REPUBLIC OF TURKEY
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

A NEW DEFINITION OF EXPECTED TRANSMISSION COUNT AS AN AD-HOC NETWORK ROUTING INFORMATION

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MSc. THESIS
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İSTANBUL, 2017

REPUBLIC OF TURKEY

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A thesis submitted by Musaab JASIM in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE** is approved by the committee on 23.03.2017 in Department of Computer Engineering, Computer Engineering Program.

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This work was partially supported by University of Diyala, Iraq, and by Yildiz Technical University, Turkey.

ACKNOWLEDGEMENTS

In the name of ALLAH's, the Merciful, praise be to ALLAH's and pray, peace be on his prophet Mohammed (ALLAH's blessing), and peace be on his relatives. Praise is to ALLAH's, who created us and gave us the ability and mentality to think and work for the benefit of human beings.

The work presented in this thesis has been performed at the Department of Computer Engineering, Yildiz Technical University, in the period from February 2014 to March 2017. During this time, many have contributed to this work.

The author wishes to express his deepest gratitude to his adviser Assist. Prof. Dr. Ferkan YILMAZ for the guidance, advice, criticism, encouragement and insight throughout the research.

Gratitude also goes to my family and friends who supported me and listened to the triumphs and difficulties of the work that I have faced.

March, 2017

Musaab JASIM

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LIST OF SYMBOLS

D	Delay
Q_S	Sender-Queuing Delay
Q_R	Receiver-queuing delay
P_S	Processing delay
P_R	Receiver-processing delay
T	Transmission delay
P	Propagation delay
Var	Variance
Cov	Covariance
DR	Delivery ratio
Lat	Median Latency
m_{del}	Message Delivery
m_{cre}	Message Created
t_{del}	Message Delivery Time
t_{cre}	Message Creation Time
$Over$	Overhead
m_{rel}	Message Relayed
CM	Composite Metric
C_m	Message Collision
T_b	Wake-Up Duty Cycle
d	Transmission Duration
Cap	Capacity
C	Estimated Capacity
V	Velocity
M_{XY}	Mobility Value between X and Y
φ	Weighted Parameter
P_s	Probability of Successful Transmissioon
P_l	Probability of Loss Transmission
d_f	Forward Delivery Ratio
d_r	Reverse Dlivery Ratio
t	Time
S_p	Data Packet Size
S_f	Frame Size
S_{prob}	Probe Packet Size
δ	Clock Offset
Ψ	Smooth Factor
STD	Smooth Transmission Delay
μ	Mean

σ^2	Variance
β	Tubable Parameter
X_j	Sum Of Transmission Times Of Hops On Channel j
$CH(.)$	Channel
$prev(.)$	Previous Hop
IR	Interface Ratio
B_{Noise}	Background Noise
$P(.)$	Single Strength of Packet fom one node to other
$\eta(.)$	Set of Nodes
TIF	Transmission Infection Factor
$IS(.)$	Set of Links Interface with Other Link
$S(.)$	Set of All Interfere Links
$d_{exp}(.)$	EXPICTED Link Delivery
NP	Non Source-Destination Path
$BW_{exp}(.)$	Expected Bandwidth
I_{exp}	Expected Interface
RC	Remaining Capacity
$\gamma_{l(.)}$	Factor of Link Quality
r	Transmission Rate
$L(.)$	Load-Balancing Component
QL	Average Queue Length
$Cont_{avg}$	Average Contention
bo	Back-off
IL	Interface load
AIL	Average Interface Load
$\mho$	Scaling Factor
T_w	Window Time
T_{sw}	Sub-window Time

LIST OF ABBREVIATIONS

AODV	Ad Hoc On-Demand Distance Vector
AMRoute	Ad hoc Multicast Routing protocol
ACK	Acknowledgment
BER	Bit Error Rate
CATT	Contention-Aware Transmission Time
CWB	Contention Window Based
CGSR	Cluster-Head Gateway Switch Routing
CAMP	Core-Assisted Mesh Protocol
CSC	Channel Switching Cost
CEDAR	Core-extraction distributed ad hoc routing
CMMBCR	Conditional Max-Min Battery Capacity Routing
CTS	Clear to Send
DSDV	Destination-Sequenced Distance-Vector
DSR	Dynamic Source Routing
DREAM	Distance Routing Effect Algorithm for Mobility
DDM	Differential Destination Multicast
ETX	Expected Transmission Count
ETT	Expected Transmission Time
EETT	Exclusive Expected Transmission Time
ENT	Effective Number of Transmissions
FSR	Fisheye State Routing
FGMP	Forwarding Group Multicast Protocol
FER	Frame Error Rate
HWMP	Hybrid Wireless Mesh Protocol
HSR	Hierarchical State Routing
iETT	Improve Expected Transmission Time
INX	Interferer Neighbors Count
IRU	Interface-Aware Resource Usage
IBETX	Interference and Bandwidth Adjusted ETX
ILA	Interference-Load Aware Routing (ILA)
IETF	Internet Engineering Task Force
LETT	Load Aware ETT
LAR	Location-Aided Routing
LGF	Location-Based Geocasting and Forwarding
ML	Minimum Loss
MD	Minimum Delay
mETX	Modified ETX
MIC	Metric of Interference and Channel-switching

MTTPR	Minimum Total Transmission Power Routing
MAODV	Multicast Ad hoc On-Demand Distance Vector
MUP	Multi-Radio Unification Protocol
OLSR	Optimized Link State Routing Protocol
ODMRP	On-Demand Multicast Routing Protocol
OWD	One-Way Delay
PROPHET	Probabilistic Routing Protocol Using History of Encounters and Transitivity
PREP	Prioritized Epidemic
PAAOMDV	Power Aware Ad-hoc On-demand Multipath Distance Vector
QAR	Quality-Aware Routing
RTT	Per-hop Round Trip Time
RARE	Resource Aware Routing for mEsh
RAPID	Resource Allocation Protocol for Intentional DTN
RREQ	Route Requesr
RREP	Route Reply
RREP-ACK	Route Reply Acknowledgment
RSSI	Received Signal Strength Indication
RTT	Round-Trip Time
RTS	Request to Send
SMETT	Sum of Motivated Expected Transmission Time
SPBM	Scalable Position-Based Multicast
SINR	Signal to Interference and Noise Ratio
SRTT	Smoothed Round-Trip Time
TORA	Temporally Ordered Routing Algorithm
WCETT	Weighted Cumulative ETT
WCETT-LB	Weighted Cumulative Expected Transmission Time with Load Balancing
ZRP	Zone Routing Protocol
ZHLS	Zone-Based Hierarchical Link State

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ABSTRACT

A NEW DEFINITION OF EXPECTED TRANSMISSION COUNT AS AN AD-HOC NETWORK ROUTING INFORMATION

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MSc. Thesis

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Although there are great efforts to enhance the current physical and MAC layers of wireless multihop networks, the performance of these networks still depends on the efficiency of the routing process in selecting the optimal path routes. In fact, selecting the optimal routes depends on the weights (costs) of the link / hops, which are determined by some routing metrics, among the nodes within a network. Each routing metrics involves a set of measurements that are mathematically merged in order to pick up the link quality. Within this context, routing metrics play an essential role in characterizing the links / hops, and hence the efficiency of routing decision. Several metrics are available in literature, which are utilized to capture single or multiple characteristics such as delivery ratios, radio resource utilization, and interferences for each link within a network. However, the reliability of the channels within a network is out of the sight of these metrics. In this thesis, we try to use a novel mathematical method to redefine the ETX routing metric. Moreover, we try to modify the ETX in order to be able to detect the reliability of the forward and reverse channels of any links within the network. The new routing metric that is called dynamic ETX (DETX) will help the routing protocols to select the high reliability and qualitative routes among the available routes. Thus, the overall network performance will be increased, especially for the network that works in a high dynamical environment.

Keywords: Wireless multihop network, Routing protocols, Routing metrics, Expected transmission count, ETX, New defention of ETX, Dynamic ETX

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ÖZET

BEKLENEN İLETİM SAYISININ AD-HOC AĞI YÖNLENDİRME BİLGİSİ OLARAK YENİDEN TANIMLANMASI

Musaab Jasim

Bilgisayar Mühendisliği Anabilim Dalı
Yüksek Lisans Tezi

Tez Danışmanı: Assist. Prof. Dr. Ferkan YILMAZ

Kablosuz çok sekmeli ağların hâlihazırdaki fiziksel ve ortam erişim kontrolü (MAC) katmanlarını iyileştirmek için büyük çabalar sarf edilmesine rağmen, bu ağların performansı hala en iyi rotanın seçilmesinde, yönlendirme işleminin verimliliğine bağlıdır. Aslında, en iyi rotanın seçilmesi, ağ içerisinde, devreler arasındaki bağlantı veya sekmelerin maliyetine bağlıdır ki bu bağlantı veya sekmeler bazı yönlendirme ölçüleri tarafından belirlenir. Her bir yönlendirme ölçüsü, bağlantı kalitesini anlamasına yardımcı olan, matematiksel olarak birleştirilmiş bir dizi ölçüden meydana gelir. Bu bağlamda, yönlendirme ölçüleri, bağlantı veya sekmeleri belirlemede ve dolayısıyla da yönlendirme kararının verimliliğinde önemli bir rol oynar. Literatürde, dağıtım oranları, radyo kaynağı kullanımı ve bir ağ içerisindeki her bir bağlantının birbirine karışması gibi bir veya birden fazla özelliği kullanılan birkaç ölçü mevcuttur. Ancak, bir ağ içerisindeki kanalların güvenilirliği bu ölçülerin erişimi dışındadır. Bu tezde, beklenen iletim sayısı (ETX) yönlendirme ölçüsünü tekrardan tanımlayacak yeni bir matematiksel metot kullanılmıştır. Ayrıca, beklenen iletim sayısı (ETX), bir ağ içerisindeki herhangi bir bağlantının ileri yönde ve ters yöndeki kanallarının güvenilirliğini saptamak üzere değiştirilmeye çalışılmıştır. Dinamik beklenen iletim sayısı (DETX) adı verilen bu yeni yönlendirme ölçüsü, var olan rotalar arasından, yüksek güvenilirliği ve kalitesi olan rotaları seçmek üzere yönlendirme protokollerine yardımcı olacaktır. Böylece tüm ağ performansı, özellikle de aşırı dinamik ortamlarda çalışan ağların performansı, artacaktır.

Anahtar Kelimeler: kablosuz çok sekmeli ağlar, yönlendirme protokolleri, yönlendirme ölçüleri, beklenen iletim sayısı, ETX, beklenen iletim sayısının (ETX) yeni tanımı, dinamik beklenen iletim sayısı (ETX)

CHAPTER 1

INTRODUCTION

1.1 Literature Review

Wireless multihop networks allow nodes to access data and services wirelessly, regardless of their geographic positions. These networks are classified as static and dynamic networks; −stationary mesh network [1–3] is considered static while wireless ad-hoc networks [4–7] are dynamic. In such wireless networks, each node is solidly equipped with a communication device that enables to send, receive, and store messages. Because of that, the wireless coverage of these devices is limited, some nodes may not be within wireless coverage of the other. Further, two nodes are considered as neighbors if the distance between them is at most R, where R is the transmission radius / the radius of the wireless coverage. In this context, exchanging messages among the nodes, which are far from each other, are normally established through several hops / links. Accordingly, the intermediate nodes between the source and destination nodes will act as routers by receiving and sending data and routing-information messages from and to the other nodes within their wireless coverage. In order to have appreciable networking performance, selecting a good route between any pair of nodes will become the most crucial issue. Thus, routing protocols, together with the route computation algorithms and routing metrics play a key role to improve the operation of the wireless multihop networks.

The primary purpose of a routing protocol is to implement a correct and efficient route establishment between any pair of nodes so messages could be delivered among nodes not only in a timely manner but also in a high data rate. A route is simply a set of wireless transmission hops / links sequentially connected as a wireless multihop path over nodes; each node expends some amount of its resource for routing processing. Therefore, the resource management plays an important role to maintain overall network. Selecting a route having minimum number of hops significantly reduces the overall resource usage.

Furthermore, a route breakage, which is most likely as the number of hops increases, causes resource wasting, and therefore the quality of the overall network becomes more prone to route breakages as the number of hops in routes increases [8], [9]. In traditional routing protocols, the number of hops, i.e. the hop-count is the metric most commonly used for route selection. The path that has the smallest number of hops as compared with the other available paths is chosen as a route between any pair of nodes [10], [11]. Resource usage for any route between any pair of nodes is also closely related to the statistical characteristics of hops / links that vary with time; and therefore the quality of each hop commonly depends on the factors such as background noise, transmission-collisions, interferers, shadowing obstacles, and channel fading. The quality of each hop is therefore often unpredictable, and accordingly, the traditional smallest hop-count metric is not feasible referring to the link quality [12], [13]. For instance, the overall quality of a single-hop route could be worse than that of the triple-hop route. Consequently, a routing protocol that will be employed in the network should be optimized to consider the link-quality metrics such as bit error probability and transmission capacity in order to improve the overall network performance.

The other important factor in the wireless multihop network is the mobility of nodes. As nodes are mobile and constantly changing their locations within the network, the links among them will change frequently, and the consequent network topology will be highly dynamic causing rapid route changes between any pair of nodes. The routing protocols have to be able to update the routing tables or cashes dynamically based on these rapid changes. Moreover, since the fact that the radio band of the wireless multihop network is limited offers a low data rate, the routing protocols must always use all available bandwidth in an optimal manner by means of keeping the improper usage of the network resources (overhead) as low as possible [14], [15].

Over the years, there exists a huge body of works on routing protocols for wireless multihop networks. These protocols implement discovering the route path and then routing the messages in spite of that the nodes are mobile and the link quality varies. In order to improve the performance of routing protocols, there has been proposed many link-quality routing metrics. Each metric can be readily considered as a set of measurements that are contributed into the route computation algorithms to estimate new weights for each hop / link in the routes. The weights, once aggregated, discourage selecting a route going through heavily loaded regions of the network topology. In this context, for delivering messages successfully, the quality-aware routing (QAR) protocols utilize the quality metrics to select the most reliable route among all available routes (from the source node to the destination node) [16]. Although different link-quality routing metrics have been proposed, there have been only a few of them implemented and practically evaluated in real network [17]. Implementing new quality metrics for wireless routing protocols involves with that adaptation of protocols and / or metrics, which is not straightforward. In this paper, we try to incorporate all metrics in one general formula that could be easily contributed into the route computation algorithms in any routing protocols.

To improve the hop count metric, the expected transmission count (ETX) metric is proposed in [12]. The ETX of a single hop path considers only the delivery ratios (message delivery probabilities) while the ETX of a multihop path considers not only the number of hops but also the delivery ratios of each hop; the summation of the ETXs along the multihop route path will give a selection cost of that route path. Similarly, the minimum loss (ML) [18] is the other metric based on the delivery ratios. ML selects the route having the lowest overall loss probability by multiplying forward and backward delivery ratios of each hop through the route path. In wireless multihop networks, not only the message size, but also the bandwidth of each hop is different. To adopt these two characteristics in route selection, the expected transmission time (ETT) metric is proposed in [19]. ETT is simply a delay-based routing metric that represents the time that the message requires to be transmitted successfully.

It is worth mentioning that there exists different delay-based routing metrics (such as improve expected transmission time (iETT) [20], minimum delay (MD) [21], and per-hop round trip time (RTT) [22]) each of which has the same shortcomings identified by ETT. In the case of wireless multihop networks with fast link quality variation, the quality metrics that based on average values computed on a time-window interval may not be able to follow the link-quality variations or may produce expensive control overhead. To deal with this problem, Koksal, C.E. et al. [23] proposed using the modified ETX (mETX) metrics. The mETX is able to capture the time-varying properties of a wireless hop/link in a way that could be directly translated into network and application layer quality constraints. Actually, the above metrics can be named as the basic routing metrics. Note that utilizing the usage of multi-channel instead of a single one can significantly improve the throughput of the wireless multihop network [24], [25]. In a multi-channel technique, the nodes can simultaneously transmit the messages to their neighborhood as long as they work in different channels [26]. However, this technique must deal with two critical issues, namely, intra-flow and inter-flow interference. As a matter of fact, the interferences have significant impacts not only on the throughput, but also on the amount of delay in the network, and thus on the overall network performance [26], [28]. In order to deal with these two types of interferences, there are available in the literature different types of interference-aware routing metrics; such as weighted cumulative ETT (WCETT) [29], metric of interference and channel-switching (MIC) [30], interference aware routing metric (iAWARE) [31], sum of motivated expected transmission time (SMETT) [32], exclusive expected transmission time (EETT) [33], interferer neighbors count (INX) [34], and interference and bandwidth adjusted ETX (IBETX) [35].

Although both the interference and transmission rate affect the network performance, the traffic load on nodes is the other phenomena that should be participating in the route selection. By considering the remaining capacity on each hop as a load-sensitive metric, the routing protocols can adapt better to the actual available resources in the overall network, especially by avoiding the congestion of resource usages. Thus, considering a load balancing in the routing protocols can enhance the route decision in the network. Currently, the load aware ETT (LAETT) metric [36] and weighted cumulative expected transmission time with load balancing (WCETT-LB) metric [37] are just variant types of the load-aware routing metrics proposed in the literature.

As a result of that the network traffic generated by nodes is the main reason of the most interference, the interference and load aware metrics are interrelated. It is possible to take into account both metrics as a hybrid (composite) metric in order to take their advantages. In this context, different types of hybrid routing metrics have emerged in the literature; such as contention-aware transmission time (CATT) metric [38], contention window based (CWB) metric [39], interference-load aware routing (ILA) metric [40], and resource aware routing for mEsh (RARE) [41]. In addition to all these metrics, there are the other factors, each of which has a serious impact on the performance of wireless multihop networks. In this paper, we consider these factors such as the mobility degree [42], latency, overload, buffer management, delivery ratio [43] and collision [44] as additional parameters that can be added to our unified formula in order to provide a better route decision.

1.2 Objective of the Thesis

Recently, several studies have been participated in driving the development of network communication strategies in order to make it adaptable to wide demands of services and applications. It is worth noting that the availability of reliable communication and effective routing protocols play an essential role to make the network capable of meeting these demands. Therefore, finding new routing protocols or development the available ones become an important issue that should be studied on a large scale.

The main research contribution of this thesis is to move the definition of the expected transmission count (ETX) metric from the intuitive definition to the mathematical definition based on the information and entropy concepts. In addition, we try to provide a new routing metric that takes into account the quality and the reliability of the forward and reverse channels of any links within a network. Our metric can be considered an extended version of the ETX metric that is called a dynamic ETX (DETX). DETX has the capability to detect the channel variability by considering the burst errors length until a predefined threshold. Therefore, DETX help the select the route with less channels variability, i.e. more reliability, and high quality, and thus increase the performance of the routing protocols.

1.3 Hypothesis

Wireless communication is a progressing subject of research that spotlights on effective and stable wireless connections between numerous nodes. There are different branches of wireless communication; however, this study will concentrate fundamentally on the routing protocols and their metrics that are utilized in an ad hoc network. An ad hoc network is composed when the nodes communicate with each other without any predetermined infrastructure. In this type of network, each node acts as both a client and a router. Thus, a message reaches its destination by travelling hop by hop along the nodes within the ad hoc network. Moreover, ad hoc networks have a dynamic nature where each node can enter and leave the network at any time, and hence ad hoc network senses these changes, then adjust routing paths in order to avoid the communication interruption within the network. The routing decision depends on the costs of each hop and each corresponding route has to be computed using routing information that consists of metrics each of which is obtained out of some measurements.

In this thesis, we will try to submit a new definition of the expected transmission count (ETX) metric that is based on the mathematical concepts instead of the previous definition that is fully intuitive. Moreover, we will try to modify the ETX metric to be able to detect the channel reliability in addition to the channel quality. Our metric dynamic ETX (DETX) will help a routing protocol to select the high reliability and qualitative routes among the available routes, and hence improve the overall network performance.

CHAPTER 2

ROUTING PROTOCOLS CLASSIFICATION

As a result of the advancement in wireless communications [45], wireless networks can operate cost-effectively in both Ad hoc and infrastructure modes [46]. In Ad hoc mode, the nodes are self-organized and self-configured; accordingly saying how to route messages efficiently within the network has turned into a crucial issue. In this chapter, we tried to present a full overview of wireless routing protocols in addition to the classification of them based on the different criteria.

For operating in Ad hoc mode, there exist different types of routing protocols are proposed in literature [47–51]. Each routing protocol has its own advantages and disadvantages from the view of operational and information-theoretical characteristics [52]. Routing protocols can be classified in different ways depending on various criteria. Such classification makes it easy to comprehend and contemplate the operational and information-theoretical characteristics in order to design some hybrid solutions to get composite advantages.

2.1 Classification Based on Updating Routing Information

One of the most popular criteria to classify wireless routing protocols is explicitly based on acquiring and updating routing information. As such, routing protocols are divided into three classes as follows [53–57]:

2.1.1 Table-Driven (or Proactive) Routing Protocols

Based on periodically exchanging of routing information among nodes [58], each node builds its own routing table and maintains the entire or partial information (link states) about the topology of the network. Whenever the source node needs to transfer data, it immediately selects the best route from available route-paths stored in its routing table.

The process of setting up a route will be achieved within a relatively small latency; but creates a big amount of signaling overhead due to periodic updates of routing table, and thus increases the waste of overall network resources. For instance, destination-sequenced distance-vector (DSDV) [59–65] and optimized link state routing protocol (OLSR) [66–71] are the well-known table-driven routing protocols.

2.1.2 On Demand (or Reactive) Routing Protocols

As compared with the table-driven routing protocols, on-demand routing protocols gather routing information reactively whenever the source node needs on-demand network access to transfer the data ready. There is no need to store any route information between any two nodes unless there is communication between them. As such, any on-demand routing protocol creates a low signaling overhead, and therefore provides a better scalability in resource management than table-driven protocols. However, any node suffers from long latency for route searching and creation before transmitting its data. The ad hoc on-demand distance vector (AODV) [72–77], the fisheye state routing (FSR) [78–83], and dynamic source routing (DSR) [84–89] are examples of on-demand routing protocols.

2.1.3 Hybrid Routing Protocols

This type of routing protocol has been proposed not only to circumvent the drawbacks of both table-driven and on-demand routing protocols but also to combine their merits. Any hybrid routing protocol tries to adapt the routing scheme to the characteristics of the network, such as mobility, size, signaling traffic and topology. For instance, it can be utilized in large wireless multihop networks in order to divide those clusters among which table-driven protocols are readily employed while on-demand protocols are used in each cluster. Since inter-cluster communication tends to occur less frequently than the intra-cluster communication, the hybrid protocols utilize on-demand strategy for inter-cluster communication while using table-driven strategy for intra-cluster communication. There exist different hybrid routing protocols have proposed in literature such as hybrid wireless mesh protocol (HWMP) [90–93], temporally ordered routing algorithm (TORA) [94–97], and zone routing protocol (ZRP) [98–102].

2.2 Classification Based on Node-Role Information

In wireless networks, each node may play different role in routing messages among the nodes. Based on node roles within the network, the routing protocols are classified into two main classes as follows:

2.2.1 Uniform Routing Protocols

In uniform routing protocols, all nodes typically have the same role with regards to the importance and functionality; and hence each node is treated equally from the view of resource management. Normally, any uniform routing protocol assumes that the topology of the whole network is certainly known by every node such that the topology has a flat structure where each node collects and distributes the routing information with its neighboring nodes [47]. Each node contributes in the delivery of messages among nodes through the route path. Indeed, both table-driven and on-demand routing protocols are uniform routing protocols.

2.2.2 Non-Uniform Routing Protocols

The topology of the whole network does not need to be known by every node, except for some essential nodes that carry out routing functions with distinct resource management. It is worth noting that utilizing distributed algorithms result in selecting those essential nodes. Therefore, any network using non-uniform routing protocols has a hierarchical structure where node organization and management are facilitated by those essential nodes. According to how routing functions and resource management are performed in addition to the organization of nodes, the non-uniform routing protocols can be divided as zone-based hierarchical routing [103], cluster-based hierarchical routing [104] and core-node based routing [105].

In zone-based routing protocols, whole network is divided into the geographical groups, i.e., the zones in each of which the nodes certainly know to reach each other, of course, with a smaller cost, i.e., without the need to know all routing information to all nodes in the whole network. The zones are constructed based on different types of zone constructing algorithms [106] that are exploited in organizing the nodes for roles. These zones may overlap or not depending on the constructing algorithms schemes. It is worth mentioning that the overhead for routing information maintenance will be significantly reduced if the zone divisions are determined effectively. The zone routing protocol (ZRP) and zone-based hierarchical link state routing (ZHLS) [103], [107–109] are accounted as this type of routing protocol.

In cluster-based routing protocols such as cluster-head gateway switch routing (CGSR) [110–113] and hierarchical state routing (HSR) [114–118], the whole network is effectively divided into the topological groups, i.e., the clusters each of which consists of nodes and generally one cluster-head node. The cluster-head node is selected based on election performed by nodes in the group using specific clustering algorithms [61]. These clustering algorithms have been included in the cluster-based routing protocols. Note that each cluster-head node is responsible for managing membership and routing functions.

In order to increase the robustness of the whole network, a routing protocol can select some nodes in order to compose a backbone for the whole wireless network. This type of routing protocol is called core-node based routing protocols. Actually, the backbone nodes are critical nodes in the network since they carry out such special functions as constructing routing paths and propagating control / data messages in the whole network. Core-extraction distributed ad hoc routing (CEDAR) protocol [119–123] is an example of this type of routing protocol.

2.3 Classification Based on Message Transmission Awareness

Messaging is the ability of communication among nodes each of which accepts a single message from the others and also delivers the copies of the message to multiple nodes at different locations. The challenge, which has to be taken into account when designing and classifying routing protocols, is to minimize the amount of network resources employed by messaging. Therefore, the routing protocols can be classified according to their messaging properties.

2.3.1 Forwarding and Replication Based Routing Protocols

There may be more than one route between any two nodes in the network; namely single route and multiple routes [124]. The routing protocols have different requirements for a reliable messaging. Thus, it is helpful to classify messaging techniques with respect to the number of message copies transmitted to the destination node. In this context, forwarding-based and replication-based routing protocols are two major classes [125]. In forwarding based protocols, each node injects a single copy of its message into the network, and then it is forwarded to the destination using the network dynamics. For example, AODV [72–77], and DSR [84–89] are the two most famous ones [125]. The other forwarding based protocols are proposed in [126–130] for the network dynamics unpredictable especially because of high mobility.

In replication based protocols, each node injects multiple copies of its message (replications) into the network, then at least one of the replication is delivered to the destination node with high probability while the network congestion increases as a result of sending replications. Some example protocols are epidemic routing [131], PROPHET [132], MaxProp [133], RAPID [134–136], and PREP [137–140].

2.4 Typical Casting Routing Protocols

The delivery of messages from source to the destination node is known as a message casting. Message casting is the type of communication mode allowed between peer entities that it considered an important aspect in the design of a routing protocol. The other classification is therefore useful being on packet casting types. There exists broadcast, multicast, geocast, and unicast groups of casting messages [141]. In a wireless multihop network where the medium is shared among the nodes, a broadcast is a basic operation mode whereby a message is received by all the source node's neighbors. The broadcasting mode is utilized by the node for periodic messages. Location-Aided Routing (LAR) [142], [143] and Distance Routing Effect Algorithm for Mobility (DREAM) [144] include broadcast operation mode in their routing mechanisms.

In a multicast operation mode, the same message or stream of data is delivered to a group of destinations that share a common interest. Multicasting can possibly improve the efficiency of the wireless link by saving the network resources such as bandwidth and energy. However, the maintenance of a multicast route that based on a routing tree or mesh is considered a difficult problem [61]. Some of the tree-based multicast protocols are AMRoute [145], DDM [146], and MAODV [147], while the mesh-based multicast protocols are CAMP [148], FGMP [149], and ODMRP [150].

In a geocast casting type, there exists a geographical area (location) associated with nodes that will receive the same message or stream of data. Thus, a geocast routing protocol can be considered as a special case of multicast routing protocol. Instead of building the routes based on a whole knowledge about of the network topology, the geocast routing protocol utilizes the location information of the group members to build the multicast route. With this context, the nodes need their updated location information along the time to deliver a message while they join or leave a certain group on the defined geographical region. The location-based geocasting and forwarding (LGF) [151], and the scalable position-based multicast (SPBM) [152] protocols are considered typical geocast routing protocols. In the case of a unicast operation mode, the source node has the ability to communicate with only a single destination node in the network. This destination node may be in a precise known location or an approximate location within a specified range of the source node. Thus, the delivery of messages will be performed for one destination instead of group of destinations as in multicast and broadcast modes [153]. The DSR and AODV are examples for unicast routing protocols.

2.5 Classification Based on Energy Awareness

In a wireless multihop network, the nodes may be attached to a battery that provides energy for their main components, such as CPU, memory unit, radio interfaces and sensors. In this case, the operational capability of each node will be limited by its battery life, and thus the battery is a valuable resource that should be effectively exploited to avoid the early shutdown of nodes. It is worth noting that energy conservation is related to all wireless network layers, including MAC [154], routing [155], and application [156] protocols. There exist three techniques: active and standby modes switching, power setting, and retransmission avoidance techniques, which must be taken into account by the protocols in order to become power-aware protocols [61].

The node failure caused by battery exhaustion has an essential effect in network connectivity and performance. In other words, relaying the packets between source–destination pairs require an adequate number of active nodes between them to forward these packets, and thus the failed node to relay packets to an intermediate node result in the network partitioning and communication interruption (route breakages). Thus, it becomes necessary to address the depletion of the node's battery at the network layer in order to maximizing the network lifetime by finding new methods for power-efficient route setup and reliably relaying data between source–destination pairs [157]. To achieve the objective of maximizing the lifetime of wireless networks, four categories of power-related metrics are necessary to incorporate them into routing protocols schemes: transmission power, remaining energy capacity, estimated node lifetime and combined energy metrics. In fact, a route cost metric based on a combination of multiple power-based metrics would be useful for route computation to extend the network lifetime rather than apply only one metric to calculate the routes to destinations [158]. Many studies have been conducted on routing protocols for wireless networks with respect to the energy efficiency [159–162]. These power-based studies share the same objective, namely, to maximize the lifetime of wireless networks. Moreover, several power-aware routing protocols are proposed to use in wireless networks, such as minimum total transmission power routing (MTTPR) [163], conditional max-min battery capacity routing (CMMBCR) [164], and power aware ad-hoc on-demand multipath distance vector (PAAOMDV) [165].

2.6 Classification Based on Location Awareness

Localization of network nodes is helpful for building a network map and establishing routes. To determine exact coordinates of these nodes in any geographical location, the best and easiest technique is the use of the Global Positioning System (GPS). However, in the case of the absence of GPS capability or satellite signals are blocked by obstacles or noise, there exist other methods such as triangulation [166], distance estimation using radio location [61], and area delimiting methods [167], that are utilized to determine the nodes location [168]. Location-aware routing schemes assume that the individual nodes are aware of the location information of all the nodes within the network. This location information is then utilized by the routing protocol to determine the routes. After building the route table, the source node will insert the destination location instead of the topological information inside the packet. During packet forwarding, each intermediate node utilizes the location information of its neighbors and the location of the destination to forward the packet to the next hop. Thus, the location aware routing protocols take advantage of the location information of nodes to provide higher efficiency and scalability [169]. Some example protocols are DREAM [143] and LAR [142], [143].

CHAPTER 3

ROUTING MEASUREMENTS

In wireless routing protocols, there exist different types of measurements that include the key factors involved in the design of routing metrics. It is important to analyze these measurements to get a good knowledge about how the routing metrics are implemented in practice. There are various methods enable the metrics from obtaining the measurements they need [170], which are listed as follows:

- Node-related: The measurements of the metric are obtained from a node and have fixed, variable, or configured values, such as the number of node's interfaces, input and output queue length, and financial communication respectively.
- Passive monitoring: In this case, the observation of the traffic coming in and going out of a node will be the method by which the measurements are gathered for the metric. Traffic load and interferences are considered examples of the measurements that can be obtained by this method.
- Piggy-back probing: By inserting probing information into the data or routing protocol messages, this method will be able to acquire the measurements for metric without creating and injecting a special probe packet into the wireless multihop network. In fact, the piggy-back probing is a common method to measure the delay.
- Active probing: With this method, special packets are inserted into the network in order to monitor and measure the link characteristics. It is worth mentioning that this method has some drawbacks such as increase the overhead, overestimation of the link quality because of loss the probe packets, and inaccurate measurements due to the intermittent nature of wireless links. However, it is considered a good solution to overcome the inability of some network card drivers to participate useful measurements such as the transmission rate.

As a result of the different characteristics and goals of the wireless multihop network systems and their applications, five major categories of measurements must be considered in the design of routing metrics [171]. These categories are traffic-based, topology-based, radio-related, geography-based, and energy-related measurements that are detailed as follows.

3.1 Traffic-Based Measurements

The design of most routing protocols relates to the network traffic and includes incorporating traffic measurements into the routing algorithms for these protocols. The main goal of this incorporating is enhancing the performance of wireless multihop networks. However, measuring traffic variables is a complex issue and the risk of obtaining unstable network behavior is high. In this subsection, we will try to define the well-known traffic-based measurements in a detailed manner.

3.1.1 Delay or Latency (D)

The total delay it takes a message to travel from one node to another. It is composed from six components: sender-queuing delay (Q_S), receiver-queuing delay (Q_R), sender-processing delay (P_S), receiver-processing delay (P_R), transmission delay (T), and propagation delay (P).

$$D = Q_S + Q_R + P_S + P_R + T + P \tag{3.1}$$

3.1.2 Delay Variation (jitter)

It is the variation of a delay with respect to a certain reference value, e.g. minimum delay or average delay. This traffic measurement has a major effect on the communication application that subject to some real-time restrictions such as video communication. The delay variation can be described by using the classical statistical variance. For instance, when two links with the delay series D_1 and D_2 are concatenated, the resulting variance can be expressed as follows.

$$Var(D_1 + D_2) = Var(D_1) + Var(D_2) + 2Cov(D_1, D_2) \tag{3.2}$$

where $Cov(D_1, D_2)$ denotes the covariance of delays of the two links.

3.1.3 Delivery Ratio (DR)

It is defined by the ratio of the total number of delivered messages (m_{del}) to the total number of created messages (m_{cre}).

$$DR = \frac{m_{del}}{m_{cre}} \tag{3.3}$$

3.1.4 Median Latency (Lat)

It is the median of the time required for a message to reach its destination.

$$Lat = Median(\forall_{delivered}(t_{del} - t_{cre})) \tag{3.4}$$

where t_{cre} denotes the message creation time, t_{del} denotes the message delivery time, and $delivered$ denotes the list of delivered messages.

3.1.5 Overhead ($Over$):

It is defined as the ratio of the total number of messages relayed (m_{rel}) to the total number of messages delivered (m_{del}).

$$Over = \frac{m_{rel}}{m_{del}} \tag{3.5}$$

The composite metric (CM) gives credit for higher delivery ratio, while penalizes for both longer latency and higher overhead [125].

$$CM = DR\frac{1}{Over}\frac{1}{Lat} \tag{3.6}$$

3.1.6 Message Collision (C_m)

A collision occurs when two nodes send their messages at the same time, and when their frequency space is too small [173]. As the system is considered slotted, the available slots for transmission during the message lifetime is T_b/d where T_b denotes the wake-up duty cycle of nodes, and d denotes the transmission duration. Moreover, the whole transmission bandwidth in our network is denoted by BW, and the frequency occupancy with respect to the carrier is $[-\mathrm{b}; \mathrm{b}]$ Hz. The collision probability will be a result of the time collision probability (d/T_b) and frequency collision probability ($2b/BW$) as follows.

$$C_m = \frac{2b}{BW}\frac{d}{T_b} \tag{3.7}$$

3.1.7 Packet Loss Ratio

The ratio of the data packets lost at destinations to those generated by the sources. It occurs due to the route failure or the overloading of the buffers. With reliable transfer routing protocols, a high packet loss ratio leads to slow down communication, increase the number of retransmissions, and reduce the usable bandwidth. While with non-reliable protocols, a high packet loss ratio will cause degradation of communication quality.

3.1.8 Throughput

It is the number of bits transmitted between source and destination per unit time. In other words, the throughput is a measure of how fast we can actually send data messages through a wireless network. Although the bandwidth in bits per second and throughput seems the same, but they are different. A link may have a bandwidth of M bps, but only N bps can be sent through this link. Therefore, the bandwidth is a potential measurement of a link while the throughput is an actual measurement of how fast we can send data messages [173].

3.1.9 Channel Capacity

In reality, we cannot have a noiseless channel; the channel is always noisy. In 1944, Claude Shannon introduced a formula, called the Shannon capacity, to determine the theoretical highest data rate for a noisy channel.

$$Cap = BW \ log_2(1 + SNR) \tag{3.8}$$

where BW denotes the bandwidth of a channel, SNR denotes a signal-to-noise ratio, and Cap denotes the capacity of a channel in bits per second.

3.1.10 Queue Length

Every wireless node has a queue for an ingress and an egress. If the interface of a network card is not able to forward the messages immediately, the incoming and outgoing messages will be stored in a queue. A queue length is the measurement that determines whether the interface of the network card is capable of processing more traffic or not. Therefore, the queue length represents an indicator for the current state of the card.

3.1.11 Buffer Management

Routing protocols also need to address a buffer management mechanism. As the buffer capacity in the nodes is limited, the buffer may deplete very quickly. Consequently, a wireless node may need to wait for a long time before it can get an opportunity to route the messages to its neighbor. Moreover, the node cannot accept any more messages from its neighbor when its buffer is full, which could lead to congestion in the network.

3.2 Topology-Based Measurements

This class of measurements includes all the measurements related to the presence or absence of links in addition to the neighborhood relations of the network nodes. The main measurements that are widely used by the routing metrics are listed as below.

3.2.1 Number of Neighbors

It is defined by how many other wireless nodes can be reached from a wireless node at a given moment. This measurement is important for minimizing the number of hops in the route. We should be aware that this measurement is unidirectional i.e., if a node can contact to another node within its coverage range this does not mean the contact is also possible in the other direction. Accordingly, we can understand that the neighborhood in a wireless multihop network is not necessarily has a reciprocal property.

3.2.2 Path Length

It is a measure of the number of hops/links that a path has between the source and the destination. By using this measurement in the design of routing metrics, the routing protocols will be able to react quickly to the topological changes and thus achieve useful results in the mobile wireless networks. However, the use of this measurement may not achieve an optimal performance in the case of static wireless networks [174].

3.2.3 Number of Paths to Node

It is a measure of the number of disjoint paths to one particular node in the network. The presence of many different paths to the destination means high tolerance against link failures. Consequently, the transmission reliability of wireless multihop networks would be improved when the routing protocols that rely on this tool for sending the traffic concurrently on multiple disjoint paths.

3.3 Radio-Related Measurements

The complexity of the physical layer in a wireless network is more than in a wired counterpart. This complexity tends to increase with multi-channel multi-radio capacity. The reason behind this complexity is the fact that the wireless links do not have a dedicated bandwidth and they are shared among the neighboring nodes in a wireless network. Therefore, the transmissions of neighboring nodes may compete for the same bandwidth and interfere with the transmissions on the other links. With this context, the phenomenon of interference must not only be taken into consideration when developing the physical or MAC layers, but it should also be taken into account for routing purposes. There are two types of interference in wireless multihop networks, which are intra-flow interference and inter-flow interference.

In inter-flow interference, a flow through wireless links contends for bandwidth with the nodes that are in the neighboring area of its path. Such interference can cause bandwidth starvation for some nodes and hence these nodes may always experience busy channels. While the intra-flow is occurred when the nodes on the path of the same flow compete with each other for channel bandwidth. Such interference leads to sharply degrade for the throughput of the flow and dramatically increase for the delay at each hop as the hop count of the flow increases. In the light of this, the routing metrics must take into account some measurements to be capable of capturing both intra-flow and inter-flow interference.

3.3.1 Measurements for Intra-Flow Interference

There exist two measurements for intra-flow interference [175], which are used heavily in most measurements that will be addressed in the next chapter. We will try to summarize these measurements as follows.

3.3.1.1 Channel Switching Cost (CSC)

By using this measurement, the path with consecutive links using the same channel will be given higher weights than paths that alternate their channel assignments. Thus, the intra-flow interference is reduced by making the routing protocols select the paths with more diversified channel assignments.

3.3.1.2 Max_X

This measurement counts the maximum number of times that the same channel appears along the path. Thus, it captures the intra-flow interference of the path by giving the low weights to paths with more diversified channel assignment on their links.

3.3.2 Measurements for Inter-Flow Interference

For inter-flow interference, there are many measurements that must be taken into account by a routing metric in order to provide efficient route decision. The most known measurements for this type of interference have been listed as below [170].

3.3.2.1 Received Signal Strength Indication (RSSI)

This measurement shows the strength of the signal that is observed on the receiver's antenna during the reception of a packet. Its calculation based on a packet (e.g. packet A) that was received correctly. Thus, RSSI will not be recorded, if the packet of the next computation (e.g. packet B) fails to operate because the interference, i.e., the loss packet is not included in the calculation. In the light of this, the RSSI does not depict the interference in the link in an accurate way.

3.3.2.2 Signal to Interference and Noise Ratio (SINR)

By using of this measurement, the received signal that exceeds the sum of noise plus interference at the receiver will be captured. Because the commercial network card usually cannot record the SINR value, it will be estimated on the base of RSSI. This means that the SINR value has acquired all the failings of RSSI and, as a result, this value will not be precise.

3.3.2.3 Bit Error Rate (BER)

This measurement represents the ratio between the error bits to the total number of bits that have been received over a specific period. In fact, it is a fine-grained measurement to capture the interference. Since it requires the processing of a large amount of previously known data, a significant overhead will be introduced by the BER computation. Moreover, when the network conditions are changing quickly over a period, this approach will be of little value.

3.3.2.4 Frame Error Rate (FER)

FER measurement is similar to BER measurement except the FER takes account of the frame rather than the bits and thus its implementation is simpler than BER. FER also depending on previously-known data and requires repeated computations over extended periods of time in order to provide a more reliable value. Consequently, the time that FER needs to capture the interference will be relatively long. However, FER is a coarse-grained measure than BER with regard to interference measurement.

3.4 Geography-Based Measurements

All measurements that their values depending on the use of the geographical position of the nodes have been falling under this class of measurements. In this approach, the location information can be used to design some routing metrics, then use them to simplify the routing process. Three major measurements that fall under this class are listed as below.

3.4.1 Distance to Destination

Another way to use the location information as a measurement is to attribute the geographical distance to the distention as other cost for the link [176], [177].

3.4.2 Link Lifetime

The quality and stability of a link are highly dependent on the position of the nodes. A link exists as long as both communicating nodes have a radio connection that allows them to transfer data. As the nodes are mobile and their positions are continuously changed over a time, finding routes that are stable over time is one of the most central challenges. To address the stability of links, using the longevity of the links as a measurement in the design of the routing protocols has been proposed in the literature [178–180].

3.4.3 Velocity Measurement (V)

As the nodes in wireless ad hoc networks have a mobility feature, their velocity will play important role in determining the quality of links among them. While the velocity of the node increases, the network topology changes rapidly and the link among the nodes can break suddenly. Moreover, the probe packets that are exchanged among the nodes to keep up the rapid topology changes will consume the network resources such as channel bandwidth, node buffer. One technique for obtaining the velocity measurement of the node is to have the location information for the node. In [181], Johansson et al. define the relative velocity measurements of the two nodes X and Y based on the position of each node.

$$V(X,Y,t) = \frac{d}{dt}\left(l(X,t) - l(Y,t)\right) \tag{3.9}$$

where $l(X,t)$ denotes the position of a node X at time t. Thus, the mobility between a pair X and Y is defined as follows.

$$M_{XY} = \frac{1}{T}\int_{t_0 \le t \le t_0+T} |v(x,y,t)|\, dt \tag{3.10}$$

where M_{XY} denotes the mobility value.

3.5 Energy-Related Measurements

One of the main factors in the mobile multihop networks is the energy consumption [182], [183]. In this case, mechanisms for energy efficiency must be inserted into routing protocols to be able to preserve the battery lifetime. The transmission energy of a packet over one link can ideally be modeled as below.

$$e_{i,j} = h_{i,j}^{\varphi} + k \qquad 2 \le \varphi \le 4 \tag{3.11}$$

where i and j denotes the nodes on both sides of the link, the variable k models a fix processing overhead for sending and receiving packet, and $h_{i,j}^{\varphi}$ denotes the geographical distance. Accordingly, we can see that it is necessary to find a balance between the number of hops and minimizing the transmission power. Many measurements such as energy consumed per packet, remaining battery capacity, and minimal maximum battery cost routing have been suggested to help the routing algorithms to maximize the network lifetime.

CHAPTER 4

ROUTING METRICS

In recent years, significant changes have been occurring in the network structure. Since 40 years ago, the only known and available network was the wired networks. However, as the wireless techniques continue to grow, the wireless multihop networks have been emerged as an efficient solution to meet the growing service requirements. However, these networks face several types of vital issues that influence on their performance and need to optimal solutions such as bandwidth constraints, power restrictions, high topology changes, etc. [184], [185]. One of the key solutions for these issues is to use of appropriate routing protocols in order to provide the optimal paths for directing of the traffic within the network. The key factor for getting an optimal path is the use of effective routing metrics in the computation routing algorithms. The design of effective routing metrics depends on the specific characteristics of a target network in addition to the measurements that set out in the chapter 3. Accordingly, the routing metrics for wireless multihop networks have followed four main trends: *basic metrics*, *interference-aware metrics*, *load-aware metrics* and *hybrid metrics*.

4.1 Basic Routing Metrics

The following sub-sections show the details of the routing metrics that take into account the packet delivery/loss ratios and delay in addition to the Internet Engineering Task Force (IETF) standard metric that is called hop-count.

4.1.1 Hop-Count Metric

It is the most popular routing metric in wireless multihop networks that is simply calculated by nodes even if they have low resources in CPU, memory and energy. Thus, it avoids any computational burden on nodes regarding to finding the best route to the destination. Based on this metric, the path weights equal to the total number of the hops/links along the path without consideration of the quality of these hops/links.

4.1.2 Expected Transmission Count (ETX)

It is the expected number of transmissions a node requires to successfully transmit a packet to a neighbor [12]. To compute ETX, each node periodically broadcasts probes containing the number of received probes from each neighbor. The number of received probes is calculated at the last T time interval in a sliding-window fashion. The node A computes the ETX of the link to a node B by using the delivery ratio of probes sent in the forward $\mathrm{d_f}$ and reverse $\mathrm{d_r}$ directions. These delivery ratios are, respectively, the fraction of successfully received probes from A announced by B and the fraction of successfully received probes from B, at the same T interval. The ETX of link AB is given as follows.

$$ETX_{AB} = \frac{1}{d_f\, d_r} = \frac{1}{P_s} = \frac{1}{1 - P_l} \qquad (4.1)$$

where P_s denotes the probability of successful transmission and P_l denotes the probability of loss transmission.

The ETX computation considers both forward and reverse directions because of data- and ACK-frame transmission. The chosen route is the one with the lowest sum of ETX along the route to the destination.

$$ETX = \sum_{i=1}^{n} ETX_i \qquad (4.2)$$

where n denotes the number of links/hops within a route, and i denotes the link number.

The implementation of ETX has revealed two shortcomings: broadcasts usually are performed at the network basic rate, and probes are smaller than typical data packets. Thus, unless the network is operating at low rates, the performance of ETX becomes low because it neither distinguishes links with different bandwidths nor considers data-packet sizes.

4.1.3 Minimum Loss (ML)

It is an alternative way to assign the link quality of a given path. ML metric calculates the link quality by multiplying the probabilities of successful transmission over the complete path. Consequently, a routing protocol will select the path with the highest success probability, i.e., the one with minimum loss probability. For example, the success probability for a route from X to Y passing through Z is given by the equation below.

$$P_{XY} = P_{XZ}\, P_{ZY} \quad (4.3)$$

where $P_{XZ}$and P_{ZY} are the probabilities of successful transmission in the links X−Z and Z−Y respectively that are given by the product of the forward and reverse probabilities $(P_f\ \ P_r)$ in each link.

Thus, a multi-hop route will be chosen if it has a higher successful transmission probability than the single-hop route. As mentioned in [18], the use of ML metric provides a slight improvement in the throughput of network comparing with ETX, but it highly increases the route stability, decrease the round trip delays, and decrease the packet loss rates (PLR).

4.1.4 Expected Transmission Time (ETT)

ETT metric is the time a data packet requires to be transmitted successfully to each neighbor [19]. ETT adjusts ETX to different PHY rates and data-packet sizes and it is obtained by multiplying the ETX with the average time t for each link as shown below.

$$ETT = t\ ETX \quad (4.4)$$

where t denotes the time a single data packet requires to be delivered. The t parameter can be calculated by dividing the fixed data-packet size S_p on the estimated bandwidth BW of each link (or data rate).Thus, the total ETT along a given path can be obtained as follows.

$$ETT = \sum_{i=1}^{n} ETT_i = \sum_{i=1}^{n} ETX_i\ \frac{S_p}{BW_i} \quad (4.5)$$

The packet-pair technique then is used to calculate BW per link. This technique consists of transmitting a sequence of two back-to-back packets to estimate bottleneck bandwidth.

4.1.5 Improved Expected Transmission Time (iETT)

In wireless multihop networks, a path with a one bad link and many excellent links may seem a good path for the hop-count, ETX, and ETT metrics. In these metrics, the low score of the bad link perhaps is smoothed out by the high scores of the excellent links.

However, this bad link may have a negative effect on the quality of the path larger than what these three metrics capture in reality. In addition, the result of ETT metric is not accurate because it does not take into account the overheads that transmit along with each signal data packet. To overcome these problems, the authors in [20] proposed a new metric called iETT that uses the MAC $Delay$ instead of ETT to approximate the expected transmission time of one data packet transmission. The MAC $Delay$ is equal to $aS_f + b$, where a and b are parameters that depend on the data rate and MAC modulation scheme, and S_f is the frame size [186].

Accordingly, the iETT metric along a given path can be obtained as follows.

$$iETT = \sum_{i=1}^{n} iETT_i = \sum_{i=1}^{n} \left[(a_i S_f + b_i)\ ETX_i \right] \tag{4.6}$$

In the single radio network, all nodes share the same channel and they are contending to get the channel for sending their packets. Thus, if the links have very different loss rates, the nodes connected to the link with low loss rate will have larger probabilities to access medium than the other nodes. This is due to the nature of the contention window mechanism of the MAC access scheme. With this context, extra medium time delay must be added to the expected transmission time that is called link interference delay (LID_1). The LID_1 expression is given as follows.

$$LID_1 = \left[\max_{1 \le j \le n} (P_j) - \min_{1 \le k \le n} (P_k) \right] (a_j S_f + b_j) \tag{4.7}$$

where j and k denote the position of the links with highest and lowest loss rates respectively, $max(P_j)$ denotes the highest loss rate and $\min(P_k)$ denotes the lowest loss rate on the path. Therefore, the iETT metric equation will be as follows.

$$iETT = \sum_{i=1}^{n} \left[(a_i S_f + b_i)\ \ EXT_i \right] + LID_1 \tag{4.8}$$

Another fact that ETT metric could not recognize it, is the position of the links with highest and lowest loss rates within a given path. In fact, a high throughput could be obtained when the link with high loss rate come before the link with low loss rate. Thus, other extra delay is added to obtain new delay link interference as follows.

$$LID = LID_1 + \alpha \left[\left(\max_{1 \le j \le n} (P_j) - \min_{1 \le k \le n} (P_k) \right) (a_k S_f + b_k) \right], \quad where\, \alpha = \begin{cases} 1\ if\, j > k \\ 0\ otherwise \end{cases} \tag{4.9}$$

The iETT equation can be given as shown below.

$$iETT = \sum_{i=1}^{n} \left[(a_i S_f + b_i)\ \ EXT_i \right] + LID \tag{4.10}$$

Accordingly, iETT metric has been designed to take into consideration the discrepancy of link loss rates within a given path, as well as the overheads that are produced by MAC layer frames.

4.1.6 Minimum Delay (MD)

To provide a good quality of service (QoS) in a wireless multihop network, a minimum delay factor must be considered when designing the routing metric. MD is a routing metric with the main goal of selecting routes based on the minimum transmission delay [21]. The transmission delay can be obtained from the estimation technique for a variation of the link capacity that is known as ad-hoc probe [187]. An ad-hoc probe is a one-way technique (instead of round-trip) that relies on sending back-to-back packet pairs (packet-pair technique) from one node to another in order to provide the capacity estimation in a link between them. It is a simple, timely and fast technique to the highly varying characteristics of the wireless networks. Probing packet pairs with fixed size are sent from sender to receiver in back-to-back fashion. After receiving the probe packets, the received node will calculate the one-way delay (OWD) and then estimate the link capacity (i.e. data rate) for the link between them based on the following formulas.

$$T = \left(T_{recv2,i} - T_{send.i} - \delta\right) - \left(T_{recv1,i} - T_{send.i} - \delta\right) = T_{recv2,i} - T_{recv1,i}\ , \tag{4.11}$$

$$C = S_{prob}/T \tag{4.12}$$

where C denotes the estimated capacity, S_{prob} denotes the probe packet size, T denotes the packet-pair dispersion, δ denotes the clock offset among nodes, $T_{send.i}$ denotes the packet sending time stamped at the sending node, and $T_{recv1,i}$ and $T_{recv2,i}$ the receiving time of each packet that is stamped at the receiver node. Accordingly, the forward formula that is used to calculate the minimum delay metric will be as follows.

$$STD_{n,A} = \sum \Psi(1-\Psi)^{n-i} D_{i,A} \tag{4.12}$$

where STD denotes the smoothed transmission delay, Ψ denotes the smoothing factor defined to reflect the applied environment, D denotes the current measured delay to node

A, and n the number of received probes that are generated by ad-hoc probe technique. While the recursive version can be shown as follows,

$$STD_{n,A} = \Psi D_{n,A} + (1 - \Psi)\, STD_{n-1,A} \tag{4.13}$$

Accordingly, the best route is selected based on the minimum sum of the transmission delays for all hops in the path. This metric will allow the routing protocols to provide better QoS for the applications, which are sensitive to delay, jitter, and packet loss, among other factors [21].

4.1.7 Per-hop Round Trip Time (RTT)

The wireless multihop networks suffer from some problems in terms of scale and performance. As the node density and the number of hops increase, the network capacity and the end-to-end throughput are rapidly decreased [188]. For this reason, a multi-radio unification protocol (MUP) with per-hop round trip time (RTT) routing metric has been proposed [22]. To capture the link quality, a node sends probe messages over the links to its neighbors on a fixed periodic basis. When a neighbor node receives the probes, they immediately respond by sending an acknowledgment packet (ACK) to the sender. After receiving the ACK, the sender node measures the round-trip time (RTT) value and incorporates this value into a weighted average called smoothed round-trip time (SRTT) as follows.

$$SRTT = \Psi\, RTT_{new} + (1 - \Psi)\, SRTT \tag{4.14}$$

Consequently, this weighted average is used as the channel quality estimate. In fact, there are two motivations for using the RTT latency as a routing metric. First, the probe messages sent on a lightly used channel are likely takes less time to gain access to the medium than the ones that sent on a heavily used channel and thus RTT able to consider the loads on the channel. Second, the external conditions such as interference can be considered as a result of increasing the round-trip time of both probe messages and probe ACKs. However, the use of per-hop RTT metric often leads to high overheads into the network in addition to increasing the route instability. Furthermore, RTT metric does not take into account the link data rate [20].

4.1.8 Modified ETX (mETX)

As a result of minimizing the total number of transmissions leads to maximize the overall network performance and minimize the transmission energy consumption, the use of the ETX metric of picking the best route looks an appealing method. However, ETX considers only the average channel behavior, i.e., averaging the loss ratio over a long-term interval. In fact, ETX may perform poorly over the links with high variability and burst loss situations. Moreover, when the path between two nodes is selected, it is unlikely to be changed from packet to packet. To overcome the short-term link variation problem, the authors in [23] proposed a new metric that is called modified ETX (mETX) that is given as shown in equation below.

$$mETX = exp(\mu_\varepsilon + \frac{1}{2}\sigma_\varepsilon^2) \tag{4.15}$$

where

$$\varepsilon_k = \sum_{t=t_k}^{t_k+S_p-1} -log(1 - P_{B,t}) \tag{4.16}$$

In (4.15), μ_ε and σ_ε^2 denotes the mean and the variance of ε_k, S_p denotes the k_{th} packet size, t_k denotes the starting transmission time of the k_{th} packet, and $P_{B,t}$ denotes the probability that bit error occurs at time t .

Although mETX metric improves the performance of the network more than ETX, mETX may pick links that violate the loss rate visible to higher layers. To solve this problem, effective number of transmissions (ENT) metric is proposed to take into account the probability that the number of transmissions exceeds a certain threshold. The formula of ENT metric has been given by taking the exponential of $\alpha(\delta)$ that its formula is given as follows.

$$\begin{aligned} \alpha(\delta) &= E\left[log\frac{1}{P_{c,k}}\right] + 2\delta\, var\left(log\frac{1}{P_{c,k}}\right) \\ &= \mu_\varepsilon + 2\delta\sigma_\varepsilon^2 \end{aligned} \tag{4.16}$$

4.2 Interference-Aware Routing Metrics

A routing protocol routes the packets from source to destination by providing one or more network paths. It computes these paths based on its metrics in order to meet some criteria such as minimum hop-count, minimum delay, etc. In wireless multihop networks, the design of routing metrics is vital issue due to three characteristics of wireless links that are (i) time varying channels and resulting variable packet loss, (ii) packet transmission rate, and (iii) interference. The interference phenomenon has a significant influence on the wireless multihop network performance. There are two types of interference the intra-flow and inter-flow interferences. Inter-flow interference caused by medium access contention between different flows that have neighboring links, while the intra-flow interference caused by medium access contention between different links along a flow.

Multi-radio, multi-channel technique [189], [190] has been proposed as a promising solution for improving network functionality. By using these techniques, the wireless nodes can send and receive messages to their neighboring nodes via multi-channel and multi-radio system features. In addition, the heterogeneity of these radios will offer tradeoffs that can improve the connectivity, robustness, and performance of these networks. The good routing metrics should help the routing protocol to find paths that have a high data rate, low loss ratio, and experience low levels of interference.

Accordingly, find high quality paths need to factor in the varying interference experienced by a wireless link into the routing metric. Because the common routing metrics such as hop count, ETX, ML, etc., do not take in their account these techniques, new routing metrics are required to be compatible with the characteristics of the multi-channel paths. In the following subsection, we will try to describe the most relevant interference-aware routing metrics.

4.2.1 Weighted Cumulative ETT (WCETT)

It is the first routing metric that explicitly accounts for the intra-flow interference among links / hops that utilize the same channel [29]. WCETT has been designed to weight each link depending on the expected transmission time of a packet that traversing over the link. Thus, it will take both bandwidth and data loss ratio into a count while estimating the link quality. In fact, there are two main assumptions in the design of WCETT metric. First, the cost of the path should increase and never decrease by adding extra hops into an existing path. There exist three reasons of this assumption: (i) the flow will consume more resources by traversing an extra hop, (ii) the flow for the extra hop will add additional interference effect on the other flows within a network, and (iii) the round trip time will be increased by existing this extra hop. Second, a path that is comprised of hops on different channels is better than a path where all the hops are on the same channel due to the intra-flow interference.

The WCETT is capable of estimating the cost of the path that consists of n hopes and k channels as follows.

$$WCETT = (1-\beta)\sum_{i=1}^{n} ETT_i + \beta \max_{1\le j\le k}(X_j),\ where \qquad X_j = \sum_{hop\ i\ is\ on\ the\ channel\ j} ETT_i, \quad 1 \le j \le k \tag{4.17}$$

where β denotes a tunable parameter that has a value between 0 and 1, and X_j is the sum of transmission times of hops on the channel j.

In fact, X_j is able to detect the bottleneck channel on the path; however, its value will not be affected by adding the hops that use non-bottleneck channels. The equation of WCETT metric can consider as a tradeoff between the throughput and the delay. It is evident that the first term represents the transmission times along all hops in the path. Thus, it can be considered as the latency measurement of the path. The second term reflects the impact of the bottleneck hops on the path and therefore it can be considered as the measure of a path throughput. Accordingly, the routing protocols that use WCETT metric will be able to select a high throughput path between the source and destination nodes by ignoring the paths with high intra-flow interferences.

4.2.2 Metric of Interference and Channel-switching (MIC)

The MIC routing metric has been proposed to exceed the two limitations of a weighted cumulative ETT (WCETT) [30]. The first limitation of WCETT is that it does not take into account the inter-flow interference when it estimates the cost of the path in the network. The second limitation is that the WCETT is not isotonic[1.] The relationship exists between the isotonicity property and the optimality of the Bellman-Ford and Dijkstra's algorithms has been shown in [191], [192]. Thus, if WCETT is incorporated inside the link-state routing protocol, this protocol will fail to find the minimum weight path which may cause a forwarding loop problem for this link-state protocol. The MIC metric of a path p has been defined as follows.

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[1] The isotonic property implies that a routing metric should guarantee that the order of the weights of two paths is preserved if there is a common third path appends or prefixes to them.

$$MIC(p) = \frac{1}{N\ min(ETT)} \sum_{link\ l \in p} IRU_l + \sum_{node\ i \in p} CSC_i, \tag{4.18}$$

where N is the total number of network nodes, $min(ETT)$ denotes the smallest ETT based on the lowest transmission rate of the wireless cards, interference-aware resource usage (IRU) and channel switching cost (CSC) are defined as follows.

$$IRU_l = ETT_l\ N_l\ , and \tag{4.19}$$

$$CSC_i = \begin{cases} w_1 & if\ CH(prev(i)) \neq CH(i) \\ w_2 & if\ CH(prev(i)) = CH(i), \end{cases}, where\ 0 \leq w_1 \leq w_2 \tag{4.20}$$

where N_l denotes the number of neighbors that their transmissions interfere with transmissions over link l, $CH(i)$ denotes the channel assigned for the node i, $CH(prev(i))$ denotes the channel assigned for the previous hop of node i along the path p.

Note that the MIC equation is comprised of two components IRU_l and CSC. The IRU_l component represents the aggregated channel time of neighboring nodes that transmission on link l. Thus, IRU_l captures the inter-flow interferences and makes the routing protocols prefer a path that consumes less channel times at its neighboring nodes. The second component CSC gives paths that alternate their channel assignments lower weights than paths with successive links using the same channel. Therefore, CSC is capable of capturing the intra-flow interference by making the routing protocols favor paths with more diversified channel assignments.

4.2.3 Interference Aware (iAWARE)

iWARE is the routing metric that has been proposed in order to capture the influences of variation link loss ratio, difference transmission rate, and interference [31]. It weights the ETT metric with interference ratio IR to capture the interference experienced by the link from its neighbors. The high quality link is the link with low ETT and high IR. The value of $IR_i(u)$ for a node u in a link $i = (u, v)$ where $(0 < IR_i(u) \leq 1)$ as follows.

$$IR_i = \frac{SINR_i(u)}{SNR_i(u)}, where$$
$$SINR_i(u) = \frac{P_u(v)}{B_{Noise} + \sum_{w \in \eta(u)-v} \tau(w) p_u(w)}, and\ SNR_i(u) = \frac{P_u(v)}{B_{Noise}} \tag{4.21}$$

where B_{Noise} denotes the background noise, $P_u(v)$ denotes the signal strength of a packet from node v at node u, $\eta(u)$ denotes the set of nodes from which node u can sense a packet, w denotes the interfering node, $\tau(w)$ is the normalized rate at which the interfering node generates traffic and it is used to give the fractional time node w occupies the channel.

The IR_i for a bidirectional communication link $i = (u, v)$ for a DATA/ACK like communication is defined as follows.

$$IR_i = min\big(IR_i(u), IR_i(v)\big) \tag{4.22}$$

Note that SINR of link i equal to the SNR (and thus $IR_i = 1$) when there is no interfering neighbors or no traffic generated by the interfering neighbors. In this case, the value of $iAWARE_i$ metric will depend on the link loss ratio and the data rate that are captured by ETT_i as shown in the formula below.

$$iAWARE_i = \frac{ETT_i}{IR_i} \tag{4.23}$$

The value of weighted cumulative path metric iAWARE of the path p is given as follows.

$$iAWARE(p) = (1-\beta)\ \textstyle\sum_{i=1}^{n} iAWARE_i + \beta \max\limits_{1\le j\le k}\big(X_j\big),\ where$$
$$X_j = \sum_{conflicting\ links\ i\ on\ the\ channel\ j} iAWARE_i, 1 \le j \le k \tag{4.24}$$

where β is a tunable parameter subject to $0 \le \beta \le 1$, k denotes the number of orthogonal channels available. Accordingly, iAWARE routing metric has the capability of estimating the average time the medium will be busy because of the transmission from each interfering neighbor.

4.2.4 Sum of Motivated Expected Transmission Time (SMETT)

A routing metric has been proposed to consider link interference based on the retransmission. By using the transmission infection factor (TIF), SMETT takes into account the idle time effect of a node’s buffer on other transmissions that are in the interference range of this node [32]. When the buffer is not empty, all packets will compete to occupy the medium due to the interference. TIF can explain both the original load on a link and the increased load due to retransmission of the lost packets. By assuming that link $k-1$ and link k are the successive links and the ETX of them are ETX_k and ETX_{k-1} respectively, the TIF_k can be defined as follows.

$$TIF_k = Min(1, TIF_{k-1}\ \frac{ETX_k}{ETX_{k-1}}) \tag{4.25}$$

Another factor that is used in SMETT metric is a motivated expected transmission time (METT). METT is an interference-adjusted ETT, which uses the TIF value to adjust the ETT metric. The METT of a link k can be shown as follows.

$$METT_k = \frac{\left(\frac{ETX_k\, S_p}{BW_k}\right)}{TIF_k} = \frac{ETT_k}{TIF_k} \tag{4.26}$$

where S_p denotes the packet size, and BW_k denotes the bandwidth of a link k.

By considering the channel diversity, the SMEET of the path p that consists of n links can be defined as follows.

$$SMETT_p = (1-\beta)\ \sum_{i=1}^{n} METT_i + \beta \max_{1\le j\le k}(X_j),\ where$$
$$X_j = \sum_{hop\ i\ on\ channel\ j} METT_i, \qquad 1 \le j \le k \tag{4.27}$$

Where β is a tunable parameter that subjects to $(0 \le \beta \le 1)$, and X_j represents the sum of transmission times of hops i on channel j. Accordingly, SMETT routing metric can improve the network performance. However, SMETT is a load insensitive metric and thus it may lead to instability of the path due to the congestion.

4.2.5 Exclusive Expected Transmission Time (EETT)

In multi-radio, multi-channel networks, a developed routing metric must be able to discriminate of the long paths with different channel distribution. EETT routing metric has the capability of giving a good estimation of multi-channel path in wireless multihop networks. For a given link / hop h, the EETT metric has been defined as below.

$$EETT_h = \sum_{link\ i \in IS(h)} ETT_i \tag{4.28}$$

where $IS(h)$ denotes a set of links that interfere with the link h including the link h itself.

The weight of the path p will be defined as the sum of estimated EETT of all links/hops within it. With this context, EETT metric represents the busy degree of the channel k that is used by the link h. In fact, the link h may have to wait a long period to do the transmission on the channel k when there are several neighboring links work on the same channel k. Consequently, the largest EETT value indicates that a path suffers from a worst-case of intra-flow interference and it needs more time to finish the transmission over all links within it. As mentioned in [33], the EETT metric can also take into account the inter-flow interference of link h by adding those links that use the same channel and do not belong to the same path with link h. Accordingly, EETT metric aims to use the channel spectrum by optimizing the channel diversity along the path.

4.2.6 Interferer Neighbor Count (INX)

Because of limited knowledge of ETX metric about its environment, it helps to select a path for an arriving connection without consideration to the impact of this choice on the resulting network state. For example, we have three paths $p_1 = [A, B, D]$ with $ETX_{p_1} = 1.6$ and $p_2 = [A, C, D]$ with $ETX_{p_2} = 1.2$ that interferes with $p_3 = [E, F]$. Assume that there are two connections have the messages M_1 and M_2 that are ready to send from A-D and E-F respectively. Based on the ETX value, the routing protocol will choose the p_2 for sending M_1 although the interference exists between p_2 and p_3. With this context, the service of one connection results in the blockage of the second one and thus the total throughput is divided by a factor of two. For maximizing the number of accepted connections, a new metric called INX has been proposed in [34]. INX is an enhanced version of ETX metric that takes into account the interference experienced by the wireless links. The value of INX metric can be estimated based on the equation shown below.

$$INX(p) = \frac{1}{N_l} \sum_{link\ l \in p} INX(l) \tag{4.29}$$

where p denotes the path, N_l denotes the total number of directional links in the network, and $INX(l)$ denotes the INX metric value of link l based on the equation below.

$$INX(l) = ETX_l \sum_{link\ j \in S(l)} r_j \tag{4.30}$$

where $S(l)$ denotes a set of all interfering links, and r_j denotes their respective bit rates in order to distinguish between high and low throughput interfering links.

Accordingly, the INX metric is capable of making the routing protocol selects a good path that alleviates the resulting interference. Thus, the good paths are preserved for the subsequent arriving connection.

4.2.7 Interference and Bandwidth Adjusted ETX (IBETX)

For selecting quality links, the delivery ratios were the primary quantity of interest and then the issue of contention due to neighbors is coming after. By considering the previous two issues, the most important task will be to find the high throughput paths in networks. IBETX is a routing metric that has been designed as threefold metric [35]. Firstly, it directly evaluates the expected link delivery (d_{exp}) of a wireless link mn as follows.

$$d_{exp}(mn) = d_f \; d_r \tag{4.31}$$

where d_f and d_r are the delivery ratios in forward and reverse directions respectively. Secondly, IBETX makes the nodes able to compute the expected link bandwidth (BW_{exp}) by providing the nodes with the information about nominal bit rates. To find the best path among a set of contending links either on a source-destination path P or on a non source-destination path NP, but in the same contention domain, then the expected bandwidth of the link mn can be defined as follows.

$$BW_{exp}(mn) = \frac{1}{\sum_{i \in P \cap NP} \frac{1}{r_i}} \tag{4.32}$$

where r_i denotes the transmission rate of the i^{th} link in the domain $P \cap NP$. Thirdly, the expected link interference (I_{exp}) can be calculated by periodically probes the MAC to find the time period for which the link is busy (T_{busy}). The interference for receiving node m is shown below.

$$i_m = \frac{T_{busy}}{T_t} = \frac{T_{Rx} + T_{RTS} + T_{CTS}}{T_t}, \tag{4.33}$$

And for sending node n is given as below

$$i_n = \frac{T_{busy}}{T_t} = \frac{T_{Rx} + T_{Tx} + T_{RTS} + T_{CTS}}{T_t}, \tag{4.34}$$

where T_{Rx} denotes the time of received packet, T_{Tx} denotes the time for sending packet, T_{RTS} denotes the time of RTS MAC packet, T_{CTS} denotes CTS MAC packet, and T_t denotes total window time. Thus, the expected interferences of the link mn has been defined as follows.

$$I_{exp} = \frac{i_{mn}}{1 + i_{mn}}, \; where \quad i_{mn} = Max(i_m, i_n) \tag{4.35}$$

Accordingly, IBETX value for end-to-end path P is calculated in the equation below, where $mn's$ are the links on the path P.

$$IBETX(P) = \sum_{mn=1}^{n} IBETX(mn) = \sum_{mn=1}^{n} \frac{d_{exp}(mn)}{BW_{exp}(mn)} I_{exp}(mn) \quad (4.36)$$

4.3 Load-aware Routing Metric

Despite the interference and transmission rate have significant effects on a wireless multihop network, balancing the load across such network will also help to improve the usage of this network and maximizing the network performance. To avoid the intricacies involved in packet reassembly and instabilities of routing decision, load balancing is achieved on a per level basis and not in individual packet. In fact, the functionality of both basic and interference-aware routing metrics will be enhanced by adding load-aware component to them.

The load balancing can be provided by using multipath routing scheme. In this case, each node maintains multipath from itself to the other. Hence, if the best path was congested or heavily loaded, the node can switch to the second best path. In this sub-section, we will try to show details about two of the load-aware routing metrics.

4.3.1 Load-Aware ETT (LAETT)

A new metric adapts the ETT metric to be load-aware routing metric. LAETT is capable of capturing both traffic load and quality by estimating the remaining capacity on the network nodes. The two goals of designing the LAETT metric are providing a path that satisfies the bandwidth request of the flow and makes room for future request by balancing the load across the network. The value of LAETT metric for the link $l(i,j)$ can be defined as follows.

$$LOAD_{l(i,j)} = ETX_{l(i,j)} \frac{S_p}{\left(\frac{RC_i + RC_j}{2\gamma_{l(i,j)}}\right)} \quad (4.37)$$

where S_p denotes the packet size, $\gamma_{l(i,j)}$ denotes the quality of link factor based on the distance between nodes that are defined depending on the table 1 in [36], RC denotes the remaining capacity of the link on each node and it is given as shown below.

$$RC_i = r_i - \sum_{flow\ k \in N_i} f_{ik}\gamma_{ik} \quad (4.38)$$

where r_i denotes the total transmission rate of node i, N_i denotes the number of flows in the node i, f_{ik} denotes the transmission rate of each flow, and γ_{ik} denotes the link quality factor of node i.

Accordingly, LAETT is able to help the routing protocol to select the path that maximizes the minimum remaining capacity of nodes and increases the network capacity and performance.

4.3.2 WCETT with Load Balancing (WCETT-LB)

A routing metric that has been derived from the WCETT metric [37]. WCETT-LB is able to achieve a global load balancing in the network by providing traffic splitting mechanism and congestion aware routing. The load balancing component that is integrated with WCETT consists of two parts: congestion level and traffic concentration level. At each node in a particular path, the congestion level is estimated by considering the average queue length at the node. When the average queue length exceeds the threshold, then path is heavily loaded. The WCETT-LB metric value of a path p can be evaluated by the equation below.

$$WCETT - LB\ (p) = WCETT(p) + L(p),\ where$$
$$L(p) = \sum_{node\ i \in p} \frac{QL_i}{r_i} + min(ETT)\ N_i \quad (4.39)$$

where $L(p)$ denotes a load-balancing component, QL_i denotes the average queue length at node i in the path p, r_i denotes the transmission rate at a node, $\min(ETT)$ denotes a smallest ETT in the network, and N_i denotes a set of nodes that uses the node i as their next hop. In fact, the higher value of $\min(ETT)\ N_i$ will indicate the traffic concentration at node i. In addition, we can note that the fraction QL_i/r_i will represent the actual time needed for transmission at node i. Accordingly, the WCETT-LB will make the routing protocols capable of considering the traffic concentration and congestion level in addition to all the features of WCETT metric.

4.4 Hybrid Routing Metric

Wireless multihop networks are a type of radio based network system, which made flexible networks to support the increasing demand for services and mobility. Because of the dynamic characteristic of the radio environment, the routing protocols in such network must dynamically adapt their routes according to the changes in the network environment.

Varying types of routing protocols are developed specifically to meet the requirements and the characteristics of such networks. Any routing protocol aims to find stable and high throughput paths based on the some metrics and measurements that are incorporated into their route computation algorithms. Two of the main concerns in routing protocols for such networks are the traffic load and interference. In fact, most of the interference is caused by the traffic generated in the nodes, which means that the interference and load traffic are interrelated. For taking the advantage of wireless resources and accurately depict the quality of the link, it is necessary to take both traffic load and interference into consideration. In this subsection, we will show the brief details about the hybrid routing metrics that combine a number of performance measurements in order to define the quality cost of a path.

4.4.1 Resource Aware Routing for mEsh (RARE)

The first isotonic routing metric that uses the passive monitoring in order to measure all its parameters, and thus it reduce the network overhead due to active probing. The main design goal of RARE is to make the routing protocol aware of the wireless resources [41]. The link cost function of the RARE metric involves three measurements comprising signal strength, bandwidth, and contention, which represent the important characteristics of a radio link. The RARE metric value can be estimated based on the formula, which is shown below.

$$RARE_i = \alpha \frac{Cap - BW_a}{BW_a} + \eta \frac{RSSI_{max} - RSSI}{RSSI} + \Phi \, Cont_{avg} \tag{4.40}$$

where Cap denotes the link capacity, BW_a denotes the available bandwidth, $RSSI_{max}$ denotes the maximum signal strength value, $RSSI$ denotes the signal strength value, $Cont_{avg}$ denotes the average contention, and α η Φ are weights that specify the relative importance of the different link cost components.

Because BW_a is based on the duration of the idle T_{idle} and busy T_{busy} intervals that are normalized and combined with the transmission rate TX_{rate}, BW_a can be considered as traffic load measures. The equation of BW_a is given as follows.

$$BW_a = \frac{T_{idle}}{T_{busy} + T_{idle}} \, TX_{rate} \tag{4.41}$$

The passive monitoring approach makes the RARE does not introduce the overhead of measurements and thus RARE is able to increase the network performance. However, the

RARE metric suffers from several drawbacks, which are (i) it does not depict path with channel diversity, (ii) RSSI is not an accurate means of measuring interference, and (iii) it does not provide accurate information about the quality of the link.

4.4.2 Contention Aware Transmission Time (CATT)

An isotonic routing metric for multi-rate multi-radio wireless networks that represents enhanced version of ETT metric. CATT is capable of capturing the link congestion as well as the inter-flow and intra-flow interferences in unifying manner by making a sum of the delays of the interfering links in 1 and 2 hop neighbors. The isotonic property of CATT metric allows efficient and loop-free computation of paths using link-state routing protocol [38]. The CATT equation has been defined as follows.

$$CATT_i = ETX_i \sum_{j \in N_i} \left(\left(\sum_{k \in N_j} \frac{S_{p_k}}{r_k} \right) \tau_j \frac{S_{p_j}}{r_j} \right) \quad (4.42)$$

where N_i denotes the set of links that can interfere with the transmission on link i, N_j denotes the set of links that interferes with the transmission on link j, S_{p_j} and S_{p_k} denote to the packet size of the links in 1 and 2 hop neighbors respectively, r_j and r_k denotes the transmission rates of the links in 1 and 2 hop neighbors respectively, and τ_j is the packet transmission attempt rate on link j.

Accordingly, CATT metric can provide a high performance by capturing both the number of interfering links and the level of their interference, which depends on their transmission rate. However, it suffers from two drawbacks, which are (i) overestimated link quality, and (ii) inaccurate manner for capturing the traffic load over wireless links.

4.4.3 Contention Window Based (CWB)

A load and interference-aware routing metric that assigns weights to individual links based on both channel utilization β and the congestion level CW. As mentioned in [39], the congestion level represents how hard to transmit successfully a frame on each link of the node. CW is measured by using average contention window used in these links. While the channel utilization represents the fraction of channel time in which the channel is sensed busy. Thus, the CWB is defined by the formula as follows.

$$CWB_i = \beta_i \, CW_i \tag{4.43}$$

where

$$CW_i = \frac{1 - FER}{1 - FER^{bo+1}} \frac{1 - (2\,FER)^{bo+1}}{1 - (2\,FER)} CW_0 \tag{4.44}$$

$$\beta_i = \begin{cases} 1 & if\ u \le T_1 \\ min\left(\alpha(u - T_1) + exp(\frac{u - T_1}{T_2 - u}), \beta_{max}\right) & if\ T_1 < u < T_2 \\ \beta_{max} & if\ u \ge T_2 \end{cases} \tag{4.45}$$

Note that the FER denotes the frame error rate, CW_0 denotes a minimum contention window, bo denotes maximum back-off stage, α denotes how fast β will increase, u denotes the percentage of channel utilization, T_1 and T_2 denote to the minimum and maximum threshold of the channel utilization, and β_{max} denotes the maximum value that the channel utilization can reach.

Accordingly, CWB is a routing metric that combines one measure of the physical model (FER) with one measure based on the logical model that reflects the traffic and interference. However, CWB has several drawbacks that are (i) it is not reliable when network conditions are rapidly changing over a period of time, and (ii) it does not deal with intra-flow interference.

4.4.4 Interference–Load Aware (ILA)

The degree of interference is defined based on the amount of traffic generated by the interfering node. The interferer closes to the sender or receiver that is not involved in any transmission simultaneously will not cause any interference. This fact is not taken into account of most routing metrics that have been mentioned such MIC. ILA is a routing metric that captures this fact in order to find paths with less congestion, low packet drop ratio, high data rate, and low level of interference. ILA is comprised of two components: metric of traffic interference (MTI) and channel switching cost (CSC). These two components enable the routing protocols to capture the effects of intra-flow and inter-flow interference, packet loss ratio, difference in transmission rates, and congested area [40]. The MTI component is able to consider the traffic load of interfering neighbors based on the equation below.

$$MTI_i(C) = \begin{cases} ETT_{ij}(CH)\, AIL_{ij}(CH), & if\ N_l(CH) \ne 0 \\ ETT_{ij}(CH), & if\ N_l(CH) = 0 \end{cases} \tag{4.46}$$

where $ETT_{ij}(CH)$ is the metric that captures both the difference in transmission rate and the loss ratio of links, $AIL_{ij}(CH)$ denotes the average load of the neighbors that interfere with the transmission between node i and j over channel CH, and $N_l(CH)$ denotes the set of interfering neighbors of node i and j. The equations of $AIL_{ij}(C\text{H})$ and N_l are given as below.

$$AIL_{ij}(CH) = \frac{\sum_{N_l} IL_{ij}(CH)}{N_l} \tag{4.47}$$

$$N_l = N_i(CH) \cup N_j(CH) \tag{4.48}$$

The Interfering Load (IL_{ij}) is the load of the interfering neighbors. Thus, MTI component is responsible for selecting the path with minimum traffic load and minimum inter-flow interference in the presence of the interfering neighbors. To capture the intra-flow interference, ILA involves the CSC component that is similar to the one in MIC metric. The CSC equation is defined as follows.

$$CSC_i = \begin{cases} w_1 & if\ CH\big(prev(i)\big) \neq CH(i) \\ w_2 & if\ CH\big(prev(i)\big) = CH(i), \end{cases} \quad 0 \leq w_1 \leq w_2 \tag{4.49}$$

where $CH(i)$ denotes the channel assigned to the node i, and $CH(prev(i))$ denotes the channel assigned to the previous hop of node i along the path p. Accordingly, the value of the ILA metric for path p has been defined as follows.

$$ILA(p) = \mho \sum_{link\ i \in p} MTI_i + \sum_{node \in p} CSC_i \tag{4.50}$$

where $\mho$ is a scaling factor that balances the impact of the difference in magnitude of the two components of ILA. With this context, MTI is made to have the same order of magnitude of CSC. The value of the factor $\mho$ is given as below.

$$1/\mho = \begin{cases} \min(ETT)\ \min(AIL), & N_l(CH) \neq 0 \\ \min(ETT), & N_l(CH) = 0 \end{cases} \tag{4.51}$$

CHAPTER 5

RESULTS AND DISCUSSION

The performance of routing protocols depends on many parameters that are classified as networking parameters and environmental parameters. Networking parameters are originated from networking design, structure, and protocols. Environmental parameters are the parameters that the system is subjected to in the environment. The main contribution in the performance of a network comes from networking protocols; therefore the performance of protocol determines the quality of the network.

The channel quality from one node to another node is defined as how much volume of information could be transmitted, namely, with a small bit error rate (BER). As it is understood from the definition of the quality, the channel quality has an averaging meaning about the volume size of information that could be transmitted. In literature, most of the existing routing protocols rely on the link quality, i.e. the forward and reverse channel qualities at the same time. The protocols are about the route selection from all available routes between any pair of two nodes. Routing protocols are optimized to take into account the quality for route selection.

However, during the transmission the information is subjected to the effects that certainly change. Within this context, the link reliability comes into the light. Almost all routing protocols are not optimized out of the reliability scope. The channel reliability from one node to another node is defined as how much successfully a volume of information could be transmitted. Let us consider two channels whose qualities are the same (i.e. their BER are the same). Note that the bit errors occurred during transmission over a channel could be sequential; the group of successive errors is called burst-error. In the second channel, the bit errors are separated from each other by successful transmission, i.e. the bit errors are distributed along the transmitted bit sequence. In consequence, the reliability of the second channel is better than the first channel even if their qualities are the same.

Accordingly, the channel reliability is about dynamic changes in the quality. Therefore, the channel reliability could be used as another metric in order to select the best reliable route for data transmission. However in literature, the channel reliability has not attracted the attention of researchers and practitioners. The channel reliability is determined or characterized by the dynamical changes in transmission performance, and hence the burst errors in transmission are important. The more length of burst errors, the less channel reliability. The length of burst errors can be used to select a more reliable links / routes. In this thesis, we try to characterize the length of burst errors of the channels, i.e., the burst-error length, in order to determine high reliable and qualitative route within the available routes and hence increase the performance of the networks.

5.1 Overview of IEEE 802.11x Standard

The IEEE 802 committee has defined the specifications for a wireless LAN, called IEEE 802.11, which covers the physical and data link layers [193]. The IEEE 802.11 standard provides many layers for a network system, including radio modulation and coding, packet formats, and the MAC protocol in order to characterize the physical communication and to manage the contention among multiple senders. IEEE 802.11 firstly introduced in 1999. The initial standards of 802.11 are designed keeping in mind the home and the office environment for wireless local area connectivity. This initial version gave a maximum data rate of 2Mbps. Then, it has been developed to provide data rate of 1Gbps with the 802.11ac version [194].

The IEEE 802.11 utilizes variety of physical (PHY) layers with the aim of increasing the aggregate throughput of the network. IEEE 802.11 standard describes three PHY layers, namely: infrared (IR) layer, a frequency-hopping spread spectrum (FHSS) layer, and a direct spread-spectrum (DSSS) layer. In addition to these main PHY layers, there exists another PHY layers such as High Rate DSSS PHY layer for IEEE 802.11b and Orthogonal Frequency Division Multiplexing (OFDM) PHY layer for IEEE 802.11a. The frequency band of operation for most of the extensions of IEEE 802.11 starting at 2.4 MHz and spaced 5 MHz apart, which specify with 11 distinct channels. These channels actually overlap with each other; however, it is possible to choose three channels without significant overlap [195].

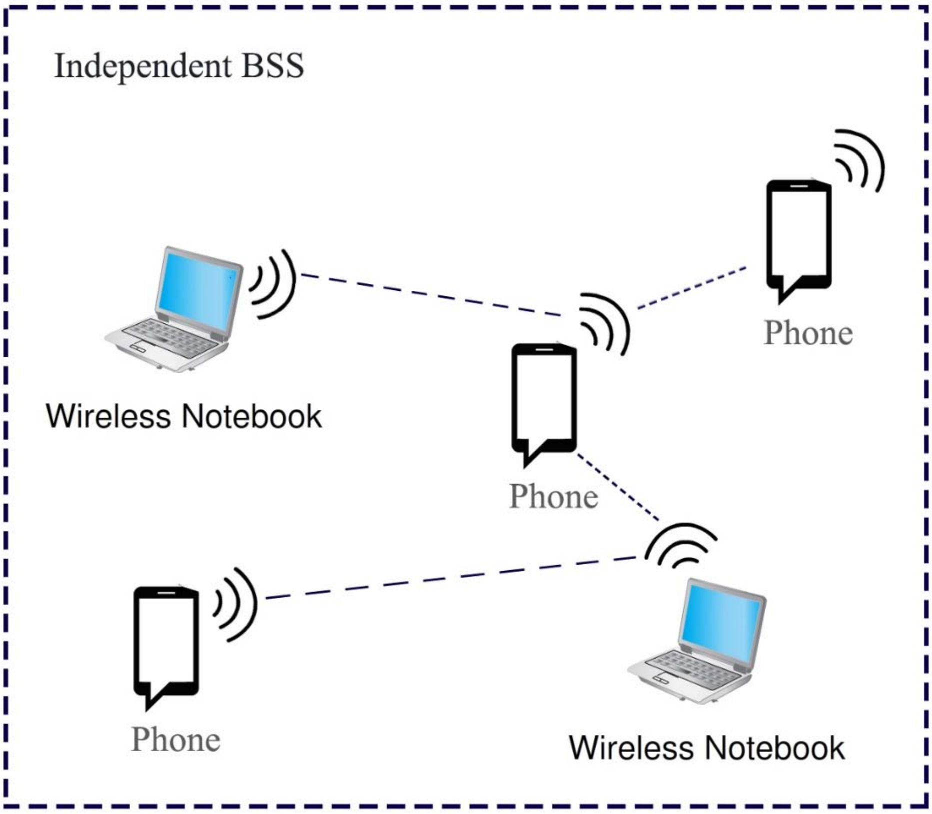


Figure 5.1 Independent Basic Service Set.

The 802.11 working group involves two kinds of services: the basic service set (BSS) and the extended service set (ESS). A basic service set (BSS) is the building block of a wireless LAN, which is made of stationary or mobile wireless nodes. The nodes in BSS execute the same MAC protocol and competing for access to the same shared wireless medium. A BSS may connect to a backbone distributed system (DS) via an access point (AP) in infrastructure mode or it may be isolated and works in ad hoc mode.

In an infrastructure mode, a node can communicate with other nodes by sending the MAC frame to the AP which in turn either relaying this frame over the DS on its way to the remote destination node or directly sending this frame to the destination node in the same BSS. The DS can be a wired network, or a wireless network. In ad hoc mode, all nodes in a BSS are mobile nodes that directly communicate to each other without the intervention of AP. Figure (5.2) depicts the BSS in ad hoc mode that is called independent BSS (IBSS). An extended service set (ESS) is made up of two or more BSSs with APs. These BSSs are interconnected through a distribution system. The ESS appears as a single logical LAN to the logical link control (LLC) level. Figure (5.1) depicts the IEEE 802.11 working group architecture.

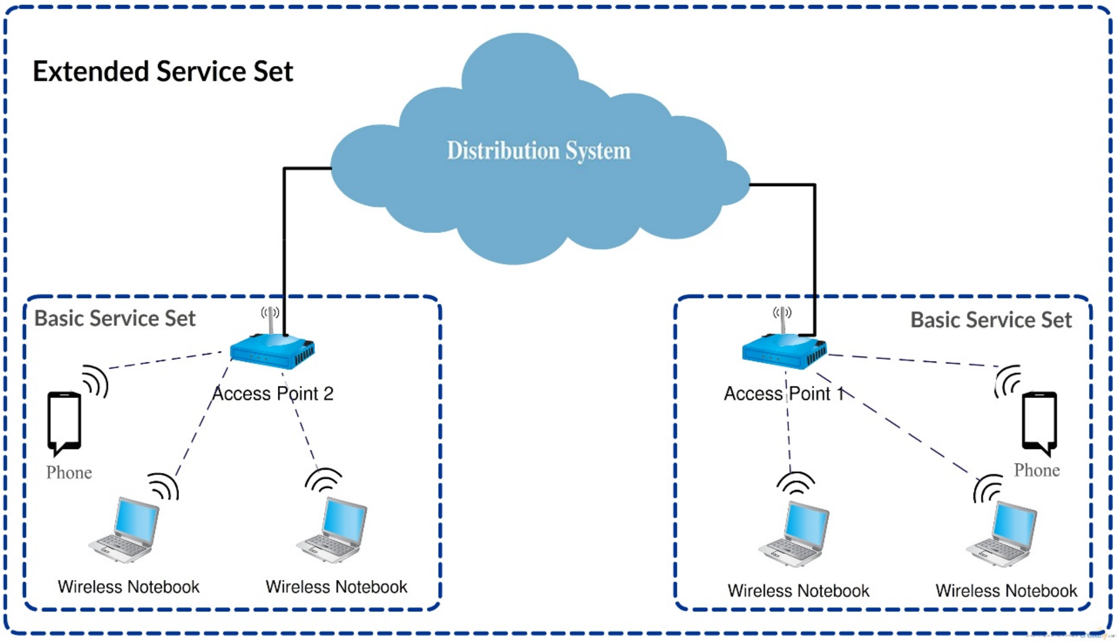


Figure 5.2 IEEE 802.11 Working Group Architecture.

5.1.1 IEEE 802.11 Medium Access Control (MAC)

IEEE 802.11 standard defines two types of MAC schemes: the point coordination function (PCF) and distributed coordination function (DCF), which are used to allow multiple competing senders to share the wireless medium without interfering with each other. The point coordination function (PCF) is implemented on top of the DCF and it is used mostly for time-sensitive transmission. PCF is considered an optional access scheme that can be implemented in an infrastructure network. We will not consider the PCF in this subsection. The distributed coordination function (DCF) is a carrier-sense multiple-access scheme with collision avoidance (CSMA/CA) that is generally used for ad hoc network. DCF distributes the decision to transmit over all nodes within the network. Because collision detection is not practical on a wireless network, DCF scheme use a collision avoidance instead of a collision detection mechanism.

Preamble (18 bytes)	Physical layer header and CRC (6 bytes)	802.11 and Ethernet headers (31 bytes)	Ethernet Payload (*n* bytes)	Data CRC (4 bytes)

(a) Data Packet Format

Preamble (18 bytes)	Physical layer header and CRC (6 bytes)	ACK frame (10 bytes)	Data CRC (4 bytes)

(b) ACK Packet Format

Figure 5.3 Packet Format For 802.11 Data And ACK Packets

There 802.11 MAC supports two types of packets: broadcast and unicast packets. The broadcast packets are received by any node which hears them. After receiving the broadcast packets, the node directly delivers them to the network layer. It is worth noting that there is no an acknowledgment (ACK) packet is sent back for the broadcast packets. Unicast packets are the packets that directed to a specific destination node. When the destination node received the unicast packets, it immediately sends back an acknowledgment packet, then delivers these packets to the network layer. Other nodes within the network that receive the unicast packet will discard it and do not send an ACK response. Figure (5.3) depicts the packet format for 802.11 data and ACK packets.

The DCF scheme includes a set of delays that amounts to a priority scheme. Before sending a packet, the sender should be listening to the shared medium to detect if any other transmission is in progress. If once such a transmission is over or there is no such transmission, the sender node will wait for a period of time called the DCF inter-frame space (DIFS). After waiting for DIFS time, the sender has to choose another delay time called back off time (BO). The selection of this delay time is achieved randomly from its own contention window (CW). A contention window has upper and lower bands between 62-2,460 microseconds. CW is doubled after each packet collision or set to its minimum value after the successful transmission. While the sender waits for BO to elapse, it checks the medium for any other transmission. If there exist transmission from other node, it stops the BO timer and does not count that time as waiting. At the end of the current transmission, the sender will resumes waiting for the remaining of BO. Thus, the sender node waits for the BO amount of idle medium time before attempting to send [196].

When the transmitted packet is received by the destination node, it waits for a period of time called short inter-frame space (SIFS), and then sends back the ACK packet to the sender node. If the sender node does not receive the ACK packet after a DIFS+SIFS period of time, it will mark the transmission as filed, and then it doubles its CW and retransmit this packet one more time. The sender will repeatedly try to retransmit a packet up to a specified maximum number of tries (threshold), and then it will give up and discard this packet.

The total time for sending a packet and then receiving the ACK called round trip time (RTT). RTT for the successful transmission (in the absence of contention) can be computed as follows.

$$RTT = T_p + DIFS + BO + T_a + 2\, T_P \tag{5.1}$$

where RTT denotes the round trip time, T_p denotes the time required to put the unicast packet over the forward channel, T_a denotes the time required to put the ACK over the reverse channel, and T_P denotes the propagation time, which is equal to $ditacne/signal\ velocity$.

Accordingly, we can compute the maximum throughput B_{max} per packet of the channel as follows

$$B_{max} = \frac{1}{T_p + DIFS + BO + T_a + 2\, T_P} = \frac{1}{RTT} \tag{5.2}$$

For reducing the contention among multiple senders, 802.11 standard also uses the handshake mechanism with request-to-send (RTS) / clear-to-send (CTS) packets, which we do not describe it further.

5.2 The Concept of the ETX Metric

As we mentioned in the previous chapters in this thesis, the delivery ratios are the important measurements used to calculate the basic link quality metric, which is called ETX. ETX metric of a link represents the predicted number of transmissions / retransmissions required to send a packet over that link. Each attempt to transmit a packet can be considered as a Bernoulli trial. By using the ETX as a routing metric, the routing protocols will be able to determine the wide range of the link loss ratios in addition to detecting the links with asymmetric loss ratios. Accordingly, we can realize that the main objective of ETX metric is to help the routing protocols to select the routes with high end-to-end throughput and thus increase the overall network performance.

For calculating ETX value, each node will probe the channels with its neighbors by sending probe packets to them within a time window. Then, the nodes compute the probability of delivery ratio (PDR) of the successful probe packets that received from its neighbors as follows.

$$PDR = \frac{count(t - T_W, t)}{T_W/\tau}, \tag{5.3}$$

where PDR denotes the probability of delivery ratio within the time window T_W, and τ denotes the average time period for broadcasting a probe packet.

By incorporating the PDR values within a certain control messages or within the probe packet itself, each node will possess a full knowledge about the quality of the links to all its neighbors. Thus, each node will calculate the ETX metric as follows.

$$ETX = \frac{1}{PDR_f\ PDR_r} = \frac{1}{PDR} \qquad (5.4)$$

where PDR_f denotes the probability of forward delivery ratio, i.e. the channel from the sender to receiver node, PDR_r denotes the probability of reverse delivery ratio, i.e. the channel from the receiver to sender node, and PDR denotes the probability of transmission that successfully received and acknowledge. By subtracting 1 from both sides of the equation (5.4), we can rewrite the ETX metric equation as follows.

$$ETX - 1 = \frac{1}{PDR} - 1 \qquad (5.5)$$

$$ETX - 1 = \frac{1 - PDR}{PDR} \qquad (5.6)$$

$$ETX = \frac{P_f}{PDR} + 1 \qquad (5.7)$$

where P_f denotes the probability of the failed transmission including acknowledgments.

We can note from the equation (5.7) that the value of ETX metric is depending on the P_f/PDR fraction. Therefore, the P_f/PDR equals to zero when the link between the sender and receiver is considered ideal link (i.e. lossless channels) and thus ETX will equal to 1. In the case of outage of the link between the sender and receiver nodes, the P_f/PDR will go to the ∞, and thus ETX will equal to ∞. Accordingly, the lower and upper bounds of ETX metric are $1 \leq ETX \leq \infty$. With this context, we can note that the ETX value will occupy a large number of bits inside the control message. The ETX of a path P is the sum of the link metrics for each link l.

$$ETX(P) = \sum_{l \in P} ETX(l) \qquad (5.8)$$

Although ETX metric has the ability to capture the link quality, the method by which the ETX metric is computed can be considered as a full intuitive method that do not provide a clear sight about how this metric mathematically computed. In addition, ETX metric is considered as a coarse grained model that its value depends on the average value of PDRs over a whole time window. Therefore, ETX metric cannot be used to characterize the burst error length, i.e., the reliability of the link. For these reasons, we need to redefine the ETX metric in order to be able to take these two issues in its account.

5.3 A New Definition of ETX Metric

Information theory studies the quantification, storage, and communication of information. It was originally proposed by Claude E. Shannon in 1948. A key measure in information theory is "entropy". Entropy quantifies the amount of uncertainty involved in the value of a random variable or the outcome of a random process [197]. As we mentioned before, each attempt to transmit a packet can be considered as a Bernoulli trial. While the probability of successful transmission PDR is considered as the probability density function (PDF) of the transmission attempts, the probability of failed transmission P_f can be considered as the complementary probability of PDR. We will attempt to redefine the meaning ETX depends on the mathematical concept of the entropy [198-200]. For each link l, our ETX depends on the average amount of information contents $I(.)$ obtained from PDR and P_f. We will evaluate the ETX value based on how much information of failed transmission is included within the total information of transmission.

$$H(PDR) = PDR\ I(PDR) = -PDR \log_2(PDR) \tag{5.9}$$

$$H\left(P_f\right) = P_f\ I(P_f)\ = -P_f \log_2(P_f) \tag{5.10}$$

$$H(TR) = \ H(PDR) + \ H\left(P_f\right) \tag{5.11}$$

$$ETX(l) = \frac{H(TR)}{H\left(P_f\right)} \cong 1 - \log_2(PDR) \tag{5.12}$$

where $H(PDR)$ denotes a portion of information about the successful transmission, $H\left(P_f\right)$ denotes a portion of information about the failed transmission, and $H(TR)$ denotes the total information about the transmission. We can mathematically prove the equation (5.12) as follows

$$ETX = \frac{-PDR\ \log_2(PDR) - P_f \log_2(P_f)}{-P_f\ \log_2(P_f)} \tag{5.13}$$

$$ETX = \frac{-P_f\ \log_2(P_f)}{-P_f\ \log_2(P_f)} + \frac{-PDR\ \log_2(\ PDR)}{-P_f\ \log_2(P_f)} \tag{5.14}$$

$$\begin{aligned} ETX &= 1 + \frac{PDR}{P_f} \frac{1}{\log_2(P_f)} \log_2(PDR) \\ &= 1 + a\, b\ \log_2(PDR) \end{aligned} \tag{5.15}$$

Where $a = \frac{PDR}{P_f}$, and $b = \frac{1}{\log_2(P_f)}$.

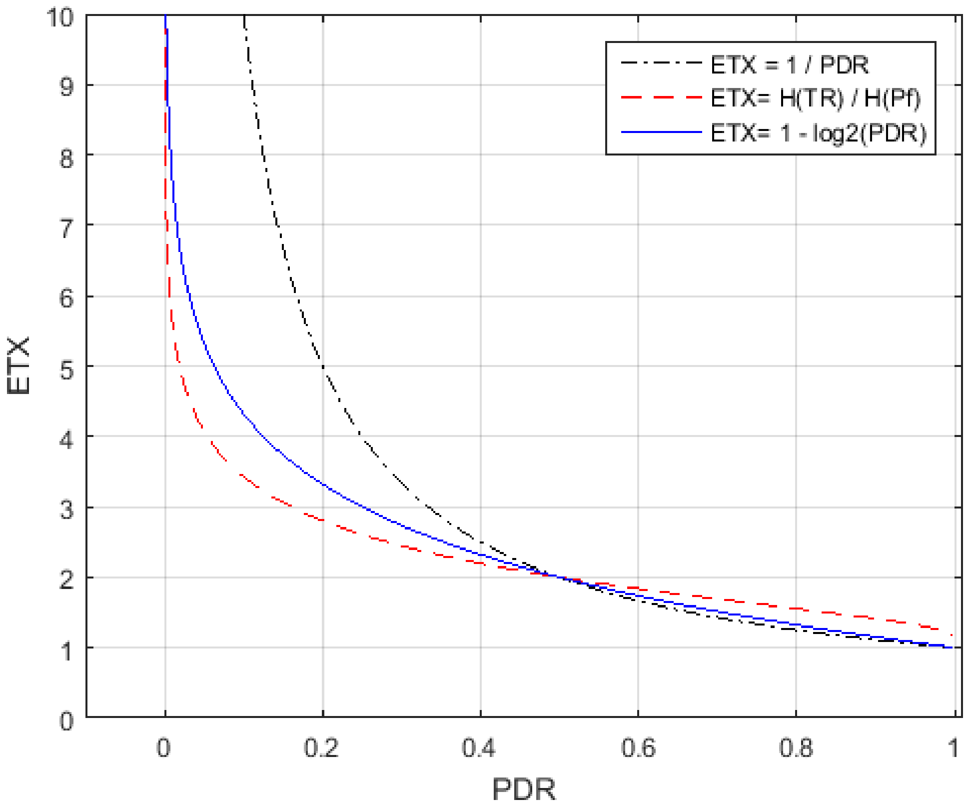


Figure 5.4 The ETX Values Based on Its New Definition

By using the Taylor series concept, we can expand $\log_2(P_f)$ as follows

$$\log_2(P_f) = \frac{1}{\ln(2)}(P_f - 1) - \frac{1}{2\ln(2)}(P_f - 1)^2 + \frac{1}{3\ln(2)}(P_f - 1)^3 - \frac{1}{4\ln(2)}(P_f - 1)^4 + \frac{1}{\infty\ln(2)}(P_f - 1)^\infty \tag{5.16}$$

It is worth noting that the value of b is always negative and the value of a is always positive. Another explanation for the fact that b is always negative is that b can be considered as $\frac{\log_{10}(2)}{\log_{10}(P_f)}$. When the value of a increases in a positive side, the value of b decreases in a negative side. With this context, the product of a and b is a roughly equal to -1. Consequently, the equation of ETX metric can be mathematically expressed as mentioned in eq. (5.12). By observing the figure (5.4), we can note that the Entropy-based ETX metric curve is slowly changed when the link variability in a high level, while the basic ETX is dramatically changed. Accordingly the bits that are needed for representing the Entropy-based ETX metric values will be less than these bits for basic ETX metric values, and thus it reduces the size of the control messages that convey these values. Entropy-based ETX metric will decrease the consumption amount of network resources such as: bandwidth, energy, memory, and overhead. This will have a significant positive impact, especially in networks that suffer from a lack of resources such as wireless sensor network. In wireless sensor networks, the sensor nodes are much more resource constrained. As a result, the heavy-weight routing protocols as those used in other networks may not suitable for using them in WSNs. The limited communication and computational resources of the sensor nodes need to utilize the routing protocols with minimum probe packet size, energy consumption, memory, and overheads.

5.4 Dynamic ETX (DETX) Metric

In order to characterize the reliability of the link based on the burst error-length (i.e., burst loss situation), the main time window, in which the ETX is computed, should be splitted into sub-windows. In each sub-window, assuming that it is sub-window k with time width of T_{sw}, namely $T_{sw} \ll T_w$ where T_w denotes the time width of the main time window, the quality of sub-window k can be readily calculated at any time t. Each node will broadcast the probe packets of a fixed size at an average period τ, and then in order to find the PDR of sub-window k, i.e., $PDR_{n,k}$ in the nth main time window, each node will calculate the number of probe packets it has received successfully, that is

$$PDR_{n,k} = \frac{count_{T_{sw}}(t - kT_{sw} - nT_w, t)}{T_{sw}/\tau}, \tag{5.17}$$

where $count_{T_{sw}}(t - t_{start}, t)$ denotes the number of probes received at time t between t_{start} and $t_{start} + T_{sw}$, and T_{sw}/τ denotes the total number of probes that actually are sent within sub-window k. It is clear that the number of successful of transmission in each sub-window will be different, so will be its PDR; the PDR of the main time window is the average of PDRs of the sub-windows as follows

$$PDR_n = \frac{1}{K}\sum_{k=1}^{K} PDR_{n,k}, \tag{5.18}$$

It is worth noting that such kind of counting method enables each node to measure the PDR of the reverse channel to its neighbor nodes from whom it has received probe packets, and then send back these PDR to their corresponding nodes in a certain control message in order to calculate the PDR of forward channel. Counting the probe packets overall nodes discloses all available route paths between nodes. Figure (5.5) depicts the variation of the PDRs of sub-windows over the main time window.

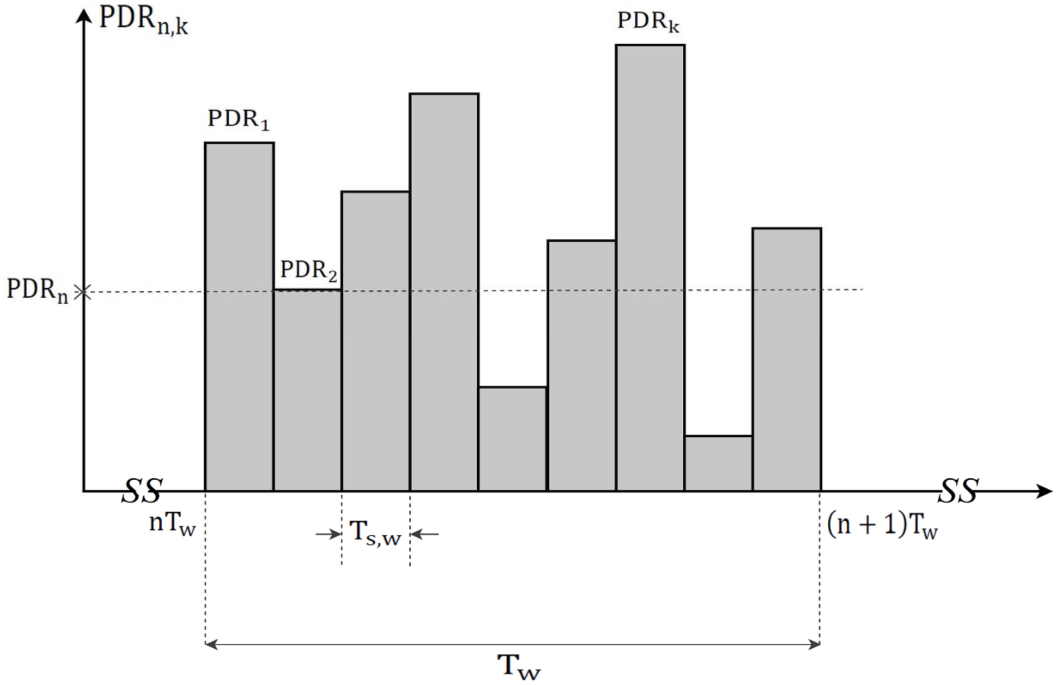


Figure 5.5 The PDRs of Sub-Windows Over The Main Window

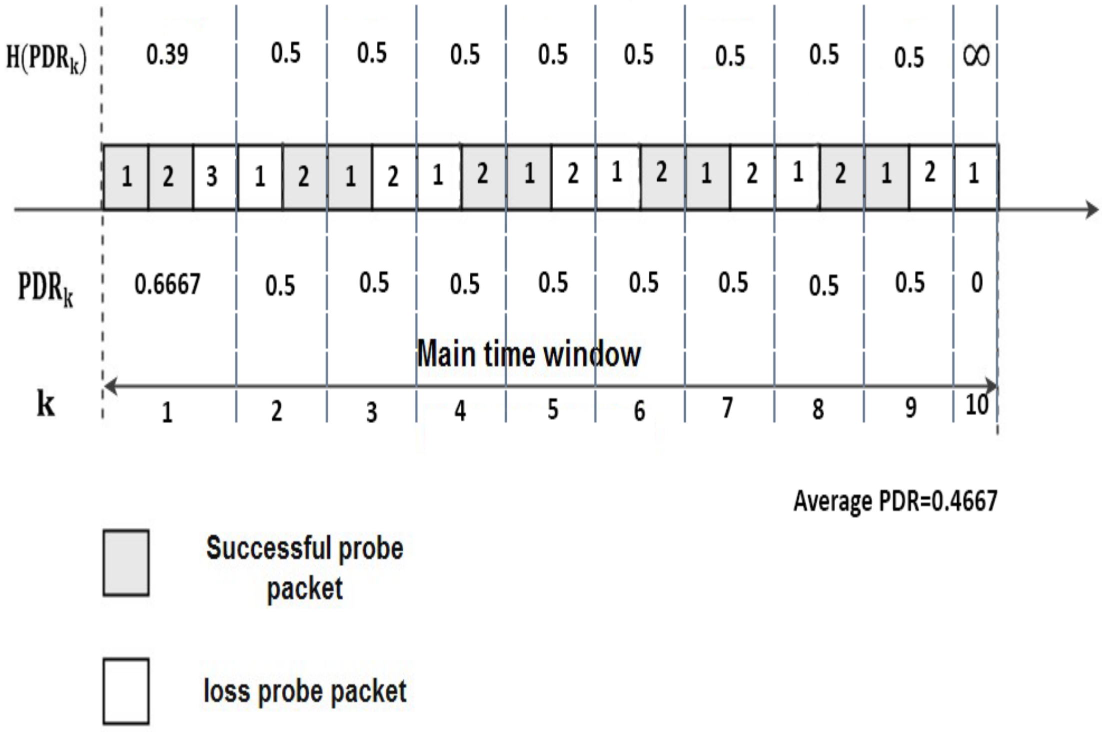
The variation of the $PDR_{n,k}$ of the sub-windows above and below the PDR_n gives us some intuition about how much the channel is reliable; namely the more consistency (ordering) of $PDR_{n,k}$, more reliability of a channel. When the channel is disordered, then the channel is unreliable since the $PDR_{n,k}$ of sub-windows will be so much different from each other. Within this context, the concept of entropy can be used as a disorder measure of the channel. In consequence, a reliability is defined as the variations in the quality. If the channel is perfectly reliable, its quality does not change over time. It is therefore possible that two channels could have the same quality with different reliabilities.

Accordingly, we will try make the Entropy-based ETX metric is reliable metric based on the entropy concept. We called this a new reliable metric as the Dynamic ETX (DETX) metric. In a dynamic ETX metric, the value of a time width in addition to the number of sub-windows K within the main window time will be changeable. These values will depend on the entropy value of the delivery ratio from the beginning of sub-window time until the end of each slot time. Each sub-window is created whenever the calculated entropy value exceed a predefined threshold value **ε**. After creating the first sub-window, the counters of delivered packets and the entropy will be restarted in order to start a new sub-window. The entropy formula of a PDR_k will be as follows,

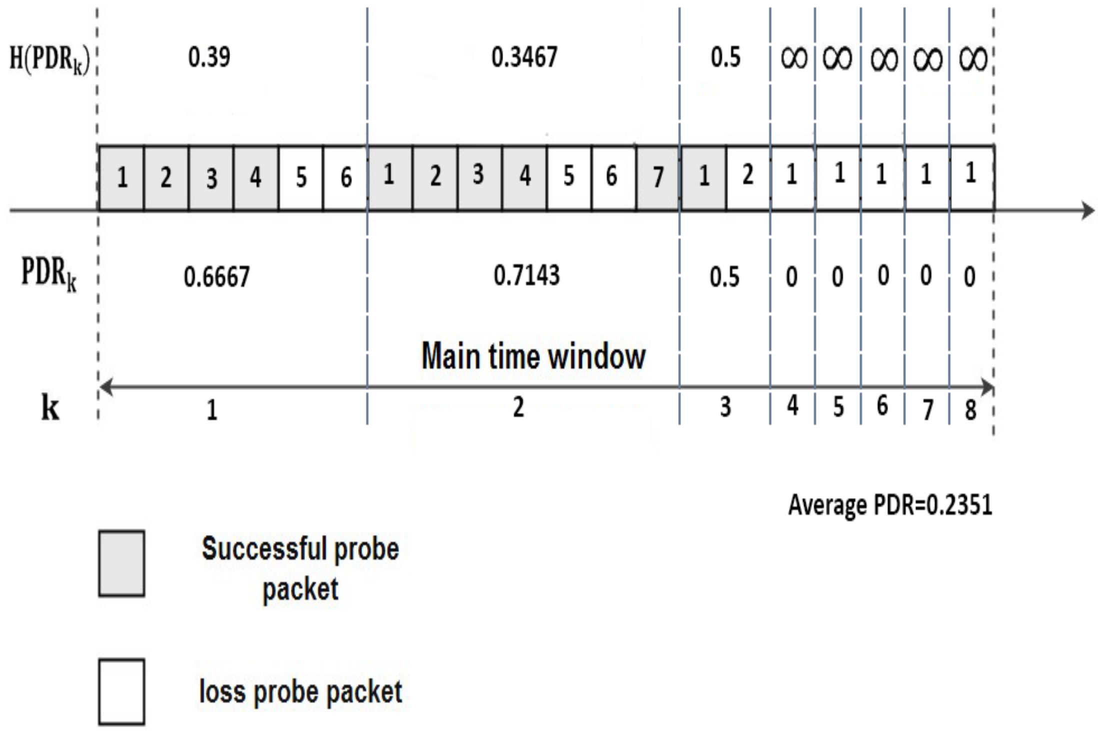
$$H(PDR_k) = -PDR_k \ \log_2(PDR_k) \qquad (5.19)$$

We assume a threshold value for this entropy as a condition and making the non-value (i.e., 0 multiplied by $-\infty$) equals to infinity. As a result of that, we will divide the main window into several sub-windows each of which contains a certain value of the entropy with different time length and number of successful packets.

Figure 5.6 and 5.7 depict the main time window belonging to two links. Where each of these tow links includes a forward and reverse channel. Moreover, we will assume the threshold (ε) value equals to 0.3. The threshold represents the acceptable disorder within the sub-window. Moreover, this threshold's value leads to split the sub-windows with a high reliability from these sub-windows with a low reliability, and thus changing the value of the average $PDR_{n,k}$ (i.e., PDR_n) of the forward and reverse channels of the link. With this context, the value of the DETX metric will also be changed as a result of changing in a PDR of a link. Although these two links have different distribution patterns of the packet delivery over a main time window, the ETX and Entropy-based ETX values for them are the same that equal to 4 and 3 respectively. It is worth noting that these metrics are unable to capture the differences of these patterns, while DETX metric has the ability to detect and capture these differences. Thus, DETX metric has different values of these two links. For the first link where the PDR of the link, i.e., the multiplication of forward and reverse average PDR_n equals to 0.1097, the DETX equals to 4.1. For the second link where the PDR of the link equals to 0.0181, the DETX equals to 6.9.

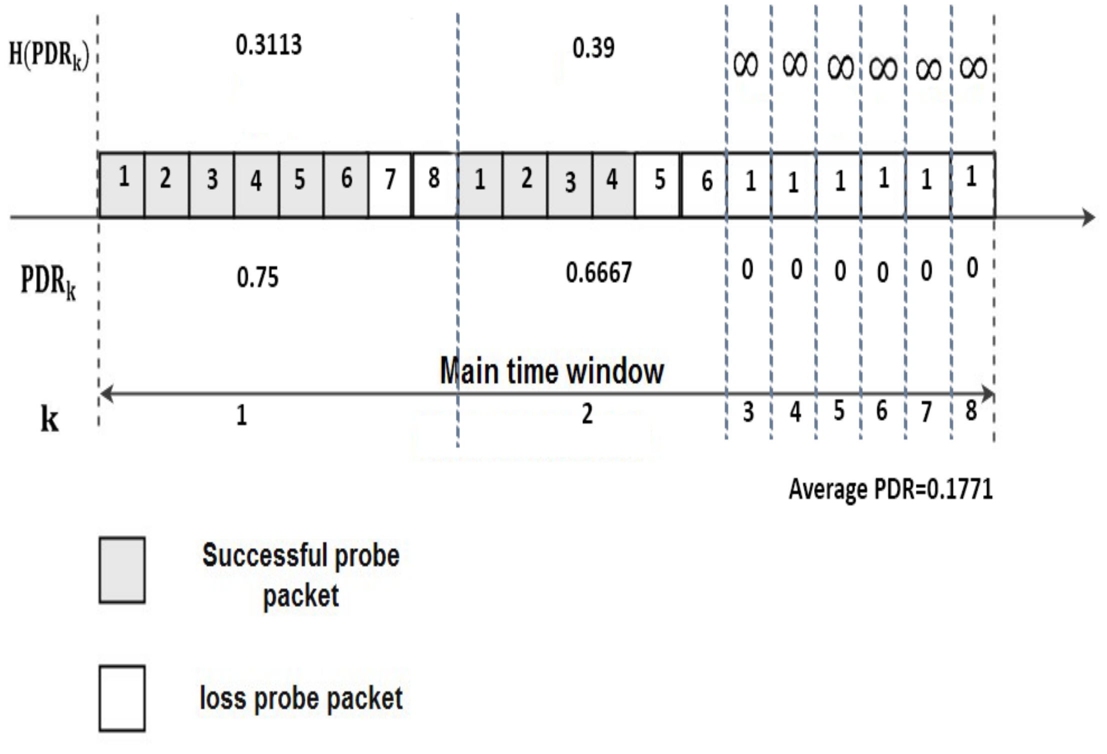


(a) Forward channel of the 1st link

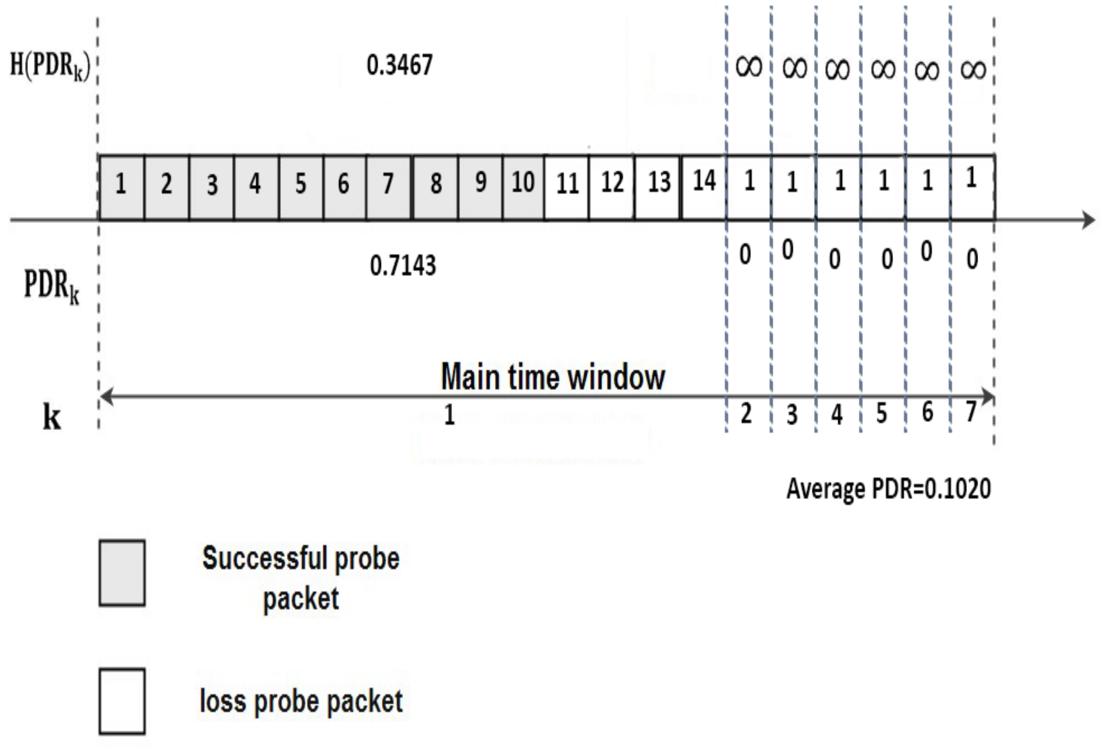


(b) Reverse channel of the 1st link

Figure 5.6 Different Distribution Patterns of a Packet Delivery Over The 1st Link



(c) Forward channel of the 2nd link



(d) Reverse channel of the 2nd link

Figure 5.7 Different Distribution Patterns of a Packet Delivery Over The 2nd Link

It is worth noting that the DETX metric is also valid in state of the link ideality (i.e., $PDR_l = 1$) and outage (i.e., $PDR_l = 0$). The DETX metric for a link l can be computed as follows,

$$DETX_l = 1 - \log_2\left(PDR_{n,f}\; PDR_{n,r}\right) = 1 - \log_2(PDR),$$
$$where\; PDR_n = \frac{1}{K}\sum_{k=1}^{K} PDR_{n,k} \tag{5.20}$$

In terms of the reliability concept, we can note that DETX metric has the capability of detecting the reliable links aptly, i.e., burst-loss situation. A reliable link within the wireless multihop networks will be a link with ordered forward and reverse channels as much as possible. Moreover, DETX metric can be considered as a *monotonic* and *isotonic* metric, that's mean It is a usable effectively on both link state and distance vector routing protocols with a good performance and result. Reliability is an important measure ignored in the literature for some reasons. In order to adapt the limited resources into an efficient usage, it can be utilized in path selection algorithms to select the best stable and consistent path from all available paths between any pair of nodes. If the path is stable / reliable, then the load and buffer management will be achieved in a better manner. Moreover, the interference occurrence will be regularly distributed along the main window instead of concentrating on a part of it. The delay due to the MAC layer mechanisms will be reduced by considering the influences of the distribution patterns of each sub-window on the consecutive nodes as it is mentioned in SMETT. Based on the iETT metric concept, the throughput and delivery ratio will be increased by using DETX, because DETX prefers the link in which the sub-window has a good consistency in the distribution of the loss ratios. Thus, the whole performance of the network will be increased [16].

5.5 Overview of MANET

With the great expansion of particularly personal and local networks, the self-organization, cost reduction, adaptability, and independence has become highly desirable. Mobile ad hoc networks (MANETs) are considered as a good solution that responds to these issues in an effective manner. The term MANET has come to be used to describe any ad hoc mobile network since the initiation of an Internet engineering task force (IETF) work group. The concept of MANETs tries to expand the notions of mobility to all parts of the environment. By using a “hopping” technique, the network will depend on the collaboration of all elements of the network in routing. MANET networks are created in a dynamic manner by an autonomous system of mobile nodes. These mobile nodes move in and out of the range of other mobile nodes and connect to each other via wireless links, without the need for an external infrastructure or a centralized administration. MANET networks are distinguished from wired networks by a number of characteristics such as *unpredictable environment*, *unreliable medium*, *limited resources*, and *limited security*. The fundamental advantages of this type of ad hoc network are *robustness*, *rapidly deployed*, *ability to deal with node mobility*, and *flexibility*.

The absence of the routing infrastructure in MANET networks makes their study and developing them is the main interest of many researchers. In general, routing is a method of transmitting data packets to the desired destination across a given network. Routing in a MANET network is based on re-emission of packets by each mobile node allows propagation within the network. The routing problem in MANET lies in calculating the “best” route to join any two given nodes in a network and then choosing the optimal one. A fixed set of rules and metrics must be applied to the routing algorithms such that the problem is transformed into a simple search for the best route from source to destination. Routing protocols in MANET networks can be classified in various ways as we mentioned in CHAPTER 2.

One of these classes is the distance-vector routing protocols. In this type of routing protocols, each mobile node in the network sends data that contain its routing table only to its immediate neighboring nodes to keep the resources by limiting the amount of data exchanged. Data are sent either when an update is triggered by topological modifications or periodically upon expiration of a counter (i.e. timeout). After receiving a neighboring node’s routing table, a mobile node uses the information to update its own routing table. For example, if a mobile node Z sends its routing table to its neighbor Y and an entry in Z’s table indicates that another node X is within two hops of Z, then Y will update its table to show that node X can be reached by Y via node Z in two hops. Another mobile node U, receiving the updated routing table of node Y, and thus U will update its own table to show that it can reach node X via node Y in three hops (unless U already has an available route to X in less than three hops), and so on and so forth. There are several advantages are offered by distance-vector routing protocols including low bandwidth utilization and low demands on the routing node in terms of memory capacity and processing power.

Based on the method used to create and maintain routes, the routing protocols in MANET networks can be classified into proactive and reactive routing protocols. Reactive routing protocols introduce new routing concepts specific to the MANET context. Searching for a route to a destination only in case of need is the basic principle of reactive protocols. Hence, the alternative denomination of reactive routing is “on-demand routing”. Generally, an on-demand routing protocol has two basic mechanisms. The *route discovery mechanism* by which a mobile node may seek a route to a destination, and the *route maintenance mechanism*, through which a mobile node maintains its routes to a destination. At a given moment, a mobile node X may not possess any route to a destination node Y. When X wishes to send traffic to Y, then S starts a path-seeking procedure to find a route to Y by sending a request to other nodes in the network to see if any mobile node possesses a route to Y. Any mobile node in possession of such a route will reply. Node X will then transmit traffic to one of these nodes, which then forwards it on to node Y. In our simulation, we will use AODV routing protocol to transmit the data packets and then trying to evaluate its performance by considering hop count, new definition of ETX and DETX as the metrics.

5.6 AODV Routing Protocol

The AODV protocol is a reactive routing distance vector routing protocol. It has been designed essentially for use in ad hoc networks. AODV is considered as one of the best-known routing protocols, and has attracted a big interest from the scientific community and the researchers in this field. In addition, AODV is currently considered as a standard routing protocol for ad hoc networks. It seeks routes when a source needs to send packets to a certain destination. After the route establishment is occurring between the source and the destination, this route must be maintained for the duration of the communication. The establishment and maintenance of routes are performed by exchanging five types of control messages:

a. Route Request (RREQ),

b. Route Reply (RREP),

c. Route Error (RERR),

d. Route Reply acknowledgment (RREP-ACK), and

e. Hello message.

Table 5.1. Encapsulation of data / message in a network using AODV

MAC header	IP header	UDP header	AODV header	Data / Message

By using an Internet protocol (IP) header, these messages are received via the user datagram protocol (UDP) protocol. Thus, the node uses its IP address as a source IP address in order to send its data / messages, and it uses the IP address (255.255.255.255) for diffusion its data / messages. The encapsulation of data follows the pattern outlined in Table 5.1.

5.6.1 AODV Control Messages and Routing Table Format

In this subsection, we will try to show the format of the AODV control and the routing table. In addition to list the configuration parameters that are used in this protocol.

5.6.1.1 Route Request (RREQ) Message Format

Table 5.2 Route Request (RREQ) message format

Type=1	J	R	G	D	U	Reserved	Hop Count
RREQ ID							
Destination IP address							
Destination Sequence Number							
Originator IP address							
Originator Sequence Number							

where J is the join flag, R is the repair flag, G is the gratuities flag, D is the destination only flag, and U is the unknown sequence number flag. In our simulation, we add a changeable field in order to contain the value of the quality metric.

5.6.1.2 Route Replay (RREP) Message Format

Table 5.3 Route Reply (RREP) message format

Type=2	R	A	Reserved	Prefix Size	Hop count
Destination IP address					
Destination Sequence Number					

Table 5.3 (cont'd)

Originator IP address
Lifetime

where R is repair flag, and A is acknowledge required. In our simulation, we add a changeable field in order to contain the value of the quality metric.

Note that, the Hello control message is a RREP message with TTL equals to 1. However, in our simulation, another field is added to the Hello message that conveys the probability delivery ratio value for the last time window.

5.6.1.3 Route Error (RERR) Message Format

Table 5.4 Route Error (RERR) message format

Type=3	N	Reserved	Descount
Unreachable Destination IP address (1)			
Unreachable Destination Sequence Number (1)			
Additional Unreachable Destination IP address (2)			
Additional Unreachable Destination IP address (2)			
....			

Where N is the no delete flag, and Descount is the number of unreachable destinations.

5.6.1.4 Route Reply Acknowledgement (RREP-ACK) Message

Table 5.5 Route Reply Acknowledgment message format

Type = 3	Reserved

5.6.1.5 Routing Table Format

Table 5.6 Routing Table format

Destination IP address	Dest. Seq. no.	Valid Dest. Seq. no.	Valid	Invalid	Repairable	Repaired	Network Interface	Hop Count	Next Hop	List of Precursor	Lifetime

In our simulation, we add another field to the AODV routing table. This field contains the total value of the quality metric for each route.

5.6.1.6 Configuration Parameters

The default AODV configuration parameters are shown in Table 5.6 as follows.

Table 5.7 AODV configuration Parameters

Parameter name	Value
ACTIVE_ROUTE_TIMEOUT	3 milliseconds
ALLOWED_HELLO_LOSS	2
BLACKLIST_TIMEOUT	RREQ_RETRIES NET_TRAVERSAL_TIME
DELETE_PERIOD	K max(ACTIVEROUTE_TIMEOUT, HELLO_INTERVAL), where K=5
HELLO_INTERVAL	1 millisecond
LOCAL_ADD_TTL	2
MAX_REPAIR_TTL	0.3 NET_DIAMETER
MIN_REPAIR_TTL	Last known hop count to the destination
MY_ROUTE_TIMEOUT	2 ACTIVE_ROUTE_TIMEOUT
NET_DIAMETER	35
NET_TRAVERAL_TIME	2 NODE_TRAVERSAL_TIME NET_DIAMETER
NEXT_HOP_WAIT	NODE_TRAVERSAL_TIME + 10
NODE_TRAVERSAL_TIME	40 milliseconds
PATH_DISCOVERY_TIME	2 NET_TRAVERSAL_TIME
RERR_RATELIMITE	10
RING_TRAVERSAL_TIME	2 NODETRAVERSAL_TIME (TTL_VALUE + TIMEOUT_BUFFER)
RREQ_RETRIES	2
RREQ_RATELIMIT	10
TIMEOUT_BUFFER	2

Table 5.7 (cont'd)

TTL_START	1
TTL_THRESHOLD	7
TTL_VALUE	The value of TTL field in IP header while the expanding ring search
WINDOW_TIME	20

5.6.2 Route Establishment

It involves all the processes by which the route is set out from source to destination. These processes are detailed as follows.

5.6.2.1 Path Discovery

The path discovery process is run when a source node wishes to communicate with a certain destination node and

a. The destination node is unknown to the source node, or

b. The previous valid route to that destination is expired, or

c. The previous valid route to that destination is marked as invalid.

Based on one of these conditions, the source node generates a RREQ message and disseminate it over whole network. The source node will fill the RREQ fields as follow

1. Copy the last destination sequence in route table entry into the corresponding field in RREQ. If the destination sequence number is unknown, the source node will set the U flag in RREQ.
2. Increment the originator sequence number by one and adding it to the corresponding field in RREQ.
3. Increment last RREQ ID by one and adding it to the corresponding field in RREQ.

   Set hop count to zero.
4. In our simulation, the originator node sets the field of link quality to zero.

Now, the originator node connects the RREQ ID with the originator IP address to the timer called PATH_DISCOVERY_TIME and thus it will reject any RREQ message comes back to it if this RREQ message has the same RREQ ID and the originator IP address. An originating node often expects to have bidirectional communications with a desired destination node. Therefore, it is important that the originating node to have a route to the desired destination node in addition the desired destination must also have a route back to the originating node. In order for this to happen, the originator node will set the flag G in order to tell any generation of a RREP by an intermediate node that it has to notify the destination about a route back to the originating node.

After broadcasting the RREQ message, the originator node will wait for NET_TRAVERSAL_TIME milliseconds in order to receive the RREP message. If the originator does not receive RREP message during this period of time, the originator node will rebroadcast another RREQ but based on the following conditions:

a. It should not rebroadcast the RREQ message more than RREQ_RETRIES times.
b. It should not rebroadcast the RREQ message more than RREQ_RATELIMIT per second.
c. It should increment the RREQ ID for each rebroadcasting.
d. The originator node may follow a ring search mechanism to broadcast the RREQ message in order to determine how far the RREQ message must be disseminated.
e. The time period between the process of rebroadcasting RREQ messages is controlled by the exponential backoff time as follows

$$2^n \text{ NET\_TRAVERSAL\_TIME}$$

Where n = 1, 2, 3…, RREQ_RETRIES.

After broadcasting the RREQ message, the data packet will wait in FIFO queue until the REP message coming. If there is no RREP message coming, the data packet will be dropped and Destination Unreachable Message will send to the application layer in the node.

5.6.2.1.1 Expanding Ring Search Technique

To prevent unnecessary network-wide dissemination, originator node can limit the dissemination diameter by setting different values of the TTL field in IP header of RREQ message. This technique called Expanding Ring technique. By using this technique, the originator node will disseminat the RREQ message as follows:

1. At the beginning, the originator node set the TTL field to TTL_START and then it waits for a RING_TRAVERSAL_TIME period in order to receive the RREP message.
2. If the originator node did not receive the REPP message during this period, it will rebroadcast a new RREQ message. In this case, the originator increases the TTL field by TTL_INCREMENT and wait for the same period above. The originator node continues rebroadcasting new RREQ messages until the TTL field value equals to TTL_THRESHOLD.
3. If the originator node also did not receive RREP massage, it will rebroadcast new RREQ messages with the TTL field equals to NET_DIAMETER and waiting for a NET_TRAVERSAL_TIME. This rebroadcasting process continues until the RREQ_RETRIES.

It is worth mentioning that if there exists an invalid route was recorded in the originator routing table to that destination node, the originator will use the value of hop count field as the initiated value for TTL instead of the TTL_START.

5.6.2.2 Processing and Forwarding RREQ Message

When the RREQ message arrives to any intermediate node in a network, the intermediate node will check this RREQ message to be sure if it has already received this RREQ message within the PATH_DISCOVERY_TIME or not. If it is the first time the intermediate node receives this RREQ message, the intermediate node should process this message then forwards it to its neighbors if needed. The processing of RREQ message results in creating or updating the reverse route to the originator node. The creating or updating is performed as follows:

A. If the destination IP address in any routing entry of the intermediate node routing table does not equal to the originator IP address of the RREQ message, the intermediate node will create a new routing entry and fills its field as follows:

   1. Destination IP address in the reverse route entry equals to the originator IP address in the RREQ message,
   2. Destination sequence number in the reverse route entry equals to the originator sequence number in the RREQ message,

3. Set the valid destination sequence number in the reverse route entry to be a true,
4. Network interface in reverse route entry equals to the intermediate node's interface that received the RREQ message,
5. Hop count in reverse route entry equals to the hop count in the RREQ message,
6. Next hop in reverse route entry equals to the IP address in the IP header of the source node (the neighbors that transmitted the RREQ message),
7. Lifetime in reverse route entry equals to the maximum of (existinglifetime, minimallifetime), and
8. In our simulation, the quality metric in the reverse route entry equals to the sum of the current value of the quality metric in the reverse route entry and the quality metric value in the RREQ message that is represented the quality metric of the previous link, i.e. the link between the source node and its neighbor that transmitted the RREQ message to it. The value of a quality metrics (ETX or a new definition of ETX or DETX) is calculated as explained in section 5.2.

B. If the destination IP address in any routing entry of the intermediate node equals to the originator IP address of the RREQ message, the intermediate node will update the current revers route entry as follows:
    1. Comparing the originator sequence number in the RREQ message to the corresponding destination sequence number in the reverse route entry and copied if greater than the existing value there.
    2. Following the same procedure in A from the point 2 until 8.

If the node already received this RREQ message within the PATH_DISCOVERY_TIME, the node will silently discard this message.

For forwarding the RREQ message, the intermediate node will search in its routing table entries to find any route entry in which the destination IP address equals to that destination IP address in RREQ message. Based on the result of the searching process the intermediate node will follow the conditions and steps below:

A. If the searching result is empty and TTL is larger than 1, the intermediate node will rebroadcast the RREQ message after filling its fields as follows:

   1. The source IP address equals to the intermediate node IP address, and receiver IP address equals to 255.255.255.255,

   2. Increment the hop count and decrement the TTL value,

   3. If the destination sequence number in the routing entry is larger than to the destination sequence number of the received RREQ message, the node will change this field to its value, otherwise it does not change it.

   4. In our simulation, the intermediate node will change the quality metric value from its entry route to the corresponding field in the RREQ message.

B. When the value of the destination IP address field in the RREQ message equals to the value of the destination IP address in a valid forward routing entry, the node will compare the destination sequence number of the forward route entry to that destination sequence number in the RREQ message. If the value is larger, the intermediate node will reply by generating a RREP message and then tells the destination node about the reverse route by sending a unicast RREQ message to it. Otherwise, the intermediate node follows the steps in A above.

5.6.2.3 Generating Route Reply (RREP) Message

There are two nodes in the network that are responsible for generating the RREP message. The first one is the destination node itself. The other is the intermediate node that has an active route to the destination. After receiving the RREQ message, the procedure for generating the RREP message is different based on the node type.

A- The receiving node is the destination itself: when the destination node receives the RREQ messages, it will process these messages for creating or updating the reverse route to the originator as we mentioned in 5.4.2.2, but it does not rebroadcast them. It chooses the best reverse route (minimum hop count and quality metric values) among the RREQ messages arriving during that time. Then, it will generate the RREP message by following the procedures below:

   1. Making the hop count equals to zero,

   2. Copy its IP address and put it into the corresponding field in RREP,

3. Copy the originator IP address from the RREQ and put it into the corresponding field in RREP,
4. The destination node increases its sequence number, then checks if its sequence number equals to that in RREQ. If the sequence after incrementing equals to that in RREQ, the destination inserts it to the RREP message. Otherwise, it inserts its sequence number before the incrementing,
5. Set the lifetime to MY_ROUTE_TIME,
6. In our simulation, the quality metric field will be set to zero, and
7. Unicasting the RREP to the next hop node in the reverse route entry.

B- Receiving node is the intermediate node with active forward route to the destination node: when the intermediate node receives the RREQ, it will search in its routing table to find any active forward route entry in which the destination IP address equals to that in the RREQ. If the intermediate node finds this IP address, it will compare the value of the destination sequence number in the RREQ with that in this forward route entry. When the sequence number in the active forward route entry is less than the sequence number in the RREQ or the D flag is set to one, the intermediate node will follow the procedures in 5.4.2.2. Otherwise, the intermediate node will perform three procedures: *Updating the forward and reverse routes*, *generating and unicasting the RREP*, and *unicasting gratuitous RREP to the destination*.

i. Updating the forward and reverse rotes: after receiving the RREQ, the intermediate node updates the reverse route to the originator as we mentioned in 5.4.2.2 with the information that got it from the RREQ. In addition, it will copy the next hop field in the forward route to the precursor list in the reverse route entry. In this case, the intermediate node will not broadcast the RREQ to its neighbors. For the forward route entry, the intermediate node will copy the source IP address from the IP header in RREQ and putting it to the list of precursor field in this forward route entry.

ii. Generating and unicasting the RREP: the intermediate node follows the same procedures in A except,

1. Hop count field in the RREP equals to the summation of the hop count in the RREQ and the value of the hop count in the forward route to the desired destination, and
2. In our simulation, the value of a quality metric field in the RREP equals to that existing in the forward route entry to the desired destination.

After generating the RREP message, the intermediate node will unicast it to the next hop in the reverse route entry to the originator node.

iii. Generating gratuitous RREP to the destination: if the G flag in the RREQ that is received by the intermediate node is set to one, the intermediate node should unicast a gratuitous RREP to the desired destination and filling its fields as follows,

1. Hop count field equals to that existing in the reverse route entry,
2. The destination IP address equals to the originator IP address in the RREQ,
3. The destination sequence number equals to the originator sequence number in the RREQ,
4. The originator IP address equals to the IP address of the desired destination,
5. The lifetime field equals to the remaining lifetime of the reverse route entry, and
6. In our simulation, the quality metric field equals to that existing in the reverse route entry.

Note that, when the gratuitous RREP reaches to the desired destination, the desired destination will update the reverse route entry and then unicast RREP to the originator.

5.6.2.4 Receiving and Forwarding Route Reply

When the node receives the RREP message, it will perform tow procedures: *creating or updating route entries*, and then *unicast the RREP message*.

A- Creating or updating route entries: after receiving the RREP message, the node will search in its routing table in order to see if there exists any route entry in which the next hop field contains the IP address of the source node (i.e., the node that currently transmits the RREP message) and the destination IP address from RREP equals to its destination sequence number field. If the node does not find like this route entry into its routing table, it will create a new forward route entry and filling it as follows,

1. Destination IP address field equals to the destination IP address field in the RREP message,
2. Destination sequence number field equals to the destination sequence number field in the RREP message,
3. The valid destination sequence number flag equals to false (i.e., invalid),
4. Network interface equals to the node's interface that received the RREP message,
5. Hop count field equals the hop count field in the RREP message,
6. Next hop field equals to the source node IP address from which the RREP message was transmitted,
7. The lifetime field equals to the sum of current time and the value of lifetime field in the RREP massage, and
8. In our simulation, the link quality metric field equals to the link quality metric in the RREP message.

If the node finds a route entry in which the next hop field equals to the source node IP address from which the RREP message was transmitted and the destination IP address from REEP equals to its destination sequence number field, the node will update this forward route entry based on four conditions:

a. The destination sequence number in the routing table is invalid,
b. The destination sequence number in the routing table is valid, but it is smaller than the destination sequence number in the RREP message,
c. The destination sequence number is valid and it is similar to the destination sequence number in the RREP message, but the forward route entry is inactive.

d. The same destination sequence number with valid forward route entry, but the hop count or the quality metric is smaller than that existing in the RREP message.

If one of the above conditions was achieved, the node will update the forward and reverse route entries by following the same procedure that we mentioned in the creating route entry except:

1. Set the valid destination sequence number to be a true,
2. Searching in the routing table to find the reverse entry in which the originator IP address equals to originator IP address in the RREP message. After finding this entry, the node will update its lifetime to be equal to the maximum of (current time + ACTIVE_ROUTE_TIMEOUT, existing lifetime). In addition, it will copy its next hop and put it in the precursor list on the forward route entry.
3. In our simulation, the quality metric should equal to the summation of the quality metric in the RREP and the current quality metric in the forward route entry.

After creating or updating process, the node will unicast the RREP message to the next hop node based on the reverse route entry. If a node forwards a RREP message over a link that is likely to have errors or be unidirectional, the node should set the 'A' flag to tell the recipient of the RREP that it waits a RREP-ACK message to send back to it.

Accordingly, the RREP messages will reach to the originator node if there is no link breakage. When the originator receives these messages, it will process them in order to create or update the forward route entries. Based on our simulation, the originator will wait for a period of time, then it compares among the forward route information that is contained in the RREP messages in order to select the best one, i.e. the one with minimum value of the quality metric and hop count.

5.6.2.5 Unidirectional Link Problem

In AODV routing protocol, the node only responds to the first RREQ message that is received and it ignores the other same RREQ messages during a specific period of time. This mechanism causes some problems, especially when the RREQ led to trigger RREP message over a unidirectional link while there exist other bidirectional route between the originator and the destination. In this case, the next hop node will not receive the RREP message and the node itself will not receive RREP-ACK message. Therefore, the originator will reattempt route discovery after a timeout, if no other RREP generated from the previous route discover attempt. However, the same scenario might well be repeated without any improvement until the number of route discovery attempt reaches the threshold.

To solve this problem, the node puts any next hop node (neighbor node) in the reverse route that failed to receive the RREP message in the Blacklist set. Then, the node will reject any message from these nodes during the BLACKLIST_TIMEOUT. In this case, another RREQ message coming over a bidirectional link will be given a good opportunity to trigger the RREP message.

5.6.3 Maintaining Local Connectivity

In AODV routing protocol, the node maintains the local connectivity by checking whether it has sent a broadcast (e.g., RREQ or an appropriate link layer message) within the last HELOO_INTERVAL. If it has not, the node will broadcast the Hello message. The Hello message is a RREP message with the following fields' values:

1. TTL of the IP header equals to one,
2. Destination IP address equals to the node's IP address,
3. Destination sequence number equals to the node's latest sequence number,
4. Hop count equals to zero, and
5. Lifetime equals to the product of ALLOWED_HELLO_LOSS and HELLO_INTERVAL.

The node determines the connectivity to its neighbors by listening to the Hello messages that are emitted from them. For each neighbor, if the node has received a Hello message within the past DELET_PERIOD, and then for that neighbor does not receive any (Hello message or otherwise) more than (ALLOWED_HELLO_LOSS multiplied by HELLO_INTERVAL), the node will assume the link to this neighbor is currently lost. In this case, the node will follow the procedures as we will mention in 5.4.4.

After the node broadcasted the hello message, it will be received by its set of neighbors. Each neighbor node will check its routing table to be sure if it has an active route to this node or not. If the neighbor node has an active route to the node, it updates the lifetime field of this route entry by making it equals to the product of ALLOWED_HELLO_LOSS and HELLO_INTERVAL. Otherwise, the neighbor node will create a new route entry and fills its fields with the information of the corresponding fields in the Hello message.

In is worth to mention that the Hello message will modified to convey the fresh delivery ratio from the each node to its set of the neighboring nodes. By using the received delivery ratio (i.e., forward delivery ratio) and using the delivery ratio that is calculated by the node (i.e., reverse delivery ratio), each node will be able to calculate the quality metric (i.e. ETX, the new definition of ETX, and DETX) for this link in order to fill the quality metric field of the route entry.

5.6.4 Processing Of Link Loss

When the node loses the links to its neighboring nodes or active next hop and precursor nodes, the node will perform either the route error (RERR) and link breakage process or the route repairing process.

5.6.4.1 Route Error (RERR) and Link Breakage Processing

A forwarding node (i.e., the node within an active route to desired destination) initiates processing for a RERR message processing in three situations:

A- It detects a link break for the next hop of an active route in its routing table while it tries to transmit data and the repairing of the route, if attempted, was unsuccessful. In this case, the forwarding node will perform the following procedures:

1. Determining all route entries from its routing table in which the next hop is the unreachable neighbor node,
2. Adding the destination IP address of these route entries to the corresponding fields in a RERR message,
3. Increasing the destination sequence number of these route entries and adding them to the corresponding fields in a RERR message,

4. Set the number of these route entries in the Destcount field in a REER message, and
5. Unicast or iteratively unicast the REER message to all nodes in the precursor list of these route entries.

B- It gets a data packet that is destined to a node for which the forwarding node does not have an active route and is not repaired. In this case, the forwarding node will perform the same procedures in A, but the procedures will be performed for only one route entry that contains the IP address of the desired destination node.

C- It receives a RERR message from its neighbor node of one or more active route. In this case, the forwarding node will perform the following procedures:

1- Determining all route entries from its routing table in which the next hop equals to the source IP address from the IP header in RERR message,

2- Determining all destination IP addresses from these route entries that equal the destination IP addresses in the RERR message and then adding them to the corresponding fields in a new RERR message,

3- copy the destination sequence number of these destinations from the receiving RERR message into the destination sequence number fields in a new RERR message,

4- Set the number of these matching destination node in the Destcount field of the new RERR message, and

5- Unicast or iteratively unicast the new REER message to all nodes in the precursor list of these route entries.

5.6.5 Local Repair

When a link in an active route is broken, a forwarding node may try to repair it. The repair of this link is acceptable if the distance between the forwarding node and the destination is smaller than a fixed maximum number of hops that is called a MAX_REPAIR_TTL. This value of TTL will make the RREQ message is invisible to the originator node. After determining the route entry of this broken active route, the forwarding node raises the sequence number of the destination and buffering the data packet coming to this destination. Moreover, it disseminates the RREQ message toward this destination in order to repair this active route.

If the forwarding node does not receive any respond during the route discovery timeout, the forwarding node will generate and disseminates a RERR message. If the forwarding node receives one or more RREP message with the same value of metric (hop count and quality metric) to the desired destination, it will process this RREP message and then forwarding it. Otherwise, if the forwarding node receives a RREP message with different value of metric (hop count and quality metric) to the desired destination, it will generate a RERR message to indicate to the other nodes that the route containing the defective link should not be deleted, then updates its routing table, replacing the old broken route with a new one, and forwarding the data packet in the buffer.

If there exist more than one destination are unreachable because of the broken link, the forwarding node will repair only the routes that it received the data packets over them. However, if there is no congestion on the network, the forwarding node will repair all routes that are affected by the breakage.

5.6.6 Simulation Results and Discussion

Currently there exist several network simulation programs, of which OPNET and Network Simulator (NS) are the well-known. OPNET has very user-friend interface and it is simple to use. However, OPNET is not in open access. The only available version is the IT Guru version that is very limited from a simulation point of view. For this reason, we have chosen Network Simulator version 2 (NS2) to run our simulation.

NS2 was developed by the VIT research group at the University of Berkeley. It deals with the node mobility, the realistic physical layer that includes propagation models and a MAC layer with IEEE 802.11 interface, using the distributed coordination function IDCF) to control the access of the channel. NS2 considers the extenuation of the signal, propagation delays, and collisions.

The Network Simulator version 2 (NS2) uses the object-oriented language OTCL to describe simulations parameters and conditions. By using this language, the user supplies the network topology, the protocol being used, the characteristics of the physical layer, the type of traffic generated by the sources, etc. for increasing the calculating power, the basic script in NS2 is written in C++. There are a large number of classes are predefined and implemented several types of routing algorithms, waiting list, sources and protocols in this simulation program. By using NS2, the text files are produced that contains all events of the simulation model. The required information are extracted by treatment these text files. Moreover, NS2 includes the network animator (NAM) graphics interface. NAM enable the visualization of simulation model by processing the animation file that is created by the simulator. The visualizer in NAM provides a visual representation of the network map, through which we can observe monitoring queue, packets circulating, etc.

The NS2 simulator has become a reference standard and it implements certain ad hoc protocols, including DSDV, DSR, and AODV.

5.6.6.1 Configuration of Simulation Model

To evaluate the performance of the metrics, we used NS2 simulator. We compared three metrics: hop count, new definition of ETX (ENTROPY-BASED ETX), and DETX in terms of delivery ratio, average packet delay, and throughput over a simulation time equals to 100sec. The simulation was performed on a 1000m multiplied by 500m field of 25 nodes as shown in figure 5.8. Each node is provided with omnidirectional antenna (OmniAntenna), which conforms to IEEE 802.11. Thus, each node has a range of 250m in the absence of obstacles, and a nominal bandwidth of 20Mbps. The two-ray ground model is the radio propagation model that is used in our simulation.

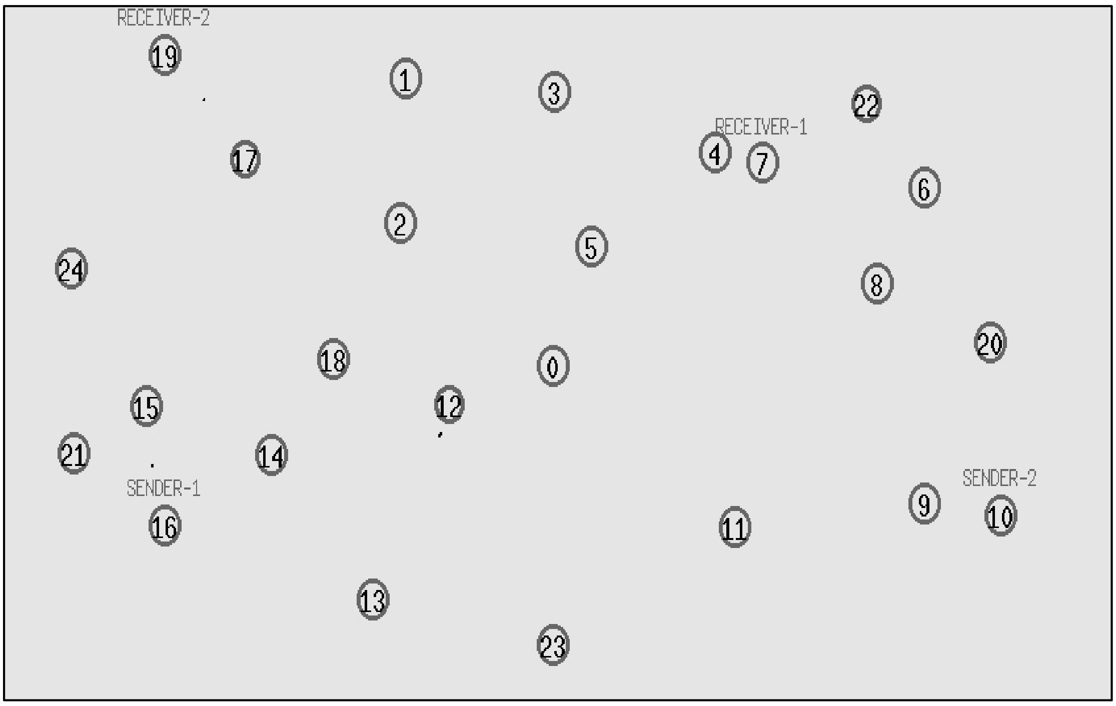


Figure 5.8 Simulation Field With 25 Nodes

Nodes exchange probe packets after being initiated and uses a CBR traffic as source traffic. These traffic sources modelize the application layer and are located on the UDP transport agent. Each source sends out packets with a size 512 bytes. In our simulation, each node has a priority queue with a maximum capacity of 50 packets, which gives priority to routing protocol packets. In our simulation, the mobility model used is a Random Waypoint model with a maximum speed equals to 25m/s. The nodes are initially placed at random position except the senders and receivers, which initial with fixed positions at the edge of simulation area and in the opposite direction. The aim of the residence the senders and receivers at the edge is to make the control message and data packet circulate over a largest possible number of intermediate nodes. It's worth noting that all results of our simulation are the cumulative results of these two senders and receivers.

Established links should be as reliable as possible to avoid data packet loss and thus decreasing in throughput and increasing in delay. This means that the maintaining and sensing the link should be robust against burst loss or the transient connectivity between nodes in a network. A link state routing protocol such as OLSR [69] tries to detect the transient connectivity among the nodes by using the link hysteresis techniques. However, the hysteresis technique provides a more robust link sensing at the cost of more delay before establishing links. For the distance vector routing protocols such as AODV, there is no technique is used to provide a robust links. Even if the AODV concerns the link quality by using the ETX metric instead of hop count metric, it will remain unable to capture the transient connectivity.

By using the dynamic ETX (DETX), the AODV routing protocol become able to capturing these links with the node passing at high speed or a node that alternates between residing just outside and just inside radio range. DETX metric enables AODV routing protocol from detecting the distribution pattern of receiving probe packets over a time window and increases the quality metric value for these links that has irregular distribution even if these links has the same ETX. Our simulation improves the validity of the new definition of ETX metric and its ability to provide high performance over the hop count metric. In addition, it shows the ability of DETX metric to establish the robust routes between sender and receiver, and thus providing a higher performance more than the performance of the hop count and entropy-based ETX metrics.

One of the main purposes of all routing protocols is to offer guarantees to application concerning the time taken to transfer data packets from source to destination. Thus, we first evaluate the delay parameter for the AODV protocol with: hop count, entropy-based ETX, and DETX metrics and compare the results. Indeed, the delay parameter gives the average time necessary to transfer a packet from source node to destination and it is calculated as follows:

$$Average\ Delay = \frac{\sum[\ T_D(i) - T_S(i)\ ]}{\sum packets\ received} \tag{5.21}$$

where $T_D(i)$ denotes the instant when the packet i is received by the destination transport agent, and $T_S(i)$ denotes the instance when data packet i is sent by the source transport agent. Effectively, the more spread out the nodes are, the lower the possibility of finding a route.

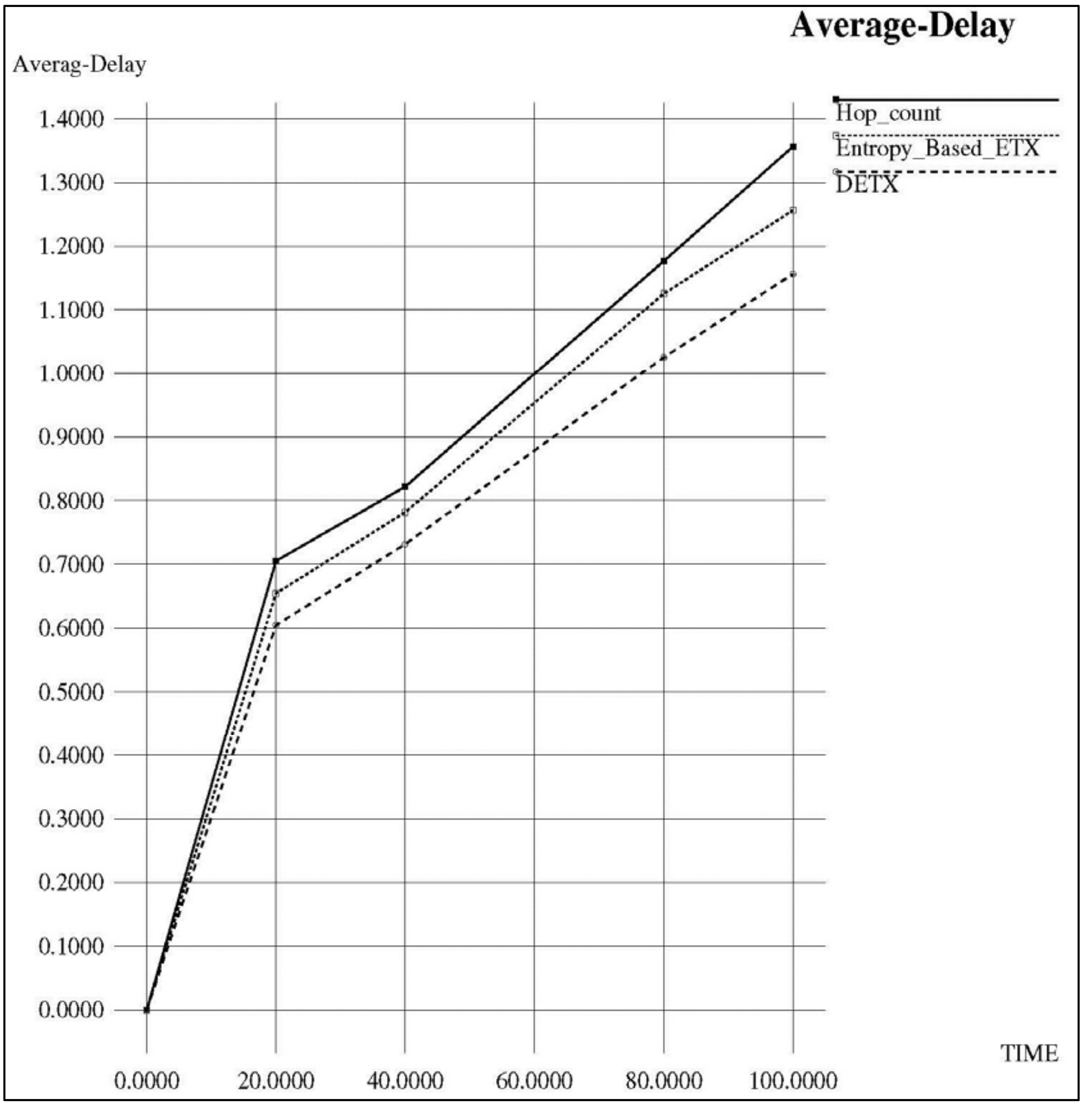


Figure 5.9 Average Delay

We can note from the figure 5.9 that the average delays in these three metrics are close to each other until the seconds 20. When the nodes begin to move a far from each other and the possibility of establishing a robust route is decreased, the average delay will increase in hop count and entropy-based ETX metrics more than the DETX metric. The main reason behind that is their selection of the links with lowest reliability, which therefore result to need of an additional time for launching a new route discovery and retransmission loss packets. After 80 seconds, the delay of hop count begins to increase more and more than the other two metrics because the distance among the nodes will be increased; and thus the hop count metric will select the smallest route even if with lower quality and reliability.

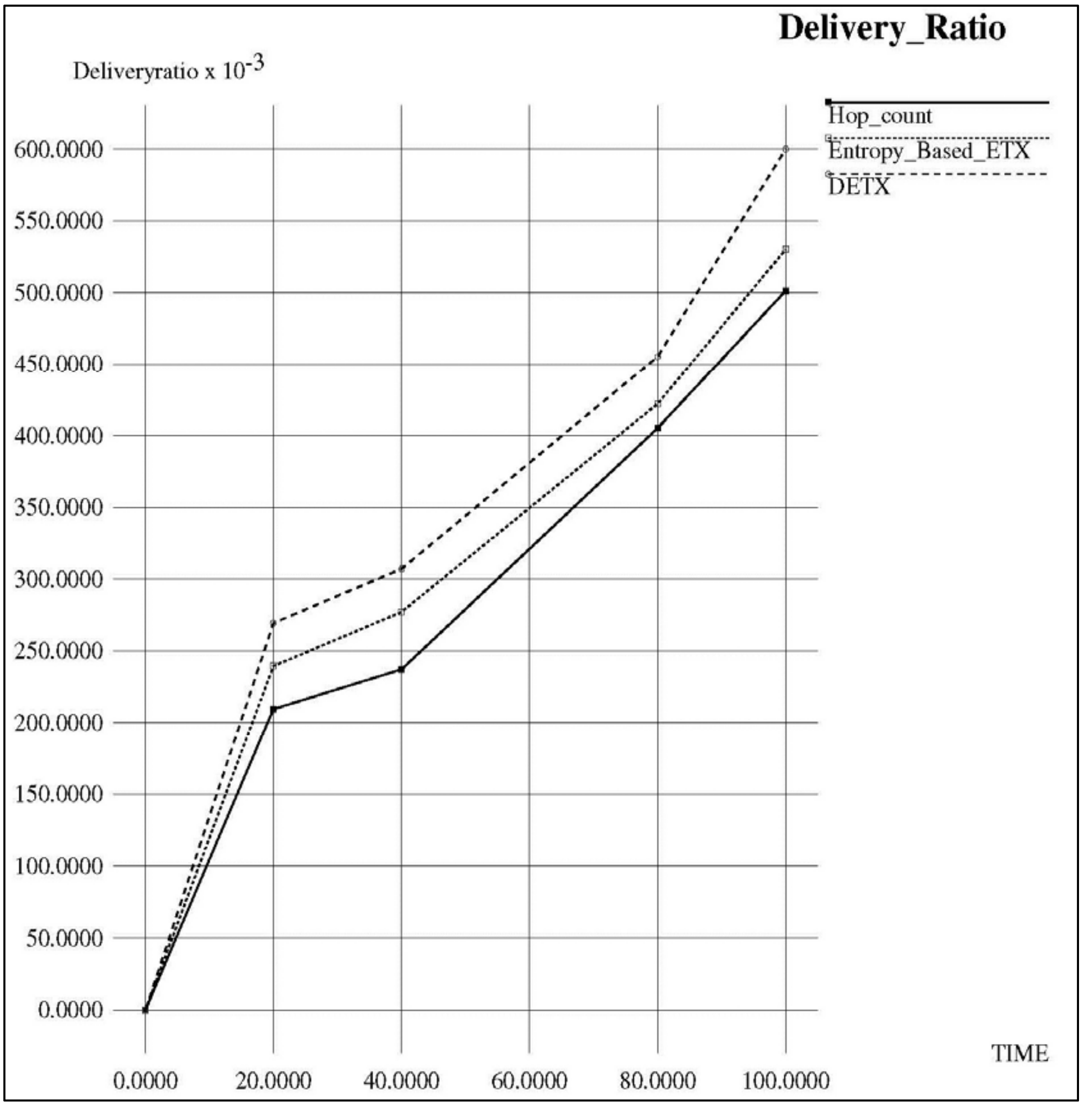


Figure 5.10 Delivery Ratio

It is very important to consider the capacity of the routing protocol to transmit data packets from the source to the desired destination node, when we want to evaluate the performance of this protocol. The packet delivery ratio is the percentage of packets that are sent over the network and they are successfully delivered to the desired destination. The packet delivery ratio is calculated as follows:

$$packet\ delivery\ ratio = \frac{\sum packets\ received}{packets\ sent}\ 100\% \tag{5.22}$$

The packet delivery ratio is the measurement used to prove the reliability of a protocol. As illustrated in figure 5.10, we can note that the validity of our new definition of ETX that provides a high delivery ratio than the hop count metric. The routing protocol with hop count metric implicitly assumes that links either work well or do not work at all. This approach is not a reasonable approximation in the wireless ad hoc networks. Indeed, minimizing the hop count maximizes the distance traveled by each hop, which is likely to maximize the collision and thus reduction in delivery ratio.

By taking the link reliability in our account, we can note that the delivery ratio of the DETX metric is larger than the other two metrics because of its ability of establishing high reliable routes. After 80 seconds, the delivery ratio of entropy-based ETX and DETX is increased more than in the hop count metric. At this time, the network topology is changed and many of the routes were broken that results in increasing the length routes from source to destination based on hop count metric. This has the effect of increasing propagation time for control messages between the moment the link breaks and the moment the source node is informed of the fact.

For the same reasons we mentioned before, we can note that the throughput of the DETX metric is a higher than the entropy-based ETX and hop count metrics as shown in figure 5.11. Throughput is the number of successfully received packets in a unit time. DETX prefers the link that involves forward and reverse channels have a good consistency in the distribution of loss ratio and delivery ratio over the main time window. This consistency will help in improving the network performance as the SMETT, iETT, and mETX mentioned before. For entropy-based ETX, the metric will not be able to detect the differences between the patterns of delivery ratios, and thus it will select the link only with high quality without consideration of the reliability. The hop-count always select the shortest path even if this path is in very bad situation.

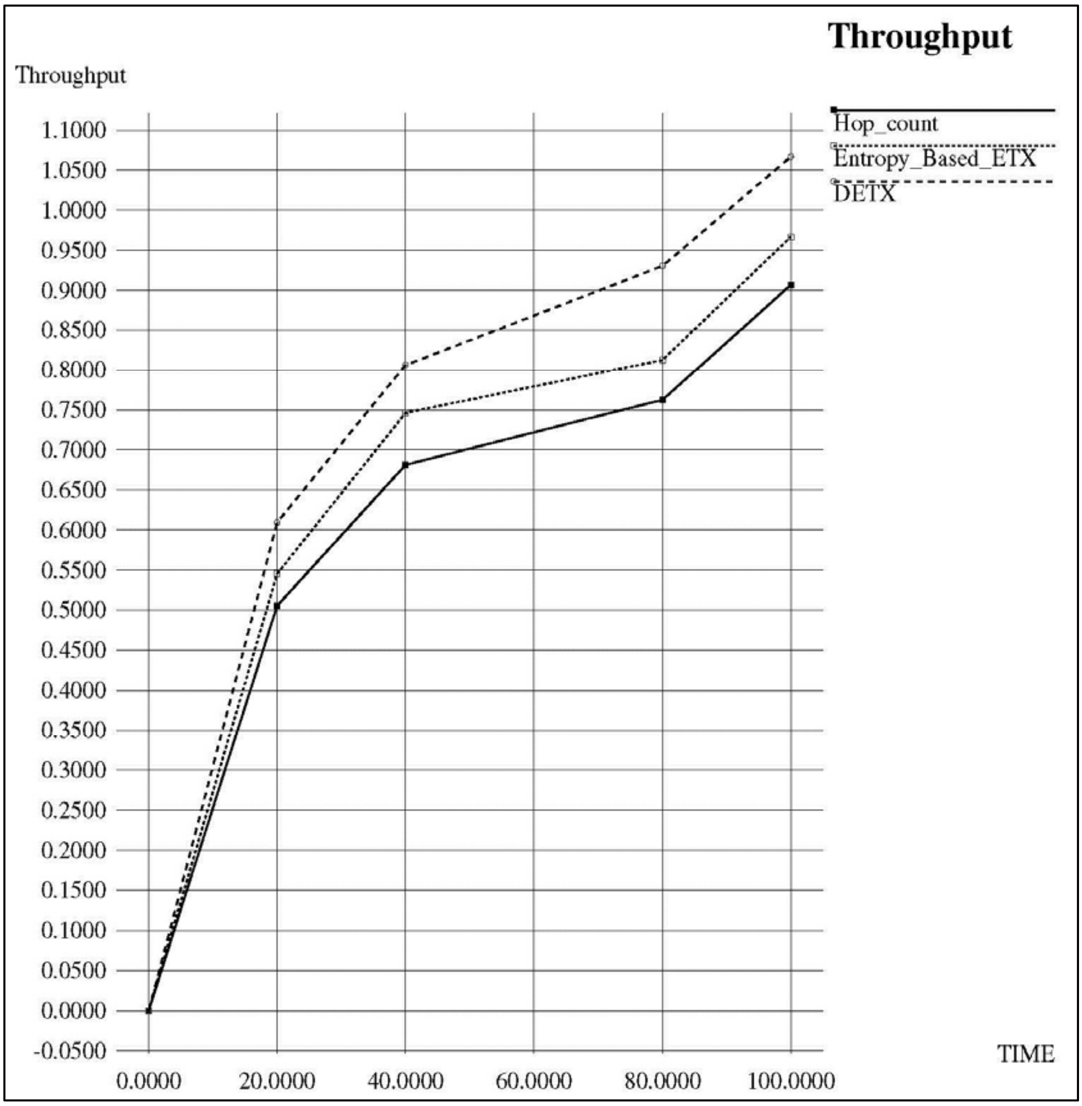


Figure 5.11 Throughput

5.7 Conclusion and Future Work

With recent technological developments in the field of wireless communications and the emergence of portable computing devices such as laptops, and smart phones, researchers have turned their attention to improving the functionality of wireless multihop networks and ensuring rapid access to information independent of time or place. There exist many types of wireless multihop networks such as mesh networks, wireless networks, and ad hoc networks. Wireless ad hoc networks are considerably more dynamic in nature than wired networks. This is particularly true in the case of mobile networks, i.e. MANETs. In such networks, the nodes are able to move in and out of the range of other nodes, and thus connections within the wireless ad hoc network can be cut and others can form. The principle advantages of this type of wireless network are its rapid deployment, robustness, flexibility, ability to deal with node mobility.

The main contribution in the performance of wireless ad hoc networks comes from networking protocols. The primary purpose of wireless ad hoc network routing protocols is to implement a correct and efficient route establishment between a pair of wireless nodes so that information could be delivered in a timely manner. There are number of routing protocols currently available in wireless ad hoc networks which have been designed and classified depending on different criteria. The routing protocols in wireless ad hoc networks can be classified based on the ways to build routing tables, node role information, message transmission awareness, energy awareness, and location awareness.

The main problem in the work of routing protocols lies in the choice of an optimal route. This essentially comes down to calculating the "best" route to join any two given nodes in a wireless ad hoc network. The key factor for getting an optimal path is the use of effective routing metrics in the computation routing algorithms. The measurements that are acquired from the networks can be considered the main parameters in the design of routing metrics. Indeed, it is important to analyze these measurements to get a good knowledge about how the routing metrics are implemented in practice. There are various methods for obtaining the measurements that we need such as passive monitoring, piggy-back probing, and active probing. The traffic based measurements, topology based measurements, radio related measurements, geography based measurements, and energy based measurements should be taken into our consideration in the design and utilization of routing metrics.

The design of effective routing protocols depends on the metrics that is used by their algorithms in order to weigh the discovered routes. The routing metrics for wireless ad hoc networks have followed four main trends: basic metrics, interference-aware metrics, load-aware metrics and hybrid metrics. The expected transmission count (ETX) metric is one of the popular metric that takes into account the link quality in order to weigh the routes links. The value of ETX metric depends on the forward and reverse probability delivery ratios. In fact, ETX metric has been improved in intuitive manner.

The main contribution of this work is a simple way to redefine the ETX metric in mathematical manner and then used it in the definition of our new metric that is called dynamic ETX (DETX). Our definition of ETX depends on the entropy concept. By taking the ratio of the total information about the transmission to the portion of information about the failed transmission. This ratio approximately equals to$1 - \log_2(PDR)$. It is worth mentioning that the bits that is used to keep the entropy-based ETX metric value is usually less than that used in the old ETX value. Indeed, the new definition of ETX metric is valid and give us higher results than the hop count metric based on our simulation.

Established links should be as reliable as possible to avoid data packet loss and thus decreasing in throughput and increasing in delay. Based on a predefined threshold, we divide the main time window into groups of sub-windows. These sub-windows has different time length and a certain delivery ratio under the threshold value. Then, we use the average of the deliver ratios of these sub-windows to calculate the forward and reverse delivery ratios. Then, by using the logarithmic definition of ETX, we calculate the value of DETX for each link. DETX metric has the ability to capture these links with the node passing at high speed or a node that alternates between residing just outside and just inside radio range. DETX metric enables the routing protocol from detecting the distribution pattern of receiving probe packets over a time window and increases the quality metric value of these links that has irregular distribution even if these links has the same ETX. Our simulation improves the ability of DETX metric to establish the robust routes between sender and receiver, and thus providing a higher performance more than the performance of the hop count and entropy-based ETX metrics.

For the future, we hope to use the DETX metric in addition to the hysteresis technique in order to improve the link state routing protocols such as OLSR. We think that by using our metric with this technique in addition to position estimation technique of the mobility nodes, the link state routing protocols will be able to select a high quality and reliable routes. We also hope that this future work will provide a high network performance, especially for the flying ad hoc networks (FANETs) that is involved nodes with a high mobility and connect to each other by high variability links.

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