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NETWORK TOMOGRAPHY APPLICATION IN MOBILE AD-HOC NETWORKS

By

Mohammad Shoeb Saeed Khan
B.Sc., Univeristy of Leicester, Leicester, England, 2000
M.A., University of Missouri,2002
M.A., Univerisity of Montana, 2005
M.Sc., University of Louisville, 2011

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Doctor of Philosophy

Department of Computer Engineering and Computer Sciences
University of Louisville
Louisville, Kentucky

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A Dissertation Approved On

July 29, 2013

by the following Dissertation Committee

Dr. Anup Kumar - Dissertation Director

Dr. Ahmed Desoky

Dr. Rammohan Ragade

Dr. Ming Ouyang

Dr. Suraj Alexander

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ABSTRACT

NETWORK TOMOGRAPHY APPLICATION IN MOBILE AD-HOC NETWORKS

Mohammad Shoeb Saeed Khan

July 29, 2013

The memorability of mobile ad-hoc network (MANET) is the precondition of its management, performance optimization and network resources re-allocations. The traditional network interior measurement technique performs measurement on the nodes or links directly, and obtains the node or link performance through analyzing the measurement sample, which usually is used in the wired networks measurement based on the solid infrastructure. However, MANET is an infrastructure-free, multi-hop, and self-organized temporary network, comprised of a group of mobile nodes with wireless communication devices. Not only does its topology structure vary with time, but also the communication protocol used in its network layer or data link layer is diverse and non-standard. Specially, with the limitation of node energy and wireless bandwidth, the traditional interior network measurement technique is not suited for the measurement requirement of MANET.

In order to solve the problem of interior links performance (such as packet loss rate and delay) measurement in MANET, this dissertation has adopted an external measurement based on network tomography (NT). Being a new measurement technology, NT collects the sample of path performance based on end-to-end measurement to infer the probability distribution of the network logical links performance parameters by using mathematical statistics theory, which neither need any cooperation from internal network, nor dependence from communication protocols, and has the merit

of being deployed flexibly. Thus from our literature review it can be concluded that Network Tomography technique is adaptable for ad-hoc network measurement.

We have the following contribution in the field of ad-hoc network performance:

- **PLE Algorithm**: We developed the PLE algorithm based on EM model, which statistically infer the link performance.
- **Stitching Algorithm**: Stitching algorithm is based on the isomorphic properties of a directed graph. The proposed algorithm concatenates the links, which are common over various steady state period and carry forward the ones, which are not. Hence in the process it gives the network performance analysis of the entire network over the observation period.
- **EM routing**: EM routing is based on the statistical inference calculated by our PLE algorithm. EM routing provides multiple performance metric such as link delay and hops of all the possible path in various time period in a wireless mesh network.

TABLE OF CONTENTS

Page

ACKNOWLEDGEMENTS iii
ABSTRACT v
LIST OF TABLES ix
LIST OF FIGURES x

CHAPTER

1 INTRODUCTION 1

1.1 Motivation of Network Tomography. 1

1.2 Network Tomography on the Internet. 2

1.3 Network Tomography on the MANET. 5

1.4 Literature Review. 7

1.5 Research Significant and Our Achievements. 11

1.5.1 Our Achievements. 13

1.6 Structure of this Dissertation. 15

2 AD-HOC NETWORK AND NETWORK TOMOGRAPHY MODEL 17

2.1 Ad-hoc Network. 17

2.1.1 Ad-hoc Network Topology Architecture. 18

2.1.2 Ad-hoc Network System Architecture. 19

2.1.3 Ad-hoc Network Protocol. 21

2.1.4 Ad-hoc Network Application. 24

2.2 Network Tomography Model. 25

3 STATISTICAL INFERENCE 29

3.1 Statistical Methods. 29

3.2 EM Algorithm. 30
3.3 Validation of EM Algorithm. 31

4 STITCHING ALGORITHM 37
4.1 Isomorphism. 37
4.2 Implementation of Stitching Algorithm. 40
4.2.1 An Example of Stitching Algorithm. 40
4.2.2 Simulation Results for Static Network. 41

5 NETWROK TOMOGRAPHY APPLICATION IN WIRELESS MESH NETWORK 48
5.1 Wireless Mesh Network. 48
5.2 Network Tomography Application on WMN. 50
5.3 EM Routing. 52
5.3.1 Mathematical Model of EM Routing. 53
5.3.2 Simulation Results 54

6 EXPERIMENTS AND RESULTS 58
6.1 Simulation Result for Dynamic Network. 58
6.1.1 PLE for an Observation Period. 58
6.2 Mobile Wireless Mesh Network. 67
6.2.1 Simulation Results for Mobile WMN. 68

7 CONCLUSION AND FUTURE WORK 74
7.1 Future Work. 75

REFERENCES 77

CURRICULUM VITAE 90

LIST OF TABLES

TABLE		Page
1	Estimation for 4-node graph in $T_{1,1}$	43
2	Estimation for 4-node graph in $T_{1,2}$	44
3	Aggregated Result	45
4	Stitched values from different time instances	46
5	Estimation for 8-node WMN	55
6	Estimation for 9-node mobile WMN	70

LIST OF FIGURES

FIGURE		Page
1.1	Typical examples of Mobile ad-hoc Network	5
1.2	Arbitrary mobile network in two different time instant T_1 and T_2	14
2.1	Ad-hoc network place topology architecture	18
2.2	Ad-hoc network layered topology architecture	19
2.3	Ad-hoc network system architecture	20
2.4	Directed network graph H with eight-nodes	26
3.1	Directed network graph G with four nodes	32
3.2	EM Algorithm Original and Estimated edge values for various Network sizes	36
4.1	Directed graph G and its corresponding path matrix P_G.	38
4.2	Directed graph G and its corresponding vertex matrix V_G.	39
4.3	Stitching algorithm implementation on a dynamic network in different time domains.	42
4.4	Directed graphs in G and H two different time instant T_1 and T_2.	42
4.5	Path analysis of 4-node network in $T_{1,1}$	43
4.6	Path analysis of 4-node network in $T_{1,2}$	44
4.7	Path analysis of 4-node network over time period $T_{1,1}$ and $T_{1,2}$	45
4.8	Path analysis of the entire monitoring period	47
5.1	Typical wireless mesh network architecture.	49
5.2	Arbitrary WMN in two different time instances T_1 and T_2	51
5.3	Path matrix of network G and H	52
5.4	Layered Source-to-Destination architecture in WMN.	55
5.5	Path analysis for 6-node WMN.	56
5.6	EM routing path and hop analysis for WMN.	57

6.1 NS-2 simulation for a dynamic network 59
6.2 Comparison of delay in light traffic load and very high traffic load. . . 60
6.3 Delay in high traffic load 61
6.4 Network Topology of a Dynamic Network 62
6.5 Estimated delay and actual delay for observation period T_1,T_2,T_3 . . . 64
6.6 Aggregated estimated delay and actual delay in the entire monitoring period 66
6.7 Source-to-Destination in mobile WMN. 68
6.8 Path matrix of network G in $T_1$and H in T_2 69
6.9 Path analysis for mobile WMN. 70
6.10 EM routing path and hop analysis for mobile WMN. 71
6.11 Aggregated estimated delay and actual delay in the entire monitoring period 73

CHAPTER 1

INTRODUCTION

1.1 Motivation of Network Tomography.

Modern networks are multi-layered, distributed systems that are loosely controlled.The largest of all is the Internet, and its structure can be described as follows. On the edge, there are local area networks (LAN) which are connected to wide area networks (WAN). WANs are further connected to the backbone. The large number and variety of service providers has allowed modern networks to expand rapidly and independently. But this has also made performance assessment and monitoring efforts difficult.

Numerous user applications have been developed for modern networks. They can be broadly classified into two categories: time-sensitive applications and time-insensitive ones. Time-sensitive applications, such as voice over IP (VOIP), require extremely high quality links, while time-insensitive applications, such as email, allow for the retransmission of corrupted messages. Different levels of service quality are required by different user applications. Hence performance assessment and network monitoring are critical to support the vast variety of user applications and for the service providers to meet the service level agreements.

Tools have been developed to discover network connectivity structure, available bandwidth of links, and other performance characteristics [1]. Despite these efforts, large scale quantitative network performance assessment is still very difficult, and the expectation of full cooperation of routers is unrealistic in most situations.

Service providers (SPs) are capable of directly collecting measurements at the routers within their own network. The associated price is a heavy overhead of extra computing, communication and hardware support. This is impractical for very fast

and/or heavily loaded networks. Moreover network traffic usually generates huge amount of data, and analyzing such data is not a trivial task.

It is helpful for a SP to gather information from a network connected to its own network but not under its control. But SPs who do not own the network cannot get access to the internal routes to collect information such as traffic rates, individual link delays, available bandwidth. These difficulties and challenges call for efficient data collection and analysis techniques that can be used by everyone. This is the motivation for the research on active network tomography [2].

1.2 Network Tomography on the Internet.

The Internet has evolved from a small tightly controlled network serving only a few users in the late 1970s to the immense multi-layered collection of heterogeneous terminals, routers, and other platforms that we encounter today when web-surfing. Unlike the telephone network which evolved in a slower and more controlled manner, the Internet has evolved very rapidly in a largely unregulated and open environment. The lack of centralized control and the heterogeneous nature of the Internet lead to a very important problem: mapping network connectivity, bandwidth, and performance as functions of space and time.

A wide variety of Internet maps have been produced using existing networking tools such as ping and traceroute. Information on these tools, along with a collection of interesting Internet mapping projects, can be found on the CAIDA (Cooperative Association for Internet Data Analysis) website [1]. The popular science book Atlas of Cyberspace [3] contains a survey of many Internet mapping projects and their results. The mapping techniques described in the references above, however, usually provide only a partial picture of the Internet because they do not produce quantitative performance information.

The decentralized nature of the Internet makes quantitative assessment of network performance very difficult. One cannot depend on individual servers and routers to freely transmit vital network statistics such as traffic rates, link delays, and dropped packet rates. The collection of network statistics at servers and internal routers can

impose an impracticable overhead expense in terms of added computing, communication, and hardware requirements. Even if such statistics can be collected, an Internet service provider (ISP) may regard such information as highly confidential. Moreover, the transmission of statistics to a central processing point may consume considerable bandwidth, adding to network load and congestion.

In certain cases, however, useful network statistics can be indirectly acquired without special-purpose cooperation from servers and routers and with little or no impact on network load. These statistical quantities can reveal hidden network structure and help to detect and isolate congestion, routing faults, and anomalous traffic. The acquisition of the statistics relies on the application of sophisticated methods of active network probing or passive traffic monitoring. These methods do not directly provide the desired information. The problem of extracting the hidden information from active or passive traffic measurements falls in the realm of statistical inverse problems, an area which has long been of interest to signal and image processing researchers. Signal processing know-how, acquired in areas such as image reconstruction, pattern recognition, system identification, and sensor array signal processing, can provide tremendous insight into networking inverse problems.

Network tomography is such an inverse problem, which is well documented in the chapter 2. It is an approach where the network performance can be inferred from incomplete traffic observations which uses statistical theory and algorithms to timely and accurately estimates the network performance. Network tomography attempts to characterize the internal performance (e.g., link delay) from some available measurements only. A large-scale network performance inference is to estimate network performance parameters, based on traffic measurements at a limited subset of the nodes. The estimation is particularly conducted by various statistical inference algorithms that determine performance attributes that cannot be directly observed. The statistical inference algorithms include complexity reducing hierarchical statistical models, moment and likelihood based estimation, expectation-maximization, Markov Chain Monte Carlo algorithms, etc.

Many software tools for active and passive measurement of the network are

developed. These tools usually require extra cooperation (in addition to the basic cooperation required for routine packet transmission) among the nodes of the network. For example, in sessions running under RTCP (real-time control protocol), summary sender/receiver reports on packet jitter and packet losses are distributed to all session participants. Active probing tools such as ping, pathchar (pchar), clink, and traceroute measure and report packet transport attributes of the round-trip path (from sender to receiver and back) of a probe (see [1] for a survey of these and other measurement tools). Trajectory sampling [4] is another example of active probing software tool. These methods depend on accurate reporting by all nodes along the route and many require special assumptions, e.g., symmetric forward/reverse links, existence of store-and-forward routers, non-existence of fire walls. As the Internet evolves towards decentralized, uncooperative, heterogeneous administration and edge-based control, these tools will be limited in their capability.

In the future, large-scale inference and tomography methods such as those discussed here will become of increasing importance due to their ability to deal with uncooperative networks. Network queuing theory offers a rich mathematical framework which can be useful for analyzing small-scale networks with a few interconnected servers [5,6]. The limitations of queuing network models for analyzing real, large-scale networks can be compared to the limited utility of classical Newtonian mechanics in complex large-scale interacting particle systems: the macroscopic behaviour of an aggregate of many atoms appears qualitatively different from what is observed at a microscopic scale with a few isolated atomic nuclei. Furthermore, detailed information on queuing dynamics in the network is probably unnecessary when, by making a few simple approximations, one can obtain reasonably accurate estimates of average link delays, dropped packet probabilities, and average traffic rates directly from external measurements. The much more computationally demanding queuing network analysis becomes necessary when addressing a different set of problems that can be solved off-line. Such problems include calculating accurate estimates of fine grain network behavior, e.g., the dynamics of node traffic rates, service times, and queue lengths.

The area of statistical modeling of network traffic is a mature and active field [7–11]. Sophisticated fractal and multi fractal models of single traffic streams can account for long-range dependency, non-Gaussian distributions, and other peculiar behaviors. Such self-similar behavior of traffic rates has been validated for heavily loaded wired networks [12]. To date these models are overly complicated to be incorporated into the large-scale network inference problems discussed in this article. Simplifying assumptions such as spatial and temporal independence are often made to devise practical and scalable inference algorithms. By making these assumptions, a fundamental linear observation model can be used to simplify the inference process. While some progress has been made on incorporating simple first order spatial-temporal dependency models into large-scale network inference problems [13] much work remains to be done.

1.3 Network Tomography on the MANET.

A mobile ad-hoc NETwork (MANET) can be characterized as a dynamic network with low bandwidth at each network node. An example of this type of network is show in Figure 1.1. Consequently, the performance monitoring for MANET has



(a) (b)

Figure 1.1: Typical examples of Mobile ad-hoc Network

additional challenges compared to that of the Internet. Different to the Internet, MANET is a highly dynamic network where each network node is a user terminal and acts as the router as well. The traffic from an ad-hoc node is forwarded to the destination node by hop-by-hop forwardness with the help of other intermediate nodes

between the source and the destination nodes. The forwarding path that connects a number nodes towards the destination is called ad-hoc route, which established by ad-hoc routing protocol in a real-time fashion. The route for a traffic flow changes frequently, according to ad-hoc node mobility. With the increase of mobility, the route changes more frequently. On the contrary, the route for the Internet traffic is generally used until the end of the traffic transmissions. Furthermore, the Internet has affordable bandwidth on the path to collect the traffic performance measurements of interest. This is not the case in the MANET as the ad-hoc node relies on the wireless link for communication whose bandwidth is very limited. Therefore, the bandwidth limitation restricts the performance monitor in the MANET.

Currently, the MANET performance mostly adopts some internal measurement techniques to evaluate network performance. In such a way, a MANET node separately monitors and predicts its network performance locally. They are unable to give a holistic and geographical view of the overall network performance as the network topology is changing in the dynamic network. In this thesis, we investigate the network tomography to study the dynamic network performance, particularly for MANETs. Network tomography for MANET has specific challenges that are significantly distinguished from the current approaches for the Internet:

- **Network Tomography in the Time Domain**: Network tomography for MANET has to address the dynamic network topology over the time domain. The movement of the ad-hoc nodes results in the high frequent changes of the network topology. Accordingly, the traffic flows are redirected to alternative paths. It is different than the Internet the network performance measurements of a flow are generally collected from a constant path. Due to the unpredictable node mobility, the MANET performance may dramatically vary over time domain such that the network tomography for MANET should be adapted to the time-varying network topology.

- **Network Tomography in the Geographical Domain**: The traffic measurements from a source to a destination should be segmented into different

observation time periods which are also called observation periods. Each observation period corresponds to a stable route or link path in the corresponding traffic. The combination of them is the continuous aggregation of the performance observation of the flow in accordance with the variation of the route. The tomographic analysis of the aggregated performance observation reflects the traffic flow performance over the frequently changing flow route. This is different to the Internet where the route for a flow is generally the same to the end of the traffic flow. As a result, the statistical network performance analysis for a traffic flow path should be adaptive to the change of the network topology. In such a way, the network tomography for an MANET should offer the multilevel performance monitoring in the time domain and geographical domain as well. The geographical performance of the network is reflected from the changes of the flow route by corresponding network performance.

- **Network Tomography Model and Algorithms** The current network tomography algorithms are developed based on the Internet network model. A novel mathematical network tomography model is required to address the MANET that considers the network probabilistic analysis from the time and geographic domains. The network tomography algorithms such as moment and likelihood based estimation, expectation-maximization, Markov Chain Monte Carlo algorithms should be remodeled before applying them to the MANET and its effectiveness should be validated by using the MANET traffic observations.

1.4 Literature Review.

Network tomography was first proposed by Vardi [14] as a tool for network performance analysis to infer the user network performance from a limited number of measurement. A matrix equation, $\mathbf{y} = A\mathbf{x}$, is constructed to model the network tomography of a computer network as a high-dimensional matrix to solve the statistical inverse problem [15]. In this equation, $\mathbf{y}$ is a vector of measurements (e.g., end-to-end delays) observed over different time instants at a number of different network nodes,

A is the routing matrix, and $\mathbf{x}$ is the estimated time-independent performance vector (e.g., mean delay vector). Given $\mathbf{y}$ and A, $\mathbf{x}$ can be evaluated by the above equation, deriving an underlying parameterized distribution $f(\mathbf{x}, \Theta)$. Varying the $\mathbf{y}$ vectors, network tomography solves link level network parameter estimation, topology inference, traffic delivery probability, etc. These network tomography problems have been broadly studied for the Internet and they can be generally categorized as below.

Network tomography in [16], [17] and [18] can be applied for discovering the network topology on the Internet, which is generally referred to as network topology identification. On the Internet, the network topology is hidden from us since complex heterogeneous domains. They are regulated by different Internet Service Providers (ISPs) and the collaboration among them cannot be assumed. The network tomography is to infer the logical network topology without the cooperation of nodes. The authors in [16] proposed a 2-by-2 components identification methodology based on the bidirectional measurements and a logical topology emerging algorithm. Furthermore, Eriksson *et al* [18] advocate the practical use of tomographic inference for accurate router-level topology discovery. The authors developed a Depth-First Search (DFS) ordering algorithm that clusters end host targets based on shared infrastructure. DFS further enables discovery of the logical tree topology of the network by using the Round Trip Time (RTT). Furthermore, Chen *et al* [17]investigate the network delay tomography in related to topology. The authors define a characteristic function that is the Fourier transform of the distribution and develop a Fourier domain inference algorithm based on flexible mixture models of link delays. Different to above work, Liang *et al* [19] developed a maximum pseudo likelihood estimation algorithm to mitigate the computational complexity as the network tomography is targeted for the analysis on the large-scale Internet.

In addition to topology discovering, the network tomography in [20], [21], [22], [23] and in [24–29] has been extensively used to evaluate the network performance such as the loss rate of a link and the delay distribution of a link. Network tomography allows the evaluations of the packet loss ratio and delay of links only from end-to-end observations, without knowing the internal network structure. Caceres *et al* [20], for

example, proposed the algorithm to characterize the internal packet loss on the Internet. Presti *et al* [21] studied the internal delay by a multicast-based inference network tomography algorithm. Zhu [24] designed an explicit estimator based on the Law of Large Numbers to evaluate the loss rate. The estimator in this work find the maximum likelihood estimate (MLE) of a link/path without using iterative approximation. Singhal*et al* [25] presents a structural model to estimate characteristics of source - destination flows based on aggregated link measurements. The work presented by Yao *et al* [22] is a study of network tomography in the presence of network failures, in particular adversarial/random errors and adversarial/random erasures. In presence of network failures, the authors developed the algorithms that not only estimate the network topology but also localize the random errors and adversarial erasures. Firooz *et al* [27] studied the network tomography using combinatorial compressed sensing. The authors assume that the likely used links incur a high delay in packet delivery and thus the focus of the network tomography is to identify these highly used links and best estimate these link delays. Ghita *et al* [28] applied the network tomography to identify the correlated link in a network, i.e., the performance of one link may depend on the performance of the other links. The network tomography for correlated links assumes the links are not statistically independent any more and the performance of one link can effect the performance of others. Gui *et al* [29] proposed a linear algebraic network-scale tomography framework to estimates the active inference of the link loss rates on mesh topologies using network tomography.

The network tomography fosters many applications using the knowledge of inferred network state. For example, a high packet loss rate at a node in the network may indicate the node selfishness or other security issues. Demir *et al* [30] developed a searchlight localization algorithm with network tomography to localize the sources of the Distributed Denial of Service (DDoS) from from sequences of DDoS attacks. Yu *et al* [31] present the Cognitive Radio Network Tomography(CRNT) to enhance network spectrum sensing capabilities. The authors develop CRN tomography to inferring the spectrum status at both the link and network levels. Specifically, CRN tomography is the way combining statistically measuring, processing, and inferring

techniques to provide the spectrum parameters and traffic/interference patterns at both the link and network levels.

Based on the different routing metrics and target of load balance in wireless mesh network, we can classify the load balance schemes into two categories: static load balance routing and dynamic load balance routing.

The static load balance routing aim at the balanced bandwidth allocation for users. It can improve overall network utilization and allow more traffic flow in MWMNs. The authors in [32] proposed the algorithm which constructs load-balanced backbone tree and balances traffic flows on each backbone tree. The authors in [33] proposed an approximation algorithm for NOC (Network Operation Center) to centralize management and balance the traffic load for nodes with different node weight. The authors in [34] proposed algorithm with lexicographic optimization to distribute the load in a min-max sense on each link in the network.

The dynamic load balance routing mainly provides efficient connection to destination. It solves the traffic congestion and improves overall network throughput, but it can't guarantee QoS (Quality of Service) requirement for each user in MWMNs. In [35], the authors proposed ETX (Expected Transmission Count) metric to provide efficient path by accounted the packet delivery ratio. However, ETX is only for single-channel environment. As the refinement of ETT (Expected Transmission Time), the authors in [36] proposed WCETT (Weighted Cumulative Expected Transmission Time) metric. Compared with ETX, WCETT accounts the transmission rate and the channel diversity to perform efficient routing for multi-radio environment. The Authors in [37] proposed IAR (Interference-Aware Routing) metric which accounts intra-flow and inter-flow interference based on the state time of the packet transmission to select an efficient path. The airtime metric proposed by [38] is to perform radio-aware routing by accounted channel access and protocol overhead, transmission rate and frame error rate. The authors in [39] proposed INX (Interference Neighbors Count) metric which extends the ETT and accounts the interference by wireless links to select a path with less interference. Authors in [40] propose methods, which can handle mesh radio with multiple interface.

1.5 Research Significant and Our Achievements.

Ad-hoc networks have now been used in both civil and military application, and have been one of the foreland research areas about network technique. At present, ad-hoc network researches mainly focus on systematic architecture, communication protocols, self-organization and self-management technique, and so on [41–47]. However, little research is focused on ad-hoc network performance measurement, there are the following reasons accounting for these phenomena:

- Ad-hoc network systematic architecture and communication protocol has not been standard for its inherent characteristic, it is difficult to adopts the traditional network measurement technique for ad-hoc network, for it depends on certain network standard communication protocol and systematic architecture. For example, IP network with solid infrastructure adopts TCP/IP reference model and has standard communication protocol, it is easy to use an universal network performance measurement method on it based on ICMP, TCP, UDP and SNMP, and so on.

- Since ad-hoc network is an autonomous system, it implements self-configuration, self-management during its different life period, such as deployment, operation and death period [48, 49]. However, the traditional network measurement technique depends on the collaboration among different nodes in the same AS(Autonomy System), which is difficult to adapt to ad-hoc network autonomous characteristic.

- The traditional network measurement technique does not consider over the limitation of network resource and the nodes energy, but all these resources are expensive and limited in ad-hoc network.

- The traditional network measurement technique is commonly used in wired networks with solid infrastructure and its network topology architecture keeps correspondingly steady, which could not adapt to the ad-hoc network with topology

dynamic characteristic. Therefore, it is necessary to find a new network measurement technique to satisfy the requirement of ad-hoc network measurement according to ad-hoc network topology dynamic characteristics.

The new applications about ad-hoc networks have required high performance, and some ad-hoc network theories and practical application systems all need to measure its performance, analyze and evaluate its performance parameters. The performance measurement could provide the new application deployment, resource optimization, system maintenance with scientific decision-making [50]. There are various reasons accounting for the importance of ad-hoc network performance measurement.

- Ad-hoc network is an important network application environment for digital battle field. However, war field situation analysis and efficiency evaluation is difficulty in information field research, it is importance to analyze and evaluate ad-hoc network running state and dynamic characteristic, to adjust, deploy network and to resume the injured nodes or areas through network measurement.

- Network measurement could provide traffic engineering, network behavior analysis and communication protocol with verification means. With the appearing of ad-hoc network new application, the flow characteristic is becoming more and more complicated in ad-hoc network than before, and different application has different network behavior characteristic. It is effective to compare different network communication protocol and evaluate new protocols by network measurement.

- Ad-hoc network measurement could provide effective technique means for network management. For example, ad-hoc network link delay, loss ratio, link connection state and congestion could be obtained by network measurement to position the network performance bottleneck and obtain its performance views. Moreover, It could also evaluate QoS of ad-hoc network, optimize network resources to meet with users end to end experience through network measurement.

In other word, it is a key problem to establish an effective ad-hoc network measurement theory and method for developing ad-hoc networks technique. NT technique adopts end to end measurement without considering the network interior architecture and communication protocol so as to solve ad-hoc network measurement. Therefore, research on ad-hoc networks measurement theory and method based on NT technique is very significant to improve its network performance and manageability. In addition, It also provides the ad-hoc network practical measurement application with necessary theory basis.

1.5.1 Our Achievements.

In our work, we present a mathematical network tomography model that probabilistically estimates the network traffic performance in a dynamic network environment. In the dynamic MANET model it is naturally to consider a number of steady states. In each steady state, the MANET has the stable network topology for traffic flows. The MANET moves to the next steady state with the change in network topology. Thus with the network tomography model, we have developed a Pseudo-log Likelihood Estimation (PLE) algorithm to evaluate the network traffic flow performance with the evolution of the MANET topology. PLE is a network tomography approach to find the probabilistic distribution of network performance parameters, such as route delay, e.g., how the end-to-end packet delay varies in the network over time. For each steady MANET state, PLE algorithm offers a multilevel monitoring and evaluation of network performance parameters. Figure 1.2 illustrates the basic idea of the proposed network tomography for MANET. In the time domain, the MANET topology is divided into subsequent graphs, based on the collected traffic measurements. These graphs again represent continuous MANET steady states and each steady state stands for a minimal measurable time period (i.e., measurement period) which can be very small and scale to MANET mobility. Figure 1.2(a) and (b) are two different time periods, denoted by T1 and T2. In the Figure 1.2(b), the wireless links (e.g., the links from node 1 to nodes 2 and 3) for communication are changed along the node mobility. For each time period, PLE algorithm is efficient

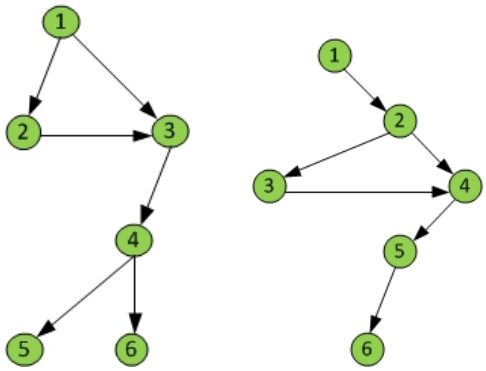


Figure 1.2: Arbitrary mobile network in two different time instant T_1 and T_2

enough to estimate the network performance in the associated period. Furthermore, a stitching algorithm is developed to aggregate the network performance for each node, link, and end-to-end path over time. As the topology changes, the stitching algorithm aggregates the end-to-end node performance such that the network performance can be tracked for each communication paths from the geographical domains. Specifically, our network tomography for MANET has the following technical contributions:

- **PLE Algorithm**: Our PLE algorithm is developed based on the Expectation-Maximization (EM) [51, 52] model. The PLE algorithm estimates the network performance parameters from various observation instances. Based on the evaluation of multiple observation instances, the expected network performance can be computed for a given steady state.

- **Stitching Algorithm**: The stitching algorithm meaningfully aggregates the network performance parameters that are estimated from multiple steady states. It evaluates the performance parameters over the time domain by following the change of the network topology.

- **Algorithm Validation and Efficiency**: We validated the correctness of the proposed PLE algorithms and demonstrated the analytical network performance in an MANET, in terms of time and geographical domains. In our implementation, we first used NS-2 [53]to simulate a number of network scenarios and

collected some observations over different time and node mobility. By using the PLE and stitching algorithm, the estimated network performance is graphically plotted from the time and the geographical domain. In such a way, the network performance can be observed in term of MANET nodes and routes at different time instances.

1.6 Structure of this Dissertation.

This dissertation is organized in the following fashion:

- **Chapter Two**: In this chapter, we present the mathematical framework for the network tomography model. In particular it talks about the matrix equation and how it represents the parameter estimation problem in computer network. Furthermore, it talks about the idea of likelihood function and how they are used in parameter estimation.

- **Chapter Three**: The Expectation-Maximization algorithm is discussed in the chapter along with its mathematical justification. Application of the EM algorithm in network tomography setting is presented. Also, we present the simulation results of various size of network and compare the estimation result and actual result. In the process of estimating the network parameter, we also compare the worst case and best case scenario with the actual estimates. In the end the EM-algorithm complexity is also compared on different network sizes.

- **Chapter Four**: This chapter offers a new algorithm called the Stitching algorithm. The proposed algorithm gives the framework and mathematical formality, to the process of stitching. Its main purpose is to give the performance evaluation of dynamic network over various study state period over a period of time. Also in the chapter we present the implementation of the proposed algorithm and compare the results in both static setting.

- **Chapter Five**: Chapter five talks about the wireless mesh network in general. Also, network tomography application in mobile wireless mesh network

is presented. We introduced a new routing scheme called EM routing and its mathematical model is discussed in detail. Lastly some preliminary simulation results are presented in static setting.

- **Chapter Six**: In this chapter all the experiments, which are dynamic in nature are discussed is great detail. Stitching algorithm is implemented on the dynamic network and the results are compared with the simulated result in NS-2. Various scenarios in dynamic network are discussed at great length pertaining to both mobile ad-hoc network and mobile wireless mesh network.

- **Chapter Seven**: In this chapter we present the findings and conclusion of our study. Also, some future research work pertaining to the application of network tomography is presented.

CHAPTER 2

AD-HOC NETWORK AND NETWORK TOMOGRAPHY MODEL

2.1 Ad-hoc Network.

An ad-hoc network [54] is a self-configuration, self-organization, multi-hop wireless and temporary wireless network, which is composed of many wireless mobile nodes with wireless transceivers. Since the range of wireless communication is limited, long distance communications between any two nodes has to depend on the forwarding of intermediate nodes [55, 56] . The mobile nodes collaborate with each other to set up a temporary network in order to implement the remote wireless communications, which is different from that in cellular wireless networks with fixed infrastructures.

In ad-hoc networks, due to the diversity of node's motion, the randomness of wireless transceiver turnoff, the variety of transmission power, the disturbance between wireless channels and the influence of from land and weather, etc., network topology architecture based on shared wireless channels among different mobile nodes and link number distribution will change with time going by [24,57]. Specially, ad-hoc network topology management, system architecture and protocol design is different from that in Cellular wireless network and IP network because of small transmission power of mobile nodes, low bandwidth of wireless channel, and energy limited or constraint. All above these facts directly influences the ad-hoc network performance measurement method to be chosen.

2.1.1 Ad-hoc Network Topology Architecture.

Ad-hoc networks commonly have two types of topology architecture, one is plane topology architecture, the other is the layered one [58]. In the plane topology architecture as in Figure 2.1, all the mobile nodes have an equal position about their topology control, traffic management, transmission and reception of data, routing information choice. Therefore, this architecture is also called as Peer-to-Peer. The shortcoming of this architecture is that its expandability is not good. When network scale increases to a certain degree, more network bandwidth will be consumed by routing protocol. Secondly, a great deal of network control information often leads to network congestion. Therefore, it only adapts to small scale networks. The merit of plane architecture is that there is no key node in theory, so it has high invulnerability that is in case if few nodes are down the network can still perform without too much dependence on any one node, and it is easy to deploy and secure for its small overlay range. Therefore, the document uses the plane topology architecture of ad-hoc network as its research objective. In layered architecture as in Figure 2.2, ad-hoc

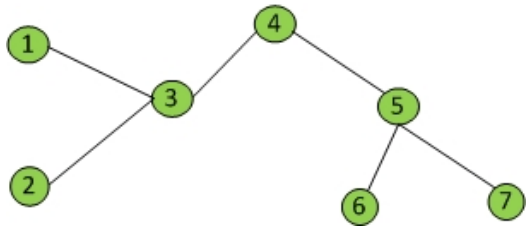


Figure 2.1: Ad-hoc network place topology architecture

network is comprised of one or more clusters, and each cluster comprises of one cluster head and more cluster members. More cluster-head constitutes the higher layer network, in which ad-hoc network is divided into different clusters until it meets with user application requirement. Therefore, there are three types of nodes in layered architecture, such as cluster head, cluster member and gateway. The cluster members in the same cluster could communicate with each other depending on the forwarding of its cluster-head transmission, which is called as interior cluster communication. The cluster-members belonging to different clusters communicate with each other

depending on the forwarding of gateway transmission, which is called as exterior cluster communication. Ad-hoc network layered topology architecture does not need

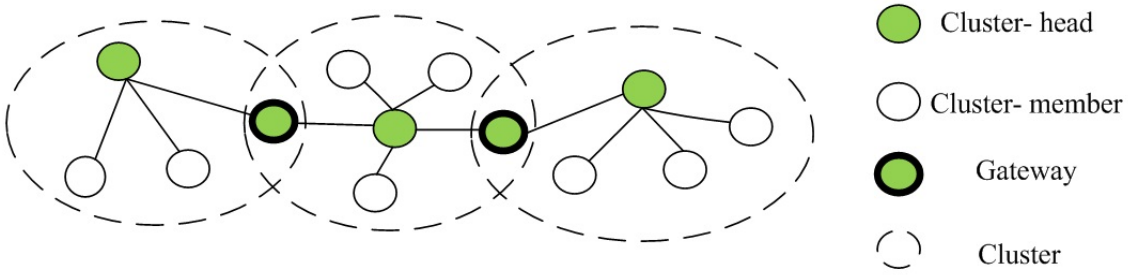


Figure 2.2: Ad-hoc network layered topology architecture

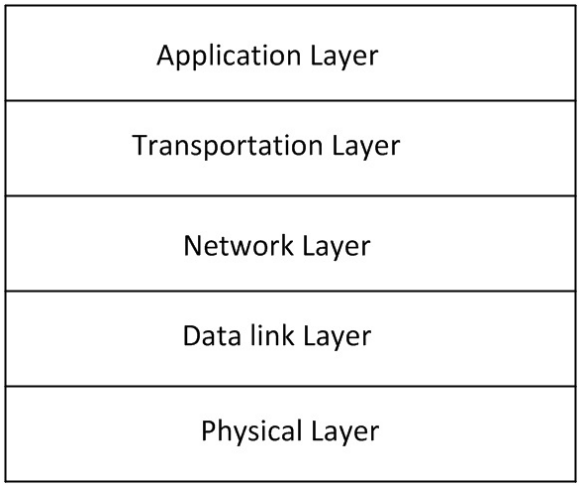
to maintain the whole routing information so as to decrease the network control packets, so it has good expandability. Its shortcoming is that gateway may become a bottleneck of network performance, and the maintenance and selection algorithm for the cluster-header is complicated. It is easy to deploy measurement proxy on the cluster-header so as to implement network performance measurement in the same cluster in the light of the traditional network measurement technique.

2.1.2 Ad-hoc Network System Architecture.

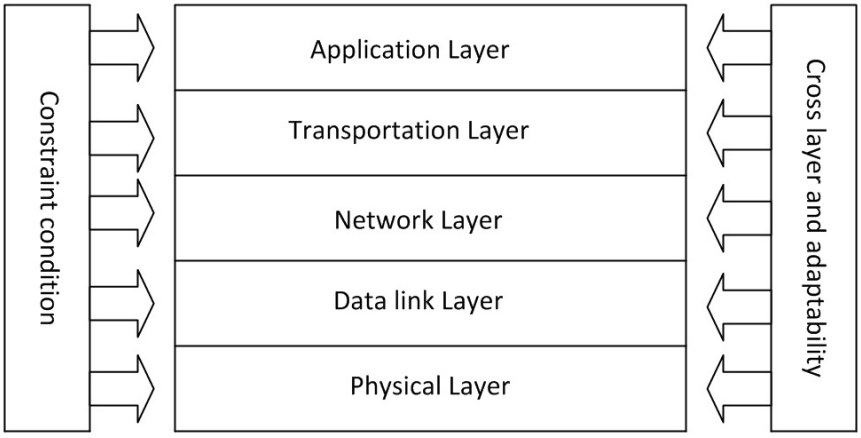
According to ad-hoc network inherent characteristics, such as self-organization,wireless multi-hop routing, dynamic topology, limitation of wireless bandwidth and energy and low security, its system architecture could be divided as the five layers as described in Figure 2.3(a), such as physical layer, data link layer, network layer, transportation layer and application layer.

In the Figure 2.3(a), physical layer mainly is in charge of wireless frequency choice, signal detection, transmission and reception, modulation/demodulation, wireless channel encryption/decryption. It also adopts wireless spread spectrum technique to implement wireless signal transmission and reception, such as DSSS and FHSS. Data link layer is divided into logical link control layer (LLC) and medium access control layer (MAC) again. The LLC has the function of assembling the data frame, checkout, flow and error control from point to point. In recent years, the MAC mainly

adopts four mechanisms to control the shared wireless channel access which is chosen by mobile nodes. The first one is stochastic competition technique, i.e., CSMA/CA. The second one is sub-channel access mechanism, such as TDMA, FDMA, CDMA and SDMA, and so on. The last two are polling method and dynamic adjusting method. Network layer mainly takes charge of neighbor discovering, routing choice and congestion control. The transportation layer could provide different processes in application layer with reliable or unreliable data transmission service. At present, transportation layer mainly adopts the traditional communication protocol, such as TCP, UDP or special protocols. Application layer provides different application service with the its application interface concerned.



(a) Ad-hoc network system architecture.



(b) Ad-hoc network adaptive system architecture.

Figure 2.3: Ad-hoc network system architecture

Considering ad-hoc network characteristics, the five layers network system architecture (seen in Figure 2.3(a)) is often extended. For example, power and topology control are commonly added between physical and data link layer, cluster management function between data link and network layer, and position, self-configuration and security mechanisms between transportation and application layer. In order to decrease the complexity of ad-hoc network system architecture, sometimes it is necessary to simplify the five layers system architecture. For example, data link and network layer, or transportation and application layer are often united as one layer, thus three or four layers ad-hoc network system architectures have appeared. Since ad-hoc networks are temporarily built up to implement special communication tasks, in different application environment, the number of mobile nodes, mobile rule, transceiver power and wireless link bandwidth are different too. In order to meet with requirements of specific applications, it is necessary to design cross layer network system architectures so as to support adaptive and performance optimization as the Figure 2.3(b). In Figure 2.3(a), different layers could share each others information to optimize network performance according to the constraint condition. Specially, this cross layer network system design could decrease information to be exchanged between different layers.

2.1.3 Ad-hoc Network Protocol.

- **Data link layer communication protocol:** Ad-hoc network data link layer is divided into two sub-layers, i.e., LLC and MAC. LLC takes charge of data link management and control, and MAC controls node's access to shared wireless channel. Wireless channels in ad-hoc networks are divided into three types, such as single channel, dual channels and multi-channels [58–60].

  In the communication protocols based on single channel, the mobile nodes share only one channel to transmit and receive data and control packet. However, collision may occur among control packets, data, and between control packet and data for the problem of propagation delay, hidden and exposed terminal. Although this type of protocol adopts a certain mechanism to avoid the collision

among data, it is difficult to solve the problem of terminals, such as multiple access collision avoidance (MACA) [61], MACA for wireless LAN (MACAW) [62], IEEE 802.11DCF [63] and Floor acquisition multiple access (FAMA) [64]. In the communication protocol based on dual channels, mobile nodes use two channels as control and data channel respectively to avoid conflicts occurring between data and control packet. This type of communication protocol has the ability to avoid the conflicts between data and control packet in theory. Basic access protocol solutions for wireless (BAPU) [65] and dual busy tone multiple access (DBTMA) [66] are all these classical dual channels communication protocols. In the communication protocol based on multi-channels, the neighbor nodes use different channels to communicate with each other at the same time t. In this case, access control is easier than in the other two cases. For example, one special channel could be used as common control one, or control packet and data could be transmitted on the same channel. But it should solve two problems, one is channel distribution, the other is access control. The former mainly solves the problem of distributing different channel for nodes to avoid conflict so that more nodes has the ability to communicate with each other at the same time. The latter focuses on when the nodes have the chance to use the channel. The classical protocols based on multi-channel is hop reservation multiple access (HPMA) [67], multi-channel CSMA [68], dynamic channel assignment (DCA) [69] and multi-channel MAC (MMAC) [70], and so on.

Besides, the data link layer protocol could also be divided into two types according to sending handshake signal method by different sources, one is sender active access channel protocol the other is receiver active access channel protocol. In the former one, before the sender sends a data, it firstly send RTS control packet to receiver to book channel, such as MACA and MACAW. In the latter one, the receiver is in charge of sending RTR(Ready to receive) control packet to the sender before its data transmission , and the sender which has received the control packet has the chance to send data so as to decrease the number of control packets and increase network throughput, such as MACA-BI [71] and

RIMA [72], and so on.

- **Network layer protocol:** When mobile nodes uses multi-hops method to implement data exchange in ad-hoc networks, they need network layer protocol to provide packet data transmission with routing information. However, some factors, i.e., irregular channel varying, nodes? moving, joining and leaving state, will influence the ad-hoc network topology dynamic characteristic [73]. Therefore, network layer protocol need to solve the following problems, routing loop avoidance, routing cost control, expansibility, and its adaptability to network topology dynamic characteristic. According to different standards, ad-hoc network layer protocols have different classification methods [50, 74, 75]. According to different routing choice algorithms, network layer protocols could be divided into distance vector protocol (DV), link state protocol(LS), source routing protocol(SR), and reverse link protocol(RL). According to the routing information obtained method, it could be divided into proactive and reactive protocol. The former one is often called as table driving routing protocol, such as DSDV [76], FSR [77], LANMAR [78], OLSR [79] and TBRPF [80], and so on. The latter one sometimes is called as demand routing protocol, such as DSR [81], AODV [82], TORA [83], ABR [84] and MSR [85], and so on. Specially, there exists another new network layer protocol which combines the merits of the two protocols to decrease the bandwidth cost and delay, and is called as hybrid routing protocol, such as ZRP [86], CEDAR [87] and SRL [88], and so on. In recent years, multicast is used to ad-hoc network layer protocol and has become a new hot point. The network layer protocol based on multicast includes ODMRP [89], MAODV [90], CAMP [91], AMRoute [92] and AMRIS [93].

In short, since ad-hoc network system architectures are not fixed, and their applications are different according to user requirement, ad-hoc network protocols are diverse and not standard [94, 95], which is different from IP network. Therefore, it is a challenge to implement measurement on ad-hoc networks.

2.1.4 Ad-hoc Network Application.

With the development of wireless communication and mobile terminals, such as PDA,mobile phones, laptops, pocket PC, some other communication devices based on wireless,infrared, and so on, Ad-h oc networks are becoming more and more interesting in the modern society [96, 97]. Compared with cellular wireless networks, ad-hoc networks have no base station. All the nodes in ad-hoc networks not only are transceivers, but also have the router function. At present, ad-hoc networks have gained lot of attention and thus, ad-hoc networks are used in many applications. Some of them are stated as follows:

- **Military communication environment:** Since battle field communication system needs some special characteristic, such as flexibility, high invulnerability, high reliability, and easily deployment, and so on, ad-hoc network justly meets with this specific communication requirement for its self-organization and nodes mobility, which makes it the fist choice in digital battle field [95–98].

- **Temporary communication environment:** In commercial conference, celebration and exhibition occasion, people often use ad-hoc networks technique to organize some mobile terminals, such as laptops, pocket PC, and PDA, as a wireless mobile self-organization network to exchange information, which could avoid wiring and deploying network routing devices to establish the temporary communication environment.

- **Mobile communication environment:** Ad-hoc networks could be used to provide some mobile vehicles with wireless communication capability. University of California at Berkeley [99] are now studying how to adopt the ad-hoc networks technique for freeway system so as to implement the autonomous wireless communication among automatic drive vehicles.

- **Urgent communication environment:** After some visitation of providence events happened, such as earthquake, flood, fire or other disasters, the network communication environment with solid infrastructure often could not work well.

Since ad-hoc networks could quickly provide urgent communications in special environment, it is very significant for rescue and relief work [96].

2.2 Network Tomography Model.

Let $G = (V, E)$ be any arbitrary directed graph. There $|V| = n$ is the number of vertices and $|E| = m < n^2$ are the number of edges in G. Then path p is define by $p = (e_1, e_2, ..., e_m)$ such that $e_1 = (v_1, v_2), e_2 = (v_2, v_3), ...$ and hence we can write $E \subseteq (V \times V)$.

Base on the above formalization, we consider a eight node network as depicted in Figure 2.4. Matrix P_H represents the path matrix of the network in Figure 2.4. In matrix P_H, 1 means the sink is connected with the node on the topology while 0 means otherwise.

$$P_H = \begin{pmatrix} 1 & 1 & 0 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Here $\mathbf{x} = (x_1, x_2, ..., x_m)^t$ be the m dimensional network performance random vectors that represents a network performance parameter such as link delay, packet delay or link available bandwidth. The superscript t is the transpose operation. Thus $x_{i,1<i<m}$ is the quantitative evaluation of the i^{th} link performance for the information flow. Let $\mathbf{y} = (y_1, y_2, ..., y_n)^t$ be the n dimensional total parameter measurement vector, which corresponds to each path and hence corresponds to $\mathbf{x}$ and $y_{i,1<i<n}$ is the observed i^{th} link performance for the information flow. The problem of the network tomography is to estimate the distribution probability of $\mathbf{x}$ from the observed $\mathbf{y}$ which can be modeled as a matrix equation

$$\mathbf{y} = P_H \mathbf{x} \tag{2.1}$$

which can be re-written as follows:

$$\begin{pmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{pmatrix} = \begin{pmatrix} 1 & 1 & 0 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_7 \end{pmatrix} \tag{2.2}$$

Given x_j that is the j^{th}component of $\mathbf{x}$, we assume our data, which consists of packet arrival time follows Poisson distribution. Then the probability mass function(pmf)is given by

$$p(x;\theta) = \frac{\theta^x e^{-\theta}}{x!}, x = 0, 1, 2, \ldots \tag{2.3}$$

Here $\theta \in \mathbb{R}^+$,equal to the expected number of occurrences that happen during the given interval and x is the number of occurrences of an event, the probability of which is given in (2.3). Considering all the components in $\mathbf{x}$, it has $\mathbf{\Theta} = (\theta_1, \theta_2, \ldots, \theta_m)^t$ that is the parameter of the whole model. The observed data vector $\mathbf{y}$ for subsequently observed vectors for T intervals and denote $\boldsymbol{x}_t, t = 1, 2, \ldots, T$ as the unknown network performance quantities corresponding to $\mathbf{y}_t$. Furthermore, $\mathbf{y}_{t,i}$ and $\mathbf{x}_{t,j}$ be the i^{th} and j^{th} element of $\mathbf{y}_t$ and $\mathbf{x}_t$ respectively.

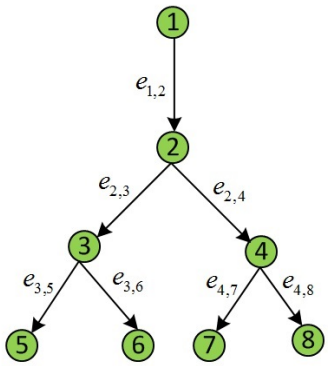


Figure 2.4: Directed network graph H with eight-nodes

We first consider $\mathbf{y}_t$ is collected from a stable network topology graph (e.g., the multicast topology for a certain period). For example, a multicast topology in the network may maintain its multicast topology for a certain period and in this period we have the corresponding observed $\mathbf{y}$ in this period is $\boldsymbol{y}_t, t = 1, 2, \ldots, T$. For this

purpose, the raw data from the dynamic network should be preprocessed according to topology. It is more convenient to work in terms of the natural logarithm of the likelihood function, called the log-likelihood, than in terms of the likelihood function itself. Because the logarithm is a monotonically increasing function, the logarithm of a function achieves its maximum value at the same points as the function itself.

A Pseudo-likelihood is an approximation to the joint probability distribution of a collection of random variables. The practical use of this is that it can provide an approximation to the likelihood function of a set of observed data which may either provide a computationally simpler problem for estimation, or may provide a way of obtaining explicit estimates of model parameters. So in (2.4), we have sum of all the random variables $\mathbf{y}$ over the parameter θ. Also pseudo-likelihood in place of the true likelihood function in a maximum likelihood analysis can lead to good estimates. In practice we may have more than one $\mathbf{y}$. So to approximate θ over all the $\mathbf{y}$ will yield better results than approximating θ for each $\mathbf{y}$. This may not be an issue, when dealing with few $\mathbf{y}$ but in problems, where we have many $\mathbf{y}$. The pseudo log-likelihood function will give better result.We now define our pseudo-log likelihood functions:

$$L^p\left(y_1, y_2, \ldots, y_T; \Theta\right) = \sum_{t=1}^{T} L^p(y_t; \Theta) \tag{2.4}$$

$$L^p(y_t; \theta) = \log p(y_t; \Theta), t = 1, \ldots, n \tag{2.5}$$

here $p(y_t; \theta)$ is the marginal likelihood function. To maximize the likelihood estimate of parameter θ is to maximize the likelihood function in(2.3);

$$\frac{\partial}{\partial \theta_t} L^p(y_1, y_2, \ldots, y_n; \Theta) = 0, t = 1, \ldots, n \tag{2.6}$$

The likelihood equation in (2.6) has a unique solution almost surely as $n \longrightarrow \infty$. Therefore, it needs to select big enough samples from the dynamic network data to have a good estimate.Since we are dealing with a big dataset, this approach is not appropriate to solve (2.6) directly. That is because we have defined (2.6) in terms of marginalized likelihood function, which are difficult to computer directly. Instead we need to adopt a numerical optimization technique, which will solve for $\mathbf{y}$ iteratively.

This give rise to a very well know algorithm called Expectation-Maximization or more commonly known as EM algorithm.

CHAPTER 3

STATISTICAL INFERENCE

3.1 Statistical Methods.

Network tomography measurement inference method aims to use end-to-end network performance measurement sample to infer the probability distribution of link performance based on measurement analysis model and performance analysis model, which mainly is composed of Maximum Likelihood Estimate (MLE), Expectation Maximization method(EM) and Bayesian estimate:

- **Maximum Likelihood Estimate Method**: It is one of the most important method on parameter estimation, which supposes that link performance parameter accords with distribution $f(\mathbf{x};\Theta)$, where $\Theta = (\theta_1, \theta_2, ..., \theta_m)$ is the estimated parameter. If end-to-end measurement sample is denoted as $\mathbf{y} = (y_1, y_2, ..., y_n)$, supposed that they follows the same distribution rule independently, the distribution function of path performance parameter $\mathbf{y}$ could be expressed as $\mathbf{y} = p(\mathbf{x};\Theta)$, then its pseudo function follows the formula:

$$L(\mathbf{y};\Theta) = \sum_{t=1}^{n} p(y_t;\Theta) \tag{3.1}$$

  The objective of MLE is to find the value of the parameter Θ when $L(\mathbf{y};\Theta)$ being its maximum value, which could be denoted as $\hat{\Theta} = argMax(\mathbf{y};\Theta)$. Nevertheless, it is difficult to find the transcendent distribution function $f(\mathbf{x};\Theta)$ of network link performance parameter $\mathbf{x}$. It is found, the computing complexity is high for parameter estimation. However, how to get the probability distribution of the former is difficult work.

- **Expectation Maximization Method**: It uses partial measurement sample

to infer maximum pseudo value of link performance distribution function. It includes two procedures, that is, E-step and M-step. The main problem about EM algorithm is that it could obtain the partially optimized solution, not the unitary optimized one. For the sake of computing complexity increasing by the scale of network, Pseudo-EM Algorithm could decompose a large scale problem to several small scale ones. The maximum likelihood of these small scale problems could be expressed as the following formula:

$$L\left(y_1, y_2, \ldots, y_n; \Theta\right) = \sum_{t=1}^{n} L(y_t; \Theta) \tag{3.2}$$

- **Bayesian Estimate Method**: It uses the transcendent probability distribution of link performance to infer the posterior one. However, how to get the former probability distribution is a difficult work. It is also difficult for Bayesian estimate method to obtain the link performance parameter with large network scale for its computing complexity. In order to solve this problem, Markov Chain Monte Carlo method is brought forth to infer link performance parameters by using Gibbs and Metropolis-Hasting sample rule based on Bernoulli and Gilbert probability model [100–102].

In short, MLE and Bayesian estimate methods need to know the transcendent distribution, but it is very difficult to obtain in practice. EM resolves the problem of computing the estimated parameter of network link performance and it also converges to a partially optimized solution locally.

3.2 EM Algorithm.

Given an inverse statistical parameter estimation model $\mathbf{y} = P\mathbf{x}$. Here $\mathbf{y}$ is the observed data and P is the path matrix of some arbitrary directed graph. A set of unobserved data $\mathbf{x}$ a vector is approximated by unknown parameters Θ, which mimics Poission type behavior. Along with a likelihood function $L^p(\mathbf{y}; \Theta) =$

$\log p(y_t;\Theta)), t = 1, \ldots, n$, the maximum likelihood estimate (MLE) of the unknown parameters is determined by the marginal likelihood of the observed data

$$L^p(\mathbf{y};\Theta) = \log p(y_t;\Theta) = \sum_{t=1}^{n} L^p(y_t;\Theta), t = 1, \ldots, n \tag{3.3}$$

In (3.3), the right hand summation represents the marginal likelihood function, where Θ is the parameter of interest with respect to $\mathbf{y}$ and $\mathbf{x}$. However, Θ sometime is intractable. We define the objective function $Q(\theta, \theta^i)$ to be maximized over θ in the $(i+1)^{th}$ step of the EM algorithm. The EM algorithm seeks to find the MLE of the marginal likelihood function iteratively by applying the following two step:

Expectation Step (E-step): Calculate the expected value of the log likelihood function, with respect to the conditional distribution of $\mathbf{x}$ given $\mathbf{y}$ under the current estimate of the parameters $\theta^{\mathbf{i}}$:

$$Q\left(\theta, \theta^i\right) = E_{X|Y,\theta^i} \log p\left(y_t;\theta\right), t = 1, \ldots, n$$

Maximization Step (M-step): Find the parameter that maximizes this quantity:

$$\theta^i = \underset{\theta\in\Theta}{argmax} Q\left(\theta, \theta^i\right) \tag{3.4}$$

The pseudo code for the algorithm is given below.

Algorithm 1 Expectation Maximization Algorithm

begin
initialize $\theta^0, \epsilon, i \leftarrow 0$
do $i \leftarrow i + 1$
E step: compute $Q(\theta, \theta^i)$
M step: $\theta^{i+1} \leftarrow \underset{\theta}{argmax} Q\left(\theta, \theta^i\right)$
until $Q(\theta^{i+1};\theta^i) - Q(\theta^i;\theta^{i-1}) \leqslant \epsilon$
return $\hat{\theta} \leftarrow \theta^{i+1}$
end

3.3 Validation of EM Algorithm.

We now present the details , as to how the EM algorithm work in the network tomography problem. Let us consider the following topology. Then we use the matrix

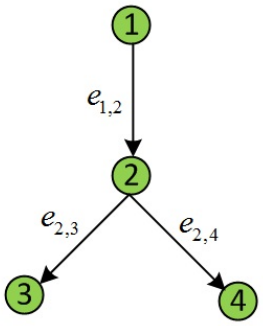


Figure 3.1: Directed network graph G with four nodes

equation $\mathbf{y} = P_G\mathbf{x}$ to represent the Figure 3.1 as shown in (3.5). Here P_G is the path matrix associated to directed graph G in Figure 3.1. We assume, $x_i \sim Poission\,(\theta_i)$:

$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} 1 & 1 & 0 \\ 1 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} \tag{3.5}$$

In (3.5), matrix P_G represents the deterministic connectivity between the two nodes in a given topology. So, from (3.5), we have the following two equations

$$1 = x_1 + x_2 \tag{3.6}$$

$$2 = x_1 + x_3 \tag{3.7}$$

So(3.6) and (3.7)has two solutions $(1, 0, 1)$ and $(0, 1, 2)$.We claim for any arbitrary given θ our scheme will converge to the MLE. We drive the likelihood equations to prove our claim. Let

$$L^p\,(\mathbf{y};\theta) = P_\theta\left\{\mathbf{y} = (1,2)^{'}\right\} \tag{3.8}$$

$$= P_\theta\left\{\mathbf{x} = (1,0,1)^{'}\right\} + P_\theta\left\{\mathbf{x} = (0,1,2)^{'}\right\} \tag{3.9}$$

$$= \left(\theta_1\theta_3 + \frac{\theta_2\theta_3^2}{2!}\right)\exp(-\theta_1 - \theta_2 - \theta_3) \tag{3.10}$$

$$= \left(\frac{2\theta_1\theta_3 + \theta_2\theta_3^2}{2}\right)\exp(-\theta_1 - \theta_2 - \theta_3) \tag{3.11}$$

Since we are computing the probability of $\mathbf{y}$ based on Poisson distribution, from(3.11) we can write the following

$$\frac{\theta_3}{2}(2\theta_1 + \theta_2\theta_3)\exp(-\theta_1 - \theta_2 - \theta_3) = 1 \tag{3.12}$$

$$\Rightarrow \exp(-\theta_1 - \theta_2 - \theta_3) = \frac{2}{\theta_3(2\theta_1 + \theta_2\theta_3)} \tag{3.13}$$

Therefore, probability of each $\mathbf{x}$ is given by

$$p(\mathbf{x} = (1,0,1)') = \theta_1\theta_3\exp(-\theta_1 - \theta_2 - \theta_3) \tag{3.14}$$

$$= \theta_1\theta_3\left(\frac{2}{\theta_3(2\theta_1 + \theta_2\theta_3)}\right) \tag{3.15}$$

$$= \frac{2\theta_1}{2\theta_1 + \theta_2\theta_3} \tag{3.16}$$

Similarly, we can compute

$$p(\mathbf{x} = (0,1,2)') = \theta_1\theta_3\exp(-\theta_1 - \theta_2 - \theta_3) \tag{3.17}$$

$$= \frac{2\theta_2\theta_3}{2\theta_1 + \theta_2\theta_3} \tag{3.18}$$

Hence, by first principle

$$E[\mathbf{x}|\mathbf{y}, \Theta] = \sum_{i=1}^{2} x_i p(x_i) \tag{3.19}$$

$$= \begin{pmatrix} 1 \\ 0 \\ 1 \end{pmatrix} \frac{2\theta_1}{2\theta_1 + \theta_2\theta_3} \begin{pmatrix} 0 \\ 1 \\ 2 \end{pmatrix} \frac{2\theta_2\theta_3}{2\theta_1 + \theta_2\theta_3} \tag{3.20}$$

We can write (3.20)in the following fashion

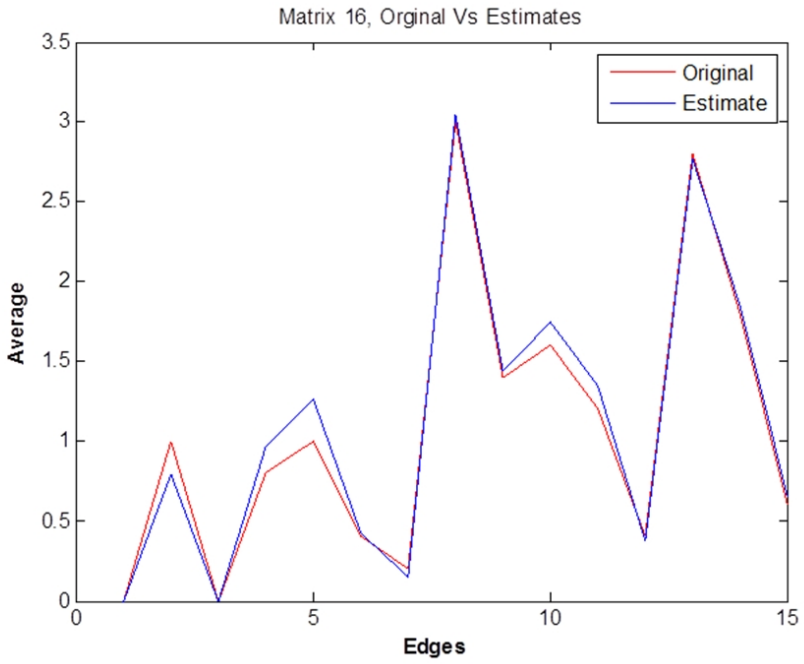
$$\begin{pmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{pmatrix} \leftarrow E[\mathbf{x}|\mathbf{y}, \Theta] = \begin{pmatrix} \frac{2\theta_1}{2\theta_1 + \theta_2\theta_3} \\ \frac{2\theta_2\theta_3}{2\theta_1 + \theta_2\theta_3} \\ \frac{1 + \theta_2\theta_3}{2\theta_1 + \theta_2\theta_3} \end{pmatrix} \tag{3.21}$$

For any arbitrary choice of $\Theta = (\theta_1, \theta_2, \theta_3)$,we plug it back in (3.21), till the difference of two consecutive iteration is minimum, i.e., we find no chance in the iteration scheme

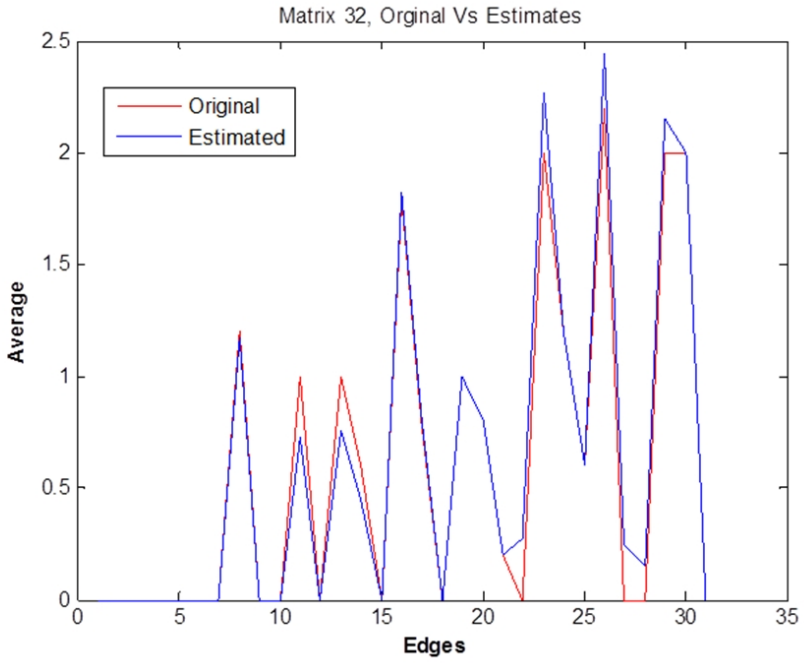
output. We get the following result:

$$\begin{pmatrix} 0.6 \\ 0.3 \\ 1.3 \end{pmatrix} \Rightarrow \begin{pmatrix} 0.75 \\ 0.24 \\ 1.24 \end{pmatrix} \Rightarrow \cdots \begin{pmatrix} 0.99 \\ 0.01 \\ 1.01 \end{pmatrix} \Rightarrow \begin{pmatrix} 1 \\ 0 \\ 1 \end{pmatrix} \Rightarrow \begin{pmatrix} 1 \\ 0 \\ 1 \end{pmatrix} \tag{3.22}$$

In a similar fashion we computed the MLE of network with 16, 32, 64 and 128 nodes.

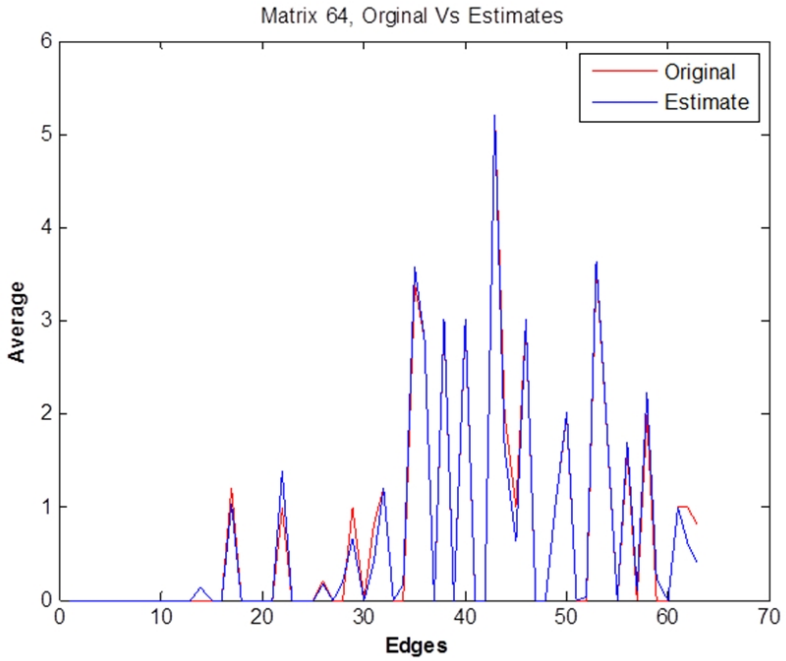


(a) 16 node network with EM estimation

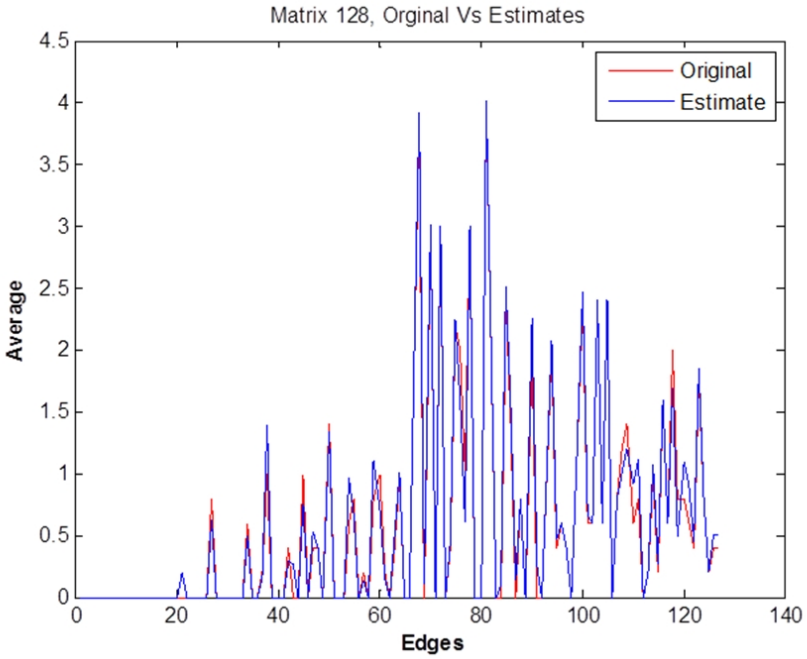


(b) 32 node network with EM estimation

It can be clearly seen from the Figures 3.2 that our estimated based on the EM algorithm are good.



(c) 64 node network with EM estimation



(d) 128 node network with EM estimation

Figure 3.2: EM Algorithm Original and Estimated edge values for various Network sizes

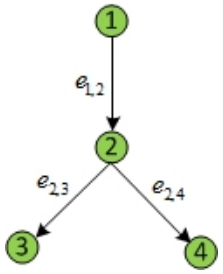
CHAPTER 4

STITCHING ALGORITHM

The proposed stitching algorithm handles the dynamic topologies that occur in MANET environment. The fundamental idea of the stitching algorithm is to observe some characteristic of the topology on which one can identify the time variations. As in most of the dynamical system, one of the most important factor is the stability of the model. Thus, knowing the behavior of the dynamic network in terms of stability, we can determine various time intervals. In our study, we observed the topology of the graph, which governs the topology of the network in time. Thus, knowing the underlying behavior or characteristic can help us determine various time slots. To connect two graphs in two different time slots we use the idea of isomorphism. Isomorphism in networks is discussed in [103] and the analysis of interconnected network is discussed in [104]. Since isomorphism is different in ad-hoc networks, we simple cannot borrow the existing methodologies. We now present the idea of isomorphism in ad-hoc networks, which is very core to the stitching algorithm and its mathematical details of the algorithm.

4.1 Isomorphism.

Let $G_{T_1}(V_{T_1}, E_{T_1})$ and $H_{T_2}(V_{T_2}, E_{T_2})$ be two directed graphs in two different time period. Here V and E are non-empty sets called the vertex-set and edge-set receptively. We now define the isomorphism mechanism in mobile ad-hoc environment. Let us consider the network in Figure 4.1(a)and its corresponding path matrix called P_G in Figure 4.1(b). In matrix P_G 1 means that a particular edge is traverse, when traveling on a path and 0 means otherwise. The matrix P_G defines the topology of a network based on the edge and their connectivity. So in the case, when the topology



(a) Directed graph

$$P_G = \begin{array}{c} \begin{matrix} e_{1,2} & e_{2,3} & e_{2,4} \end{matrix} \\ \begin{pmatrix} 1 & 1 & 0 \\ 1 & 0 & 1 \end{pmatrix} \end{array} \begin{matrix} path1 \\ path2 \end{matrix}$$

(b) Path matrix

Figure 4.1: Directed graph G and its corresponding path matrix P_G.

changes we expect to get a different path matrix. We formalize the isomorphism between the edges in the following lemma:

Lemma 1. *Let $G_{T_i}(V_{T_i}, E_{T_i})$ and $H_{T_j}(V_{T_j}, E_{T_j})$ be two directed graphs with P_{G_i} and P_{H_j} path matrices associated with these two graphs respectively in two different time period. Then the topology of the network will not change in terms of edges if the following rule holds:*

$$P_{G_i} - P_{H_j} = 0.$$

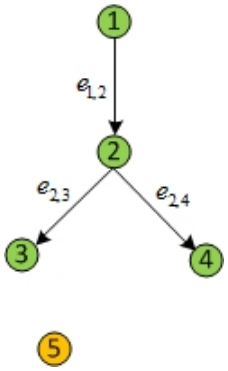
Proof. The proof to the lemma is straight forward. It is clearly seen that two matrices can only be subtracted if the dimensions are same. So in our case if:

$$P_{G_i} - P_{H_j} = 0.$$

Then it is clear that the topology in terms of edges are same and hence we got 0. In the case topology has changed, we will get a non zero matrix or maybe even matrices are of different sizes and subtraction is not possible. But in any case we can conclude that topology has changed. □

It is important to notice in Figure 4.2(a) that node 5 is not communicating or part of the active communication at that moment but still it is considered to be the part of the network.

Lemma 2. *Let $G_{T_i}(V_{T_i}, E_{T_i})$ and $H_{T_j}(V_{T_j}, E_{T_j})$ be two digraphs with V_{G_i} and V_{H_j} be the vertex matrices associated with the two graphs respectively in two different time*



(a) Directed graph

$$V_G = \begin{array}{c} \begin{matrix} v_1 & v_2 & v_3 & v_4 & v_5 \end{matrix} \\ \begin{pmatrix} 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 0 \end{pmatrix} \end{array} \begin{matrix} \\ path1 \\ path2 \end{matrix}$$

(b) Path matrix of the graph

Figure 4.2: Directed graph G and its corresponding vertex matrix V_G.

period. Then the topology of the network will not change in terms of vertex if the following rule holds:

$$V_{G_i} - V_{H_j} = 0.$$

Proof. The proof of the lemma is straight forward. It follows very close to the proof of lemma 1. □

Now, to show two graphs in ad-hoc network environment are isomorphic, we present the following theorem:

Theorem 1 (*Strict Isomorphism*)**.** *Two directed graph G_{T_i} and H_{T_j} are isomorphic to each other if the following two properties hold:*

$$P_{G_i} - P_{H_j} = 0 \tag{4.1}$$

$$V_{G_i} - V_{H_j} = 0 \tag{4.2}$$

Proof. To show two simple directed graphs are isomorphic to each other, we consider the following cases:

Case 1: Suppose the path matrix P_{G_i} and P_{H_j} of the two graph are not same i.e. $P_{G_i} - P_{H_j} \neq 0$. Then we know the edge topology has changed and we begin a new monitoring period. So lemma 1 is sufficient enough to guarantee the change in topology.

Case 2: Suppose the lemma 1 holds, but it is not sufficient enough to guarantee the

isomorphism in ad-hoc network. If the topology of the network is same from the previous time slot but the nodes are labeled different. This situation from an ad-hoc network point of view is consider as change in topology. To handle this we must show isomorphism at vertex level as well, this is achieved by lemma 2. So to show any two arbitrary simple digraph are isomorphic to each other $V_{G_i} - V_{H_j} = 0$ should hold. □

4.2 Implementation of Stitching Algorithm.

Let us consider the scenario is Figure 4.3. When the network topology changes between measurement instances t_{1,n_1} and $t_{2,1}$, we cannot take simple average across observation periods. In this case, stitching of two topologies has to take place. The stitching is performed based on theorem 1 such that the performance parameters of isomorphic edge values between the two graph are aggregated and non-isomorphic edges are kept as it is. The stitching procedure is to average the common edges of the network topologies while the remaining elements are concatenated into a new vector, representing as new *T's*. To understand the way *T's* work, we illustrate the procedure in the following example.

4.2.1 An Example of Stitching Algorithm.

Let us consider the topology of the two graph presented in Figure 4.3 over two distinct measurement period T_1 and T_2. As we can observe from the two graphs, edges $e_{1,2}, e_{2,3}, e_{2,4}$ are common to both topologies and others are not. In calculating combined network performance parameters for both graphs, the average of $e_{1,2}, e_{2,3}, e_{2,4}$ will be taken while parameters values of other edges will be added to the edge set. The edge set for observation period T_1 can be expressed as:

$$Edge\,set(T_1) = \{e_{1,2}, e_{2,3}, e_{2,4}\} \tag{4.3}$$

The edge set for the observation period T_2 can be expressed as:

$$Edge\,set(T_2) = \{e_{1,2}, e_{2,3}, e_{2,4}, e_{3,5}, e_{3,6}, e_{4,7}, e_{4,8}\} \tag{4.4}$$

Then the new T_2 is represented by the following stitching operation:

$$\Phi = \{Edge\,set(T_1) \cup Edge\,set(T_2)\} \tag{4.5}$$

$$= \{e_{1,2}(T_1 \cup T_2), e_{2,3}(T_1 \cup T_2),$$

$$e_{2,4}(T_1 \cup T_2), e_{3,5}, e_{3,6}, e_{4,7}, e_{4,8}\}, \tag{4.6}$$

We define the stitching operation is the following definition;

Definition 1 (*Stitching Operation*). *The stitching operation*

$$\prod_{k=1}^{n} e_{i,j}(T_1, t_{1,k})$$

means how many time the edge $e_{i,j}$ appears in the time interval T_1 over the time instances t_k for $k = 1, ..., n$.

Definition 2 (*Stitching Performance Metric*). *The number $e_{i,j}(T_1 \cup T_2) \in \mathbb{R}$ is defined by*

$$e_{i,j}(T_1 \cup T_2) = \frac{\prod_{k=1}^{n_1} e_{i,j}(T_1, t_{1,k}) + \prod_{l=1}^{n_2} e_{i,j}(T_2, t_{2,l})}{(n_1 + n_2)} \tag{4.7}$$

measures the performance of the network over two time period T_1 and T_2.

In (4.7), $e_{i,j}(T_1, t_k)$ is the performance evaluation for t_k during observation period T_1 and similarly $e_{i,j}(T_2, t_l)$ is the performance evaluation for t_l during the T_2. Also n_1 and n_2 are the number of measurement periods for T_1 and T_2 respectively. In (4.7), we assume that $i \neq j$. As shown in (4.6), only the common link performance parameters are naturally aggregated with the previous evaluations. So, in general (4.7) can be expressed in the following closed form:

$$e_{i,j}(\bigcup_{v=1}^{m} T_v) = \frac{\sum_{k=1}^{m} \sum_{l=1}^{n} e_{i,j}(T_l, t_{l,n_k})}{\sum_{w=1}^{m} n_w}, l \leq k \tag{4.8}$$

4.2.2 Simulation Results for Static Network.

We now present two cases, which presents variation of applying stitching algorithm. Stitching is applied on network presented in Figure 4.4(a) and 4.4(b).

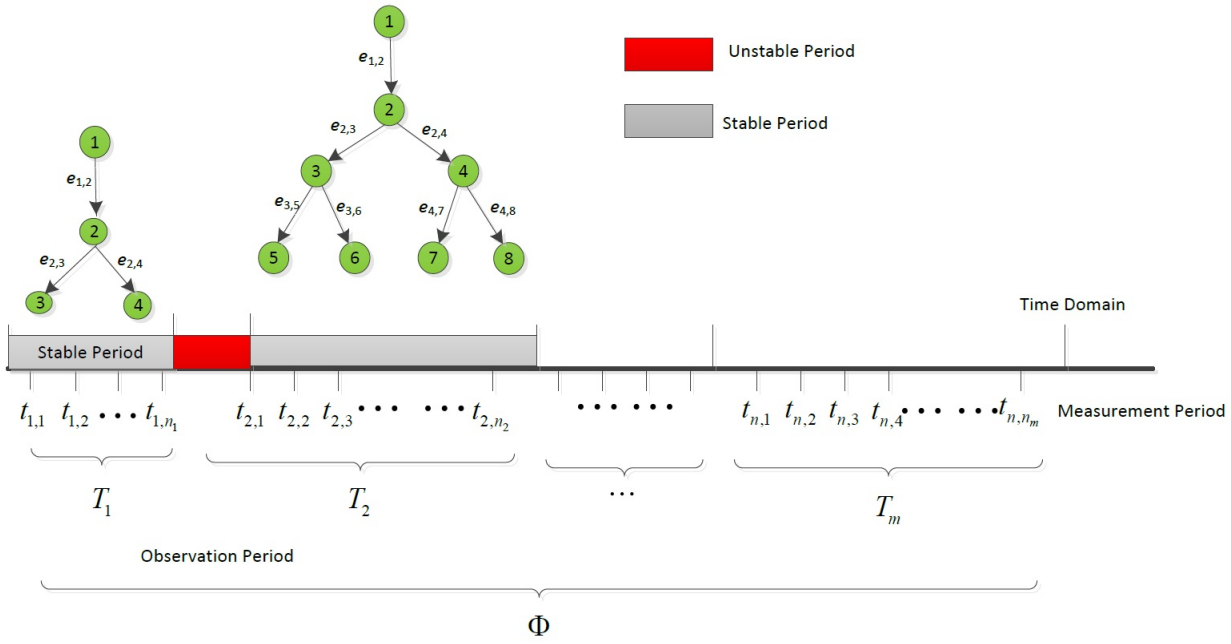
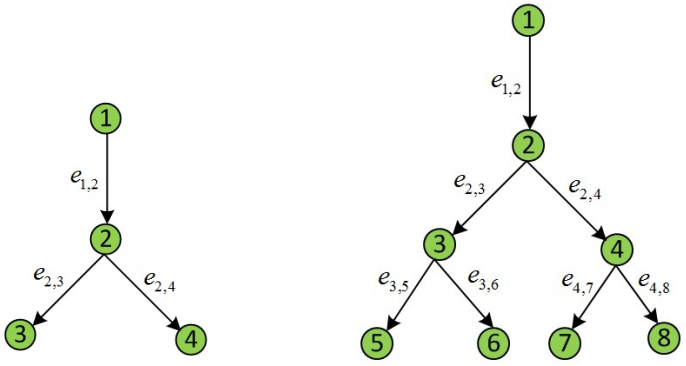


Figure 4.3: Stitching algorithm implementation on a dynamic network in different time domains.



(a) Four-Node Directed Network

(b) Eight-Node Directed Network

Figure 4.4: Directed graphs in G and H two different time instant T_1 and T_2.

Case 1: In this case we consider the topology is unchanged from one time instance to another. Assume that the current state of topology is of size 4 nodes and next topology is also of size 4 from Figure 4.4(a). Topology of the network didn't change from 4 node graph and its observations are presented in Table 4.1. It can

TABLE 1

Estimation for 4-node graph in $T_{1,1}$

	Edges		
	$e_{1,2}$	$e_{2,3}$	$e_{2,4}$
Original	2	2	0
Estimates	1.998	2.002	0.002

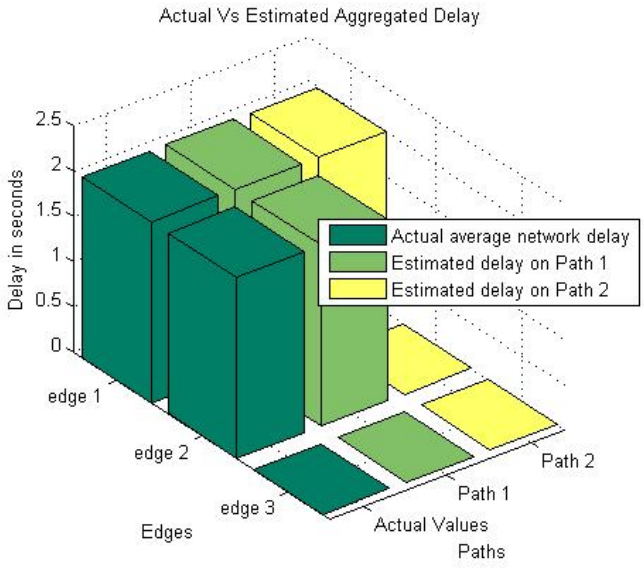


Figure 4.5: Path analysis of 4-node network in $T_{1,1}$

be seen in the Figure 4.5 that our approximation on the two distinct paths are very good, when comparing with the actual delay on the network.

Once again the network topology remained same and we computed the edges performance on all the edges. This result is presented in Table 4.2.

As expected the approximation on the two distinct paths of the network are

TABLE 2

Estimation for 4-node graph in $T_{1,2}$

	Edges		
	$e_{1,2}$	$e_{2,3}$	$e_{2,4}$
Original	7	0	13
Estimates	6.9860	0.0140	13.0140

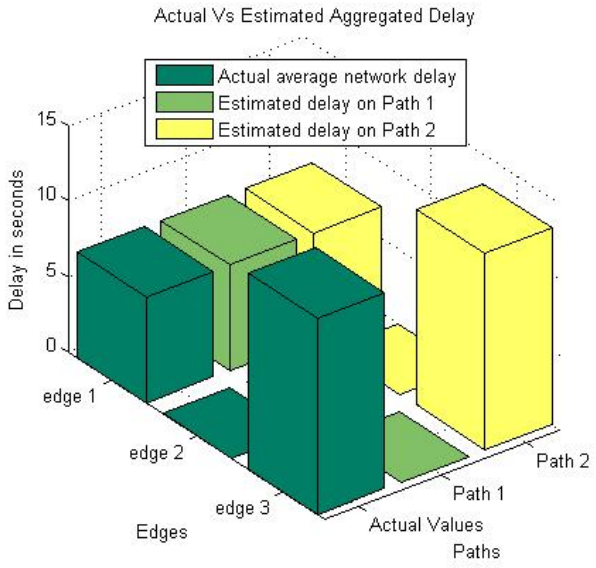


Figure 4.6: Path analysis of 4-node network in $T_{1,2}$

very good as compare to the actual delay of the entire network. This is clear seen in the Figure 4.6. Since the topology is changed to 8-node graph. Stitching algorithm

TABLE 3

Aggregated Result

	Edges		
	$e_{1,2}$	$e_{2,3}$	$e_{2,4}$
Average Original	4.5	1	6.5
Average Estimates	4.492	1.008	6.508

aggregated the performance of the all the common edges over the stable period till the topology changed again. This aggregated performance in presented in Table 4.3. Figure 4.7 shows the edge by edge analysis of two different paths and it can be clearly from the accuracy of our approximation is accurate compare to the actual delay of the network.

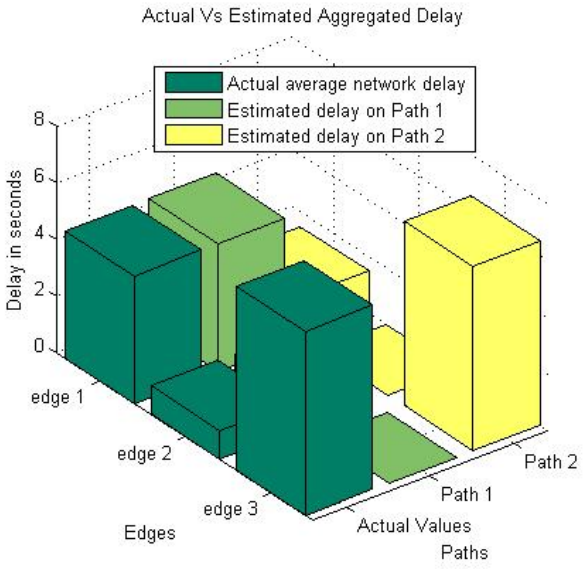


Figure 4.7: Path analysis of 4-node network over time period $T_{1,1}$ and $T_{1,2}$

Now, we wishing to observe the performance of the network over a period of time. To do this, we implemented the proposed stitching algorithm. Stitching

algorithm uses the idea of isomorphism to to stitch the common edges and carry forward the non-common edges.

Case 2: Now suppose, next topology is changed and it is a 8 node graph as presented in Figure 4.4(b). So according to our stitching algorithm, values in Table 4.3 will be concatenated with the common edges of the new graph. The non-common edge values are carried forward as show in Table 4.4.

TABLE 4

Stitched values from different time instances

	Edges						
	$e_{1,2}$	$e_{2,3}$	$e_{2,4}$	$e_{3,5}$	$e_{3,6}$	$e_{4,7}$	$e_{4,8}$
Avg Original	4.5	1	6.5				
Original	4	0	4	2	0	0	4
Avg Estimates	4.492	1.008	6.508				
Estimates	3.8652	0.1339	4.0078	2.0009	0.0009	0.1269	4.1269
New Avg Est	4.1786	0.5709	5.2579	2.0009	0.0009	0.1269	4.1269
New Avg Orig	4.25	0.5	5.25	2	0	0	4

Table 4.4 presents the entire network performance from the initial edges and the concatenated edges over time and also those edges which were not aggregated over the monitoring period.

In network performance analysis it is important to know the global performance of the network. But network performance monitoring becomes difficult when the nework are dynamic and ad-hoc in nature. Pertaining to these attributes our proposed stitching algorithm is different. Apart from providing global performance evaluation without any or less cooperation from the nodes, it also provides local performance analysis, that is edge by edge performance. Local performance analysis is very critical in overall performance of the network specially, when the network is ad-hoc in nature.

In Figure 4.8, we see the path by path and edge by edge performance comparison with

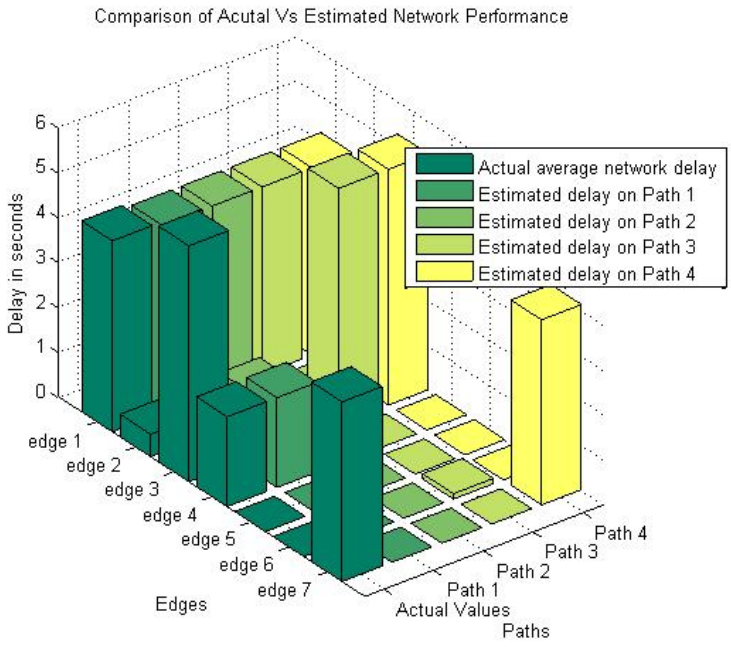


Figure 4.8: Path analysis of the entire monitoring period

the actual performance of the network. This fine grain analysis of the network gives the proposed stitching algorithm edge over the existing performance analysis tools in ad-hoc network.

CHAPTER 5

NETWROK TOMOGRAPHY APPLICATION IN WIRELESS MESH NETWORK

Ad-hoc networks are multi-hop networks consisting of wireless autonomous hosts, where each host may serve as a router to assists traffic from other nodes. Wireless ad-hoc networks cover a wide range of network scenarios, including sensor, mobile ad-hoc, personal area, and rooftop/mesh networks. Sensors provide service to monitoring stations. Mobile ad-hoc networks are pure infrastructure less networks used in disaster relief, conference, hospital, campus and battlefield environments, with laptops, palmtops, cellular phones or other devices serving as nodes. Rooftop/mesh networks provide high-speed wireless Internet access to homes and offices.

In general Mobile ad-hoc network is a dynamic, hostile, hierarchical, and hybrid system that operates in the peer-to-peer mobile ad-hoc network (MANET) [105, 106] environment. Without or with very less infrastructure support, MANET wirelessly interconnects mobile nodes (user terminals, command and control devices like routers, gateways, application servers, or other terrestrial communication components) to provide persistent communications [106].

5.1 Wireless Mesh Network.

With the rapid development of networks in recent years, people nowadays want to access high-bandwidth network anytime and anywhere for the use of ubiquitous network services. Owing to its high transmission rate, low deployment cost, and high coverage, wireless mesh networks (WMN)have replaces wired network gradually and even performs well in residential areas that are incapable of line-of-sight transmission. In Figure 5.1 we present a general wireless mesh network framework (WMN). A

wireless mesh network is a communications network made up of radio nodes organized in a mesh topology. Wireless mesh networks often consist of mesh clients, mesh routers and gateways. The mesh clients are often laptops, cell phones and other wireless devices while the mesh routers forward traffic to and from the gateways which may but need not connect to the Internet. The coverage area of the radio nodes working as a single network is sometimes called a mesh cloud. Access to this mesh cloud is dependent on the radio nodes working in harmony with each other to create a radio network. A mesh network is reliable and offers redundancy. When one node can no longer operate, the rest of the nodes can still communicate with each other, directly or through one or more intermediate nodes. In typical WMN as shown in Figure

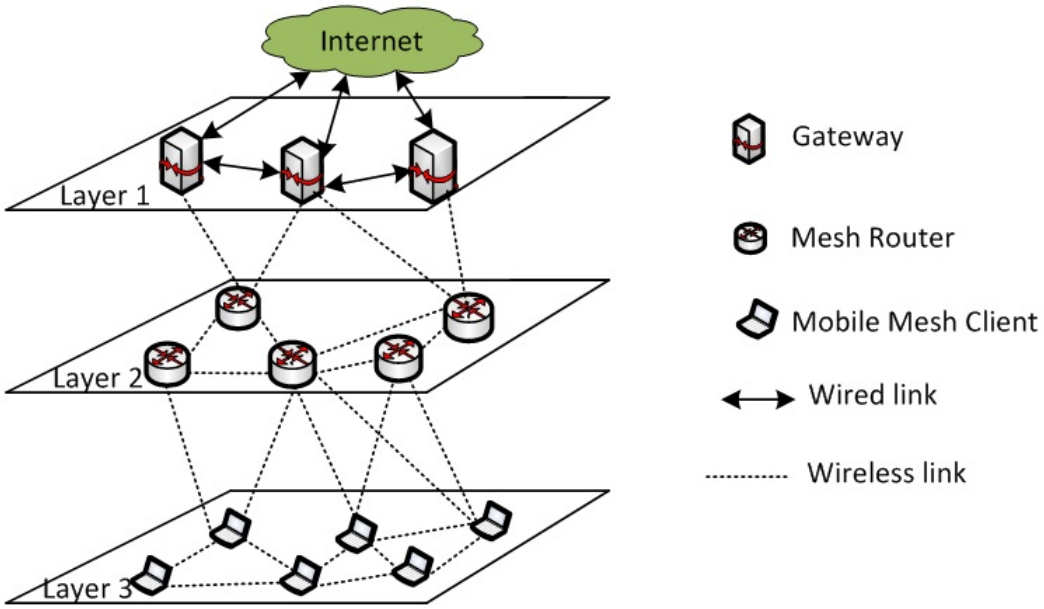


Figure 5.1: Typical wireless mesh network architecture.

5.1, the constitution of the nodes can be divided into three layers. The first layer is composed of Internet Gateways (IGWs), which is responsible for connecting external wired networks and internal MR (Mesh Router) to provide network services. MR in the second layer takes the responsibility for connecting the Mesh Clients (MCs) in the third layer and the IGW in the first layer [107]. According to this constitution, WMNs can be classified into three kinds, Infrastructure WMNs, Client WMNs and

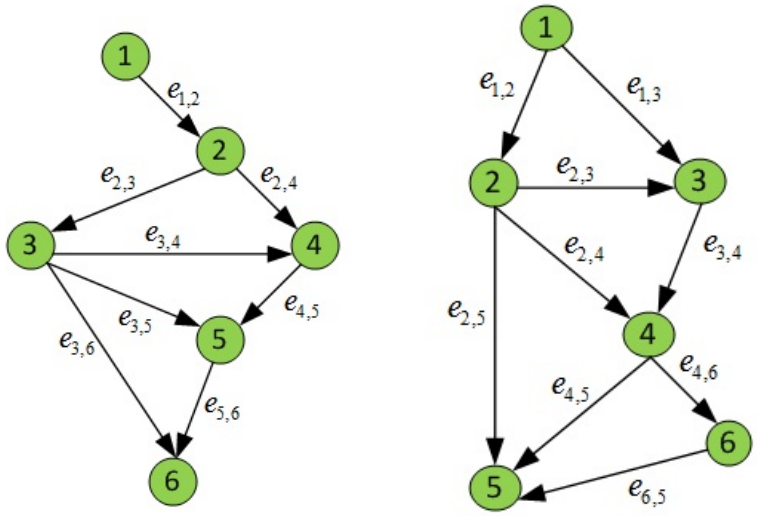
Hybrid WMNs [108]:

- **Infrastructure WMNs**: MR connects the IGW and MCs,and MR can form a backbone for MCs transmissions.
- **Client WMNs**: This peer-to-peer structure is constructed by MCs. In such an ad-hoc network, MCs manage the routing and the organization. Mesh Routers are not necessary.
- **Hybrid WMNs**: This hybrid architecture is composed of Infrastructure WMNs and Client WMNs as shown in Figure 5.1. MCs can connect to MR or connect with one another through MCs.

5.2 Network Tomography Application on WMN.

It is of great importance to monitor the performance of a Wireless Mesh Network (WMN) in terms of resource allocation, detecting faults in the network or detecting alternative routes in case of communication failure between the nodes, in a timely and accurate way.

Network Tomography along with the proposed Stitching Algorithm is a natural and a very effective way to monitor the performance of WMN over a period of time. One of the major advantage of using NT approach over the existing approaches is that requires least or no cooperation from the nodes. Figure 5.2 illustrates the basic idea of the proposed network tomography for WMN. In the time domain, the WMN topology is divided into subsequent graphs, based on the collected traffic measurements. These graphs again represent continuous WMN steady states and each steady state stands for a minimal measurable time period (i.e., measurement period) which can be very small and scale to WMN mobility. Figure 5.2(a) and (b) are two different time periods, denoted by T_1 and T_2. In Figure 5.2(b), the wireless links (e.g., the links from node 1 to nodes 2 and 3) for communication are changed along the node mobility. For each time period, PLE algorithm is efficient enough to estimate the network performance in the associated period. Furthermore, the stitching algorithm is developed to aggregate



(a) Network G (b) Network H

Figure 5.2: Arbitrary WMN in two different time instances T_1 and T_2

the network performance for each node, link, and end-to-end path over time. As the topology changes, the stitching algorithm aggregates the end-to-end node performance such that the network performance can be tracked for each communication paths from the topological stand point of view. Path matrix of the network G nd H in Figure 5.2 are presented below:

In Figure 5.3 (a) and (b), each row represents the unique possible paths in a network, with 1 means that particular edge has traverse and 0 means otherwise.

Assuming that the topology of the WMN changes in the above two path matrix. To determine, whether or not the topology has changed, stitching algorithm will use the idea of isomorphism. It of great importance to that we need at least 30 percent of connectivity in a network. This is critical to avoid the sparsity of the path matrix. Sparse matrices regularly occur in solving the inverse problems. Equation (5.1)

$$\mathbf{y} = P_G \mathbf{x} \tag{5.1}$$

with a know $\mathbf{y}$ and P_G and unknown $\mathbf{x}$ becomes a very challenging and numerically intense problem to solve directly. So, to solve this problem we have to solve it indirectly and estimate the solution statistically using the maximum likelihood and expectation-maximization like algorithm.

$$P_G = \begin{array}{c} \begin{matrix} e_{1,2} & e_{2,3} & e_{2,4} & e_{3,4} & e_{3,5} & e_{3,6} & e_{4,5} & e_{5,6} \end{matrix} \\ \begin{pmatrix} 1 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix} \end{array} \begin{matrix} \\ path1 \\ path2 \\ path3 \\ path4 \end{matrix}$$

(a) Path matrix of network G

$$P_H = \begin{array}{c} \begin{matrix} e_{1,2} & e_{1,3} & e_{2,3} & e_{2,4} & e_{2,5} & e_{3,4} & e_{4,5} & e_{4,6} & e_{6,5} \end{matrix} \\ \begin{pmatrix} 1 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 1 \end{pmatrix} \end{array} \begin{matrix} \\ path1 \\ path2 \\ path3 \\ path4 \\ path5 \\ path6 \\ path7 \end{matrix}$$

(b) Path matrix of network H

Figure 5.3: Path matrix of network G and H

5.3 EM Routing.

In WMNs, the nodes usually choose the shortest path or the path with the fewest hops for their transmissions, but this cannot guarantee the quality and efficiency of the path. For this reason, we need a routing metric for choosing the path of high quality and efficiency, and maintaining the optimal path whenever the net flow changes so that the load balance of the network can be guaranteed. We propose EM routing to decide the optimal path for MCs in term of minimum hops. But it is not necessary that the shortest path is the optimal path. EM routing will choose the optimal path in terms of hops and also in terms of performance parameter like delay. Thus, increase the communication efficiency and decrease the interference impact by improving the load balancing scheme.

5.3.1 Mathematical Model of EM Routing.

To the very core of the proposed EM routing is to solve the following inverse problem

$$\mathbf{y} = P_G \mathbf{x} \tag{5.2}$$

In equation (5.2) $\mathbf{y}$ is the total performance parameter value from source to destination and P_G is the path matrix of all the possible paths between source and destination. Here $\mathbf{x}$ is the global performance parameter of the network at a given instance of time. The equation in (5.2)can be expanded in the following fashion using the network in Figure 5.2(a) and it corresponding path matrix in Figure 5.3(a):

$$\begin{pmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_8 \end{pmatrix} \tag{5.3}$$

The optimum paths in terms of hops and performance parameter can be obtain from equation (5.3).

EM Routing Algorithm.

EM routing algorithm essentially base on solving the inverse problem presented in (5.2). Once the $\mathbf{x}$ are estimated using PLE algorithm , we can rewrite (5.3) in the following fashion:

$$\begin{pmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{pmatrix} = \begin{pmatrix} x_1 + x_3 + x_7 + x_8 \\ x_1 + x_2 + x_4 + x_7 + x_8 \\ x_1 + x_2 + x_4 + x_5 + x_8 \\ x_1 + x_2 + x_6 \end{pmatrix} \tag{5.4}$$

In (5.4), we can see the total network performance associated with each path, where each x represents the performance parameter in terms of delay for the entire network. Based on (5.4) we can compute the optimum network path with minimum delay. This

formulation is presented below:

$$y_j = \sum_{i=1}^{8} \omega(j,i) x_i, j = 1, \cdots, 4 \tag{5.5}$$

$$Optimum_{path} = min(y_j) \tag{5.6}$$

In the similar fashion we can compute the optimum path in terms of hops. Every non-zero entry on each path is equal to a hop. Thus counting the number of non-zero elements on each path will suffice to give us a optimum path with minimum hops. This can be formulated in the following way:

$$y_k = \sum_{i=1}^{4} \sum_{j=1}^{8} a_{i,j}, \forall a_{ij} \in A, k = 1, \cdots, 4 \tag{5.7}$$

$$Optimum_{Hop} = min(y_k) \tag{5.8}$$

Once we have calculated the $Optimum_{Hop}$, we can calculate the optimum path by just multiplying the $\mathbf{x}$ with the matrix A. The pseudo code of the algorithm is given below.

Algorithm 2 EM Routing Algorithm

begin

initialize $\mathbf{y}, P_G, count = 0$

Estimates x: compute $\mathbf{y} = P_G\mathbf{x}$

Delay: $y_i = min(\sum_{j=1}^{n} edge_{delay_{i,j}}), i = 1, \cdots, m$

Hop: $y_i = min(\sum_{i=1,j=1}^{m,n} count(a_{ij} = 1)), \forall a_{ij} \in P_G$

return $min(delay, hop)$

end

5.3.2 Simulation Results

Let us consider the following source to destination network. In this network node 1 is the source and node 6 is the destination. In the Figure 5.4, it is important

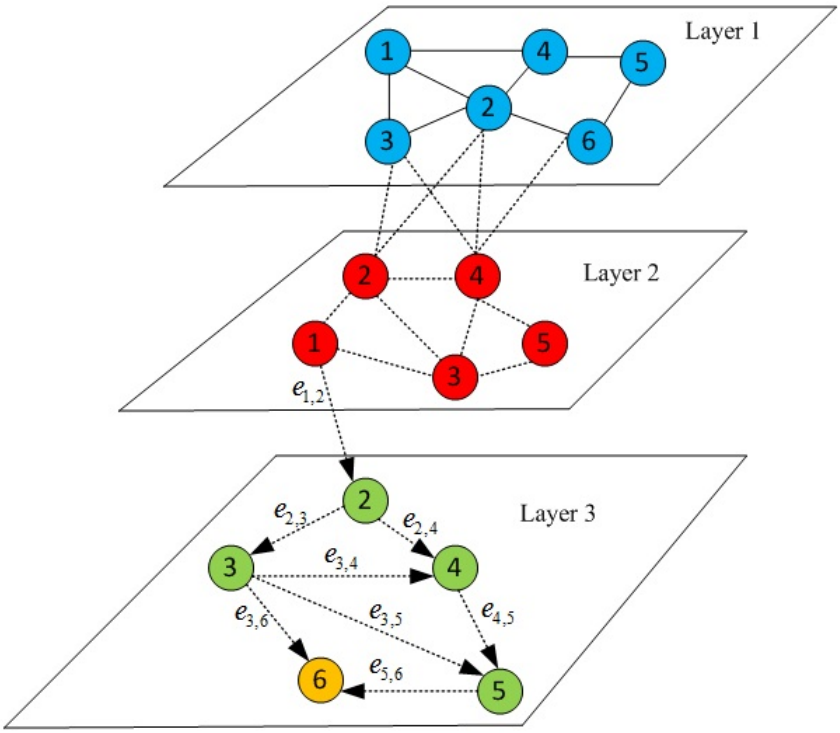


Figure 5.4: Layered Source-to-Destination architecture in WMN.

to notice that red node 1 is actually a mesh router, which belongs to network layer 2. Rest of the architecture in Figure 5.4 is same as in Figure 5.1.

TABLE 5

Estimation for 8-node WMN

	Edges							
	$e_{1,2}$	$e_{2,3}$	$e_{2,4}$	$e_{3,4}$	$e_{3,5}$	$e_{3,6}$	$e_{4,5}$	$e_{5,6}$
Original	1	0	1	1	1	0	3	0
Estimates	0.7193	0.2557	1.1403	0.9122	1.1403	0.1127	3.1127	0.0249

In Table 5.1, we present the estimates per edges on the entire network. It can be clearly seen from the Table 5.1 that our estimates are good, when comparing with the original data. In Figure 5.5, we present the path by path analysis of the 6 node WMN in Figure 5.2(a). With the implementation of the EM routing algorithm on the entire network after computing the estimates per edge. The optimum path in terms

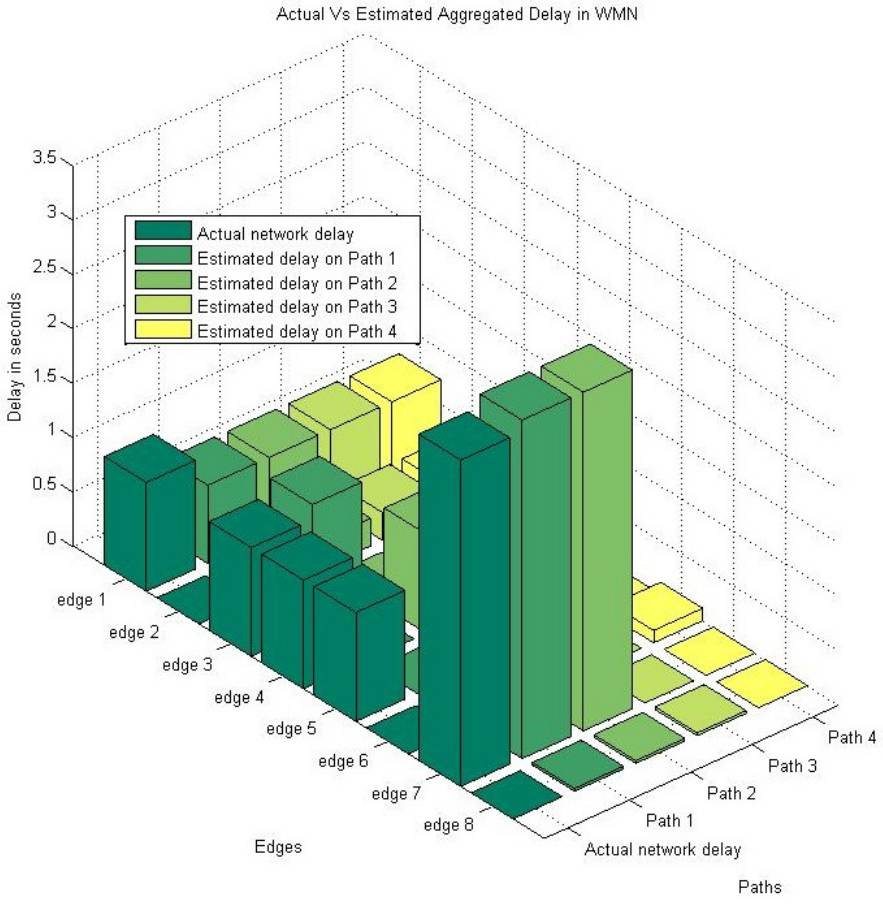


Figure 5.5: Path analysis for 6-node WMN.

of delay and hop, we present the in Figure 5.6.

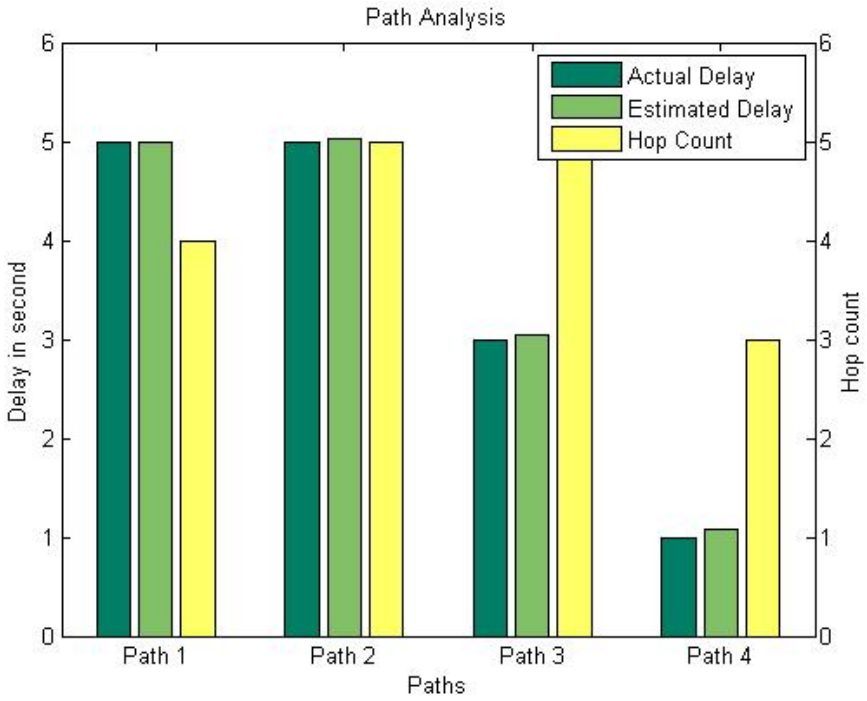


Figure 5.6: EM routing path and hop analysis for WMN.

In Figure 5.6, we compare all the possible paths with the actual delay on those paths and their respective hop count. It is worth nothing that our scheme not only can give path performance in terms of delay but also in terms of number of hops are taken on each path. This is absolutely vital in WMN because shortest path may not necessary be the best path. Thus our methodology provides multiple network performance monitoring.

Our proposed methodology is also useful in load balancing scheme in a WMN network by providing congestion on each link and hence causing delay for the information to travel to it destination.

CHAPTER 6

EXPERIMENTS AND RESULTS

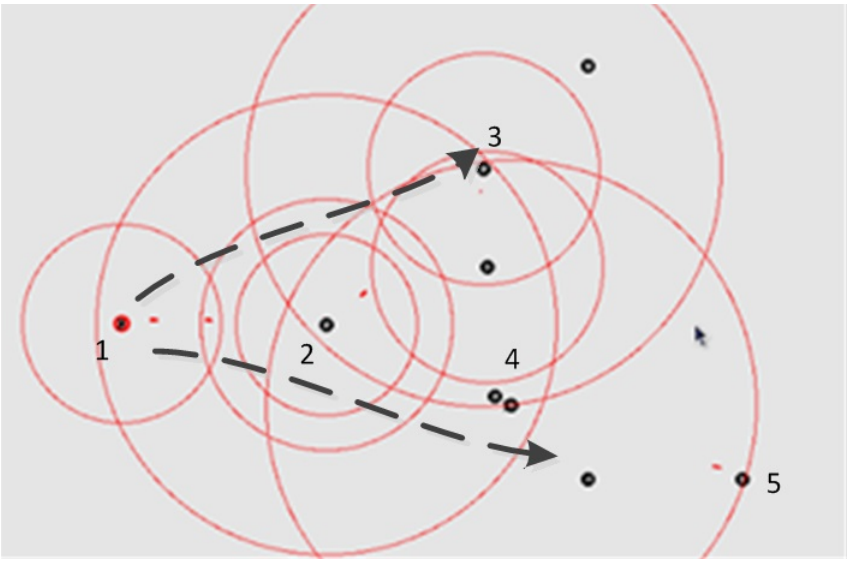
6.1 Simulation Result for Dynamic Network.

In Figure 6.1, we show the simulation of information flow in a dynamic network using NS-2 simulator. Simulations were performed on different scenarios with different nodes as shown in Figure 6.1(a). In the dynamic network, the traffic flow are generated between any two nodes. In our simulation, we consider two flows that are generated in the network domain in Figure 6(a). The Figure 6.1(b) depicts these flows that represent the traffic in Figure 6.1(a). The first flow is from node 1 to node 3 and the other flow from node 1 to node 5 as shown in Figure 6.1(b). Data is then collected in different dynamic network scenarios with different traffic load and node mobility. We analyze the delay in terms of:

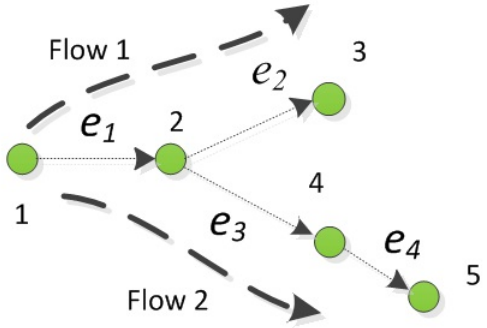
- **Edge estimated delay:**The estimated delay is evaluated by the PLE algorithm.
- **Edge actual delay:** The actual result is computed from the actual network datasets.
- **End-to-end flow delay:** The network performance is represented by the path delay. We ignore this since it can be easily computed from the edge delay.

6.1.1 PLE for an Observation Period.

In the dynamic network, we use the PLE algorithm to estimate the delay for four edges ($e_1 - e_4$) in Figure 6.1. The monitoring is based on the stable observation period and we compare the estimated results with the actual delay. In the observation period, the network topology is maintained the same as in Figure 6.1. In Figure 6.2(a),

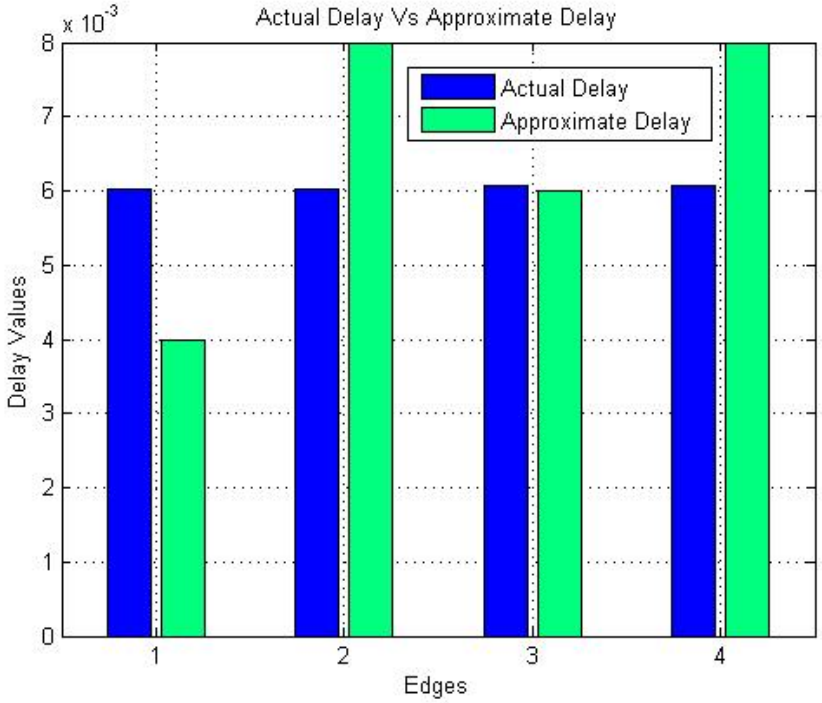


(a) Part of a simulated MANET with flows

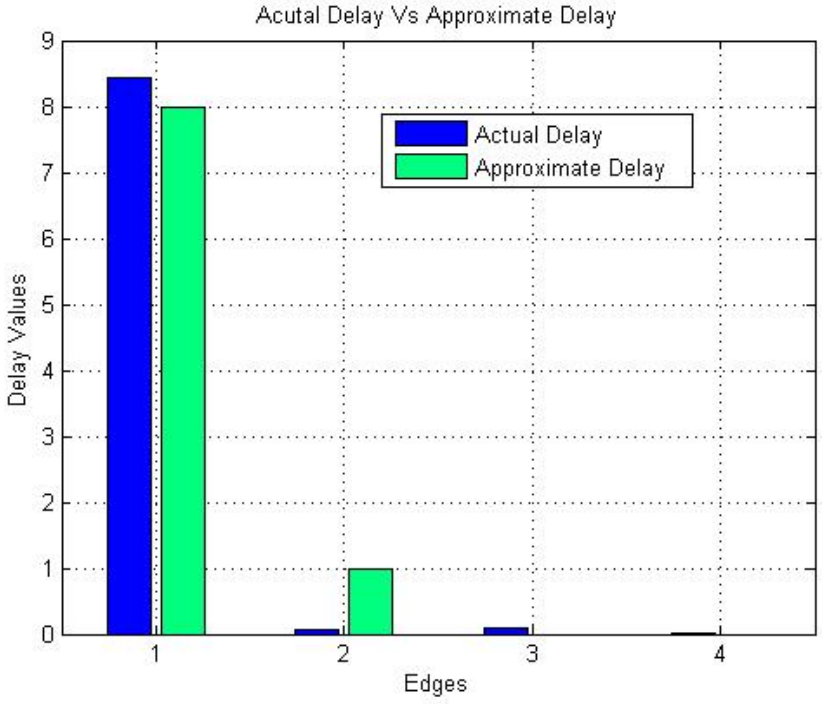


(b) Two monitored flows from (a)

Figure 6.1: NS-2 simulation for a dynamic network



(a) Delay for light traffic load



(b) Delay for very high traffic load

Figure 6.2: Comparison of delay in light traffic load and very high traffic load.

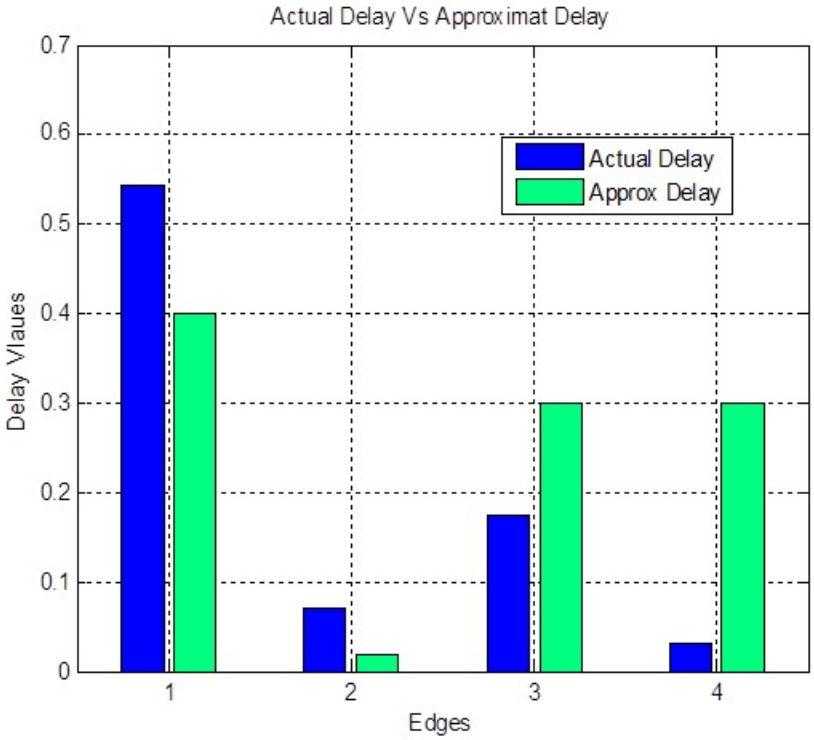
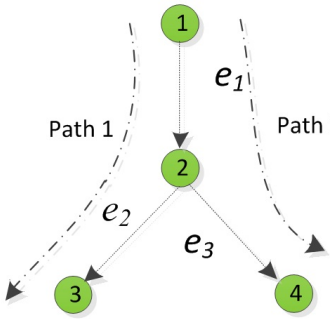
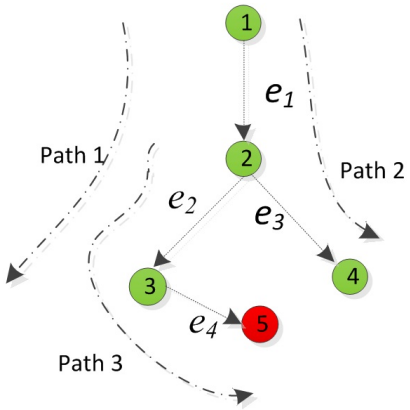


Figure 6.3: Delay in high traffic load

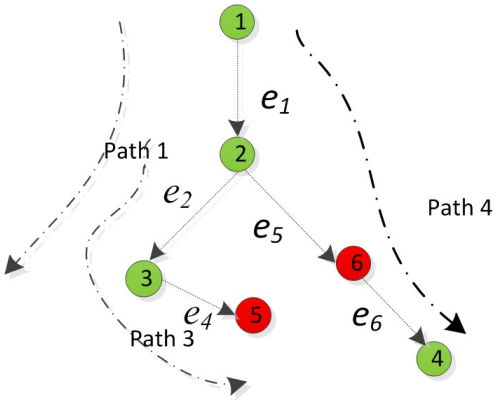
we can see the estimated and actual results in the scenario while the traffic flow loads are light. We say light traffic means that the traffic queue is not overflowed. In such a case, the estimated delays for $e_1 - e_4$ are close to the actual result and they are in the scale of 10^{-3} second. On the other hand, Figure 6.2(b) shows the estimated and actual results in the scenario that both information flows (e.g., Flow 1 and Flow 2 in Figure 6.1) are overloaded. In such a case the estimated result shows that the delay on edge 1 (i.e., from node 1 to node 2) is very high (e.g., about 8 seconds in Figure 6.2(b)). We checked the actual network condition and found the delay is caused by long buffering time at node 1. The long buffering delay is caused by overloaded traffic at node 1. Node 1 could not transmit its packets in time, due to high volume of traffic and interference with other transmissions in the vicinity. Thus from the result in Figure 6.2(b), we can see that the PLE algorithm is able to estimate the delay and correctly identify the overloaded node. In Figure 6.3, we notice another observation period with a relative high traffic load. By using the PLE algorithm, the delays at



(a) Observation Period T_1



(b) Observation Period T_2



(c) Observation Period T_3

Figure 6.4: Network Topology of a Dynamic Network

edges 1, 3, 4 are all still high. Edge 1 still has the highest delay. The estimated results match to the actual situation. In addition to high traffic load, we checked the dynamic network condition and found there are other transmissions in the vicinity that increases the delay at nodes 3 and 4.

Monitoring Period with Dynamic Network Topology.

We continue to use the simulation system in Figure 6.1 to illustrate delay estimation for a dynamic network. As we discussed, a monitoring period T for a dynamic network consists of a number of observation periods, and each observation period represents a stable network topology. Figure 6.3 depicts the simulated dynamic network in Figure 6.1 for us to illustrate the network topology over the monitoring period which includes three observation periods. It is important to notice that in Figure 6.3 only the connected nodes for traffic transmissions are show. In other words, the nodes without communicating with nodes 1-4 are not plotted in Figure 6.4. In Figure 6.4 there are several traffic flow paths that are interconnected. The movement of node 4 and node 6 causes the topology to change. The observation periods shown in Figure 6.4 are:

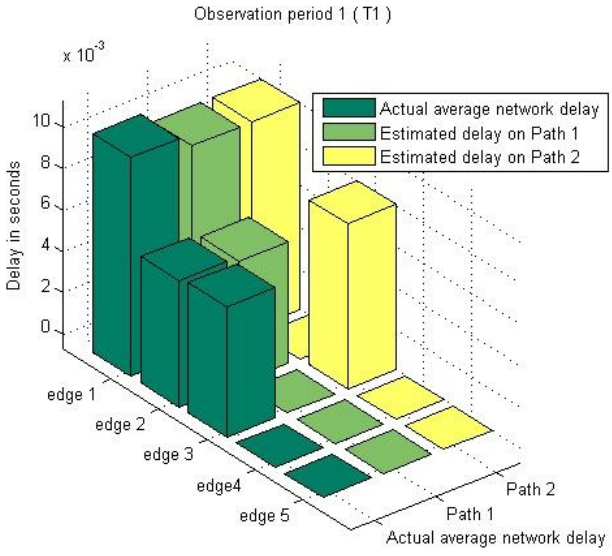
- **Observation Period 1** (i.e.,T_1):The observation period starts with two flows on Path 1 and Path 2 respectively. In our collected data, observation period 1 is the time period from 3.000 second to 5.3115 second after the network is started, e.g.,T_1 [3.000, 5.3115].

- **Observation Period 2** (i.e.,T_2):Node 5 is a mobile node and it communicates with node 2 when moves close to node 3. It starts a new flow over Path 3 and thus a new observation period starts. In our collected data, observation period 2 is the time period from 5.3115 second to 11.3020 second, e.g., T_2 [5.3115, 11.3020].

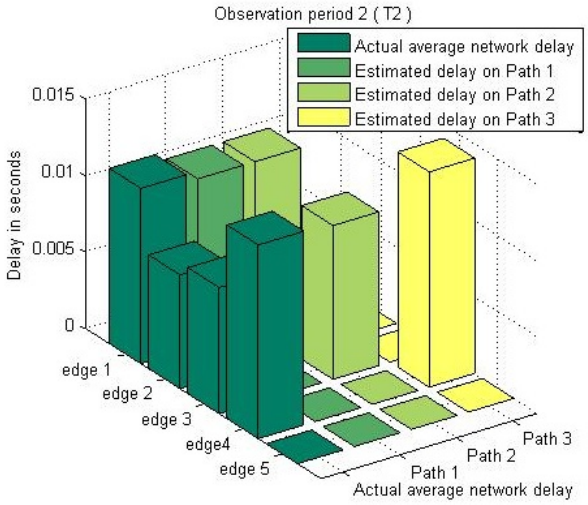
- **Observation Period 3** (i.e.,T_3):The link from node 2 to node 4 is broken and a new node (i.e., node 6 in Figure 6.4) is discovered. In our collected data,

observation period 3 is the time period from 11.3020 second to 24.9767 second, e.g.,T_3 [11.3020, 24.9767].

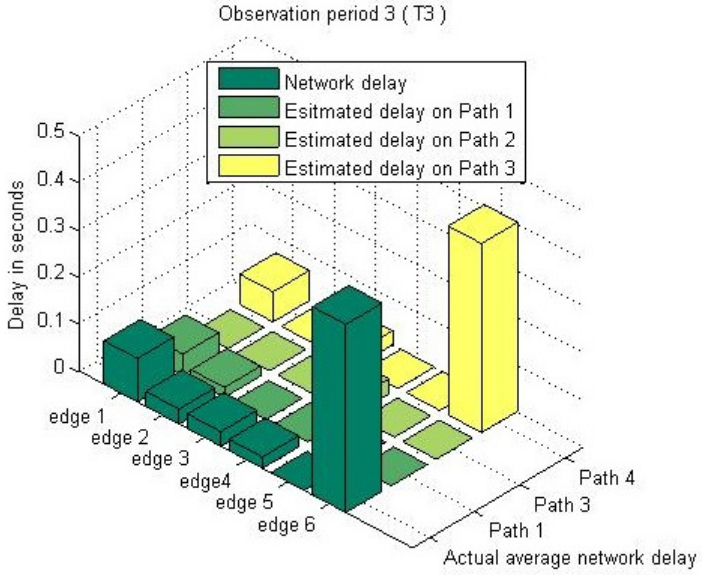
The observation periods are automatically generated by analyzing the time points with the change of links or nodes in the collected dataset. The delays for edges in



(a) Delay comparison in T_1



(b) Delay comparison in T_2



(c) Delay comparison in T_3

Figure 6.5: Estimated delay and actual delay for observation period T_1,T_2,T_3

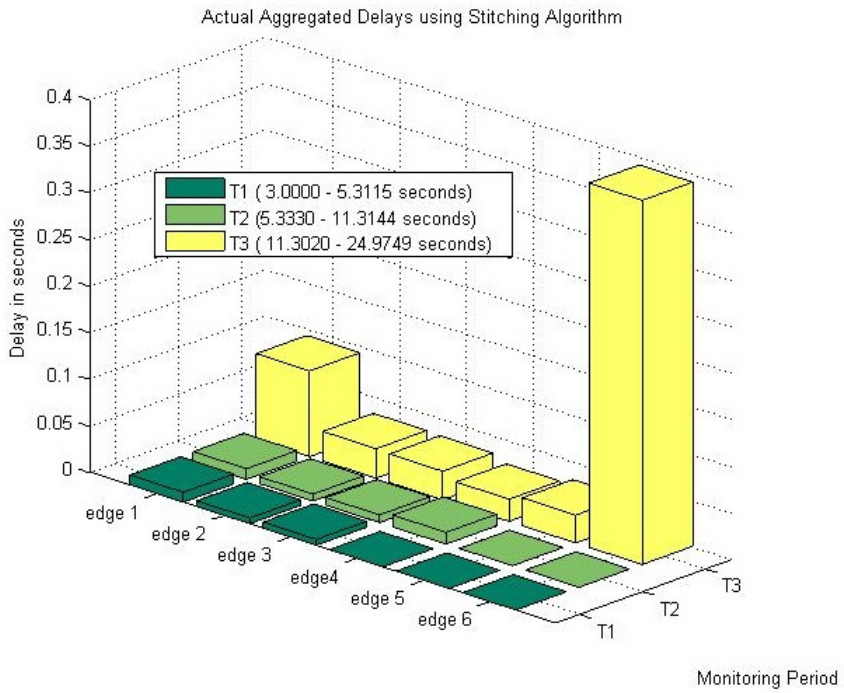
each observation period are estimated by using the PLE algorithm and are plotted in

Figure 6.5. It is noted that the value of zero in the edge delay in Figure 6.5 means that it has no transmissions so that the delay is not estimated in this observation period. We present the delay in Figure 6.5 in three dimensions:

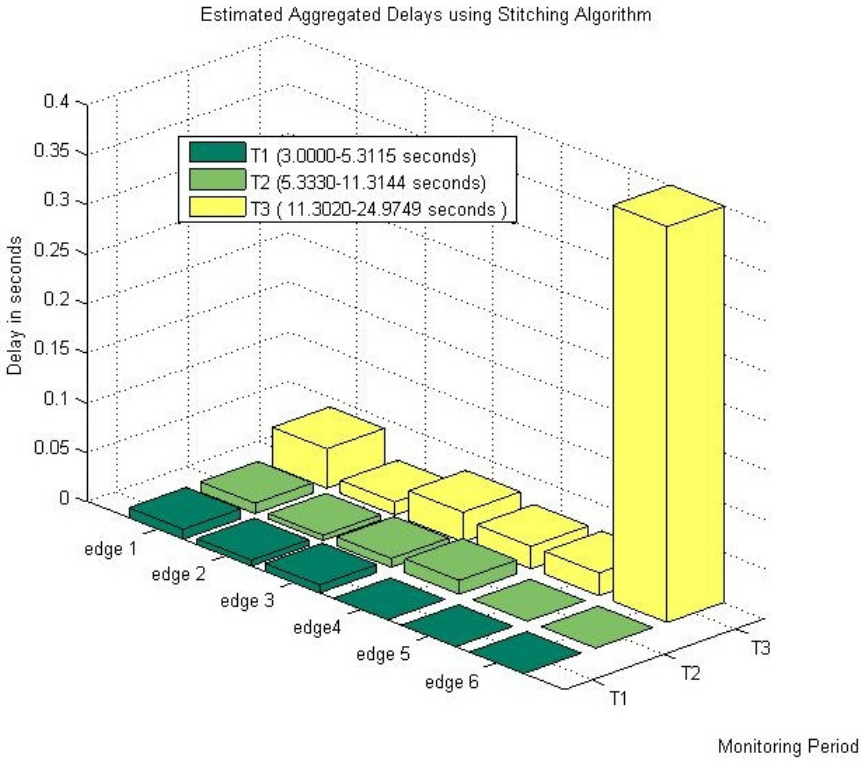
- **Edge:** The edge represents the link is used for traffic transmission.
- **Path:** The path consists of the edges in the multi-hop route from the source to the destination. The edge and path indicate the geographical information of the traffic flows.
- **Time:** The time is subsequently organized by observation periods in the monitoring period. It shows how the performance (e.g., delay) changes over the time domain.

The results in Figure 6.5 are based on the scenarios in Figure 6.3 that have three observation periods. In each observation period, we can see the delay according to edge and path. In Figure 6.6, the actual delay is plotted against the estimated delay. The estimated results indicate the network performance as:

- The plotted results indicate the estimated delays are very close to the actual delay
- We can see edge 1 has a higher delay than edge 2 and edge 3. It is because two traffic flows travel through it.
- Edge 4 has a relative high delay at observation period 2 when node 5 on this edge is just added for transmitting traffic. This is caused by a process of route discovery while the traffic is buffered.
- Edge 4 has better performance than edge 1 at the observation period 3.
- Edge 6 has the worst performance. This is caused by node (i.e., node 4 and node 6) mobility. The movement of node 4 causes link breakage and the new path from node 1 to node 4 is re-established until node 6 moves close to node 2. Before the new path, some packets are buffered and some of them may be dropped.



(a) Aggreated actual delay on edges using stitching algorithm



(b) Aggreated estimated delay on edges using stitching algorithm

Figure 6.6: Aggregated estimated delay and actual delay in the entire monitoring period

Based on the above analysis, we can say that PLE algorithm is able to estimate the network performance in terms of network nodes. The performance estimation at each observation period, the stitching algorithm aggregates the estimated delay and creates a time-varying change of the network performance. Figure 6.6 shows the aggregated delays over the time domain. The aggregated delays are the results after applying the stitching algorithm. We compare the results by using the estimated delays and the actual delays on edges as shown in Figure 6.6.

It is worth noting that Figure 6.6 shows how the edge performance (e.g., delay) changes from observation period 1 to observation period 3. On each edge (e.g., edge 1 and edge 2), the delay increases in the scenario of Figure 6.4. This matches to the actual situation that the traffic load in the network increases (i.e., a new flow is added from node 5 to node 3). Figure 6.6 also shows that the node mobility could significantly degrade the performance (e.g., higher delay) since it involves the link stale and link re-establishment. In the scenario of Figure 6.4, for example, the delay on edge 6 is much higher than other in the observation period 3. With the stitching algorithm, PLE can monitor the network performance for any given monitoring period.

6.2 Mobile Wireless Mesh Network.

The WMNs have a stable topology [109], which may changes due to MR failures, or new MR joints to WMNs. The components in WMNs usually have very low mobility, which is called Static WMNs. However, MCs usually are mobile between MRs which is called Mobile WMN (MWMN). In MWMNs, mesh node routes packets to destination with multi-hop. The most concerned traffic is oriented between MCs and IGWs to access Internet resource for users. The transmission efficiency may decrease owing to the lack of the bandwidth, packet loss or channel interference. Therefore, to optimize the transmissions, the routing metric is needed for selecting best path for nodes and distribute the flow to achieve the load balance of MWMN.

In WMNs, the nodes usually choose the shortest path or the path with the fewest hops for their transmissions, but this cannot guarantee the quality and efficiency of the path. For this reason, we need a routing metric for choosing the path

of high quality and efficiency, and maintaining the optimal path whenever the net flow changes so that the load balance of the network can be guaranteed. We propose the EM routing to decide the optimal path for mobile MCs and increase the communication efficiency and decrease the interference impact. By analyzing the path delay,which is associated to the nodes attached to a particular path, our proposed scheme can select the optimal path for nodes and distribute the flow to the MR with lower load. In this way, not only the load balance can be achieved, but also the transmission efficiency of the network can be improved.

6.2.1 Simulation Results for Mobile WMN.

Let us consider the following mobile wireless mesh network scenario. In Figure

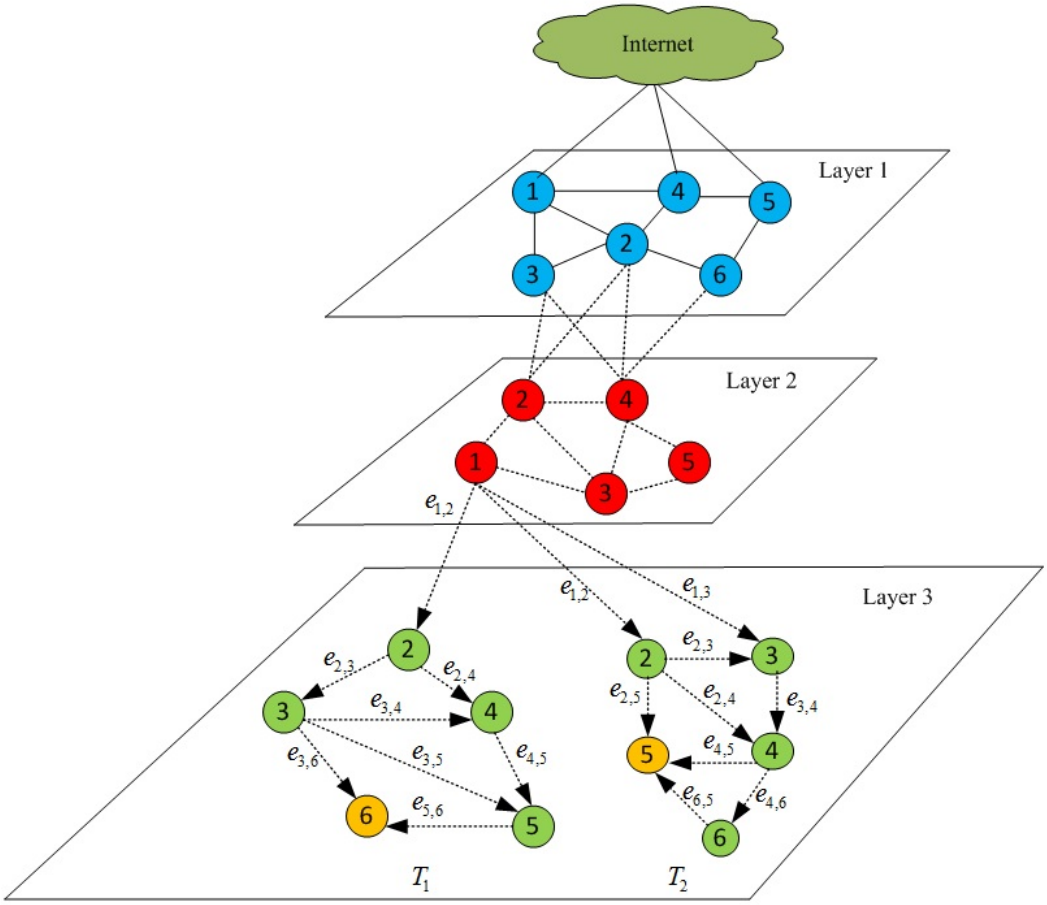


Figure 6.7: Source-to-Destination in mobile WMN.

6.7 the basic architecture of the mobile wireless mesh network is same as described in section 5.1. It is important to notice that the destination in two topologies over two time instances are different. Also, since we have dynamic topology, we can notice some nodes have moved and hence resulting in establishing new links, which result in establishing new paths.

Let graph G and H have the path matrices P_G and P_H respectively in two different time instances T_1 and T_2. We now implement the PLE algorithm from

$$P_G = \begin{array}{c} \begin{matrix} e_{1,2} & e_{2,3} & e_{2,4} & e_{3,4} & e_{3,5} & e_{3,6} & e_{4,5} & e_{5,6} \end{matrix} \\ \begin{pmatrix} 1 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix} \end{array} \begin{matrix} path1 \\ path2 \\ path3 \\ path4 \end{matrix}$$

(a) Path matrix of network G

$$P_H = \begin{array}{c} \begin{matrix} e_{1,2} & e_{1,3} & e_{2,3} & e_{2,4} & e_{2,5} & e_{3,4} & e_{4,5} & e_{4,6} & e_{6,5} \end{matrix} \\ \begin{pmatrix} 1 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 1 \end{pmatrix} \end{array} \begin{matrix} path1 \\ path2 \\ path3 \\ path4 \\ path5 \\ path6 \\ path7 \end{matrix}$$

(b) Path matrix of network H

Figure 6.8: Path matrix of network G in $T_1$and H in T_2

section 2.2 on the path matrix P_H. We compare the estimated results with the actual delay on each links. It can be observed that out estimates are good, when compare to the actual link performance. These result are presented in Table 6.1 below. We now present the path by path analysis of the mobile mesh network in time instance T_2. It can be see from Figure 6.7, that connectivity of links $e_{2,5}$ and $e_{4,6}$ has changed hence to establish connectivity there is a high delay these edges. The link delay on $e_{2,5}$ and $e_{4,6}$ is relatively high on all paths as shown in Figure 6.9, where these links are utilized. This can be confirm from our simulation result as well. In Figure 6.10 one can see all the possible paths and corresponding number of hops taken on each

TABLE 6

Estimation for 9-node mobile WMN

	Edges								
	$e_{1,2}$	$e_{1,3}$	$e_{2,3}$	$e_{2,4}$	$e_{2,5}$	$e_{3,4}$	$e_{4,5}$	$e_{4,6}$	$e_{6,5}$
Original	1	2	2	1	4	0	5	2	1
Estimates	0.9997	1.5470	2.0003	1.0003	4.0003	0.0003	5.0003	2.4530	1.4530

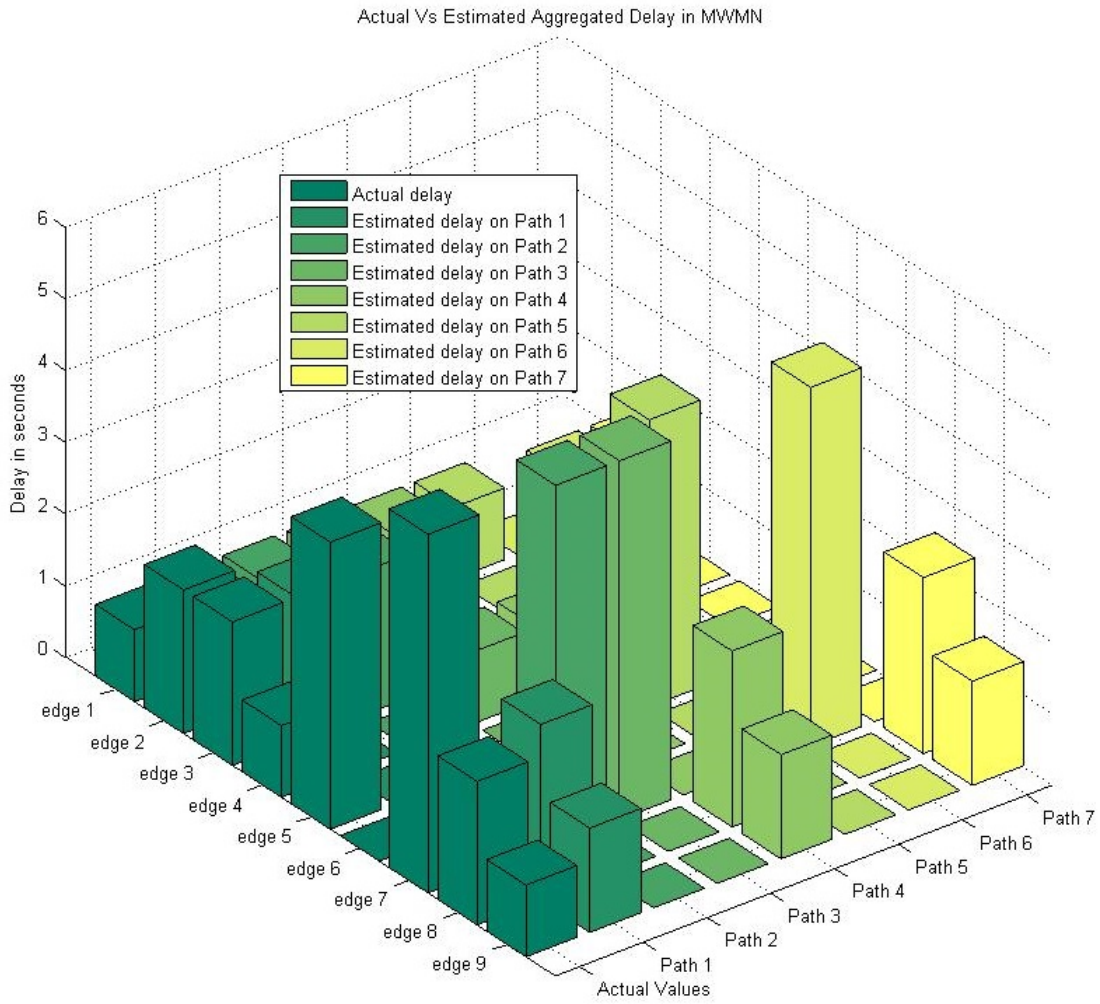


Figure 6.9: Path analysis for mobile WMN.

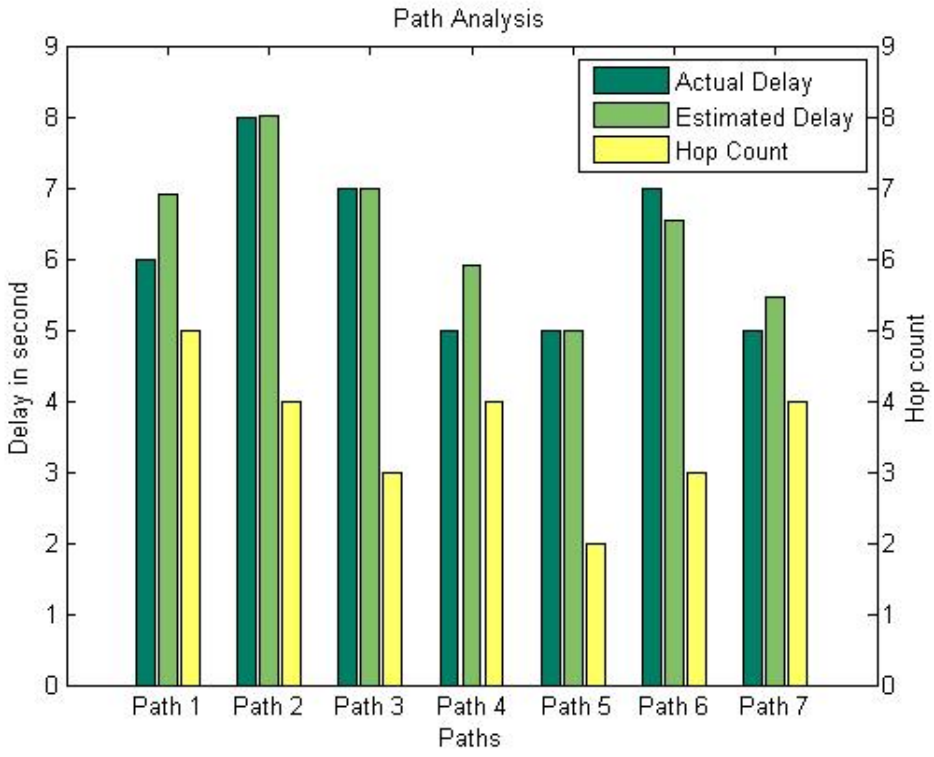
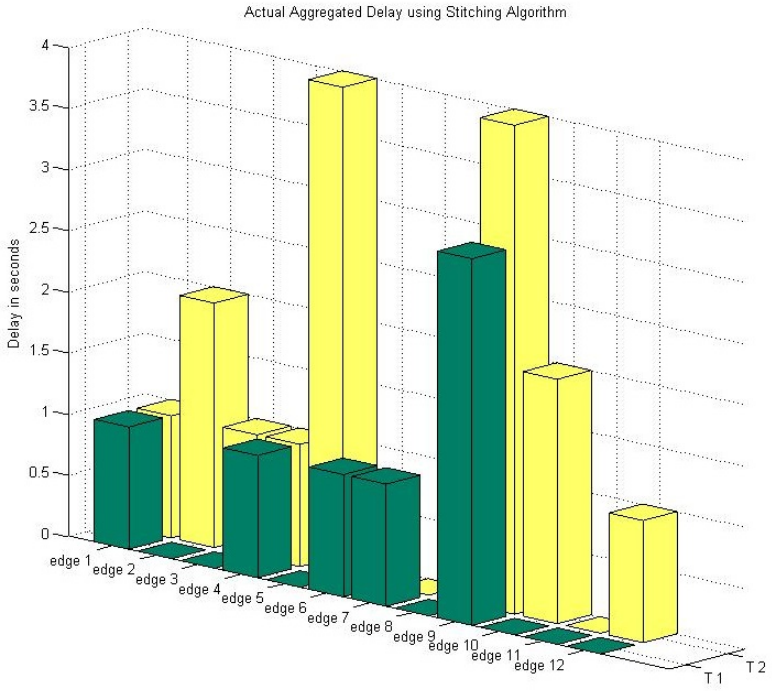


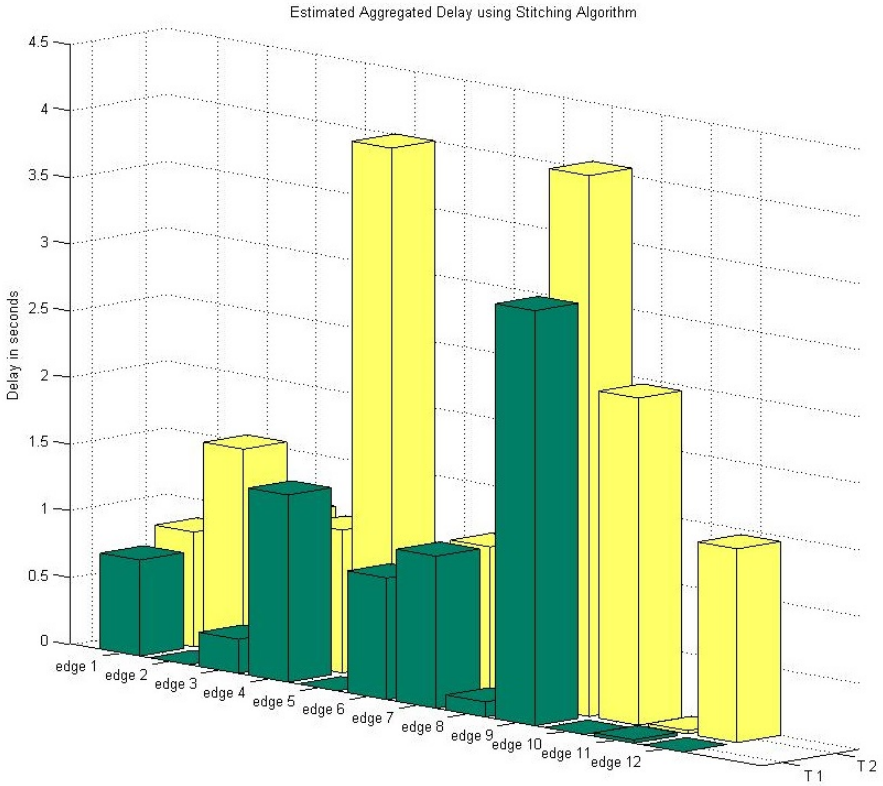
Figure 6.10: EM routing path and hop analysis for mobile WMN.

path respectively. It is interesting to note that in Figure 6.10, that path 5 has the minimum total delay and hop count, but when comparing with path 7 to total delay is relatively same though number of hops taken is slightly higher. So, this confirms the fact that shortest path is not necessary the optimum path in terms of total delay incurred on the path.

We will now implement the proposed network performance analysis algorithm, stitching algorithm over the two time period T_1 and T_2 to analyze the performance of each link. It can be clearly seen that the stitching algorithm along with the EM routing scheme gives us good estimates.



(a) Aggreated actual delay on edges using stitching algorithm in MWMN



(b) Aggreated estimated delay on edges using stitching algorithm in MWMN

Figure 6.11: Aggregated estimated delay and actual delay in the entire monitoring period

CHAPTER 7

CONCLUSION AND FUTURE WORK

This dissertation has analyzed and proposed contributions on the following key issues about ad-hoc network performance measurement based on NT technique.

- This document summarizes and analyzes traditional network measurement technique and wired network measurement method based on NT technique. Then we discuss the application of NT technique in measurement model, measurement methods, and link performance inference methods.

- It also presents an ad-hoc network topology dynamic characteristic analysis technique based on the stitching algorithm. This method is based on the steady state of each topology. Then it analyzes the two consecutive topology architecture to find a steady state period in an ad-hoc network topology. Moreover, it adopts to the duration of steady state period of the topology for NT measurement i.e., measurement window time. This measurement window with he number of steady state period has probability distribution in certain time t accords with Poisson distribution. For the ad-hoc network topology snapshots, EM process with discrete time and state is used to obtain the link state matrix. Under this condition, if the current state of ad-hoc network topology is know, the probability of its state variability or invariability after n snapshots time could be obtained according to link state matrix. Moreover, for the topology snapshots with short snapshot time, EM process with consecutive time and discrete state is used to infer the forecast formula of topology state keep invariable and the warning formula of topology state variability, which provides the measurement window time for ad-hoc network with theory basis. The simulation results verify that the effectiveness of all the methods above has the universal

property, and they could be used for all the mobility models in NS-2.

- This dissertation studies deeply in ad-hoc network link performance inference based on PLE and stitching algorithm. In the process of ad-hoc network measurement, how to bring forth an light link performance inference methods is a challenge for its topology dynamic characteristic. The document firstly analyzes the relationship between path and link performance, and propose isomorphism theory for ad-hoc network. Next, the document presents and ad-hoc network link performance inference method based on matrix equation. In this model, the path matrix is equal to that of its augmented matrix, linear algebra theory could be used to obtain the solution space of the non-homogeneous linear equations, and furthermore to infer the network link performance. Otherwise, when the rank of routing matrix is not equal to that of its augmented matrix, there is no solution for the non-homogeneous linear equations.

- We also studied the NT methodology developed so far on the mobile wireless mesh network. In this process, we developed routing algorithm based on the probabilistic computation of the link or path performance called EM routing. We analyzed the link performance with the original data and our computation and routing matched with the actually routing scheme.

7.1 Future Work.

Ad-hoc network performance measurement based on NT technique is still in its infancy. Although the we have done some exploratory works on ad-hoc network performance measurement based on NT technique, there are still some open issues need to be studied on, such as:

- The ad-hoc network link performance inference methods mainly focused on delay and loss rate, for other network performance parameters, such as energy, available bandwidth and traffic, are also required for further study in the future.

- The characteristic information extraction of ad-hoc network steady period is

only determined by path delay jitter. How to find other characteristic information to improve the accuracy of this algorithm is still need to be further studied on.

- There has been some work done on optimizing the deployment of Internet gateway in wireless mesh network [110]. I wish to use the NT methodology to study this area for future research.

- I would also like to study NT approach on the graph theoretical description of epidemic propagation and computational epidemiology [111].

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CURRICULUM VITAE

Name: Mohammad Shoeb Saeed Khan

Address: Department of Computer Engineering and Computer Science
University of Louisville
Louisville, KY 40292

Education: B.Sc., Univeristy of Leicester, Leicester, England, 2000
M.A., University of Missouri,2002
M.A., Univerisity of Montana, 2005
M.Sc., University of Louisville, 2011

Awards: Sponsored Research Fellowship Award
Graduate Teaching Assistantship Award
Student Member of *IEEE, ACM, SIAM*