$f(P) = min_{l \in P} ETP(l) \tag{2.25}$$

2.6.11 Expected Data Rate (EDR) Metric

(Park and Kasera, 2005) attempt to overcome the limitations of the ETX and ETT metrics by incorporating the time sharing effects of MAC in the routing metric. They define a quantity called the Transmission Contention Degree TCD(l) of link l as the average time the outgoing queue of the transmitter link l is not empty. Whenever the outgoing queue of a link is not empty, it contends with other links in its neighbourhood for channel access. For a given path on which link l lies, (Park and Kasera, 2005) define the quantity $I(l)$ as the sum of the TCDs of all the links on the path that contends with link l. $I(l)$ also includes TCD(l). A routing metric for link l, referred to as Expected Data Rate (EDR) is defined by (Park and Kasera, 2005) as:

$$EDR(l) = \frac{\omega}{ETX(l) \times I(l)} \tag{2.26}$$

where ω is the nominal bit rate of the link l. In the above equation (2.26), ETX(l) and $I(l)$ are used to account for throughput reduction due to packet losses and time sharing with contending links, respectively. In the equation (2.26), (Park and Kasera, 2005) assume that all the contending links get an equal time of sharing the channel; this is true when all the links have the same nominal bit rate. However, when links have different nominal bit rates, they receive the same average throughput but different time-sharing of the channel. Thus, the above model of time sharing through $I(l)$ fails to capture the bandwidth sharing mechanism of 802.11 Distributed Coordinated Function (DCF).

2.6.12 Expected Link Performance (ELP) Metric

Interference among nodes is a significant limiting factor for wireless multi-hop networks. The ETX metric was not designed to take link interference into consideration whereas the degree of contention on the wireless link plays an important role. The ETX metric uses small probe packets that are more resistant to collisions and packet corruption than the actual data packets. Moreover, a large window size (typically 10 seconds) is used in ETX, which tends to dampen any variations in delivery ratios due to interference. Hence, it is possible that a link that is congested will give good delivery ratios for small probe packets that are significantly larger. (U. Ashraf and Juanole, 2008) propose the Expected Link Performance (ELP) metric. This is a hybrid metric that uses both link quality and link traffic information to estimate link performance. The success probability of a link is the probability that a packet will be successfully transmitted over it and the corresponding Acknowledgement (ACK)will be received. It is defined by (U. Ashraf and Juanole, 2008) as:

$$P(T_x success) = P(DataSuccess) \times P(ACKSuccess) \qquad (2.27)$$

where the values of $P(DataSuccess)$ and $P(ACKSuccess)$ are approximated by the delivery ratios of broadcast packets in the forward and reverse directions. The link success probability is:

$$P(Success) = d_f \times d_r \tag{2.28}$$

The ETX and other ETX based metrics give equal weight to forward and reverse links in their calculations. However, this is not correct because the packet size in each direction is considerably different. Acknowledgments are considerably smaller than data packets and hence rarely experience packet corruption or collision. Acknowledgments are much more resistant to disturbance on the wireless link and are more likely to be successfully received than data packets. The ETX mechanism of giving equal importance to forward and reverse delivery ratios over a link is clearly flawed. In the ELP metric, (U. Ashraf and Juanole, 2008) assign a higher weight to the forward link in order to mitigate the asymmetry of the packets. This is logical because the reverse link is only meant for the ACK packets (for a particular route), which are loss resistant and would probably be successfully received regardless of the estimated reverse delivery ratio. Therefore, assigning higher weights to forward links would give more priority to data packets. By biasing delivery rates in favour of forward links, (Borges *et al.*, 2009) aim to improve the link delivery ratio calculations. The link delivery ratio is given by (U. Ashraf and Juanole, 2008) as:

$$P(Success) = \alpha \times d_f + (1 - \alpha) \times d_r \tag{2.29}$$

$$0.5 < \alpha < 1 \tag{2.30}$$

where α represents the weight assigned to the forward delivery ratio on a link. The larger the value of α, the more is the weight that is given to the forward link. The link delivery ratio computed in the previous section mainly represents the link quality and does not portray the interference experienced by the link. Interference encompasses medium congestion and collisions due to hidden stations. Interference among nodes is a performance bottleneck for multi-hop wireless networks. Since the broadcast probe packets used for link quality estimation are small in size, they are successfully received even over congested wireless links, therefore giving a false impression of link quality. High delivery ratios would thus make this link appear as a strong link when in fact, the link may be unable to deliver any more data. The ELP metric proposes a new mechanism to estimate and incorporate interference on the link in the metric so that optimal routes can be selected. (U. Ashraf and Juanole, 2008) define the interference factor (IF_n) of a node n as an estimate by node n of the medium congestion around it. Each node uses carrier sensing at the MAC layer to estimate the medium congestion. With a cross-layered approach, the MAC is probed periodically to determine if the medium is busy (either the node is receiving packets or there is communication between other nodes that is Network Allocation Vector (NAV) pending). The ratio of the number of times that the medium is busy compared to the observed window time gives the node an estimate of the medium congestion. The interference for node n is given by (U. Ashraf and Juanole, 2008) as:

$$IF_n = \frac{MacBusy_n(R_x) + MacBusy_n(NAV)}{TotalWindowTime} \tag{2.31}$$

For the node on the end of the link that is receiving data packets, the interference factor also includes the time the medium is busy and this due to the transmission from this node. Since this would interfere with the transmission from node n it is given by (U. Ashraf and Juanole, 2008) as:

$$IF_m = \frac{MacBusy_m(R_x) + MacBusy_m(NAV) + MacBusy_m(T_x)}{TotalWindowTime} \tag{2.32}$$

For link (m, n) from node n to node m, the link interference factor ($IF_{m,n}$) is defined as the maximum interference factor at the nodes at the two ends of the link. This is because each transmission over the link involves the nodes at both ends, and the degree of interference experienced by a packet is equal to the maximum interference at either end of the link as demonstrated by (U. Ashraf and Juanole, 2008):

$$IF_{m,n} = max(IF_m, IF_n) \tag{2.33}$$

Each node remembers its interference factor for a window period of the last w seconds. In each broadcast probe, the node piggybacks its interference factor for the last w seconds. The destination node saves this information. Using its own interference factor and the interference factors from its neighbours, each node estimates the interference factor of the link. The higher the degree of interference of a link, the lower the throughputs since the nodes contend for access to the medium. The ELP metric is defined by (U. Ashraf and Juanole, 2008) as:

$$ELP_{m,n} = \frac{1}{\alpha \times d_f + (1 - \alpha) \times d_r} \times \frac{max(IF_m, IF_n)}{1 + max(IF_m, IF_n)} \tag{2.34}$$

The denominator in the interference part of the formula is used to void rapid changes. The end-to-end path metric for a path p is given by (U. Ashraf and Juanole, 2008) as:

$$ELP(P) = \sum_{l \in p} ELP(l) \tag{2.35}$$

2.6.13 Interference and Bandwidth Adjusted ETX (IBETX)

Simple path selection based on the ETX metric may often lead to poor performance due to the fact that it does not consider differences in the transmission rates of the links. Since it does not consider the load of the link, it will route through heavily loaded nodes, leading to unbalanced resource usage. Better paths can be obtained by characterising the actual quality of a wireless link. (Javaid, 2010) and (Nadeem Javaid and Djouani, 2010) propose the IBETX metric. This is a threefold metric. Initially, it calculates the Expected Link Delivery (ELD), d_{exp}, which avoids the overhead generated by the ETX and bypasses congested regions in the network. This part of the IBETX metric finds paths or routes with a lower number of retransmissions that may be used for onward delivery of data packets. In wireless networks, slow links receive more time to transmit compared with the faster links. Therefore, IBETX provides the nodes with the information of the nominal bit rates and makes them compute the Expected Link Bandwidth (ELB), b_{exp}, of all the wireless links in the same contention domain using a cross-layer approach. Finally, IBETX overcomes long path penalisation of ETX by calculating the interference referred to as Expected Link Interference (ELI), I_{exp}. The IBETX metric is defined by (Javaid, 2010) as:

$$IBETX = \frac{d_{exp}}{b_{exp}} \times I_{exp} \tag{2.36}$$

For a bidirectional wireless link (m, n), the Expected Link Delivery d_{exp} is obtained by (Javaid, 2010) as:

$$d_{exp} = d_f \times d_r \tag{2.37}$$

where d_f is the forward delivery ratio, which is the measured probability that a data packet successfully arrives at the receiver, and d_r is the reverse delivery ratio which is the probability that the acknowledgment packet is successfully transmitted. The delivery ratios are measured using link layer broadcast probes, which are not acknowledged at the 802.11 Medium Access Control (MAC) layer. Each node broadcasts a probe packet of 134 bytes every second and also remembers the number of probe packets received from each neighbouring node over the last 10 seconds. Once this information is obtained, the Expected Link Delivery for all the wireless links from that node to its neighbours is calculated. The Expected Link Bandwidth b_{exp} captures the bandwidth sharing mechanism of 802.11 Distributed Coordination Function (DCF). It also considers the accurate throughput reduction of the faster links as a result of the slower links. Moreover, b_{exp} takes into account the longer paths that are ignored by the ETX and ETX-based metrics (Javaid, 2010). For a link (m, n) , the Expected Link Bandwidth is given by (Javaid,

2010) as:

$$b_{exp}(m,n) = \frac{1}{\sum\limits_{i \in P \cap NP} \frac{1}{r_i}} \tag{2.38}$$

In the above expression; P is the source destination path or route and NP is the non-source destination path; and r_i is the nominal bit rate of the i^{th} link in the domain $P \cap NP$ which is the set of links in path P that contend with the link (m,n). Since the probes used to calculate the delivery ratio are very small in size, they are successfully received even in a congested network, thus depicting the wrong image of link qualities. For example, if a link only has the capacity to carry probe packets, it pretends that the congested link is the one with better quality because of its high delivery ratios when in fact, it is not able to carry data packets (U. Ashraf and Juanole, 2008). Therefore, a mechanism is incorporated to calculate the interference in the IBETX metric, which is defined as Expected Link Interference (ELI). This is an expected value calculated by all the nodes on the same source-destination path. The basic MAC of 802.11 is the Distributed Coordination Function (DCF), which besides enabling the nodes to sense the link before sending data, also avoids collisions by employing virtual carrier sensing. The DCF uses Request-To-Send (RTS) and Clear-To-Send (CTS) control packets for unicast data transmission to a neighbouring node and consequently sets the Network Allocation Vector (NAV). The NAV stores the channel reservation information to avoid the hidden terminal problem. Using the cross-layer approach, DCF periodically probes the MAC to find the time period for which the link is busy, τ_{busy}. The interference that a node m has to suffer is expressed by (Javaid, 2010) as:

$$i_m = \frac{\tau_{busy}}{\tau_t} \tag{2.39}$$

where τ_{busy} denotes the duration for which the medium remains busy. In the case of receiving packets, it is the R_x state (communication is going-on with other nodes)with the NAV still pending. The total window time is tau_t is the total window time. If node

n is at the transmitting end, the τ_{busy} value is given as: $\tau_{R_x} + \tau_{T_x} + \tau_{CTS} + \tau_{RTS}$. Thus, the interferences for the sending node n and the receiving node m are given by (Javaid, 2010) as:

$$i_m = \frac{\tau_{R_x} + \tau_{CTS} + \tau_{RTS}}{\tau_t} \tag{2.40}$$

$$i_n = \frac{\tau_{R_x} + \tau_{T_x} + \tau_{CTS} + \tau_{RTS}}{\tau_t} \tag{2.41}$$

The link (m, n), formed by nodes m and n will suffer from interference, $i_{(m,n)}$, that is, the maximum of the interferences calculated in equations (2.40) and (2.41). This is represented by (Javaid, 2010) as:

$$i_{(m,n)} = max(i_m, i_n) \tag{2.42}$$

The receiving node m saves the information of interference computed by equation (2.40) and the sending node by equation (2.41) . The expected interference of the link is then evaluated as:

$$I_{exp}(m, n) = \frac{max(i_m, i_n)}{1 + max(i_m, i_n)} \tag{2.43}$$

Since the wireless medium is shared, there is the problem of interference due to contention. This causes packets to be lost due to collisions, and consequently, reduces the bandwidth of links. Therefore, I_{exp} is added to address the inter-flow interference among contending nodes. The weight of a path is defined as the summation of the IBETX's of all the links along the path. Therefore, according to (Javaid, 2010) the IBETX path metric for a path p is :

$$IBETX(P) = \sum_{l \in p} IBETX(l) \tag{2.44}$$

It follows that the routing metric for the best route or path P_{best} from source to destination is the minimum value of all available $P's$ and may be represented according to (Javaid, 2010) as:

$$P_{best} = min(IBETX(P_1), IBETX(P_2), IBETX(P_3), ..., IBETX(P_n)) \tag{2.45}$$

2.7 Conclusion

In this chapter, a comprehensive analysis of the various routing metrics that have been proposed for routing protocols in wireless static or mesh networks has been performed. There are different criteria that need to be considered in the routing metric design (interference, link capacity, link loss). This study revealed that load and interference aware cross-layer routing metrics are more efficient in highly congested traffic areas to pick up link quality parameters compared with simple metrics (hop count) and interference and load (ETX and ETT) aware routing metrics. An important result of this survey is that it is possible to gain good performance by using cross-layered information, which particularly is aimed at the interaction of the lower layers with the network layer. A major deficit of current routing metrics is the lack of ability to use a wide range of bandwidth due of the lack of multi-channel usage. By enabling nodes to communicate on more than one channel, it is possible to reduce interference, increase the capacity of the network and raise throughput. In conclusion, a good routing metric should find paths with component links that have a low loss ratio, a high data rate and experience low levels of interference.

CHAPTER 3. Performance Comparison of IBETX Routing Metric With DSDV and AODV Routing Protocols

3.1 Introduction

In networking, routing metrics provide a mechanism to predict the cost of using a selected route or path; the most suited route is calculated using routing protocols. The routing metric provides quantifiable values that can be used to judge the cost or efficiency of a specific route. This chapter presents a performance comparison of the recently proposed routing metric IBETX with a reactive and a proactive routing protocol.

3.2 Simulation Tool

In the network research area, establishing a network in a real time scenario is very complicated. A single test bed will take a large amount of time, incur great cost and will also require the use of a system with many components. To simulate and obtain close to accurate results, researchers need powerful simulation tools. These tools are known as network simulators. A network simulator is a piece of software that predicts the behaviour of a network, without the actual network being present. Network simulators attempt to model the real world networks in real time. They cannot replicate exactly all the details of the real network. However, if well designed or modelled, they will be close enough so as to give the researcher a significant insight into the network under test, and how changes will affect its operation. There is a large variety of network simulators available. Among them, GloMoSim (Global Mobile Information System Simulator) (Zeng *et al.*, 1998) is an open source network simulator based on the parallel discrete event scheduler. It can emulate the real world more accurately. However, it is very hard to debug parallel programs. As stated by (Varga, 1999) OMNET++ (Optical Micro-Networks ++) is also an open source simulator, which is a component based modular open architecture, discrete event simulator framework. Its main drawback is that it does not offer a great variety of routing protocol models. The tool, OPNET (Optimized Network Engineering Tools) (Incorporation, 2000) is a powerful commercial network simulator used for simulations of both wireless and wired networks. It supports a wide range of wireless technologies such as, IEEE 802.11 wireless Local Area Networks (LANs), WIMAX, MANETs and satellite networks, but it does not give the flexibility of making changes.

In this dissertation, all the simulations were conducted on the network simulator version 2 (NS-2.34) (Laboratory, 1997). This was mainly due to the variety of ad-hoc routing protocols, the large number of available models (mobility model, energy model, traffic and movement patterns) and wireless network interfaces that it offers. It also includes the capability of creating custom applications and protocols as well as modifying several parameters at different layers.

3.2.1 Overview of Network Simulator Version 2 (NS-2)

The NS-2 is an objective oriented, discrete event network simulator widely used in the networking research community. It was originally developed at the University of California, Berkeley (Laboratory, 1997) as a part of the Virtual Internet Test bed (VINT). It is an open source developing network simulator. The NS-2 couples a C++ discrete event structure with an Object-oriented Tool Command Language (OTcl) interpreter as a frontend. In fact, since the network research involves both varying parameters and configurations and studying network protocol operations, it is advisable to have a programing language (C++) that is in charge of managing bytes, packet headers, algorithms and a more user friendly interface (OTcl) for easily modifying the network model, traffic definitions, queue policy, etcetera. The C++ and the OTcl are linked together using TclCL. These objects are combined through Tcl scripts. During simulation, the NS creates an output trace file that keeps the main simulation information and registers each packet when it is transmitted and received. The information includes addresses, packet size, etcetera and an output Network Animation (NAM) file, which is a graphical tool that is useful for checking the node placement in the network and tracking the packets exchange.

3.3 Simulation Details

This section provides the simulation details and the different parameters used to evaluate the performance of the IBETX routing metric.

3.3.1 Routing Protocols

A number of routing protocols have been proposed and implemented for MANETs in order to improve the bandwidth utilisation, increase the throughput, reduce overhead per packet and minimise energy consumption among others. All these routing protocols have advantages and drawbacks under certain circumstances. The ad-hoc routing protocols may be generally categorised as table-driven (proactive) or source initiated on-demand driven (reactive). In proactive routing protocols, consistent and up-to-date routing information for all nodes is maintained at each node. Packets are transferred over the predefined route specified in the routing table. In reactive routing protocols, the routes are created as and when needed; when a source wants to send a packet to a destination, it invokes the route discovery mechanism to find the path to the destination. The route discovery mechanism is based on the flooding algorithm which employs the technique that a node broadcasts the packet to all of its neighbours and intermediate nodes then forward that packet to their neighbours, this is a repetitive technique until the packet reaches the destination. The following paragraphs present an overview of two prominent routing protocols, namely the Ad-hoc On Demand Distance Vector (AODV) (Perkins and Royer, 1997) and the Destination Sequenced Distance Vector (DSDV) (Perkins and Bhagwat, 1994) routing protocols.

Among the reactive routing protocols, AODV is chosen in this dissertation. (Perkins and Royer, 1997) specify that AODV can better handle a wireless network of thousands of nodes and varying rates of data loads. Another reason for the ability of AODV to outperform other reactive routing protocols such DSR (Johnson and Maltz., 1996) and DYMO (Chakeres and Perkins, 2006), is its dissemination of data packets. In AODV, the routing packet contains the information of the next hop to destination and not the complete source information of the distance vector. This consumes less bandwidth, which is essential for an increased number of data packets and an increased number of flows. The AODV is a dynamic routing protocol and is characterised by a dynamic network topology that affects routing decisions. In this routing protocol, routes are set up on demand, and only active routes are maintained. This reduces the routing overhead, but introduces some initial latency due to the on demand route setup. The AODV uses a request-reply mechanism for route discovery. When the source has a packet to send to a destination, it will first check its routing table to find out whether a route to the destination exists. If no route exists, it will broadcast a route request (RREQ) to its neighbours, which in turn will forward the request to their neighbours until the destination or a node with a valid route to the destination is found. The RREQ packet includes the RREQ identifier, source and destination IP addresses, hop count value, and source and destination sequence numbers. If the RREQ packet reaches the destination or an intermediate node with a valid route to the destination, the node will unicast a route reply (RREP) packet to the source via the reverse path. The route maintenance mechanism in AODV is triggered when a link breaks either due to node movement or transmission errors. When a node detects a link breakage it will send a route error (RERR) message to its active upstream neighbours to inform them of the link breakage and to update their route table entries.

The DSDV is a table driven proactive routing protocol based on the Bellman-Ford algorithm. In this routing protocol, each node in the network maintains a routing table, that lists all available destinations, the metric and the next hop to each destination and the sequence number provided by the destination node. To avoid routing loops and the use of stale routes, DSDV tags each route with a sequence number and favours the router with the greater sequence number. If two routes have equal sequence numbers, the route with the lower metric will be chosen. Each node in the network updates its routing table with periodic advertisement or when new information is available to maintain consistency of the routing table with the dynamic topology of the network.

3.3.2 Physical Layer, MAC Layer and Radio Propagation Model

The physical layer is in charge of transmitting bits over a physical medium connecting nodes and allocating the channel. In NS-2 the physical layer is referred to as the class in which the computation of the received power takes place according to the chosen propagation model. In general, the effective role of the physical layer is to set the power attenuation experienced by the packet from the transmitter to the receiver according to the different propagation models that NS-2 provides. The propagation model directly influences the system behaviour because it affects the received power and modifies the interference level at each node.

In this dissertation, the Two Ray Ground propagation model acting in an outdoor environment has been chosen. In this model, the transmitter and the receiver have a clear, unobstructed line-of-sight between them. Also, there is a ground-reflected propagation path between the two. The presence of a ground-reflected propagation allows a more realistic definition of the propagation attenuation. There is no other object in the environment. At the Medium Access Control (MAC) layer, the simulator uses the Distributed Coordination Function (DCF) compliant with the IEEE 802.11b standard. The DCF uses a Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) protocol for sharing the wireless medium. The following table lists the simulation parameters used at the physical and MAC layers in the performance evaluation.

Table 3.1: Simulation parameters at the physical and MAC layers

Simulations parameters	Values
MAC protocol	IEEE 802.11b
Physical layer	WirelessPhy
Frequency	2.4 GHz
Antenna	Omni-directional
Propagation model	Two ray ground model
RTS threshold	3000

3.3.3 Topology and Traffic Settings

Due to the long time window ($10s$) over which the IBETX and ETX routing metrics are obtained, a fixed network topology is adopted in this dissertation. Because of the simplicity of architecture and the cheap cost of the single radio, single interface, all the evaluations are performed in a single-radio single-channel static wireless network. The static wireless network consists of 50 nodes randomly placed in an area of $1000m$ by $1000m$. The radio propagation range for each node is $250m$. Each node has a queue buffer link layer of 50 packets managed with a drop-tail mode. The scheduling packet transmission technique used is the First In First Out (FIFO). The traffic sources transmit Constant Bit Rate (CBR) with User Datagram protocol (UDP) at the transport layer. The bandwidth provided to all the wireless links is 2 Mbps. The AODV and DSDV native codes in NS-2.34 are both modified to integrate the IBETX and ETX as routing metrics. Each simulation runs for 10 different topologies for $900s$ each, and each data point represents an average of 10 runs. The simulations were performed on a Pentium Dual-Core with a 2.30 GHz processor and 2.00 GB Random Access Memory (RAM) over the operating system Ubuntu 12.04. The simulation parameters that were considered in this study are listed in the table below.

Table 3.2: Traffic and topology parameters

Parameters	Values
Network area	$1000m \times 1000m$
Number of nodes	50
Random topology	10
Number of connections	10, 20, 30, 40
Packet rate	1, 2, 4, 6, 8, 10 (packets/second)
Packet size	512, 1024, 1536, 2048 bytes
Traffic type	CBR
Transport protocol	UDP
Data rate	2 Mbps
Routing protocols	AODV, DSDV
Simulation time	900 s

3.4 Performance Metrics

This section provides certain performance metrics that have been used to compare the performance of the two routing protocols. These are as follows:

3.4.1 Throughput

Throughput is defined as the total amount of data a receiver obtains from the sender divided by the time it takes for the receiver to acquire the last packet. It is actually the measure of how fast packets can be sent through the network.

$$THROUGHPUT = \frac{\sum Received\_Total\_Data\_Packet}{Duration\_of\_Simulation} \tag{3.1}$$

3.4.2 Average end-to-end Delay

The average end-to-end delay indicates the time it takes for a packet to travel from the source to the application layer of the destination. The delay is calculated per packet for all packets reaching their destination, and the result is the average of all the packets of all the flows. This includes all possible delays caused by buffering during route discovery, retransmission delays at the Medium Access Control (MAC), queuing delay at the interface as well propagation and transfer times.

3.4.3 Normalised Routing Load (NRL)

The Normalised Routing Load is the number of routing packets that need to be transmitted by a routing protocol for a single data packet to be delivered successfully at the destination. It describes how many routing packets for route discovery and route maintenance need to be sent in order to propagate the data packets. Moreover it can measure the scalability of a routing protocol, the energy consumption efficiency under low bandwidth or congested environments.

$$NRL = \frac{\sum Total\_Routing\_Packets\_Received}{\sum Total\_Data\_Packets\_Received} \tag{3.2}$$

3.5 Simulation Results

To evaluate the IBETX routing metric, several parameters were varied: the packet rate, the packet size and the number of connections in the network. Varying the number of connections is important to see the impact of increased traffic in the network (interference) on the performance of the routing metric.

3.5.1 Effect of Traffic Load

To examine the performance of the IBETX routing metric under a different number of connections, the number of connections is varied from 10 to 40. Fifty nodes are placed randomly to form a static wireless network. Each source transmits data packets at four packets per second with a packet size of 512 bytes until the simulation run ends (900s).

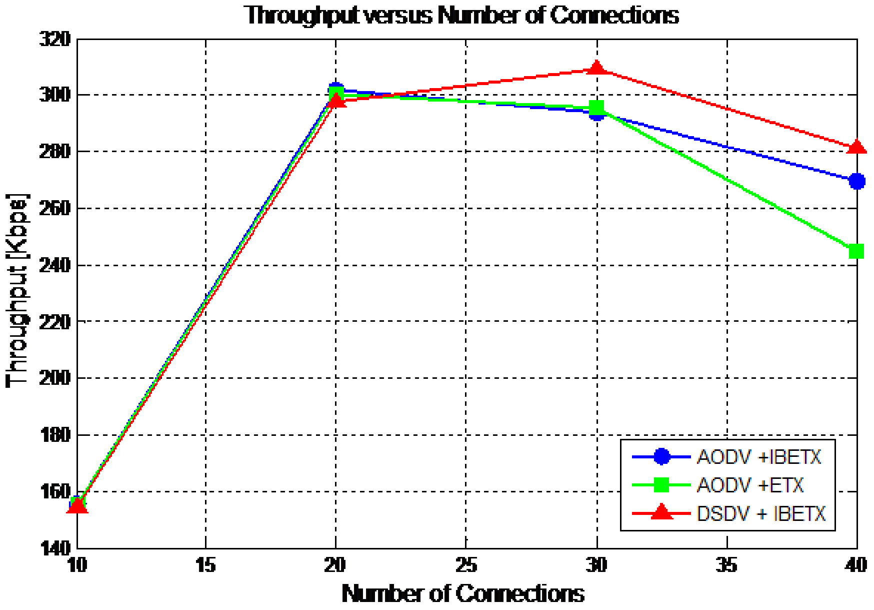

Figure 3.1: Throughput versus number of connections

Figure 3.1 demonstrates that with a low number of connections (number of sources less than or equal to 20), all the routing metrics exhibit similar performance. This is because there is negligible interference in the network due to the low number of connections. The choice of any path would yield approximately the same result. As the number of connections increases (above 20 sources), there are some noticeable differences. The AODV and DSDV routing protocols that make use of IBETX as the routing metric outperform the AODV with ETX metric since both capture the inter-flow interference experienced by wireless links together with the link loss ratios and the link bandwidth. However, the DSDV with IBETX routing protocol performs better than the AODV with

IBETX. It also observed that as the number of sources increases (above 30 sources), the throughput in the network starts dropping. This is due to a high level of network congestion and multiple access interferences in certain regions of the ad-hoc network. No routing protocol that makes use of IBETX or ETX as a routing metric has any mechanism for load balancing, that is, choosing routes in such a way that the data traffic can be more evenly distributed in the network.

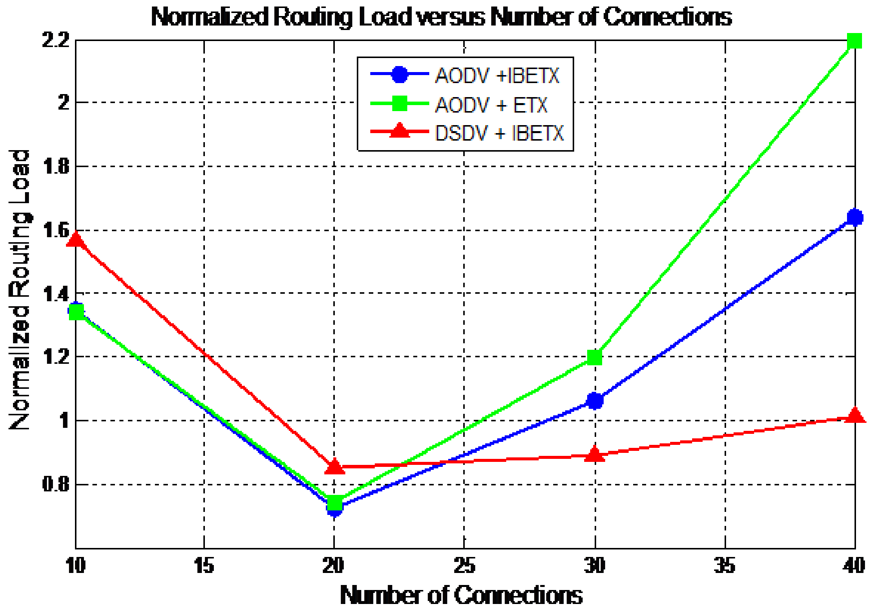

Figure 3.2: Normalised Routing Load versus number of connections

Figure 3.2 demonstrates that for a low number of connections (below 20 connections), the AODV routing protocol that makes use of ETX or IBETX as the routing metric has a low normalised routing overhead compared to the DSDV routing protocol with IBETX as the metric. This can be explained by the fact that in the DSDV routing protocol, routing updates are exchanged even if the network is idle, which uses up battery and network bandwidth. As the network becomes saturated (above 20 connections), DSDV with IBETX as the routing metric achieves a lower normalised routing load compared with AODV with IBETX or ETX as metrics. This is explained by the numerous number of control overheads due to many route reply messages for a single route request in the AODV routing protocol.

3.5.2 Offered Packet Rate Analysis

To examine the performance of the different routing protocols with distinct routing metrics under various offered loads, the packet rate is varied from 1 to 10 packets per second. Fifty nodes are randomly placed to form a static network. The CBR traffic is randomly generated by 30 source-destination pairs with a packet size of 512 bytes.

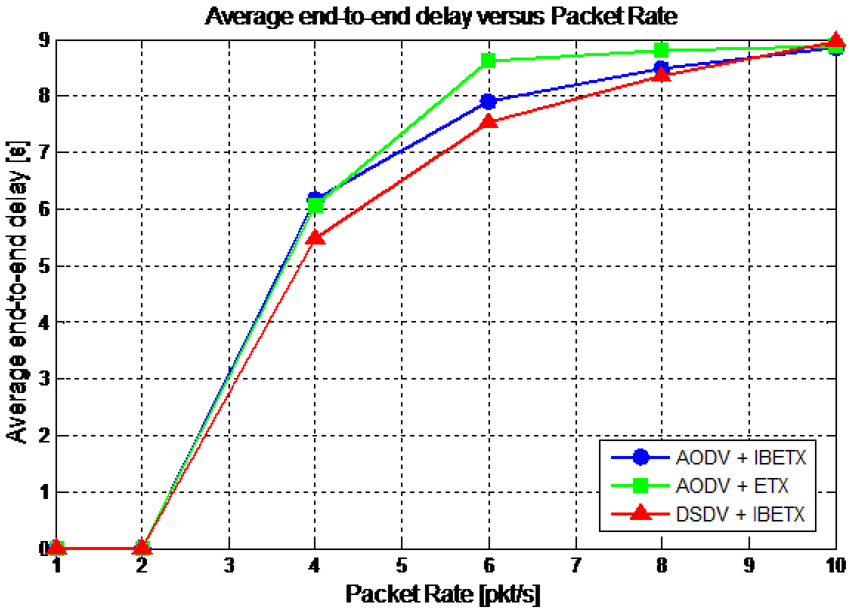

Figure 3.3: Average end-to-end delay versus packet rate

Figure 3.3 demonstrates that at a low packet rate (less than two packets per second) all the routing protocols have a similar average packet end-to-end delay. As the packet rate increases (above four packets per second) DSDV with IBETX as the routing metric exhibits lower average packet end-to-end delay when compared with AODV that makes use of IBETX or ETX as the routing metric. This was predictable because DSDV always holds optimal paths to all other destinations in their routing tables and, therefore, the delay involved in sending data packets at high packet rate is much less. With DSDV routing protocols, packets wait for a shorter period during route acquisition compared with AODV since the route to the destination is already known. It can be also noted for both routing protocols that the average packet end-to-end delay increases with the packet rate.

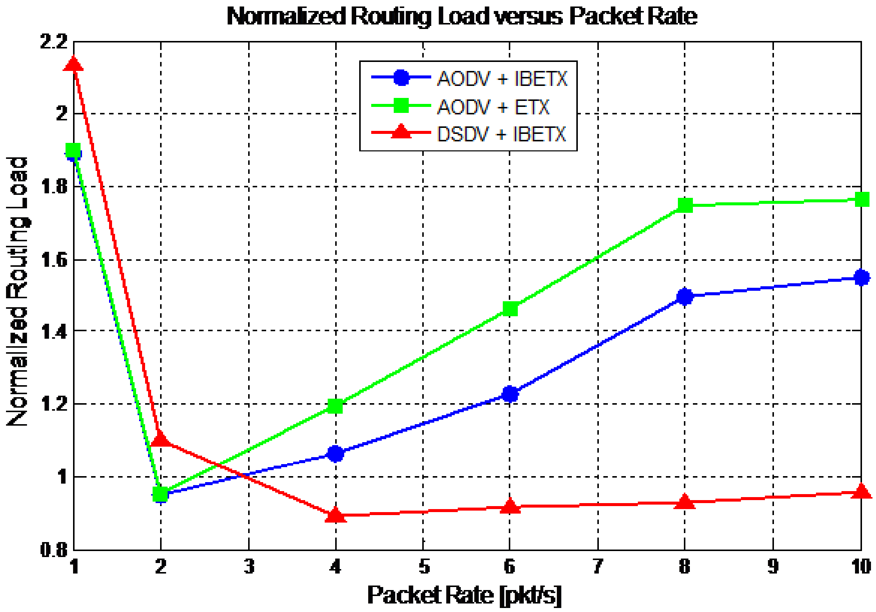

Figure 3.4: Normalised Routing Load versus packet rate

As seen in Figure 3.4. Considering a stressful situation (above four packets per second) the normalised routing load of DSDV with IBETX as the routing metric is fairly stable and low when compared with AODV with IBETX or ETX as the routing metric. A relatively stable, normalised routing load is a desirable property of the routing protocol, since this indicates that the routing load increases linearly with the number of connections. The major contribution to the routing overhead of AODV is from route requests.

3.5.3 Packet Size Analysis

To analyse the effect of the packet size in the network, the packet size is varied from 512 bytes to 2048 bytes. Fifty nodes randomly spread in the network are considered with 30 source-destination connections. The packet rate is set to four packets per second.

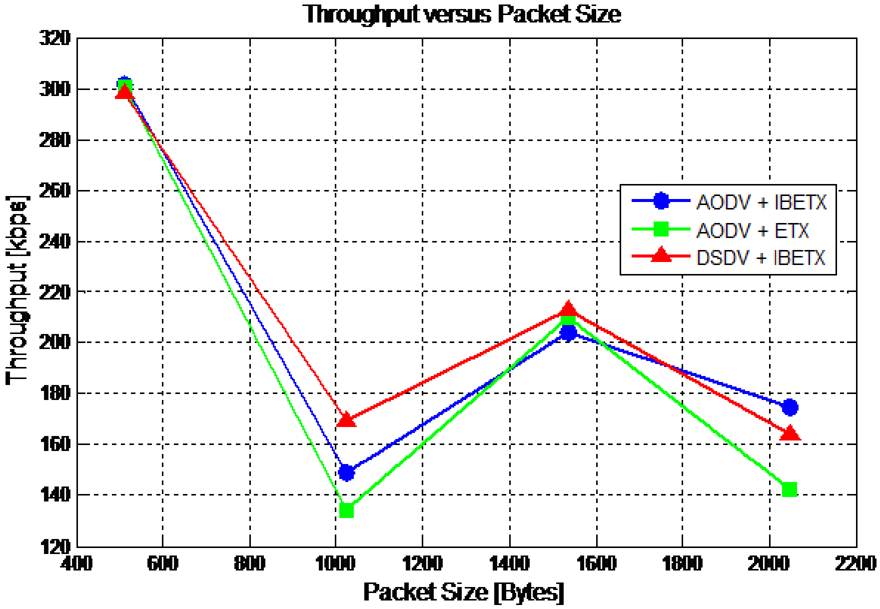

Figure 3.5: Throughput versus packet size

Figure 3.5 demonstrates that for a low packet size (512 bytes), all the protocols have approximately the same throughput. However, when the packet size doubles (1024 bytes), there is substantial drop in the throughput for all the routing protocols. Once again, DSDV with IBETX as the routing metric outperforms AODV with IBETX or ETX as the routing metric.

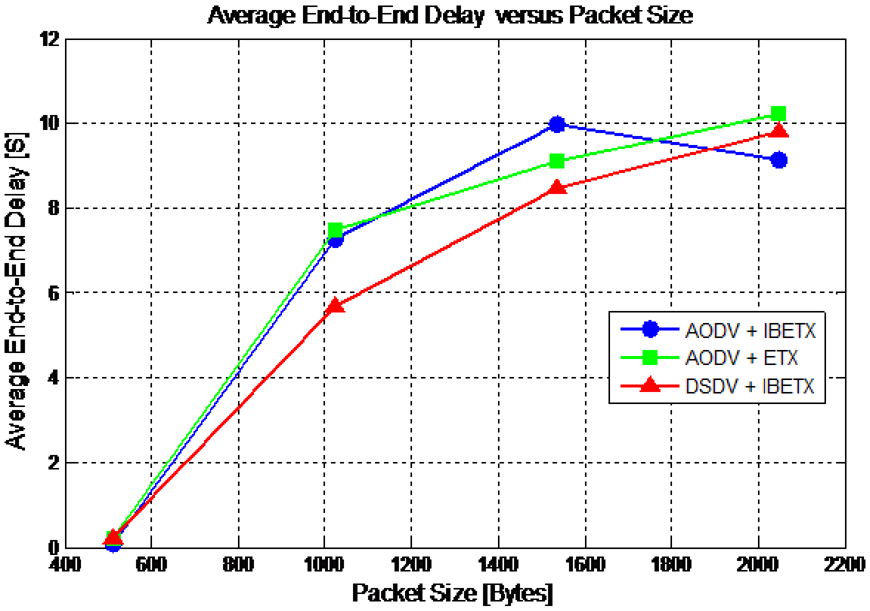

Figure 3.6: Average end-to-end delay versus packet size

In terms of average packet end-to-end delay, DSDV with IBETX as the routing metric achieves a lower average packet end-to-end delay when compared with AODV with IBETX as the routing metric as shown in Figure 3.6. This can be explained by the proactive nature of the DSDV routing protocol where routes are set before transmission of the packet.

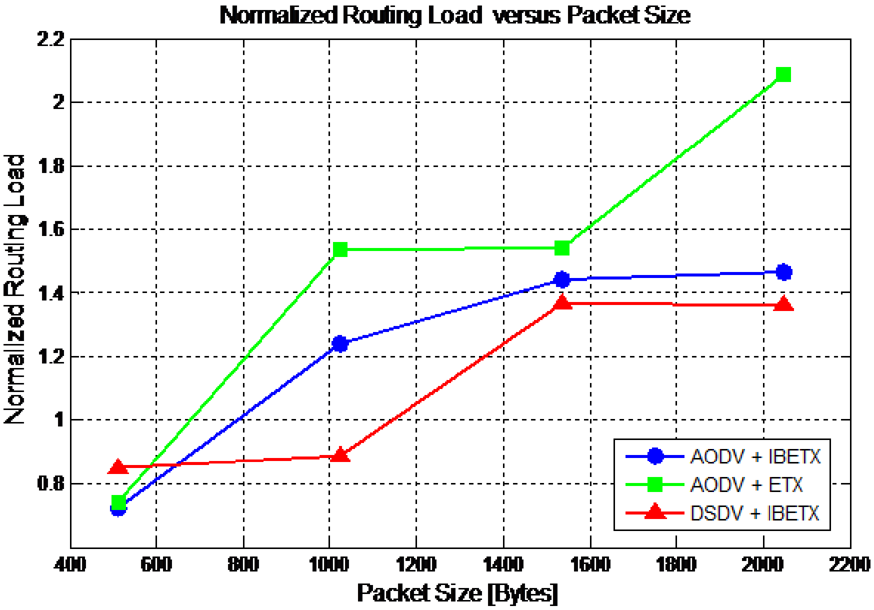

Figure 3.7: Normalised Routing Load versus packet size

For the normalised routing load (Figure 3.7) with small packet size (512 bytes) both AODV with IBETX and AODV with ETX have a low normalised routing load when compared with DSDV with IBETX as the metric. As the packet size increases, the normalised routing load increases for both routing protocols. However, it is low for the DSDV routing protocol with IBETX as the routing metric. An interesting observation is that the routing overhead for the routing protocols increases as the packet size is increased, and this leads to more collisions in the network.

3.6 Conclusion

Contention for transmission slots among various nodes in wireless ad-hoc networks becomes more pronounced as the traffic and packet size increase. How effective a routing protocol is in dealing with these challenges under constraints of network congestion and low bandwidth, is therefore, paramount in wireless ad-hoc networks. In this chapter, a performance comparison of a recently proposed quality link metric for wireless multi-hop networks over two prominent routing protocols (AODV and DSDV) is presented. This quality link metric overcomes the limitations in ETX and Expected Link Performance (ELP) metrics due to its limited awareness of the MAC layer and bandwidth sharing mechanism of the 802.11 standard.

The general observation from the simulations is that for application-oriented performance metrics such as delay, routing overhead and throughput, AODV that makes use of IBETX as the routing metric outperforms DSDV with IBETX as the metric in less stressful situations (low number of connections, traffic load, packet rate and packet size). However, DSDV that make uses of IBETX as the routing metric outperforms AODV with IBETX as the metric in more stressful situations, with widening performance gaps with increasing stress (more traffic load, higher packet rate and larger packet size). This can be explained by the shorter route cache in the AODV routing protocol. Frequently, discarding the valid routes and rediscovering them causes unnecessary delay in routing and increases control overheads.

CHAPTER 4. Proposed Approach

4.1 Introduction

Based on the simulation results of the previous chapter, it was observed that the performance of both routing protocols (AODV and DSDV) that make use of IBETX as the routing metric degrade as the sending rate or the traffic load increases in the network. This can be explained by the conservative and restrictive nature of the interference model implemented in this routing metric. In this chapter, an enhanced version of the IBETX metric based on the physical interference model is proposed.

4.2 Interference Modelling

The performance of wireless networks is highly dependent on the amount of interference experienced by the wireless links. Wireless networks suffer much from interference due to the absence of a dedicated bandwidth of wireless links and the shared nature of the wireless medium. Interferences degrade wireless networks by their strong contribution to the generation of wireless losses. They also increase the contention level when an interfering signal is above the carrier-sense threshold, causing frame emission to be delayed or lost until the channel is clear. This unsuitable feature of wireless networks necessitates a prudent modelling of interference to be used in several design areas such as channel assignment and routing. Understanding and managing interference is essential to the performance of wireless networks.

There are several interference models that have been proposed in literature and used in transmission scheduling studies. The range based or protocol interference model (Gupta and Kumar, 2000) is based on transmission and interference ranges. The transmission range is the maximum range in which a radio signal can be properly received and the interference range is defined as the area in which a sending node can disturb the transmission from a third node. The challenge is relevant to the complexity of measuring such ranges in the real world, especially in ad-hoc networks where the topology is unpredictable. The range-based is also very strict since it was designed to guarantee that the links do not interfere with each other through the particular channels assigned to each one. However, due the limited number of available channels in the IEEE standard 802.11 (IEEE, 1999) the physical specifications do not allow a channel to be assigned to each wireless link. For this reason, the range based model or protocol cannot be used in the routing metric to capture interference.

The logical interference (U. Ashraf and Juanole, 2008) refers to the interference arising from the CSMA-CA based MAC, which prevents a node from transmitting on the channel because another node is transmitting in the carrier sense range of this node. This model is less restrictive compared with the protocol model. Since the logical interference is computed before the data transmission (Vinicius C. M. Borges and Monteiro, 2011), it may not be an accurate indicator of the current channel interference and may result in performance deterioration in mobile networks.

Based on the limitations of previous models, a physical interference model is used in this dissertation to capture the interference experienced by links in the network , This model is simpler and less restrictive compared with the protocol and logical interference models since it relies solely on the interfering signal strength values, such as the Signal to Interference plus Noise Ratio (SINR) and the Signal-to-Noise Ratio (SNR). Furthermore, the physical model is more realistic because it physically models the interferences by accounting for the physical quality of wave superposition where interfering signals superpose to produce the resulting signal.

Regarding interference at the receiving side, this model does not count from only neighbouring nodes, but from all transmitting nodes in the same contention domain (S. Jinzhao and Wei, 2012). In contrast to the protocol and logical interference models that capture interference that occurs before transmission, the physical model has the immense advantage of displaying the actual transmission of the packet when the interfering signal may cause failed transmissions. Under the physical interference model (Padhye *et al.*, 2005), successful reception of a packet sent by a node i to node j depends on the signal quality perceived by the receiver j that is given by the Signal to Interference plus Noise Ratio (SINR) value. This value must be higher than a predefined threshold, and this default threshold is called the capturing threshold.

The SINR is defined as the quotient of the power of the wanted signal and the total power of unwanted signals (noises generated by other ongoing transmissions and the ambient noise in the network). Specifically, denoting the signal strength of a packet from node i at node j by $P_j(i)$, a packet on the link (i, j) from i to j is correctly received only if:

$$\frac{P_j(i)}{N + \sum_{w \in V'} P_j(w)} \geq \beta \tag{4.1}$$

where N is the ambient or background noise, V' is the set of nodes that are transmitting simultaneously, and β is a constant threshold that depends on the data rate, the modulation scheme, etecetera. The interference experienced by a packet for a node i for a link $l = (i, j)$ is defined as follows:

$$Interference\_Ratio_{(i,j)} = \frac{SINR_l(i)}{SNR_l(i)} \tag{4.2}$$

where

$$SNR_l(i) = \frac{P_l(j)}{Noise_i} \tag{4.3}$$

$$SINR_l(i) = \frac{P_i(j)}{Noise_i + \sum\limits_{k \in InterferenceSet[(i)-(j)]} \theta(k) P_i(k)} \tag{4.4}$$

Here $Interference\_Set[(i)-(j)]$ is the set of nodes that can interfere with node i, $P_i(k)$ is the signal power of a packet from node k at node i, and $\theta(k)$ is the normalised rate at which node k generates traffic over a period of time. It also represents the fraction of the transmitter k's received signal power that is projected onto the signal space of user i. In addition, $\theta(k)$ depends on the modulation schemes, spreading codes and data rates of the user. $P_i(j)$ is the signal strength of a packet from node j at node i and $Noise_i$ is the ambient or background noise at i. Considering a bidirectional communication link $l = (i, j)$ for a $DATA/ACK$ communication, the interference experienced by the link l is defined as:

$$Link\_Interfence_l = min(Interference\_Ratio_l(i), Interference\_Ratio_l(j)) \tag{4.5}$$

For estimating the link interference, the link SINR is considered in contrast to the local SINR of the listen mechanism as used in the MIND metric (Borges *et al.*, 2009) since it works locally at a node without considering the link. The two end nodes may have an asymmetric view of the channel which may introduce some inaccuracy. For a wireless link (i, j), $SINR(i, j)$ denotes the SINR measured at node j for data received from i. Considering a link (i, j) , the receiver j maintains the SINR of the frames received from node i for a sliding window of time. Node j periodically unicasts small packets (probes) to the node i that contain the average SINR of the frames received from node i. This technique will be more precise and accurate because the SINR of frames is captured in both directions. It should be noted that the proposed model does not fully capture sender-side interference, which results in back off and increases the Expected Transmission Time. both SINR and SNR are widely considered as good indicators of link because they provide measurements from the physical layer. However, the variations in the physical layer are very fast (in the order of microseconds) compared with the routing layer. These different time scale variations suggest that each layer should attempt to compensate for variation at the physical layer first. Therefore, there is a need to define a method or algorithm to measure these values in a simple and accurate way and make them available at the network layer for routing decisions with the help of a cross-layered approach. The proposed algorithm is based on a historical window.

Algorithm 1 SINR CALCULATION

```
$n \rightarrow$ number of samples

SumSinr $\rightarrow 0$

$Sinr\_[i] \rightarrow$ SINR of frames received at node j from node i

for $i = 0 \quad to \quad n - 1$ do
    $SumSinr = SumSinr + Sinr\_[i]$
end for
$SinrMean = \frac{SumSinr}{n}$
```

The number of samples n is actually the ratio of the duration of a frame at the network layer to the duration of the frame at the physical layer. The value of $SINRMean$ is cross-layered to make it available at the network layer for routing decisions.

4.3 Probability of Success

This part of the metric is aimed at estimating the expected delivery ratio or the probability of success of the link. A node may need to retransmit a packet several times (at the link layer) due to repeated losses. This is an indication of poor link quality and represents an inefficient use of resources. In this technique, the ratio of probes successfully delivered within a window of time from the current node to its neighbour is called the forward delivery ratio $d_{forward}$ and represents the delivery probability of data packets. The ratio of probes received from neighbours is called the backward delivery ratio $d_{backward}$ and is the successful transmission probability of the acknowledgment packet measured by the data sender. For a link l formed between node i and node j, the probability of success is given by (Javaid, 2010) as:

$$Probability\_of\_Success_l = d^{(l)}_{forward} \times d^{(l)}_{backward} \tag{4.6}$$

The routing metric should select links with higher delivery ratios or lower packet loss since minimising the number of transmission does not only optimise the overall throughput of the network, it also minimises the total consumed energy if a constant transmission power level is considered (Koksal and Balakrishnan, 2006). Similar to statements by (Couto, 2004), (Draves *et al.*, 2004), (U. Ashraf and Juanole, 2008), (Javaid, 2010) and (V.P. Mhatre and Diot, 2007), nodes broadcast probes once every second, and a moving window of time is used to compute the expected delivery ratio or the probability of success of a packet over a link. The probe based loss ratio measurement is the active component of the proposed improved routing metric. This active component is important because it can give an idea about certain aspects of the quality of the link that could otherwise be difficult to capture.

4.4 Bandwidth Estimation

This part of the metric integrates the transmission rate of the wireless link. It is important that the routing metric considers the transmission rate of the wireless link at each hop since a link with a high transmission rate takes a small amount of channel time while a link with a low transmission rate or bandwidth takes a greater amount of channel time. This means that the node will occupy the channel for longer and disturb other nodes that are transmitting in the neighbourhood. The aim of this component is to help the routing metric to favour wireless links with higher transmission rates or bandwidth in order to achieve better performance. For a wireless link (i, j), the bandwidth is given as:

$$Link\_Capacity_{(i,j)} = Bandwidth_{(i,j)} \tag{4.7}$$

4.5 Formula for the Proposed Improved Routing Metric

The proposed improved routing metric is defined for a wireless link l as follow:

$$IBETX_{improved} = \frac{Probability\_of\_Success_l}{Link\_Capacity_l} \times Link\_Interference_l \tag{4.8}$$

To capture the long-term quality of the wireless link, link loss, link capacity and link interference are calculated over a moving window of 10 seconds for each outgoing link at a node. This will reduce the issue of transient problems and will give an idea of the long-term performance of the wireless link. By selecting an interval that is too short would result in frequent route breakages because even transient link quality problems would result in link breakages. Selecting an interval that is too long result in a very slow responding route maintenance mechanism, which may force the protocol to continue using poor quality links for a long time. Ten seconds appears to be a good compromise and results from the ETX metric (Couto, 2004) validate the fact that a moving window of 10 seconds is a good choice for mesh or static networks. The end-to-end path metric for a path P is given as:

$$IBETX_{improved_P} = \sum_{l \in P} IBETX_{improved_l} \tag{4.9}$$

The routing metric of the path is then defined as the throughput of the bottleneck link of the path, as given below:

$$f(P) = \min_{k \in P} IBETX_{improved_k} \tag{4.10}$$

4.6 Conclusion

In this section of Chapter 4, a model of the proposed improved routing metric is shown. The improved metric is three dimensional because it addresses three severe issues that badly affect the performance of wireless mesh or static networks. Firstly, the proposed improved routing metric takes into consideration the link loss by measuring the number of MAC transmissions and retransmissions needed to recover from the frame losses. Secondly, it provides all the nodes in the same contention domain with the information about the nominal bit rate by considering the bandwidth sharing mechanism of 802.11. Lately it addresses the issue of interference, which is the main degrading issue for performance in wireless networks. In contrast with (U. Ashraf and Juanole, 2008) and (Javaid, 2010), a less restrictive and more accurate and realistic interference model based on the SINR and SNR is proposed to capture the inter-flow interference. It has the advantage of depicting measures by using online data traffic. However, it is difficult to obtain signal strength accurately since it has a high variation over the time at the physical layer. With the aid of a cross-layered approach and a fixed history window, a simple and appropriate method is proposed to measure the signal strength at the physical layer and make it available to the network layer for routing decisions.

CHAPTER 5. Simulation Results

5.1 Introduction

The simulations results of the proposed improved routing metric are presented in this chapter.

5.2 Simulation Environment

The wireless network consists of 10, 30, 50, and 70 static nodes randomly placed in a square flat area of $1000m$ by $1000m$. For 10 nodes, the number of connections is 4, for 30 it is 12, and each increment of 20 nodes, 8 connections are added. The effective carrier sensing range is $447m$. Each node maintains a send buffer of 50 packets with a drop-tail mode. This buffers all data packets waiting for a route. To prevent the buffering of packets indefinitely, packets are dropped after a specific time of waiting in the send buffer. All packets, both data and routing, are sent via the routing layer and are filed at the interface queue until the MAC layer can transmit them. The interface queue is a First In First Out (FIFO) technique with a maximum of 50 packets. Routing packets are given higher priority than data packets in the interface queue. The traffic sources transmit Constant Bit Rate (CBR) with User Datagram Protocol (UDP) at the transport layer. The bandwidth provided to all the wireless links is 6 Mbps. Each simulation runs for ten runs with identical traffic models but different randomly generated topology scenarios.

Each run is for 900s and each data point on the graph represents an average of 10 runs. All the simulations were performed on an Intel(R) Core(TM) i5-2400 with 3.10 GHz processor and 4.00 GB Random Access Memory (RAM) over the operating system Ubuntu Pangolin 12.04 LTS.

Table 5.1: Traffic and topology parameters

Parameters	Values
Network area	$1000m \times 1000m$
Number of nodes	10, 30, 50, 70
Random topology	10
Number of sources	4, 12, 20, 28, 30
Packet rate	1, 2, 4, 6, 8, 10 (packets/second)
Packet size	512, 1024, 1536, 2048 bytes
Traffic type	CBR
Transport protocol	UDP
Data rate	6 Mbps
Simulation time	900 s

The original IBETX routing metric was implemented over a proactive routing protocol, which is a Destination-Sequenced Distance Vector (DSDV) (Perkins and Bhagwat, 1994) routing protocol. It is a non-adaptive routing protocol in which routes are pre-computed. It has the advantage of guaranteeing loop-free paths and higher efficiency in route discovery (low latency). Its disadvantage is that the packet delivery ratio dramatically decreases with network size (M. S. Kabiwa and Kurien, 2013). Network resources are unnecessarily consumed when the network is stable and congestion control is very low. It is not suited for low powered devices. Based on the drawbacks of the DSDV routing protocol, the improved metric along with other metrics is implemented over a reactive routing protocol (AODV). In order to maintain routes between nodes, AODV normally requires that each node in the network periodically broadcasts a HELLO message, with a default rate of once per second. Failure to receive three consecutive HELLO messages from a neighbour is taken as an indication that the link to respective neighbour is broken or down. In addition to neighbour discovery, HELLO messages sent by each node to their neighbours are also used here to compute $Probability\_of\_Success$. Each node broadcasts periodic (every second) HELLO packets and computes the forward delivery ratio $d_{forward}$ and the backward delivery $d_{backward}$. A moving window of 10 seconds is used to compute the $Probability\_of\_Success$. Using HELLO packets to compute the $Probability\_of\_Success$ helps the routing protocol to avoid the extra overhead that would be caused by using special probes. Each node remembers its $Interference\_Ratio$ for a window of 10 seconds. In each broadcasted HELLO packets, the node piggybacks its $Interference\_Ratio$ for the last 10 seconds so there will be no extra routing overhead.

At the Medium Access Control (MAC) layer, the simulator uses the Distributed Coordination Function (DCF) compliant with the enhanced IEEE 802.11a standard (802.11Ext) (Qi Chen *et al.*, 2007). The 802.11Ext standard introduces two new modules: Mac802.11Ext and WirelessPhyExt. These extensions are based on Mac802.11 and WirelessPhy but underwent a considerable modifications from the original code, aiming at a significantly higher level of simulation accuracy. The enhanced IEEE 802.11Ext includes the following key features:

- structured design of MAC functionality modules: transmission, reception, transmission coordination, reception coordination, backoff manager and channel state monitor;
- cumulative SINR computation;
- MAC frame capture capabilities; and

- multiple modulation scheme support (Qi Chen *et al.*, 2007).

At the physical layer, there are different modulation schemes that can be used to modulate the data namely Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK) and the 64-QAM (64 Quadrature Amplitude Modulation)(J.S.Chitode, 2009). Using higher modulation schemes (QPSK or 64-QAM) will achieve a very high data rate (transmitting more bits per unit bandwidth), but this results a very high SINR, complexity of the receiver and a higher energy consumption. Based on these compromises, the BPSK modulation scheme for the raw data transmitted and received is used in this evaluation. The following table summarises the simulation parameters used at the physical and MAC layer in the performance evaluation.

Table 5.2: Simulation parameters at the network, MAC and physical layers

Simulations parameters	Values
Routing Protocol	AODV
MAC protocol	IEEE 802.11a Ext
Physical layer	WirelessPhyExt
Frequency	5.2 GHz
Antenna	Omni-directional
Propagation model	Two ray ground model
RTS threshold	2346
Transmission power	0.001W
Noise floor	2.512×10^{-13}
SINR data capture	10dB
Modulation scheme	BPSK

Different performance metrics are used in the evaluation of the improved routing metric.

They represent the different characteristics of the overall network performance. In this chapter, three metrics are used to study their effects on the overall network performance. These metrics are normalised routing load, packet average end-to-end delay and network throughput.

5.3 Simulation Results

To evaluate the improved routing metric, three parameters were varied: the packet sending rate (traffic rate), the packet size and the network density.

5.3.1 Offered Traffic Load Analysis

To examine the performance of the routing protocol with distinct routing metrics under various traffic rates, the packet rate is varied from 1 to 10 packets per second. Fifty nodes are randomly placed to form a static network. Constant Bit Rate (CBR) traffic is randomly generated by 30 source-destination pairs with a packet size of 512 bytes. This value is chosen because smaller payload sizes penalise protocol if source routes are appended to each data packet.

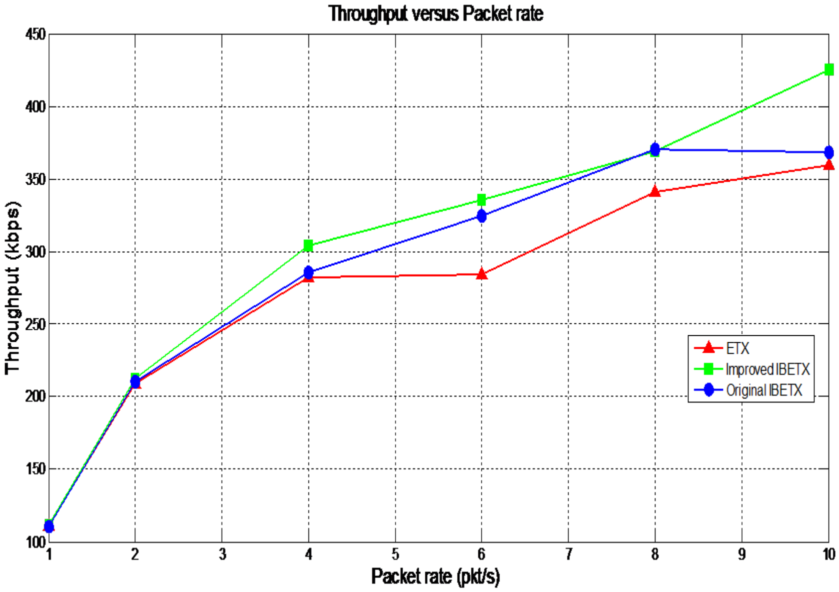

Figure 5.1: Throughput achieved for varying packet rate

Figure 5.1 demonstrates that at a low packet rate (below 2 packets per second), all the routing metrics have similar throughput. This is because there is minimal interference in the network due to the low traffic rate. The choice of any route yields equally favourable results. As the traffic rate increases, both the improved IBETX and the original IBETX routing metrics exhibit higher throughput compared with the ETX metric. This is due to the fact in addition to measuring the probability of success for data packest using probes (HELLO packets in this work) as the ETX metric, the improved metric and the original IBETX address the issue of the bandwidth sharing mechanism in wireless networks, that is the links with a lower bit rate degrade the performance of the faster links. Taking the bandwidth of all links in the same contention domain into account gives accurate information about the link status compared with only considering the probability of success. Since, HELLO packets are smaller in size compared with the data packets, measuring the link quality by calculating the bandwidth of the link along with the probability of success is not sufficient. Routing metrics must incorporate the interference.

The interference phenomenon takes place at the physical layer of the receiver terminal, as an interfering (undesired) signal, disturbing the reception of a desired signal. The original IBETX implements a logical interference model that rightly predicts medium congestion and collision. This model is very conservative due to the fact that several nodes in the network are silenced when certain communication is ongoing, and this occurs before the transmission of the data packet. At a high traffic rate, it can be observed that the improved routing metric achieves 6% more throughput than the original IBETX and 11% more than the ETX metric overall.

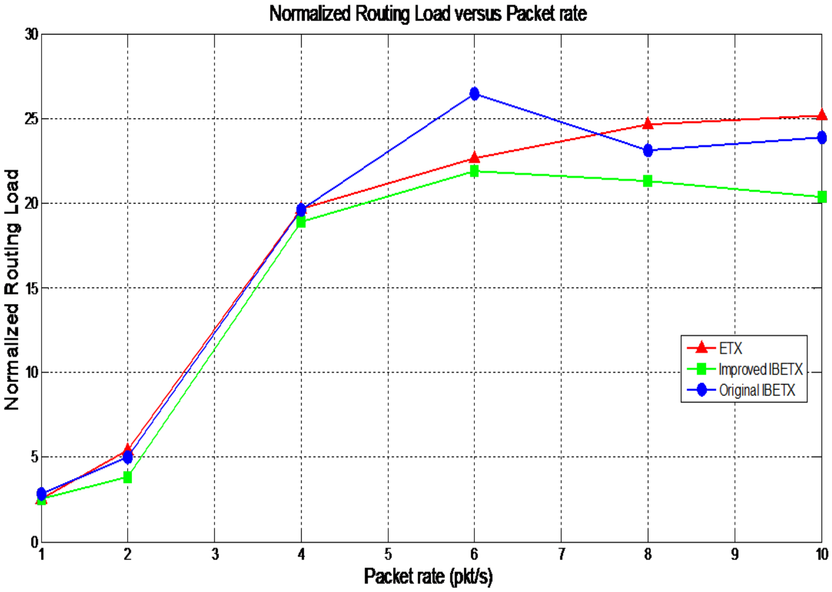

Figure 5.2: Normalised Routing Load generated for varying packet rate

The normalised routing overhead is an important performance metric for comparing these routing metrics, because it measures the scalability of a protocol, the degree to which it will function in congested or low-bandwidth environments, and its efficiency in terms of consuming node battery power. Protocols that make use of routing metrics that send large numbers of routing packets can also increase the probability of packet collisions and may delay data packets in network interface transmission queues. Figure

5.2 demonstrates that as the traffic rate increases, the normalised routing load increases for all routing metrics. However, it is slightly lower for the enhanced routing metric compared with the original IBETX and ETX routing metrics. overall, the enhanced routing metric offers a normalised routing load reduction of 12% compared with the original IBETX routing metric and 11% when compared with the ETX metric.

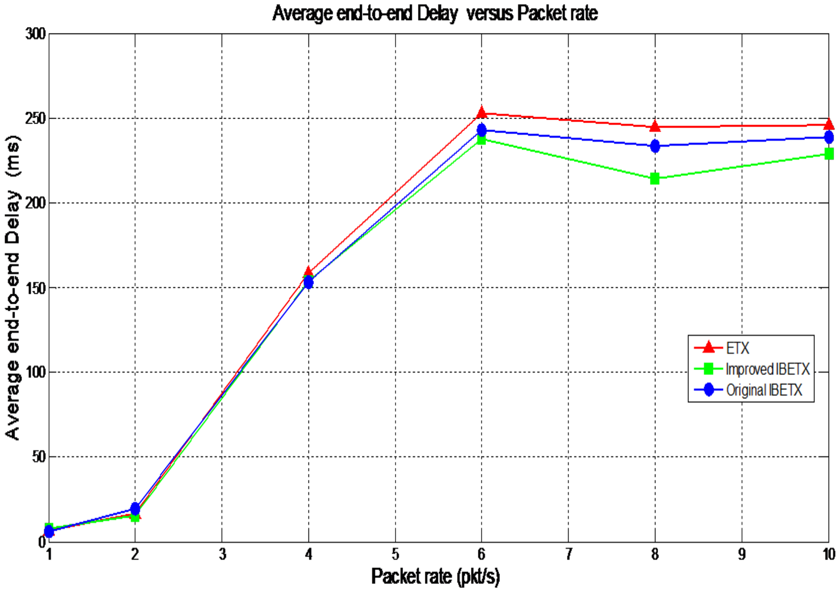

Figure 5.3: Average end-to-end delay generated for varying packet rate

Figure 5.3 demonstrates that when considering a stressful situation (above four packets per second), the enhanced routing metric offers a reduction in delay of 5% compared with the original IBETX routing metric and 8% when compared with the ETX metric. It is also observed that for all the routing metrics the packet average end-to-end delay increases with the traffic rate.

5.3.2 Effect of the Packet Size

To examine the performance of the improved routing metric with other routing metrics under different packet sizes, the packet size is varied from 512 to 2048 bytes. Fifty nodes are randomly placed to form a static network. The CBR traffic is randomly generated by 30 source-destination pairs with a packet rate of four packets per second.

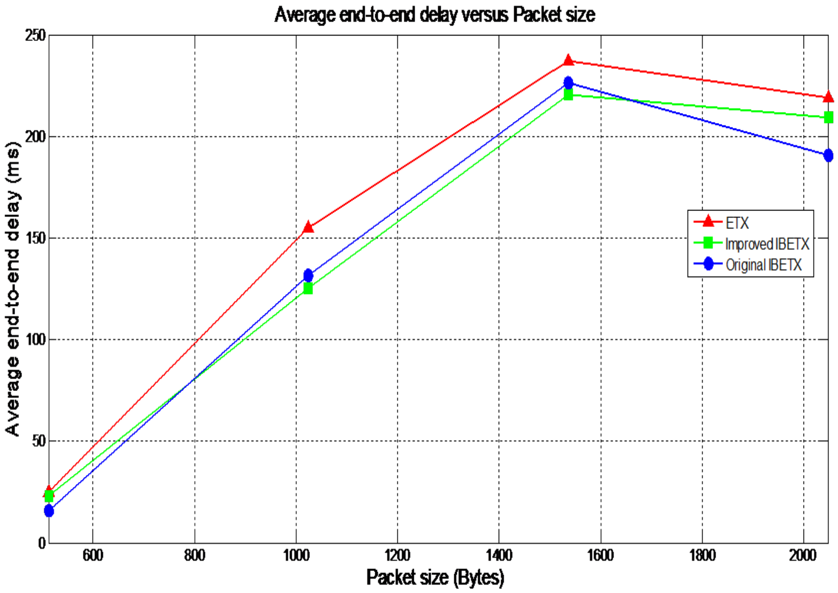

Figure 5.4: Average end-to-end delay generated for varying packet size

When the packet size is varied, it is observed that at low and moderate data packet size (below 1536 bytes), the enhanced routing metric slightly outperforms the original IBETX metric in terms of average packet end-to-end delay (Figure 5.4). This also produces 9% less delay compared with the ETX metric. In addition, as the size of the data packet increases, the average packet end-to-end delay for all the routing metrics also increases due to the fact that there is more congestion in the network.

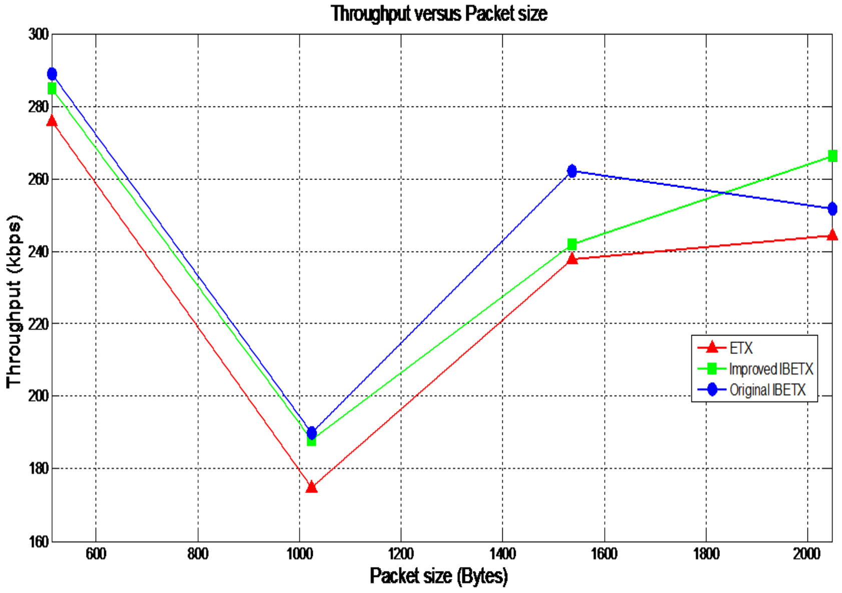

Figure 5.5: Throughput achieved for varying the packet size

An interesting observation is when using 1024 bytes packets (Figure 5.5), the congestion due to lack of spatial diversity becomes a problem for all the routing metrics, and one or two nodes drop most of the packets they receive to forward. It is also observed that at low packet size (below 512 bytes), both the improved metric and the original IBETX achieve approximately the same throughput. At a moderate packet size (1024 bytes), the original IBETX metric slightly outperforms the enhanced metric. When the packet size is very big (2048 bytes) the enhanced metric achieves a 9% higher throughput than the ETX metric and a 6% higher throughput than the original IBETX.

5.3.3 Scalability Analysis

For the network density analysis, the number of nodes was increased from 10 to 70 nodes. For 10 nodes, the number of sources was 4, for 30, it was 12, and for each increment of 20 nodes, 8 sources were added. These sources were randomly selected to generate

Continuous Bit Rate (CBR) traffic with a packet size of 512 bytes. The packet rate was set to four packets per second.

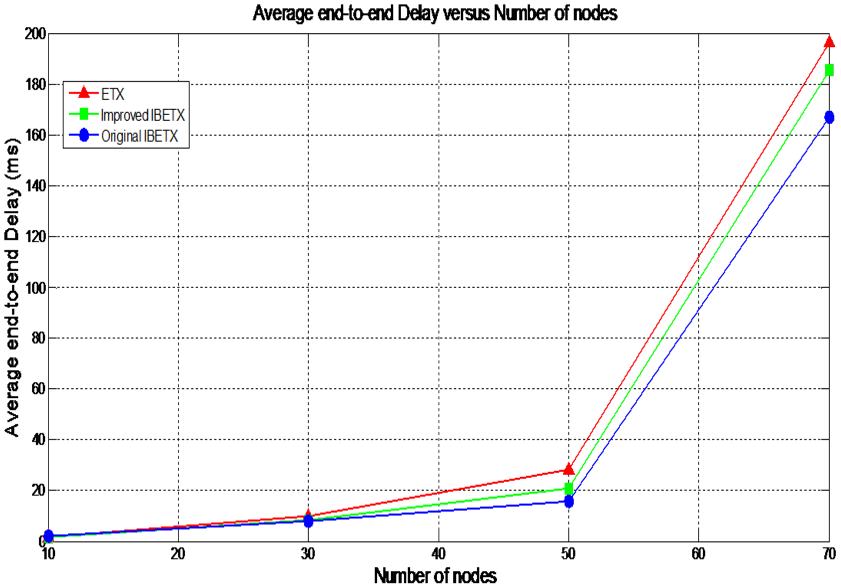

Figure 5.6: Average end-to-end delay generated versus number of nodes

When the number of nodes is low (below 30 nodes), all routing metrics offer similar average packet end-to-end delay results. As the network density increases (from 50 nodes) the improved routing metric exhibits a reduction of 7% average packet end-to-end delay compared with the ETX metric. However, compared with the original IBETX, it offers 12% higher average packet end-to-end delay. This can be explained by the fact that the number of connections and the packet rate are both low and the enhanced routing metric only considers the interference viewed at the receiver. It does not fully incorporate the interference at the sender, which results in back off and increases the Expected Transmission Time as showed in Figure 5.6.

5.4 Conclusion

Selecting efficient end-to-end routes in wireless static networks is a significant problem because interference plays an important role in limiting the performance of the network. In this chapter, a detailed performance evaluation of the enhanced routing metric was carried out. The scalability and the traffic load were both taken into account. The performance parameters, throughput, average packet end-to-end delay, and normalised routing load were used for measuring the capabilities of the enhanced routing metric in different scenarios. Using extensive simulations over a discrete event simulator (NS-2.34), it was observed that in a moderate density and high data traffic rate network, the improved routing metric achieved higher throughput and reduced normalised routing overhead and delay compared with the original IBETX and ETX routing metrics.

CHAPTER 6. Conclusions and Recommendations

6.1 Introduction

This chapter provides the concluding remarks of the research. An overview of the objectives of the study is is given. The contributions and the achievements of the research are sated and the benefits and recommendations for future work are presented.

6.2 Final Conclusion

One of the important research areas in MANETs is establishing and maintaining the ad-hoc network through the use of routing protocols (Murthy and Manoj, 2004). An essential role of routing protocols in wireless networks is to find and establish routes between node pairs. Traditional routing protocols attempt to find the shortest path between the source and destination based on the hop count metric. This metric is suitable for wireless networks with a high mobility scenario. However, in some wireless ad-hoc networks (static networks or mesh networks) where mobility is not an issue it may choose paths with low throughput and poor medium utilisation since it treats all the links in the network alike.

To overcome the limitations of the hop count metric various link quality metrics have been proposed in literature. One of the most popular metric in the domain of link quality metrics is the ETX metric. It predicts the average number of data frame and ACK frame transmissions necessary to successfully deliver a packet over a link. After the ETX metric, a number of routing metrics were proposed which further improved link quality estimation. (Javaid, 2010) proposed the IBETX metric, an improvement on ELP and ETX metrics. This metric considers the bandwidth sharing mechanism of 802.11 DCF standard that is throughput reduction of fast links due to contention from slow links neglected by the ELP and ETX metrics.

An important result from the review of existing routing metrics is that interference is the main performance-limiting factor in most wireless ad-hoc networks. It causes congestion and collisions that seriously affect the capacity of the network. Another important result from the literature review is that routing in wireless ad-hoc networks can be significantly improved by cross-layering with lower layers (MAC and physical layers).

The simulation results show that AODV, which makes use of IBETX as the routing metric, performs better with a lower number of connections and a lower packet rate in terms of average end-to-end delay and normalised routing load when compared with DSDV which also makes use of the IBETX routing metric. As both the packet rate and the number of connections increase, it is shown that DSDV outperforms AODV in terms of throughput, average packet end-to-end delay and normalised routing load.

An interesting observation from the simulation results is that at a high traffic rate or sending rate, the performance of both routing protocols with IBETX as the routing metric decreased. This is explained by the fact that the IBETX metric uses a very conservative and restrictive interference model to capture interference, and this model does not use online measurements to depict the interference experienced by wireless links.

Based on these limitations, an enhancement of the IBETX metric was proposed. As is the IBETX metric, the enhanced metric is a hybrid metric. It uses a cross-layering channel to gather wireless channel information that considers the interference at the physical layer. Capturing interference at the physical layer is simpler, more realistic and less restrictive compared with capturing the interference at the MAC layer. The enhanced metric relies solely on the interfering signal strength values such as the SINR and SNR. Using the SINR and SNR values to capture interference is worthwile since these are good metrics. They have the immense advantage of displaying the transmission of the packet when interfering signals may cause failed transmission. However, the variations in the physical layer are very fast (in the order of microseconds) compared with the routing layer. These different time scale variations suggest that each layer should attempt to compensate for variation at the physical layer first.

As with the IBETX metric, the enhanced metric bypasses congested regions using the expected delivery ratio or the probability of success. it also addresses the issue of the bandwidth sharing mechanism in 802.11 DCF by considering the bandwidth reduction of fast links due to links with a low transmission rate or nominal bit rate in the same contention domain.

The enhanced metric was compared with several existing metrics, including ETX and IBETX, through extensive simulations over a discrete event simulator (NS-2) and the results show performance improvement in terms of throughput, average packet end-to-end delay and normalised routing load in moderate density and high data traffic rate networks.

6.3 Recommendations for Future Studies

During the simulations, a Constant Bit Rate Constant Bit Rate (CBR) was used as traffic flow. Constant Bit Rate uses User Datagram Protocol (UDP) as the default transport layer protocol. Transport Control Protocol (TCP) has certain traffic shaping characteristics, such as timeouts and window back-offs. These can have an increased impact on throughput compared with UDP connections. The TCP can increase the negative impact of poor route selection, which in turn, might improve the performance of the proposed routing metric. In future, it would be interesting to see the impact of the congestion control mechanism of TCP on the performance of the metric.

In this research, only the interference viewed by the receiver side was considered. Future research it will investigate ways to incorporate the sender side.

Single radio wireless mesh networks are basic wireless mesh networks wherein each node has a single radio, and all are tuned to the same frequency. They have severe performance limitations due to the channel access procedure of several nodes contending for the same channel and hence causing much interference. Such a type of interference is known as intra-flow interference. Intra-flow interference increases the bandwidth consumption of the flow at each of the nodes along the path. This causes the throughput of the flow to degrade sharply, and the delay at each hop to increase dramatically. Achieving channel diversity is an optimistic solution to alleviate intra-flow interference. Therefore, in future, it will be interesting to enhance the functionality of the proposed routing metric to support a multi-channel multi-interface environment.

Simulations can help to accurately model the behaviour of the routing protocols in different network topologies. Although simulators can obtain results in a matter of hours, they cannot comprehensively consider all the conditions in a real network. Even when accurate physical models are used, simulation results cannot strongly depict the physical wireless network. Therefore, in future, a static wireless network test bed will be set up to evaluate the performance of the improved metric under identical conditions. A test bed setup will provide realistic results and will also help to gauge the differences between simulation models and physical experiments.

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