

TRAFFIC MATRIX ESTIMATION WITH ENHANCED ORIGIN DESTINATION  
GENERATOR ALGORITHM USING SIMULATION OF REAL NETWORK

SAMI ABBAS NAGAR ADAM

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*To my My parents, great mother and father (late), to my beloved wife for all the patience and sacrifices she made and always with me, her advices and support all these years to ensure that I obtained the best education possible, and our children Mohamed, Aya, Basmala, Ryan and Alaa for their prayers. To my supportive brother Sadig. The love and encouraging words from all of you have really inspired me to achieve my goals and dream. Also, to the spirits of my son and brother.*

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*Sami Abbas Nagar, Johor Bahru, Malaysia*

## ABSTRACT

The rapid growth of the Internet has made the issue of ensuring reliability and redundancy a big challenge. Studies of these issues using Traffic Engineering and simulation have been extensively done. In Traffic Matrix Estimation (TME), the Origin–Destination Generator algorithm (ODGen) is limited to the number of hops, where the Expectation Maximization (EM) accuracy is 92%. Most studies have not taken into account real traffic parameters and integration of TME models with routing protocols in their simulation models. Also, there is no a comprehensive model consisting of TME, Border Gateway Protocol (BGP) and Hot Potato (HP) routing in the NS-2 network simulator based on real networks. In this research, Integrated Simulated Model (ISM) is introduced consisting of ODGen-HP algorithm and BGP integrated into the NS-2 network simulator. ISM is then used to simulate the infrastructure of a real production network using actual captured traffic data parameters. Validation is then done against the changes in network topology based on packet loss, delay and throughput. Results gave the average error for packet sent by simulated and production networks of 0% and the average error for packet received by simulation and production networks of 3.61%. The network is modelled with a baseline topology where 5 main nodes were connected together, with redundant links for some nodes. The simulations were repeated for link failures, node addition, and node removal. TME used in ISM is based on ODGen, that is optimized with unlimited number of hops, the accuracy of EM increases to 97% and Central Processing Unit complexity is reduced. HP helps in improving the node which experiences a link failure to select shorter distance route to egress router. In the case of a link failure, HP switching time between the links is 0.05 seconds. ISM performance was evaluated by comparing trace file before and after link failure or by adding nodes (up to 32) or removing nodes. The parameters used for comparison are the packets loss, delay and throughput. The ISM error percentage obtained for packets loss is 0.025%, delay 0.013% and throughput 0.003%.

## ABSTRAK

Pertumbuhan pesat Internet telah menjadikan isu kebolehpercayaan dan lewahan satu cabaran besar. Kajian isu-isu di atas menggunakan Kejuruteraan Trafik dan penyelakuan telah dibuat dengan meluas. Algoritma Penjana Asal-Destinas (ODGen) pada Anggaran Matriks Trafik (TME) mempunyai had pada bilangan lompatan, di mana ketepatan Pemaksimuman Jangkaan (EM) hanya 92%. Kebanyakan kajian tidak mengambil kira parameter trafik sebenar serta integrasi Matriks Trafik TME dengan protokol penghantaran dalam model penyelakuan mereka. Selain itu, tidak wujud model menyeluruh mengandungi TME, Protokol Gerbang Sempadan (BGP) serta Penghalaan Kentang Panas (HP) pada penyelaku rangkaian NS-2 berasaskan rangkaian sebenar. Di dalam penyelidikan ini, Model Penyelakuan Bersepadu (ISM) diperkenalkan merangkumi ODGen, algoritma HP dan BGP diintegrasikan dengan penyelaku NS-2. ISM kemudian digunakan untuk menyelakukan infrastruktur Pembekal Perkhidmatan Rangkaian menggunakan parameter hakiki mewakili data trafik sebenar yang diambil. Pengesahan kemudian dibuat terhadap perubahan pada topologi rangkaian berasaskan kehilangan paket, lengah dan kadar celus. Dapatan menunjukkan purata ralat untuk paket dihantar rangkaian diselaku dibandingkan rangkaian pengeluaran adalah 0% dan purata ralat untuk paket diterima rangkaian diselaku dibandingkan rangkaian pengeluaran adalah 3.61%. Rangkaian dimodel dengan topologi asas dengan 5 nod utama dirangkai dengan sambungan lewah untuk beberapa nod. Penyelakuan diulang bagi kegagalan sambungan, tambahan nod dan penyingkiran nod. TME yang diguna pada ISM adalah berdasarkan kepada algoritma ODGen, dioptimumkan dengan bilangan lompatan tanpa had, ketepatan EM bertambah menjadi 97% dan kerumitan unit pemprosesan utama (CPU) berkurangan. HP membantu memperbaiki nod yang mempunyai kegagalan sambungan sambil memilih jarak lebih kecil kepada penghala egres. Bagi kes kegagalan sambungan, masa pensuisan HP antara pautan adalah 0.05 saat. Prestasi ISM dinilai dengan membandingkan fail jejak sebelum dan selepas kegagalan sambungan atau apabila menambah nod (sehingga 32 nod) atau menghapus nod. Parameter yang digunakan untuk perbandingan adalah kehilangan paket, lengah dan kadar celus. Peratusan ralat ISM yang diperolehi untuk kehilangan paket ialah 0.025%, lengah 0.013% dan kadar celus 0.003%.

## TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	<b>DECLARATION</b>	ii
	<b>DEDICATION</b>	iii
	<b>ACKNOWLEDGMENT</b>	iv
	<b>ABSTRACT</b>	v
	<b>ABSTRAK</b>	vi
	<b>TABLE OF CONTENT</b>	vii
	<b>LIST OF TABLES</b>	xv
	<b>LIST OF FIGURES</b>	xx
	<b>LIST OF ABBREVIATIONS</b>	xxiv
	<b>LIST OF MATHEMATICAL SYMBOLS</b>	xxvii
	<b>LIST OF APPENDICES</b>	xxviii
<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
	1.1 Introduction	1
	1.2 Background	3
	1.3 Motivation	5
	1.4 Research Questions	6
	1.5 Problem Statements	7
	1.6 Research Objectives	8
	1.7 Scope of Work and Assumptions	8
	1.8 Contributions of research	10
	1.9 Organization of Thesis	10
<b>2</b>	<b>LITERATURE REVIEW</b>	<b>12</b>
	2.1 Introduction	12
	2.2 Use the real data captured in simulation	13

Environment	
Overview	13
2.2.1 Type of Simulators	13
2.2.2 State of Art in Using the Real Data in Network in Simulators	14
2.2.3 Validation and Verification	16
2.2.3.1 Comparison between the Simulation Result with Real network	16
2.2.3.2 Reducing the Processing Overhead	16
2.2.4 Issues not addressed in simulation network for real production network	17
2.3 Traffic Matrix Estimation	18
2.3.1 An Overview of Traffic Matrix Estimation	18
2.3.2 What is Traffic Matrix?	19
2.3.3 Construction of Traffic Matrix	20
2.3.4 Determining the Traffic Matrix	20
2.3.4.1 Direct Measurement	20
2.3.4.2 Traffic Matrix Estimations	20
2.3.4.3 Why Traffic Matrix Estimation	22
2.3.5 The State of the Art in TME	22
2.3.5.1 Comparison between TM Estimators	25
2.3.6 Traffic Matrix Estimation Routing Weights	27
2.3.7 Heuristic Use in the OD Matrix	28
2.3.8 Expectation Maximization (EM) Method	28
2.3.8.1 EM Algorithm used in Generating the O-D TM	28
2.3.8.2 EM algorithm Gaussian Mixture used in OD TM	29
2.3.9 TM uses by ISP's	29

2.3.10	Validation and Verification TME	
	methods	30
	2.3.10.1 Comparison of Methodology	30
	2.3.10.2 Numerical Validation	30
2.3.11	Discussion and Extended Work in TM	31
	Generation	
2.4	Dynamic Routing Protocol (BGP and HP)	31
2.4.1	Static Routing	32
2.4.2	Dynamic Routing	32
	2.4.2.1 Interior Gateway Protocol (IGP)	32
	2.4.2.1.1 Distance Vector	
	Algorithm	33
	2.4.2.1.2 Link State	35
	2.4.2.1.3 Selecting IGP Routing	
	Protocols	38
	2.4.2.1.4 Determining the traffic	
	routes	42
	2.4.2.2 Exterior Gateway Protocol (EGP)	43
	2.4.2.2.1 Border Gateway	
	Protocol (BGP)	43
	2.4.2.2.2 Why select the HP to	
	Use with BGP?	46
	2.4.2.2.3 The State of Art in	
	BGP and Hot Potato	49
	2.4.2.2.4 The State of Art in	
	ISP's with BGP	50
2.4.3	Discussion and Extended Work on BGP	
	and HP	52
2.5	The State of Art in Integrated Simulation Model	53
2.5.1	TME and NS-2	53
2.5.2	Traffic Matrix Estimation and Hot Potato	53
2.5.3	The State of Art in Conceptual	
	Integration between BGP,HP and TME	54



2.5.4	Further Discussion on Integration	
	Simulation Model	54
2.6	Tools	54
2.6.1	Data Collections	54
2.6.2	Network monitoring Software (Layer 2 and Layer 3)	55
2.6.3	Comparison between the Network Simulators	56
2.6.4	NS-2 Simulator Version 2.34	58
	2.6.4.1 NS-2 Communication Entity	58
	2.6.4.2 Classifier	59
	2.6.4.3 Link	59
	2.6.4.4 Agent	60
	2.6.4.5 TCL Language	60
	2.6.4.6 Ns-2 Trace File	60
	2.6.4.7 Explanation of Simple.tcl File Component of NS-2	61
2.6.5	BGP Applied In Open Source Network Simulators	65
2.6.6	ns-BGP Conceptual Validation Tools	68
	2.6.6.1 Cisco Packet Tracer	68
	2.6.6.2 GNS3	69
2.6.7	Validation and Verification Tools (AWK, T-Test and Java Script)	69
2.6.8	Addition new components to ns-BGP in NS-2	70
2.6.9	The R language	71
	2.6.9.1 EM Algorithm Package in R Version 3.1.1 (10-7-2014)	71
2.7	Summary	72

3.1	Introduction	73
3.2	Overall Research Methodology Framework	74
3.3	Methodology Based on Research Objectives	77
3.4	Modeling of the Production Network in NS-2	79
	3.4.1 Network Production	81
	3.4.2 Data Reprocessing	82
	3.4.3 NS-2 Modeling	82
	3.4.4 Validation and Verification	83
3.5	Traffic Matrix Estimation Model	83
	3.5.1 Why TME approach and its application	84
	3.5.2 Traffic Matrix Algorithm	85
	3.5.3 Validation	87
	3.5.4 Simulation of TME Traffic Text File in NS-2	87
	3.5.4.1 TME NS-2 Simulation Feature	87
	3.5.4.2 Validation	88
	3.5.5 Integration of TME With HP	89
	3.5.5.1 TME NS-2 Simulation Feature	89
	3.5.5.2 Validation	90
3.6	Integrated Simulation Model (ISM)	90
	3.6.1 Corporation Dual-Homed Network Topology	90
	3.6.2 Hot Potato (HP)	91
	3.6.2.1 Hot Potato Validation	93
	3.6.3 Modification to existing Border Gateway Protocol (BGP)	94
	3.6.3.1 ns-BGP Validation Tests	95
3.7	Integrated Simulation Model (ISM) Evaluation	96
	3.7.1 ISM Evaluation without Link or Node Failure Scenarios	97
	3.7.2 Global Control	97
	3.7.2.1 HP Scenarios	98
	3.7.2.2 TME Scenarios	99

3.8	Tools	101
3.9	Summary	102
<b>4</b>	<b>TRAFFIC MATRIX ESTIMATION MODEL BASED ON PRODUCTION NETWORK</b>	<b>103</b>
4.1	Introduction	103
4.2	Generative NS-2 Traffic Model Based on Real Network Parameter	103
4.2.1	Model Description	104
4.2.2	Network Data	105
4.2.3	Network Production	105
4.2.4	Data Collection	107
4.2.5	Assumptions made in the simulation model	108
4.2.6	Simulation Parameters	109
4.2.7	Model Description	109
4.2.8	The Model Code	110
4.2.9	Numerical example	112
	4.2.9.1 Results	113
	4.2.9.2 Model Validation and Verification	115
4.3	O-D Traffic Matrix Estimation Model	117
4.3.1	ODGen Method	117
	4.3.1.1 Algorithm Assumption	118
	4.3.1.2 O-D Matrix Generation Numerical Example for validation	119
4.3.2	Generating O-D TME	127
	4.3.2.1 Data and Assumption	129
	4.3.2.2 Maximum number of hops	129
	4.3.2.3 Computing the shortest path	129
	4.3.2.4 End-to- End node probabilities	131
	4.3.2.5 Originating traffic matrix for each node	131

	4.3.3	Generation of Traffic text file for NS-2	139
	4.3.3.1	Validation O-D TME text file in NS-2	141
	4.3.4	Generation of the routing tables for each node to be used by Hot-Potato routing protocol	141
	4.4	Summary	144
<b>5</b>		<b>INTEGRATED SIMULATION MODEL</b>	<b>145</b>
	5.1	Introduction	145
	5.2	Building the Integrated Simulation Model (ISM)	145
	5.2.1	Hot Potato Algorithm	146
	5.2.1.1	HP Conceptual Validation	146
	5.2.1.2	HP Algorithm	147
	5.2.1.3	Implementation of HP Algorithm	149
	5.2.2	BGP Integrated with NS-2 Simulators (ns-BGP2.0)	155
	5.2.2.1	Unicast Routing Structure in NS-2	155
	5.2.2.2	BGP Conceptual Validation	156
	5.2.2.3	ns-BGP Validation	159
	5.2.2.3.1	Result in Different Scenarios Applied to reflection2.tcl	160
	5.2.2.3.2	Step 2 Validation Procedure	166
	5.2.3	Validation	169
	5.2.3.1	Comparing the Results of ns-BGP with and without HP	170
	5.3	Applying the complete ISM to the Proposed Corporation Network Topology	172
	5.3.1	Dual-homed Network Design Consisting of 5 Sites	172

5.3.1.1	TME for New Dynamic Routing Design	172
5.3.1.1.1	Production Network	172
5.3.1.1.2	Data Collection	173
5.3.1.1.3	Maximum Number of hops	175
5.3.1.1.4	Computing the Shortest Path	175
5.3.1.1.5	End-to- End Site Probabilities	178
5.3.2	Generation of Traffic text file for NS-2	187
5.3.3	Discussion I	189
5.4	ISM Evaluation	190
5.4.1	Evaluation for HP Enabled Scenarios	191
5.4.1.1	Dual-Homed Network Topology	191
5.4.1.2	Link Failure Scenario	192
5.4.1.3	Site Failure Scenario	194
5.4.1.4	Validation ISM with HP Scenarios	195
5.4.2	TME Scenarios	197
5.4.2.1	Addition of New Link	197
5.4.2.2	Adding New Site	203
5.4.2.3	ISM Tested with 32 Sites	206
5.4.2.4	Discussion II	207
5.5	Summary	208
<b>6</b>	<b>CONCLUSIONS</b>	<b>209</b>
6.1	Introduction	209
6.2	Conclusion	209
6.3	Future Works	211
	<b>REFERENCE</b>	<b>214</b>
	Appendices A - B	226 - 230

## LIST OF TABLES

<b>TABLE NO.</b>	<b>TITLE</b>	<b>PAGE</b>
1.1	Sudan internet usage and population growth	3
1.2	The scope of involvement: current versus future states	5
2.1	Types of network simulators	14
2.2	Comparison result between LP, Bayesian and EM	26
2.3	The error percentage between LP, Bayesian and EM	26
2.4	EIGRP metrics	34
2.5	EIGRP K-value defaults	34
2.6	Comparison of protocols, ports, reliability, and default timers	37
2.7	The reference bandwidth default value of OSPF, IGRP and EIGRP	38
2.8	The transmission cost for IGRP, EIGRP, OSPF, and RIP	39
2.9	Different traffic routing	43
2.10	Adaptive routing algorithm	47
2.11	Non-adaptive routing algorithm	48
2.12	Some of Network Monitoring Products (RMON2)	56
2.13	Comparison between network simulators based on modeling capability	57
2.14	Pre-connection core memory demands	58
2.15	Design and implementation of ns-BGP	66
2.16	Validation methodology	67
3.1	Steps according to the numbers in the colored arrows	79
3.2	List of tools used in the research	101
4.1	Links probabilities	106
4.2	Comparison between network captured file and simulator	113

	trace file	
4.3	Error percentage between real and simulation network parameters	115
4.4	t-test: of real and simulation transmission time calculation	115
4.5	t-test: of real and simulation received time calculation	115
4.6	AWK verification (One input)	116
4.7	Java script verification (Two inputs)	116
4.8	Load and end-to-end probabilities based on Fischer network for node 1	122
4.9	Load and end-to-end probabilities based on Fischer network for all nodes	122
4.10	Hits along O-D paths and nodal originating traffic (shown for Iteration 1) in Fischer network	123
4.11(a)	Node 1 O-D Traffic Matrix	124
4.11(b)	Node 2 O-D Traffic Matrix	124
4.11(c)	Node 3 O-D Traffic Matrix	124
4.11(d)	Node 4 O-D Traffic Matrix	124
4.11(e)	Node 5 O-D Traffic Matrix	124
4.11(f)	Node 6 O-D Traffic Matrix	124
4.11(g)	Node 7 O-D Traffic Matrix	124
4.11(h)	Node 8 O-D Traffic Matrix	124
4.12	Estimated link loads (Iteration 1) in Fischer network	125
4.13	Estimated link loads (Iteration 2) in Fischer network	126
4.14	Routing matrix of Fischer network	127
4.15	O-D pair packet traffic in links in production network	130
4.16(a)	Node 0 O-D Traffic Shortest Path	130
4.16(b)	Node 1 O-D Traffic Shortest Path	130
4.16(c)	Node 2 O-D Traffic Shortest Path	130
4.16(d)	Node 3 O-D Traffic Shortest Path	130
4.17	Loads and end-to-end Probabilities for example network for all nodes	131
4.18	Comparison the calculation accuracy for R and Excel in production network	132

4.19	The EM iteration outcomes estimated parameters in the production network	133
4.20	The execution estimated parameters output in the production network	134
4.21	The epsilon test for execution estimated parameters output in the production network	135
4.22	Nodes from and to multipliers good values in the production network	137
4.23	Hits along O-D paths in production network	137
4.24	Nodal originating traffic in production network	137
4.25(a)	Node 0 O-D Traffic Matrix	138
4.25(b)	Node 1 O-D Traffic Matrix	138
4.25(c)	Node 2 O-D Traffic Matrix	138
4.25(d)	Node 3 O-D Traffic Matrix	138
4.26	Estimated link loads in production network	139
4.27	Routing matrix in production network	139
4.28	The nodes bidirectional SD error percentage in real network	141
4.29(a)	Node 0 O-D Traffic Shortest Path	143
4.29(b)	Node 1 O-D Traffic Shortest Path	143
4.29(c)	Node 2 O-D Traffic Shortest Path	143
4.29(d)	Node 3 O-D Traffic Shortest Path	143
5.1	The program input parameters assigned by the user	150
5.2	The program input parameters assigned by the user	153
5.3	Result comparison	154
5.4	EBGP comparison between ns-BGP and CPT based on show routes result	157
5.5	IBGP comparison between ns-BGP and GNS3 based on show routes result	158
5.6	Default values of parameters used in routereflection2.tcl	159
5.7	The Throughput, Packet loss and average Delay values for reflection2.tcl trace file	160
5.8	The Throughput, Packet loss and average Delay values for	161



	reflection2.tcl after link failure trace file	
5.9	The Throughput, Packet loss and average Delay values for reflection2.tcl trace file running HP	170
5.10	The Links information's for the proposed network	176
5.11	O-D pair packet traffic in links in the production network	177
5.12(a)	Site 0 O-D Traffic Shortest Path	177
5.12(b)	Site 1 O-D Traffic Shortest Path	177
5.12(c)	Site 2 O-D Traffic Shortest Path	178
5.12(d)	Site 3 O-D Traffic Shortest Path	178
5.12(e)	Site 4 O-D Traffic Shortest Path	178
5.13	Load and end-to-end probabilities based for site 0	179
5.14	Load and end-to-end probabilities based on production network for all sites	179
5.15	EM iteration outcome for the estimated parameters in the production network	180
5.16	The execution estimated parameters output in the production network for traffic out site 0	180
5.17	The execution estimated parameters output in the production network for traffic in site 0	181
5.18	The epsilon test for execution estimated parameters output in the production network	182
5.19	Sites from and to multipliers good values in the production network	183
5.20	Hits along O-D paths in production network	184
5.21	Nodal originating traffic in production network	184
5.22(a)	Site 0 O-D Traffic Matrix	185
5.22(b)	Site 1 O-D Traffic Matrix	185
5.22(c)	Site 2 O-D Traffic Matrix	185
5.22(d)	Site 3 O-D Traffic Matrix	185
5.22(e)	Site 4 O-D Traffic Matrix	185
5.23	Estimated link loads in production network	186
5.24	Routing matrix in production network	187
5.25	The sites bidirectional SD error percentage in Real Network	188

5.26	The TME text file SD and Mean error percentage and real production network text file	188
5.27	Site 0 the information of next hop to next AS	189
5.28	The Throughput, Packet loss and average Delay values based on reflection2.tcl trace file	192
5.29	The Throughput, Packet loss and average Delay values for reflection2.tcl trace file running HP	193
5.30	The Throughput, Packet loss and average Delay values based on reflection2.tcl trace file running HP	195
5.31	The links information's	198
5.32	The weights of links endpoints and the total packets	198
5.33(a)	Site 0 O-D Traffic Shortest Path	199
5.33(b)	Site 1 O-D Traffic Shortest Path	199
5.33(c)	Site 2 O-D Traffic Shortest Path	199
5.33(d)	Site 3 O-D Traffic Shortest Path	199
5.33(e)	Site 4 O-D Traffic Shortest Path	199
5.34	Estimated link loads in production network	200
5.35	The routing matrix for the scenario network topology	201
5.36	Site 0 the information of next hop to next AS	202
5.37	Link information's	204
5.38(a)	Site 0 O-D Traffic Matrix	204
5.38(b)	Site 1 O-D Traffic Matrix	204
5.38(c)	Site 2 O-D Traffic Matrix	205
5.38(d)	Site 3 O-D Traffic Matrix	205
5.38(e)	Site 4 O-D Traffic Matrix	205
5.38(f)	Site 5 O-D Traffic Matrix	205
5.39	Information of next hop to next AS for Site 0	205

## LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
1.1	Internet users in the world distribution by world regions – 2013- fourth quarter	1
1.2(a)	Company uses the Cloud Computing for their activities	2
1.2(b)	Company uses the Dual-homed network for redundancy	2
1.3	IPv4 allocation by prefix in Sudan (SD)	4
1.4	The steps to develop the ISM	9
2.1	Components terminology of network	19
2.2	Four-node-topology with links loads	25
2.3	AVG and MAX error percentage	27
2.4	The cost of link	38
2.5(a)	Router updates comparison of various protocols	39
2.5(b)	Route addition comparison of various protocols	40
2.5(c)	Number of next hop updates of various protocols	40
2.5(d)	Link utilization of various protocols	41
2.5(e)	Throughput of various protocols	41
2.5(f)	Delay encountered by various protocols	42
2.6	eBGP and iBGP	44
2.7	BGP Route Reflection setup	45
2.8	BGP Confederation setup	45
2.9	The node details and links between nodes	59
2.10	Process of node creation	62
2.11	Details of the link creation	63
2.12	Process of attaching the traffic agent to node	64
2.13	The simulation is ready for running	65
2.14	ns-BGP progress and timeline	68

3.1	Methodology in relation to the research objectives	78
3.2	Comparison of production network to the simulation model	80
3.3	Network production topology and links information	82
3.4	Traffic Matrix Estimation (TME) model block diagram	84
3.5	The original ODGen algorithm setup (Left side) and enhance ODGen algorithm (right side)	86
3.6	Steps to generate TME traffic text file	89
3.7	Enhance the corporation WAN topology	91
3.8	Steps for HP routing table updates based on output of TME	92
3.9	The HP validation procedure	93
3.10	The HP new function added to ns-BGP	94
3.11	The ns-BGP functionality validation test	95
3.12	The network topology in reflection2.tcl validation test file	96
3.13	The ISM internal sequence process	97
3.14	The Global Controller (GC) used to switching between HP or and TME scenarios	98
3.15	The HP scenarios	99
3.16	The TME scenarios	100
4.1	Framework for developing NS-2 near real model based on actual network parameters	105
4.2	Production network topology	106
4.3	Router to router data collection	107
4.4	Example of captured text file	108
4.5(a)	NS-2 Model emulating real world network-data captured online	111
4.5(b)	NS-2 Model emulating real world network-network information	111
4.5(c)	Model Emulating real world network-simulation running	112
4.6	Time comparison between real world packets sent and simulation packet sent	114

4.7	Time comparison between real world packet received and simulation packet received	114
4.8	Traffic Matrix algorithm pseudo-code phases	118
4.9	Fischer network, with directional link loads (packets per second)	119
4.10	The ISM- TME phase implementation flow chart	128
4.11	Real topology in production network	129
4.12	The good value of mean estimated in production network	135
4.13	The good value of standard deviation estimated in production network	136
4.14	O-D TME implementation steps to generate the traffic text file	140
4.15	The implementation for shortest path and O-D TME for all possible link failure in the example network	142
4.16	New network topology based in Link failure	143
5.1	Router running BGP and IGP	146
5.2	HP validation steps	147
5.3	The dual-homed network topology	148
5.4	BGP without HP function	151
5.5	HP learned from EIGRP	152
5.6	HP learning from TME	154
5.7	Unicast structure in NS-2	155
5.8	BGP unicast structure in NS-2	156
5.9	EBGP scenario topology (In the left side ns-BGP, right side Cisco Packet Tracer)	157
5.10	iBGP scenario topology (In the left side ns-BGP, right side GNS3)	158
5.11	The reflection2.tcl topology	159
5.12	Comparisons between the trace file without link failure and with link failure	161
5.13	The topology and trace file when site 0 failures	162
5.14	Hot Potato routing function to BGP in NS-2 with IBGP	163

5.15	HP function added to rtProtoBGP	164
5.16	How HP function deals with site classifier	164
5.17(a)	Normal execution of reflection2.tcl	165
5.17(b)	Execution with link failure of reflection2.tcl	165
5.18	The modification of trace by using HP function	167
5.19	The alternative link 4 between site 4 to site 2 via site 1 starts to be used	168
5.20	HP selects the alternative path	169
5.21	Comparisons between the trace files for both without link failure and with link failure	171
5.22	Production network topology	173
5.23	Aggregation router data collection	174
5.24	Example of reprocessing captured text file	174
5.25	The new network design	175
5.26	The captured text file and TME text file	189
5.27	The dual-homed network for corporation	192
5.28	The link down and up scenario between site 0 and site 3	193
5.29	Site down/ up between site 0 and all other sites scenario	194
5.30	Comparison between ISM and link failure scenarios based on Throughput, Delay and Packets loss	195
5.31	Comparison between the ISM and node failure scenarios Based on Throughput, Delay and Packets loss	196
5.32	New links are added between site3 and site4 in the existing network	197
5.33	TME traffic text file	202
5.34	Adds two new sites (multi-homed network topology)	203
5.35	The ISM model runs 32 sites topology	207
6.1	Flow for HP selection of egress point based on distances and end-to-end link endpoint probabilities	212

## LIST OF ABBREVIATIONS

ISP	-	Internet Service Provider
ICT	-	Information and Communication Technology
IPv4	-	Internet Protocol version 4
IPv6	-	Internet Protocol version 6
DC	-	Data Center
DRC	-	Data Recovery Center
ERP	-	Enterprise Resource Planning
STP	-	Spanning Tree Protocol
TE	-	Traffic Engineering
TME	-	Traffic Matrix Estimation
O-D	-	Origin –Destination
BGP	-	Border Gateway Protocol
IBGP	-	Interior Border Gateway Protocol
RR	-	Route Reflection
HP	-	Hot Potato
ISM	-	Integrated Simulation Model
EM	-	Expectation Maximization

EIGRP	-	Enhanced Interior Gateway Routing Protocol
NS-2	-	Network Simulator v2
NS3	-	Network Simulator v3
OPNET	-	Optimized Network Engineering Tools
OMnetT++	-	Operation and Maintenance New Equipment Training
SSFNet	-	Scalable Simulation Framework Network Models
POP	-	Point of Presence
DV	-	Distance Vector
MIS	-	Management Information System
LAN	-	Local Area Network
WAN	-	Wide Area Network
NSP	-	Network Service Provider
VoIP	-	Voice over Internet Protocol
SLA	-	Service Level Agreement
AS	-	Autonomous System
RRC	-	Route Reflector Client
CPU	-	Central Processing Unit
ER	-	Edge Router
MED	-	Multiexit-Discriminator
TM	-	Traffic Matrix
SD	-	Standard Deviation
ICMP	-	Internet Control Message Protocol



TCP	-	Transmission Control Protocol
UDP	-	User Datagram Protocol
C	-	C language
C++	-	C ++ Language
NAM	-	Tcl/Tk Based Animation Tool
FIFO	-	First in First out
ACK	-	Acknowledgement
Pkt	-	Packet
ELLFD	-	Estimated Link Load from Direction
ELLTD	-	Estimated Link Load to Direction
Mu	-	Mean
Sigma	-	Standard Deviation

## LIST OF MATHEMATICAL SYMBOLS

$R_a$	-	Packet Received time in the Production Network
$R_b$	-	Packet Received time in the Simulation Network
$ES$	-	Cell Transmission Time
$\rho$	-	Link Utilization
$P_{init_{ij}}$	-	The End-to-End Probabilities for All Nodes
$pps_{in_j}$	-	Total Packets Coming in to Node j
$p_{ij}$	-	The End-to-End Probability from Node i to Node j
$\lambda_{orig_i}$	-	Traffic Originating at Node i
$pps_{out_i}$	-	Total Packets out from Node i
$TM_{ij}$	-	Traffic matrix Between Node i and Node j
$ELLFD_{ij}$	-	Estimated Link Load from Direction between node i and node j
$ELLTD_{IJ}$	-	Estimated Link Load to Direction between node i and node j
$e$	-	Epsilon
$SD$	-	Standard Deviation

**LIST OF APPENDICES**

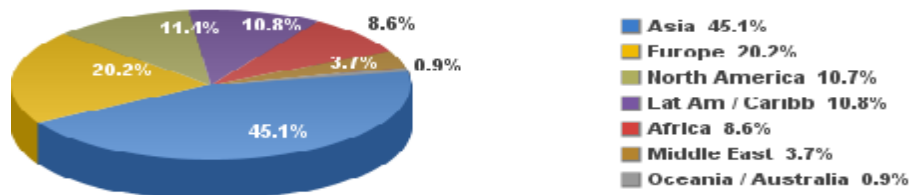
<b>APPENDIX</b>	<b>TITLE</b>	<b>PAGE</b>
A	Network Topology Design (Partial)	226
B	Code for reflection2,tcl	227

## CHAPTER 1

### INTRODUCTION

#### 1.1 Introduction

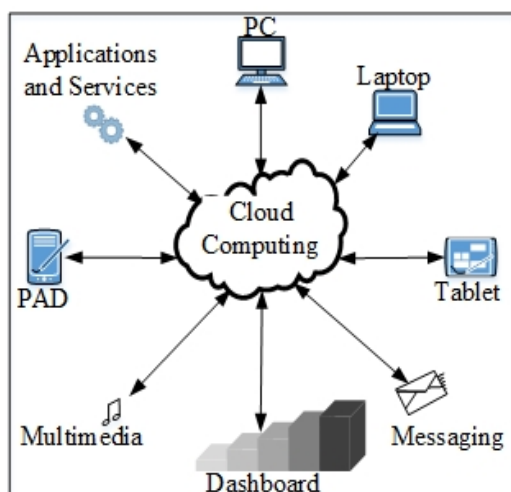
Internet has become an enabler of information in our society and is today a fundamental element of the worldwide communication infrastructure playing a major role in enhancing education, entertainment, business, and social life. This proliferation of content has been followed by a sustained growth of starving Internet consumers. Nowadays Internet traffic is rapidly increasing, not only in volume but also in heterogeneity and complexity of composition. Internet users now demand a faster, a higher-quality, a more reliable, and more secure Internet. Figure 1.1 shows the number of Internet users in fourth quarter of 2013 (2,802,478,934). With this volume of users, many challenging issues and more pressure is faced by the Internet Service Providers (ISPs) to provide quality services with limited resources. At the same time, better traffic monitoring and analysis is needed to ensure the delivery of services to the end users.



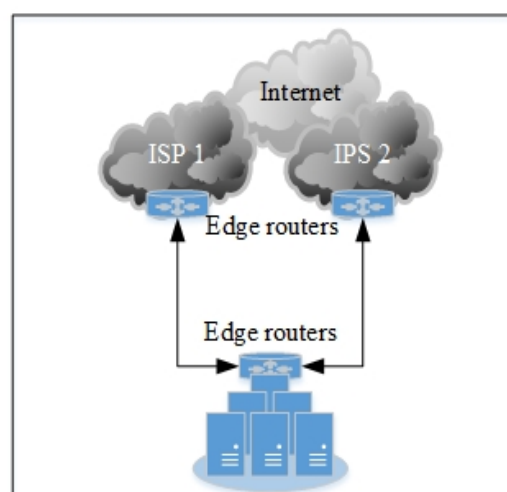
**Figure 1.1** Internet users in the world distribution by world regions – 2013 – fourth quarter

Source: Internet World Stats – [www.internetworldstats.com/stats.htm](http://www.internetworldstats.com/stats.htm) (last accessed June 2015)

Currently, many big companies are providing redundant and cheap cloud computing services. These cloud computing services provide a highly flexible environment enabling on-demand network access over the Internet (ISP's), thus allowing small companies to run their business without spending too much money in creating their own infrastructure to run their business applications, as in Management Information System (MIS). One of such infrastructure is shown in Figure 1.2a. In MIS, a Dashboard, as shown in this figure, is an easy to read, often single page, real-time user interface showing a graphical presentation of the current status and historical trends of any cooperation. To overcome the issue of availability of access, companies invest on redundant connections to the Internet ISPs using a dual-homed network (Karol *et al.*, 2007) setup. Figure 1.2b shows a setup of dual-homed network using BGP routing to connect to two ISPs. Dual or multi homed network is applicable in the real enterprise and medium companies world with their own private network (Abdullah *et al.*, 2014).



**Figure 1.2(a)** Company uses the Cloud Computing for their



**Figure 1.2(b)** Company uses the Dual-homed network for redundancy

In the ever challenging world, ISPs will constantly need to study and analyse the existing traffic over existing infrastructures and predict their future demands. This has to be done smoothly and skilfully without any impacts on end users interactions. To achieve these tasks, simulation is normally carried out in order to

have minimal or no impact on users (Mahdi and Hussain, 2013). The simulation has to represent the real environment and uses as much as possible real parameters to increase the estimated accuracy. A number of network simulators are available nowadays, either free or commercial.

## 1.2 Background

Sudan is a developing country with a population of 35.5 million; her advancement in ICT is also evolving. Consequently, the number of Internet users is also growing very fast. Table 1.1 shows the increment of Internet users, from 30,000 to 9.3 million over the periods of 2000 to 2014. This is a sharp increase compared to the decreasing population. This demand adds more pressure to the ISPs and introduces challenges which need to be addressed.

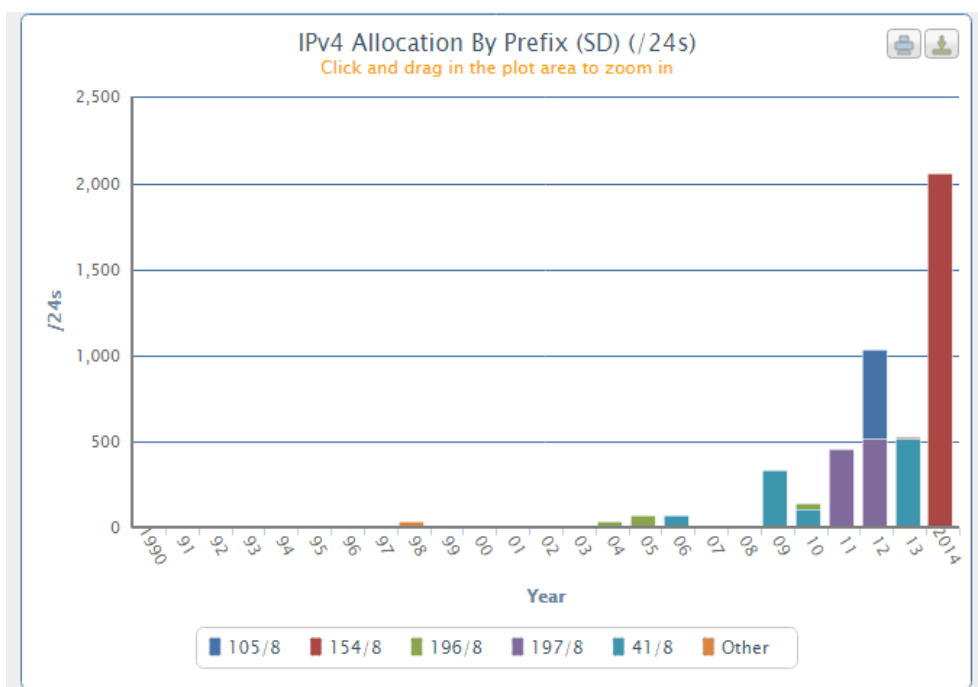
**Table1.1** : Sudan internet usage and population growth

Year	Users	Population
2000	30,000	36,841,500
2003	300,000	35,035,677
2009	4,200,000	34,206,710
2014	9,307,189	35,482,233

Source: Internet World Stats

<http://www.internetworldstats.com/af/sd.htm> (last accessed) June 2015)

The need for global IPs for Internet users and companies is becoming a challenge with limited availability of IPv4 addresses. Figure 1.3 shows the increase in demand for year 2014. Migration to IPv6 is a challenge because most people are experts in IPv4. Thus, ISPs must increase the user knowledge through workshops.



**Figure 1.3** IPv4 allocations by prefix in Sudan (SD)

Source: Internet Numbers Registry for Africa

<http://www.afrinic.net/en/services/statistics/country-stats> (last accessed June 2015)

In this research, the ICT services provided by Sudan's Internet Service Provider for the population is used for the case study; in addition, these services are also aimed to be enhanced and developed for optimum provision of services. This Sudan ISP (also referred to as 'Corporation'), has more than sixty four (64 egress points) sites, represented by different industrial cities, complexes and companies, that are located around the country.

The management of the Corporation decided to centralize the ICT departments into one body, in order to reduce investment, budget and to finally ensure that the technical and supervisory control that are currently outsourced to other commercial companies are now directly taken care of by the Corporation. Thus the Corporation can apply and implement the future ICT infrastructure based on their strategic plan.

### 1.3 Motivation

The Corporation dream is not impossible. However, at the same time, it is not an easy task and risks have to be managed properly in the migration effort. Some challenges are more related to management issues and culture. Technical issues, which are the main focus of this research, involve migrating from the current static routed configuration environment to the enhanced dynamic routed environment.

**Table 1.2** : The scope of involvement: current versus future states

Current State	Future State	Scope of involvement
A few sites has own independent ICT department	Centralize the ICT	Management
Running cost is very high	Initial cost is high (DC, DRC)	Management
A variety of network topologies	Apply new topology to achieve all corporation needs in next 15 years	Technical
A variety of ERP applications	Apply centralized ERP for the corporation	Management
ICT does not support the decision makers such as Dashboard	Fully support the decision makers on click	Management
Manually maintaining the routing protocol (Static)	Apply suitable dynamic routing	Technical
Network High availability, Available through Passive Link controlled by Spanning Tree Protocol (STP).	Network Connectivity must be fully utilized for maximization performance	Technical



## 1.4 Research Questions

Based on the literature reviewed and existing setup requirements as applicable to this case study, the following questions are generated:

1. How can Traffic Matrix Estimation (TME) method that is based on combination of end-to-end recovery (probability) and method of generating traffic matrix be classified?
2. How can the selected method be enhanced and implemented; and the results validated?
3. Based on the survey, which tools can be used to make the computation complexity easy?
4. How can an existing method that is easy to modify, enhanced and aligned with the research needs be selected?
5. How can the traffic generated between each O-D pair in a flow structure, including offset time, source, destination, protocol, type and length, in text file be save?
6. How can the network simulators be classified; and suitable ones that is cheap (possibly free) and has inherent libraries in modeling dynamic routes such as Border Gateway Protocol (BGP), Interior Gateway Protocol (IBGP) and Route Reflection (RR) be selected for the purpose of this research?
7. How to inject the real data captured from case study network or outcomes from TME text file into selected simulator and disable their traffic generator functionality?
8. How can the result from selected network simulator be validated, and which tools should be used?
9. How can the Hot-Potato routing algorithm be implemented; and their outcomes validated?

10. How can the TME outcomes as input parameters to support Hot-Potato in generating Hot-Potato routing changes plan be used and validated?
11. How can the BGP which run in selected simulator to use Hot-Potato routing protocol instead of the default routing in Interior Border Gateway Protocol (IBGP) within the cluster that uses Route Reflection (RR) setup be enforced?
12. How can the outcome when disabling the default routing in IBGP and use Hot-Potato Routing validated?
13. Since there is no work that integrates TME, HP and BGP, to the best of our knowledge in a simulator environment, how do we synchronize between them and validate the outcome based on the three metrics packet: loss, delay and throughput?
14. How can the impact of link failure in the network when using such integrated model be reduced?
15. How can the scalability when adding new nodes and increase the performance when adding new links when using the integrated model be extended?

## **1.5 Problem Statements**

The problem of the Corporation is to move from the current network configuration which uses static routing protocol to future state network that is based on Traffic Engineering (TE). In TE, the ODGen algorithm TME is limited to the number of hops, the Expectation Maximization (EM) accuracy is 92% and the complexity of calculations that consumes the CPU time (ODGen problem runs in about 19 seconds for each iteration). Thus, there is a need to minimize the real experimental risks as much as possible by using a suitable network simulator NS-2 is normally used to simulate the real network based on the topology and link probabilities. However, networks parameters representing the real network traffic are not used in NS-2. The error percentage observables with BGP simulated in NS-2

with three matrices are 22% for packet losses, 12% average delay and 22% throughput. There is lack of such comprehensive model consisting of TME, BGP and HP in NS-2 based on real network from previous studies and analysis. Previous work such those found in (Teixeira *et al.* 2008), only HP functionality were tested in BGP and which were used to generate the traffic matrix in order to study the network impacts.

## 1.6 Research Objectives

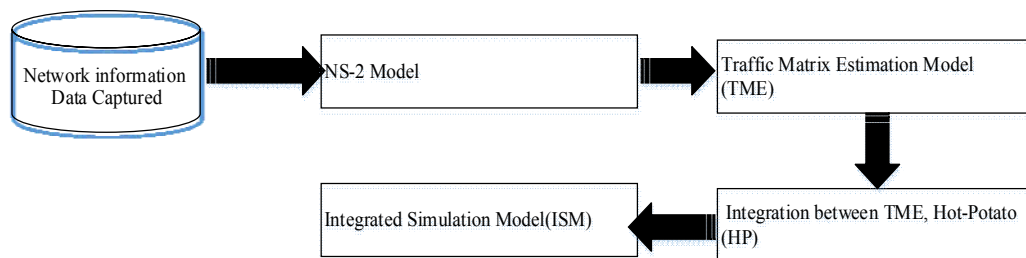
The ultimate aim of this research is to assist in providing the best solution to migrate from the current ISP network setup based on static routes to network based on enhanced auto dynamic updates. To enhance this auto dynamic update, the research views the issues based on traffic engineering problems utilized by TM (TME). The proposed Border Gateway Protocol (BGP) which provides scalable internetworking and redundant for ISP's to be implemented will use Hot-Potato (HP) routing protocol to get the dynamic updates, wherein in turn, HP will get their parameters from TME which are based on the real network setup and traffic data. Specifically, the following are the objectives of the research:

1. Enhanced the Origin – Destination Generator algorithm (ODGen) by increasing the accuracy, simplify the calculation and visualization of the traffic in the NS-2 network simulator instead of using their interior traffic generators based on the real network.
2. Develop an Integrated Simulation Model (ISM) which consists of TME, BGP and HP by using NS-2 simulation based on the real network to study the impacts and visualize- the changes in real network topologies based on Packet loss, Delay and Throughput.

## 1.7 Scope of Work and Assumptions

This research involves four phases. The first is development of simulation environment (using NS-2) phase. In this phase parameters representing the actual

data packets are injected into the real production network in the NS-2 model. Next, is the TME phase, which is to develop and enhance the existing TME model. The enhanced TME model will include the combination of the end-to-end probability path and traffic matrix algorithms based on Expectation Maximization (EM) whose parameters are based on the real production network traffic. In Phase Three, the Hot Potato (HP) integrated with TME will provide the dynamic updates for IBGP when using Route Reflection (RR) method. The last, is the ISM phase, where here TME, HP with BGP functions are all integrated within an open source network simulator. The four phases are illustrated in Figure 1.4.



**Figure 1.4** The steps to develop the ISM

The scope of this research is as follows:

1. Dataset are captured from the Corporation in Sudan which is collected at router-to-router level through a modified sniffer program.
2. The simulation uses NS-2 Network simulator.
3. In generating the TME model, the following are used:
  - i. The R tools are to be implemented with EM algorithm for the Gaussian mixture model.
  - ii. Dijkstra's Minimum Weight Path Algorithm to compute the shortest paths.
  - iii. The weights used by Dijkstra's Algorithm and Hot-Potato Algorithm are the Enhanced Interior Gateway Routing Protocol (EIGRP) metric.
4. The work does not include Traffic Matrix optimization.

## 1.8 Contributions of Research

1. ODGen is enhanced by unlimited number of hops, the accuracy of EM increases from 92% to 97% and computations (in which the average of 10 execution elapsed time equal to 0.07 seconds) is simplified.
2. Injecting the real network traffic in NS-2 instead of using readily available NS-2 internal traffic generators. The results shows that the characteristics of injected traffic and the real traffic are very similar with an average error packet time send 0% and error packet time received 3.61% with 0% packet loss when comparing between them. Thus we are using parameters representing real traffic instead of NS-2 packet traffic generators based on certain distribution function.
3. Development of an Integrated Simulation Models based on NS-2 using real traffic parameters. With the ISM, various scenarios, such as link or node removal and addition can be studied and its impact evaluated. The model, wherein Hot Potato learns the weight from TME optimizes further the switching time for BGP from primary link to the alternative to 0.05 seconds.

## 1.9 Organization of the Thesis

This thesis includes six chapters and the appendices.

Chapter 2 discusses four main topics. Firstly, NS-2 model based on the real network parameter methods are discussed. This is followed by traffic matrix estimation methods. Thirdly, Hot Potato routing functions in simulators network is described. This is finally followed by a discussion on Border Gateway Protocol functionality on network simulators. At the end of the chapter, the research questions that are generated from these reviewed literatures are discussed.

Chapter 3 shows the steps involved in the research methodology as applicable to this study. Likewise, the models and the proposed data collection strategies are explained.

Chapter 4 explains further on generating NS-2 traffic model based on real network parameter. Development and enhancement of the traffic matrix estimation model based on a production network is elaborated. This chapter also discusses the data collection, experimental setup and implementation of the production network to test the accuracy of the NS-2 model and the TME.

Chapter 5 deals with the TME outcome for Hot-Potato routing algorithm and how IBGP could get dynamic update from Hot-Potato protocol. This chapter also discusses the experimental setup and implementation of the production network to test the effectiveness of the ISM in dealing with link or node failure, as well as the addition of new node or link.

Chapter 6 concludes the thesis by discussing the achievements. The future work also described.

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