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Empirical Modeling of End-to-end Jitter

by
Mihai Lazar

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the School of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

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Abstract

This thesis presents an empirical study of the end-to-end jitter in a multi-node network. Extensive simulations for a basic twelve node network have been conducted. An empirical relation between the accumulated node delay variance and the end-to-end node delay variation is obtained for various simulation scenarios. This study has a direct practical purpose: the knowledge of end-to-end jitter allows network planners to design and dimension integrated data, voice and video networks.

Keywords: Jitter, Delay Variation, Simulation, Empirical Polynomial Expression, Network Model, OPNET.

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Table Of Contents

Abstract..ii
Acknowledgments iii
List of figures ix

CHAPTER 1 INTRODUCTION 1

1.1 Overview of Existing Work..4
  1.1.1 Jitter Characterization in ATM Networks 4
    1.1.1.1 Analytical Methods 4
    1.1.1.2 Existing Simulations and Empirical Data Analysis 6
  1.1.2 Jitter Control 7

1.2 Motivations and Approaches 7

1.3 Objectives and Contributions 10

1.4 Thesis Organization..10

1.5 Symbols, Acronyms, Notations and Glossary.................................11
  1.5.1 Glossary 11
  1.5.2 Notations, Abbreviations and Acronyms 12

CHAPTER 2 NETWORK OPERATION, MODELING AND ASSUMPTIONS.14

2.1 Network Model 14

2.2 Node Model 20

2.3 General Assumptions..23

2.4 Traffic Models..23
  2.4.1 Bursty Traffic 24
  2.4.2 Self-Similar Traffic 25
    2.4.2.1 Self-Similar Traffic Model 27

2.4.3 Single versus Multiple Background Traffic Sources 28

2.5 OPNET Simulation Model 28

2.5.1 Simulation Parameters 34

CHAPTER 3 PERFORMANCE EVALUATION 35

3.1 End-to-end Jitter 36

3.2 Confidence Interval 37

3.3 Simulation Assumptions 41

3.4 Simulation Results 41

3.4.1 Bursty Traffic 43

3.4.1.1 Single Background Traffic Sources 43

3.4.1.2 Multiple Background Traffic Sources 49

3.4.2 Self-Similar Traffic 50

3.4.2.1 Single Background Traffic Sources 50

3.4.2.2 Multiple Background Traffic Sources 56

3.5 Other Investigation 57

3.5.1 Dependency of the End-to-end Jitter vs. the Average End-to-end Delay 57

3.5.1.1 Effect of Large Average End-to-end Delay on the End-to-end Jitter 60

3.5.2 Cell Loss Probability 61

3.5.2.1 Total Loss Probability as a Function of Service Rate 63

3.5.2.2 Loss Probability as a Function of Background Traffic 64

3.5.3 Effect of Intermediate Node Input Buffer Size on the End-to-end Jitter 64

3.5.4 Effect of Queue Length on the End-to-end Jitter 65

3.5.5 Effect on the Number of Stages on the End-to-End Jitter 66

3.5.6 Effect of Priority Traffic on the End-to-End Jitter 67

3.6 Concluding Remarks 67

CHAPTER 4 EMPIRICAL FORMULATION 68

4.1 Polynomial Expression 68

4.2 Relation of the Polynomial Coefficients to the Background Traffic Intensity 69

4.2.1 Bursty Traffic 69
4.2.2 Self Similar Traffic 71

4.3 Relation of the Polynomial Coefficients to the Service Rate 72
4.3.1 Bursty Traffic 72
4.3.2 Self Similar Traffic 73

4.4 Dependency of Polynomial Coefficient on the Simulation Parameters 73

4.5 Relation of the Polynomial Coefficients to the Intermediate Node Utilization Factor 78

4.6 Verification 81
4.6.1 Estimation Accuracy 83
4.6.2 Prediction Accuracy 86

4.7 Chapter Summary 91

CHAPTER 5 CONCLUSION 92

CHAPTER 6 REFERENCES 94

APPENDIX A. 97

A.1 Theory of Self-Similar Traffic 97
A.1.2 Stationary Random Processes 97
A.1.3 Self-Similar Processes 97

A.2 Average End-to-end Delay 99
A.2.1 Average End-to-end Delay as a Function of Service Rate 99
A.2.2 Average End-to-end Delay as a Function of the Background Traffic 101

A.3 Effect of Cell Loss on End-to-end Jitter 101

A.4 Complete Simulation Results 104
A.4.1 Bursty Traffic 105
A.4.1.1 Single Background Traffic Sources 105
A.4.1.1.1 Effect of Background Traffic on the End-to-end Jitter 105
A.4.1.1.2 Effect of Service Rate on the End-to-end Jitter 106
A.4.1.1.3 Effect of Two Priorities Traffic 108

A.4.1.1.3.1 Effect of Background Traffic on the End-to-end Jitter 108
A.4.1.1.3.2 Effect of Service Rate on the End-to-end Jitter 109
A.4.1.2 Multiple Background Traffic Sources 111
A.4.1.2.1 Effect of Background Traffic on the End-to-end Jitter 111
A.4.1.2.2 Effect of Service Rate on the End-to-end Jitter 112
A.4.1.2.3 Effect of Two Priorities Traffic 113
A.4.1.2.3.1 Effect of Background Traffic on the End-to-end Jitter 113
A.4.1.2.3.2 Effect of Service Rate on the End-to-end Jitter 114
A.4.2 Self Similar Traffic 116
A.4.2.1 Single Background Traffic Sources 116
A.4.2.1.1 Effect of Background Traffic 116
A.4.2.1.2 Effect of Service Rate 117
A.4.2.1.3 Effect of Two Priorities Traffic 118
A.4.2.1.3.1 Effect of Background Traffic 118
A.4.2.1.3.2 Effect of Service Rate 119
A.4.2.2 Multiple Background Traffic Sources 121
A.4.2.2.1 Effect of Background Traffic on the End-to-end Jitter 121
A.4.2.2.2 Effect of Service Rate on the End-to-end Jitter 122
A.4.2.2.3 Effect of Two Priorities Traffic 123
A.4.2.2.3.1 Effect of Background Traffic on the End-to-end Jitter 123
A.4.2.2.3.2 Effect of Service Rate on the End-to-end Jitter 125

A.5 Polynomial Coefficient for the End-to-end Jitter Empirical Formula 127
A.5.1 Relation of the polynomial coefficients to the background traffic 127
A.5.1.1 Bursty Traffic 127
A.5.1.1.1 Single Background Node Simulations 127
A.5.1.1.1.1 No Priority Traffic 127
A.5.1.1.1.2 Two Priorities Traffic 128
A.5.1.1.2 Multiple Background Nodes 129
A.5.1.1.2.1 No Priority Traffic 129
A.5.1.1.2.2 Two Priorities Traffic 130
A.5.1.2 Self Similar Traffic 131
A.5.1.2.1 Single Background Node Simulations 131
A.5.1.2.2 No Priority Traffic 131
A.5.1.2.2.1 Two Priorities Traffic 132
A.5.1.2.3 Multiple Background Nodes 133
No Priority Traffic 133

A.5.1.2.3.2 Two Priorities Traffic 134
A.5.2 Relation of the polynomial coefficients to the service rate 136
A.5.2.1 Self Similar Traffic 136
A.5.2.1.1 Single Background Node Simulations 136
A.5.2.1.1.1 No Priority Traffic 136
A.5.2.1.1.2 Priority Traffic 137
A.5.2.1.2 Multiple Background Sources 138
A.5.2.1.2.1 No Priority Traffic 138
A.5.2.2 Bursty Traffic 139
A.5.2.2.1 Single Background Node Simulations 139
A.5.2.2.1.1 No Priority Traffic 139
A.5.2.2.1.2 Two Priority Traffic 140
A.5.2.2.2 Multiple Background Sources 142
A.5.2.2.2.1 No Priority Traffic 142
A.5.2.2.2.2 Two Priority Traffic 143

A.6 OPNET Simulation Models 145
A.6.1 Sub-networks 146
A.6.2 OPNET Process Models 149
A.6.2.1 Bursty Traffic Generator 149
A.6.2.2 Self-Similar Traffic Generator 150
A.6.2.3 Tandem Queue Process 152

List Of Figures

Figure 1 Problem Context 3
Figure 2 Network traffic flow 14
Figure 3 General network model 17
Figure 4 Network model for prioritized traffic 18
Figure 5 Standard tandem queue model 21
Figure 6 Prioritized tandem queue model 22
Figure 7 Ethernet traffic for different time intervals [MORI95] 26
Figure 8 OPNET Model (regular traffic) 31
Figure 9 OPNET Model (prioritized traffic) 32
Figure 10 End-to-end delay Samples, for Bursty Traffic, Single Background Sources 39
Figure 11 End-to-end Delay Samples, for Self-Similar Traffic, Single Background Sources 40
Figure 12 End-to-end Jitter vs. Accumulated Delay Variance for Varying Background Traffic with Single Priority Bursty Stream 44
Figure 13 End-to-end Jitter at Destination Nodes vs. the Normalized Background Traffic Intensity 45
Figure 14 Comparison of the End-to-end Jitter vs. Accumulated Delay Variance for Different Service Rates: (A) 12 cells/second and (B) 20 cells/second 46
Figure 15 End-to-end Jitter at Destination Nodes vs. Service Rate 47
Figure 16 Comparison Between High and Low Priority Reference Traffic Streams: (A) High Priority Traffic (B) Low Priority Traffic 48
Figure 17 Comparison of Single and Multiple Background Traffic Sources Results for End-to-end Jitter: (A) Single Background Sources and (B) Multiple Background Sources 49
Figure 18 End-to-end Jitter vs. Accumulated Delay Variance for Varying Background Traffic with Single Background Sources and a Single Priority Self-Similar Stream 51
Figure 19 End-to-end Jitter at Destination Node vs. Background Traffic with Single Background Sources and Single Priority Self-Similar Traffic 52
Figure 20 End-to-end Jitter vs. Accumulated Delay Variance for Varying the Service Rate with Single Background Sources and Single Priority Self-Similar Stream 53
Figure 21 End-to-end Jitter at Destination Nodes vs. Service Rate 54
Figure 22 Comparison of the End-to-end Jitter for (A) High and (B) Low Priority Traffic for Varying Service Rate 55
Figure 23 Comparison of (A) Single and (B) Multiple Background Traffic Sources Results for End-to-end Jitter for Self-Similar Traffic 56
Figure 24 End-to-end Jitter at the Destination Node vs. the End-to-end Delay Average for Bursty Traffic with Single Background Sources and Single Data Stream. Parameter: Increasing Background Traffic Rate 57

Figure 25 End-to-end Jitter at the Destination Node vs. End-to-end Delay Average for Bursty Traffic and Single Background Source for a Single Data Stream. Parameter: Decreasing Service Rate..............58

Figure 26 End-to-end Jitter at the Destination Node vs. Average End-to-end Delay for Self-Similar Traffic with Single Background Sources and a Single Data Stream; Parameter: Increasing Background Traffic Rate..............59

Figure 27 Effect of Large Average End-to-end Delay on the End-to-end Jitter A. End-to-end Jitter vs. Accumulated Delay Variance and B. Average End-to-end Delay vs. Background Traffic..............60

Figure 28 Comparison of Cell Loss Probability as a Function of Service Rate, for Self Similar, Two Priority Traffic. (A) Low Priority and (B) High Priority Traffic..............63

Figure 29 Cell Loss Probability as Function of Background Traffic, for Self Similar Traffic..............64

Figure 30 Effect of Cell Loss/Finite Input Buffer Size on the End-to-end Jitter..............65

Figure 31 End-to-End Jitter vs. Accumulated Delay Variance at Two Different Stages..............66

Figure 32 Polynomial Coefficient p_1 for Bursty Traffic, Single Background Sources, No Priority Traffic Stream 69

Figure 33 Polynomial Coefficient p_1 for Bursty Traffic, Single Background Sources, Two Priority Traffic Streams 70

Figure 34 Polynomial Coefficient p_1 for Self Similar Traffic, Single Background Traffic Source, No Priority Data Streams..............71

Figure 35 Polynomial Coefficient p_1 vs. Service Rate for No Priority Bursty Traffic, Single Background Traffic Sources..............72

Figure 36 Polynomial coefficient p_1 vs. service rate, self-similar no priority traffic, multiple background traffic sources..............73

Figure 37 Comparison of actual and estimated values of p_1, for varying background traffic rate for self-similar traffic, multiple background sources. (A) High Priority Traffic and (B) Low Priority Traffic 75

Figure 38 Comparison of actual and estimated values of p_1, for varying background traffic rate for self-similar traffic and single background sources. (A) High Priority and (B) Low Priority Traffic....76

Figure 39 Comparison of the p_1 variation with the background bursty traffic. (A) Single Background Sources and (B) Multiple Background Sources..............77

Figure 40 Polynomial Coefficient Relationship to the Reference Traffic Rate for Bursty Traffic..............78

Figure 41 Polynomial Coefficient vs. Intermediate Node Utilization Factor for Bursty Traffic..............80

Figure 42 Estimation Accuracy for Varying Background Bursty Traffic, Single Reference Stream and Single Background Traffic Sources. (A) Relative Estimation Error and (B) Measured vs. Estimated End-to-end Jitter..............83

Figure 43 Estimation Accuracy for Single Bursty Traffic Stream and Varying Service Rate (A) Relative Estimation Error and (B) Measured and Estimated End-to-end Jitter vs. Accumulated Delay Variance..............84

Figure 44 Estimate Relative Error for End-to-end Jitter Varying Service Rate for Self Similar Traffic. (A) Relative Error (B) Measured and Estimate End-to-end Jitter 85
Figure 45 Verification of Prediction Accuracy for Self-Similar, Two Priority Traffic. (A) Measured and Calculated End-to-end Jitter and (B) Relative Error of End-to-End Jitter 87
Figure 46 Verification of Prediction Accuracy for Self-Similar, Two Priority Traffic with p_I calculated as a function of ρ_{mean}. (A) Measured and Calculated End-to-end Jitter and (B) Relative Error of End-to-End Jitter 88
Figure 47 Verification of Prediction Accuracy for Self Similar, No Priority Traffic. (A) Measured and Calculated End-to-end Jitter and (B) Relative Error for the End-to-end Jitter 89
Figure 48 Verification of Prediction Accuracy for Self Similar, No Priority Traffic, with p_I calculated as a function of ρ_{mean}. (A) Measured and Calculated End-to-end Jitter and (B) Relative Error for the End-to-end Jitter 89
Figure 49 Verification of Prediction Accuracy for Bursty, No Priority Traffic, with p_I calculated as a function of ρ_{mean}. (A) Measured and Calculated End-to-end Jitter and (B) Relative Error for the End-to-end Jitter 90
Figure 50 Comparison of Average End-to-end Delay as a Function of Service Rate for Self-Similar Traffic. (A) High Priority Traffic and (B) Low Priority Traffic 99
Figure 51 Comparison of Average End-to-end Delay as a Function of Service Rate for Self Similar Traffic. (A) High Priority and (B) Low Priority Traffic 100
Figure 52 Average End-to-end Delay as a Function of the Background Traffic 101
Figure 53 End-to-end Jitter vs. Accumulated Delay Variance for variable Background Traffic Intensity with Bursty Traffic and Single Background Sources. Study of Cell Loss 102
Figure 54 End-to-end Jitter at Destination Node vs. Background Traffic for Bursty Traffic and Single Background Sources 102
Figure 55 Effect of Cell Loss Probability on the End-to-end Jitter Polynomial Coefficient 103
Figure 56 End-to-end Jitter vs. Accumulated Delay Variance for variable Background Traffic Intensity with Bursty Traffic and Single Background Sources 106
Figure 57 End-to-end Jitter at Destination Node vs. Background Traffic for Bursty Traffic and Single Background Sources 106
Figure 58 End-to-end Jitter vs. Accumulated Delay Variance when varying the Service Rate, for Bursty Traffic and Single Background Sources 107
Figure 59 End-to-end Jitter at Destination Node vs. Service Rate, for Bursty Traffic and Single Background Sources 107
Figure 60 End-to-end Jitter vs. Accumulated Delay Variance with variable Background Traffic Intensity, for Bursty High Priority Traffic and Single Background Sources 108
Figure 61 End-to-end Jitter vs. Accumulated Delay Variance with variable Background Traffic Intensity, for Bursty Low Priority Traffic and Single Background Sources 108

Figure 62 End-to-end Jitter at Destination Node vs. Background Traffic, for Bursty High Priority Traffic and Single Background Sources 109
Figure 63 End-to-end Jitter at Destination Node vs. Background Traffic, for Bursty Low Priority Traffic and Single Background Sources 109
Figure 64 End-to-end Jitter vs. Accumulated Delay Variance with varying Service Rate for Bursty High Priority Traffic and Single Background Sources 110
Figure 65 End-to-end Jitter vs. Accumulated Delay Variance when varying the Service Rate, for Bursty Low Priority Traffic and Single Background Sources 110
Figure 66 End-to-end Jitter at Destination Node vs. Service Rate for Bursty High Priority Traffic and Single Background Sources 110
Figure 67 End-to-end Jitter at Destination Node vs. Service Rate for Bursty Low Priority Traffic and Single Background Sources 110
Figure 68 End-to-end Jitter vs. Accumulated Delay Variance for variable Background Traffic Intensity, for Bursty Traffic and Multiple Background Sources 111
Figure 69 End-to-end Jitter at Destination Node vs. Background Traffic, for Bursty Traffic and Multiple Background Sources 111
Figure 70 End-to-end Jitter vs. Accumulated Delay Variance when varying the Service Rate, for Bursty Traffic and Multiple Background Sources 112
Figure 71 End-to-end Jitter at Destination Node vs. Service Rate, for Bursty Traffic and Multiple Background Sources 112
Figure 72 End-to-end Jitter vs. Accumulated Delay Variance when varying the Background Traffic Intensity, for High Priority Bursty Traffic and Multiple Background Sources 113
Figure 73 End-to-end Jitter vs. Accumulated Delay Variance when varying the Background Traffic Intensity, for Low Priority Bursty Traffic and Multiple Background Sources 113
Figure 74 End-to-end Jitter at Destination Node vs. Background Traffic, for High Priority Bursty Traffic and Multiple Background Sources 114
Figure 75 End-to-end Jitter at Destination Node vs. Background Traffic, for Low Priority Bursty Traffic and Multiple Background Sources 114
Figure 76 End-to-end Jitter vs. Accumulated Delay Variance when varying the Service Rate, for High Priority Bursty Traffic and Multiple Background Sources 115
Figure 77 End-to-end Jitter vs. Accumulated Delay Variance when the Service Rate, for Low Priority Bursty Traffic and Multiple Background Sources 115
Figure 78 End-to-end Jitter at Destination Node vs. Service Rate, for High Priority Bursty Traffic and Multiple Background Sources 115
Figure 79 End-to-end Jitter at Destination Node vs. Rate for Low Priority Bursty Traffic and Multiple Background Sources 115

Figure 80 End-to-end Jitter vs. Accumulated Delay Variance when varying the Background Traffic Intensity, for Self-Similar Traffic and Single Background Sources.......116

Figure 81 End-to-end Jitter at Destination Node vs. Background Traffic, for Self-Similar Traffic and Single Background Sources.......116

Figure 82 End-to-end Jitter vs. Accumulated Delay Variance when varying the Service Rate, for Self-Similar Traffic and Single Background Source.......117

Figure 83 End-to-end Jitter at Destination Node vs. Service Rate, for Self-Similar Traffic and Single Background Source.......117

Figure 84 End-to-end Jitter vs. Accumulated Delay Variance when varying the Background Traffic Intensity, for High Priority Self-Similar Traffic and Single Background Sources.......118

Figure 85 End-to-end Jitter vs. Accumulated Delay Variance when varying the Background Traffic Intensity, for Low Priority Self-Similar Traffic and Single Background Sources.......118

Figure 86 End-to-end Jitter at Destination Node vs. Background Traffic, for High Priority Self-Similar Traffic and Single Background Sources.......119

Figure 87 End-to-end Jitter at Destination Node vs. Background Traffic, for Low Priority Self-Similar Traffic and Single Background Sources.......119

Figure 88 End-to-end Jitter vs. Accumulated Delay Variance when varying the Service Rate, for High Priority Self-Similar Traffic and Single Background Sources.......120

Figure 89 End-to-end Jitter vs. Accumulated Delay Variance when varying the Service Rate, for Low Priority Self-Similar Traffic and Single Background Sources.......120

Figure 90 End-to-end Jitter at Destination Node vs. Service Rate, for High Priority Self-Similar Traffic and Single Background Sources.......120

Figure 91 End-to-end Jitter at Destination Node vs. Service Rate, for Low Priority Self-Similar Traffic and Single Background Sources.......120

Figure 92 End-to-end Jitter vs. Accumulated Delay Variance when varying the Background Traffic Intensity, for Self-Similar Traffic and Multiple Background Sources.......121

Figure 93 End-to-end Jitter at Destination Node vs. Background Traffic, for Self-Similar Traffic and Multiple Background Sources.......121

Figure 94 End-to-end Jitter vs. Accumulated Delay Variance when varying the Service Rate, for Self-Similar Traffic and Multiple Background Sources.......122

Figure 95 End-to-end Jitter at Destination Node vs. Service Rate, for Self-Similar Traffic and Multiple Background Sources.......122

Figure 96 End-to-end Jitter vs. Accumulated Delay Variance when varying the Background Traffic Intensity, for High Priority Self-Similar Traffic and Multiple Background Sources.......123

Figure 97 End-to-end Jitter vs. Accumulated Delay Variance when varying the Background Traffic Intensity, for Low Priority Self-Similar Traffic and Multiple Background Sources.......123

Figure 98 End-to-end Jitter at Destination Node vs. Background Traffic, for High Priority Self-Similar Traffic and Multiple Background Sources 124
Figure 99 End-to-end Jitter at Destination Node vs. Background Traffic, for Low Priority Self-Similar Traffic and Multiple Background Sources 124
Figure 100 End-to-end Jitter vs. Accumulated Delay Variance when varying the Service Rate, for High Priority Self-Similar Traffic and Multiple Background Sources 125
Figure 101 End-to-end Jitter vs. Accumulated Delay Variance when varying the Service Rate, for Low Priority Self-Similar Traffic and Multiple Background Sources 125
Figure 102 End-to-end Jitter at Destination Node vs. Service Rate, for High Priority Self-Similar Traffic and Multiple Background Sources 126
Figure 103 End-to-end Jitter at Destination Node vs. Service Rate, for Low Priority Self-Similar Traffic and Multiple Background Sources 126
Figure 104 Polynomial Coefficients for Bursty Traffic, Single Background Sources, Single Stream Traffic 127
Figure 105 Polynomial Coefficients for Bursty Traffic, Single Background Sources, Dual Stream Traffic 128
Figure 106 Polynomial Coefficients for Bursty Traffic, Multiple Background Sources, No Priority Traffic 129
Figure 107 Polynomial Coefficients for Bursty Traffic, Multiple Background Sources, Two Priorities Streams Traffic 130
Figure 108 Polynomial Coefficients for Self-Similar Traffic, No Priority Traffic, Single Background Traffic Sources 131
Figure 109 Polynomial Coefficients for Self-Similar Traffic, Single Background Nodes, Two Priority Traffic 132
Figure 110 Polynomial Coefficients for Self-Similar Traffic, Single Background Traffic Sources, No Priority Traffic 133
Figure 111 Polynomial Coefficients for Self-Similar Traffic, Multiple Background Sources, Two Priorities Traffic 134
Figure 112 Comparison of Polynomial Coefficients for (A) High Priority Traffic and (B) Low Priority Traffic 135
Figure 113 Polynomial Coefficients for Self-Similar, Single Background Sources, No Priority Traffic136
Figure 114 Polynomial Coefficients for Self-Similar, Two Priority Traffic with Single Background Sources (High Priority Traffic) 137
Figure 115 Comparison of Polynomial Coefficients for Self-Similar with Single Background Sources: High and Low Priority Traffic 137
Figure 116 Polynomial Coefficients for Self-Similar, No Priority Traffic with Multiple Background Sources 138

Figure 117 Polynomial Coefficients for Bursty, No Priority Traffic, Single Background Sources..........139
Figure 118 Polynomial Coefficients for Bursty, Two Priority Traffic, Single Background Sources......141
Figure 119 Polynomial Coefficients for Bursty, No Priority Traffic with Multiple Background Sources 142
Figure 120 Polynomial Coefficients for Bursty, Two Priority Traffic with Multiple Background Sources 144
Figure 121 General OPNET Simulation Model..........145
Figure 122 OPNET Source Network nd_1..........146
Figure 123 OPNET Intermediary Network nd_2..........147
Figure 124 OPNET Destination Network nd_3..........148
Figure 125 OPNET Bursty Traffic Generator Finite State Machine..........149
Figure 126 OPNET Self-Similar Traffic Generator Finite State Machine..........150
Figure 127 OPNET Tandem Queue Process Finite State Machine..........152

Chapter 1
Introduction

The most recent trend in the telecommunication industry is the convergence of voice, video and data services.

In recent years, there has been a great interest in video transport over telecommunications networks. Since most voice and video services require a practically continuous stream of data cells, they impose strict real-time requirements on the arrival of transmitted data. In this context, one of the most important requirements is keeping a quasi-constant delay between consecutive data cells of a voice or video stream (in fact, a constant bit rate). This requirement can be quite easily inferred from the following type of reasoning: assume that a video source sends thirty frames per second (this is the rate at which the human eye perceives a series of images as a motion picture), at equally spaced time intervals. Also assume that the destination of that video stream has a limited buffer capacity (a quite natural limitation) - say it can only store three frames. When the first image frame arrives, the destination device would store the first three frames of the stream, and only then would start playing back the movie. However, if at a certain moment no frames arrive for more than one tenth of a second, the destination buffer will be emptied and the displayed image will flicker (since no new frame will be available to be displayed at its due time). The same type of reasoning can be used for voice streams.

This type of behaviour - the time interval between the data packets emitted by the source node is not preserved when the data packet arrives at the destination node occur in all data packet networks. This phenomenon is called delay jitter. A formal definition for delay jitter or delay variation will be given in the following section of this thesis.

ATM networks are one of the most popular transport environments for high bandwidth data streams, due to their statistical multiplexing capability and increased transmission bandwidth capacity (e.g. ATM over high speed optical networks). We can consider these networks as highly representative for large bandwidth, high speed packet (cell) oriented data networks. ATM can support multimedia applications (i.e. audio, video and data) simultaneously. Video can be transported over ATM networks either at a constant bit rate (CBR) or variable bit rate (VBR). Recent research has been focused on VBR [ZHWZ98] since it utilizes network resources more efficiently than CBR video.

In ATM networks, the phenomenon described above (delay jitter) is also known as Cell Delay Variation (CDV). One of the causes of CDV in ATM networks is the use of statistical multiplexing. Delay jitter is also introduced by queuing within network buffers. Each node introduces a random queuing delay depending on the applied loading condition. The packet oriented transmission of information in ATM networks also causes additional delays besides the inevitable propagation delay: cell assembly time, cell transmission time and queuing delay within buffers. However, the variable portion of the end-to-end delay (between the source and destination nodes) - the delay jitter, is one of the most important parameters of data networks [KETKB92]. The delay jitter may affect the video or voice quality at the receiving end; basically, the quality of service of a given network.

Note that in traditional data communications, incoming packets can usually be consumed immediately by the applications when the packets arrive correctly and in sequence. The variation in delay, or jitter, has little real impact on these applications as the performance is largely dominated by the average delay that the packets have experienced. However, an important part of the traffic in the new integrated networks is multimedia (voice and/or video, images, audio). In these types of communications, delay jitter becomes an important issue. Multimedia applications such as video and audio must accurately recreate the original data stream at the receiver by playing back the data after a fixed delay offset from the original departure time. The packets arriving with shorter delay may have to wait in the receiver's buffer, in order for the packets with worst delay to arrive before the former can be played [WACR93]. Therefore, the tail of the source to destination end-to-end delay distribution often determines the performance of the multimedia applications.

Multimedia streams have critical timing constraints, especially when multiple multimedia streams belong to the same application. The support of such multimedia traffic in ATM networks adds further complexity due to jitter. Furthermore, according to [EES96], there is no guarantee that if each traffic stream is delivered according to its own jitter constraints, the inter-stream jitter is also conserved and vice-versa. For instance, for some ATM services, the delay jitter has to be compensated within the ATM adaptation layer, in order to restore a continuous bit stream at the receiving side. However, if the variable delay exceeds a certain limit, the payload of the cell may become useless [KETKB92].

Jitter often results from contention for resources. When packets have to wait in a queue, the inter-packet timing is often lost. According to [WACR93], however, for well-behaved sources, contention for resources can be reduced to minimum with fair queuing algorithms such as Fair Queuing, Virtual Clock, HRR and PGPS. One of the problems in analyzing jitter is how to model the traffic. Again according to [WACR93], it is hard to fit multimedia traffic into conventional statistical models as they are often time varying and algorithm dependant.

An end-to-end jitter problem in packet data networks can be formulated as follows. Given a source node, a destination node and a number of intermediate nodes, what is the delay jitter for the reference traffic between the source node and destination node in the presence of background traffic at each of the intermediate nodes? Note that the *reference traffic* is the data flow between the source node and destination node. Besides the reference traffic, each intermediate node must carry a certain amount of background traffic. Part of the background traffic may be addressed to the intermediate node where it joins the reference data stream, while part of it may continue towards other nodes along with the reference traffic.

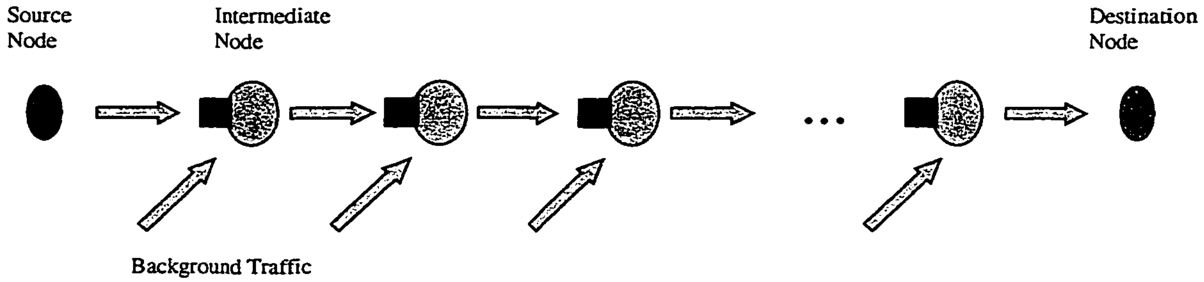


Figure 1 **Problem Context**

Each of the intermediate nodes has a finite queue capacity and stores in its buffers both reference and background traffic data packets (cells).

1.1 Overview of Existing Work

The literature concerning the study of jitter in computer networks is fairly extensive. The papers listed in the **References** section are only the part we considered relevant for this thesis among those that we found as part of the literature research.

Most papers deal with particular cases. For instance, MPEG-2 streams over ATM networks, is described in [ZHWZ98], while jitter recovery for multimedia traffic is described in [EES96].

Papers concerned with the theoretical study of jitter can be categorized into two large categories:

- Jitter characterization
- Jitter control.

Since the current thesis is concerned only with jitter characterization, we have focused our literature research mainly in this area.

1.1.1 Jitter Characterization in ATM Networks

The literature provides a number of interesting studies of jitter in ATM networks. A number of authors provide both analytical results and limited simulation results (for a small amount of network nodes - usually less than six).

1.1.1.1 Analytical Methods

In [KETKB92], the authors provide an approximate analytical approach to jitter for isolated network node as well as for a reference (or tagged) connection or stream of data. Their study concerns only bursty traffic. The authors argue that the obtained approximation results are in good agreement with simulation results and indicate that the end-to-end delay jitter for bursty traffic is in the range of the maximum transfer delay of one queuing node, *if the bursty input traffic is controlled by adequate traffic control mechanism.* It is important to emphasize that the result obtained in the paper only holds in the case a control mechanism can be put in place. The result cannot be used in the generalized case when no traffic control mechanism is available, or the mechanism has other purpose than jitter control.

In the analysis of jitter for a single node, [KETKB92] assumes an M/D/1/K (K places in the queue) model for short-term fluctuations and a fluid flow approximation for long-term fluctuations of the jitter. In the analysis of the "reference connection" from the source node to the destination node, the authors suggest that the convolution of the transfer times of all intermediate network nodes provides only a rough estimate of the delay jitter. Note that no attempt is done in [KETKB92] to evaluate the impact of background traffic on the jitter of the tagged data stream. Also, the authors only consider bursty traffic, while no attempt is made to study other types of traffic (e.g. self-similar).

A study of burstiness and jitter in multimedia communications is done in [WACR93] - for isolated network nodes only. The approach used in this paper is to divide the traffic stream into groups of packets called synchronization units and look for the general shape of the traffic curve. The traffic in each synchronization unit is characterized by a pair of values (ρ_{min}, ρ_{max}). ρ_{min} is the highest traffic rate at which the server is never idle and ρ_{max} is the peak rate of the incoming traffic. The length of a synchronization unit is considered to be M packets.

The authors obtain a relationship between burstiness and jitter and also between the upper bounds of burstiness and jitter. Assuming that the server is work conserving with service rate $\mu > \rho_{min}$, the authors prove that the jitter is bound by the value:

$$J_{max} = (M-1)(1/\mu - 1/\rho_{max})$$

This paper only studies a particular type of traffic, namely, bursty traffic. Furthermore, no attempt is done to characterize the jitter in more detail, that is, only an upper bound is obtained.

A very interesting theoretical approach to the calculus of jitter in ATM networks is done in [MSB94] and [MSB97]. In these papers, the authors provide techniques for estimating the end-to-end jitter of ***periodic*** traffic in an ATM network. The authors analyze light and heavy traffic behaviour of jitter incurred to a general tagged renewal stream in a single node. They propose to build a simple filter associated to each node (node *N*) in the network, in order to capture the impact of the background traffic on the jitter incurred to the tagged stream coming to a node. The output of the filter N gives the departure process of the tagged stream from node N. The authors argue that the departure process of the tagged stream can be approximated by a renewal process characterized by its inter-arrival time distributions of the cells, as described in [OMM91]. [MSB94] and [MSB97] only study particular cases of traffic (periodic), and for light or heavy load conditions only.

The queuing model used in [MSB97] consists of the superposition of a renewal stream (the tagged stream) and the background traffic. The background traffic is modeled as batches with a distribution that depends on a Markov chain. The FIFO (first in first out) queue used in the model is assumed to serve one cell per slot. Besides giving analytical estimates for the heavy and light traffic jitter, [MSB97] also provides numerical results for the case of the general "tagged" traffic and background traffic modeled as independent and identically distributed batches with arbitrary distribution in successive slots.

According to [MSB94], the jitter variance is (almost) proportional to the variance of background traffic competing for resources with the tagged stream. In general, as the number of nodes increases, the jitter distribution approaches a limit (result similar to [WACR93]). The authors prove that under heavy load, the variance of the jitter converges to the following limit value:

$$\sigma^2 = T \times \sigma_B^2 / [\, 1 - (1-1/T)^2 \,]$$

where T is the period of the tagged stream at node 1 (one tagged cell enters node 1 each T slots) and σ_B^2 is the variance of the background traffic. The jitter variance in heavy traffic can be shown to be the upper bound for the jitter variance in all range of traffic levels and arbitrary number of nodes.

1.1.1.2 Existing Simulations and Empirical Data Analysis

The literature research done for this thesis provided a number of interesting papers concerning the study of delay jitter using simulations. However, they are mostly limited to some particular cases (e.g. MPEG-2 streams over ATM networks) or to providing validation for analytical results. Only a relatively small number of nodes from the source node to destination node (usually between 6 and 8) is used in the simulations shown in these papers. Also, the effect of the background network traffic on the reference traffic is not studied.

In [PABI95] for instance, the authors developed a simulation model to analyze ATM traffic entering the network at the User Network Interface (UNI) from a single traffic source feeding the network after it is shaped. Their work attempts to study through simulation the contribution of a leaky bucket plus cell spacer subsystem to the delay and jitter at the end-station in a network.

[ZHWZ98] provides a model and simulation of MPEG-2 streams delivered through an ATM network with jitter. The probability density function of the inter-arrival time of the ATM adaptation layer 5 (AAL5) protocol data unit is derived from an MPEG-2 source model and an ATM network jitter model.

1.1.2 Jitter Control

A number of authors have also investigated means to control (minimize) delay jitter. Since jitter control is not the topic of this thesis, we only summarize these papers here. In [MAPS98], the authors propose on-line (i.e. real-time) algorithms to both minimize ***delay jitter*** and ***rate jitter***. Their aim is to compare the performance of such algorithms to off-line algorithms. In [EES96] the jitter and inter-flow jitter of multimedia traffic in ATM networks are analyzed. The authors show that jitter is accumulating when the number in the path increases. To counter the effect of multiple nodes in the data stream path, the authors suggest two recovery strategies: *Destination Only* (DO) and *Intermediate Also* (AI). [HCN97] proposes a specific network architecture (VGAnet) to support certain quality of service parameters (jitter control, bandwidth guarantee and so on) for compressed video/audio traffic.

[LIRI95] studies policies for deciding which cells will be lost or dropped when losses occur at a finite buffer ATM node and how the policies affect performance criteria such as delay and jitter. The paper shows that usually the rear dropping in which cells that arrive to a full buffer are lost stochastically maximizes delay, while front dropping, in which cells at the front of the buffer are lost, stochastically minimizes delay. On the other hand, *rear dropping stochastically minimizes the jitter*. The authors also propose policies that have both stochastically smaller delay and less lost cell burstiness than the rear dropping policy.

1.2 Motivations and Approaches

As shown in the previous subsection, jitter is one of the major problems of packet-switched networks. Hence, it is important to understand the variance of the end-to-end delay or jitter.

The main aim of this thesis is to provide an empirical relationship between jitter at each intermediate node (that can be calculated analytically) and end-to-end delay jitter (between the traffic source and destination nodes). Such a relationship would allow network planners to determine whether a certain level of network traffic allows video and voice streams to be transmitted in good condition from the source to the destination nodes in a given integrated network, or to dimension integrated networks to allow certain levels of traffic. By having a means to simply calculate the jitter between any source and destination nodes, network planners can determine whether the jitter is acceptable for the voice or video stream or whether the available bandwidth needs to be increased in order to allow good reception. An empirical relation describing the end-to-end jitter would also allow a quick estimate of the delay jitter at various points in the network, which is also important for network planning.

Although quite informative and interesting, the papers on this topic, found in the literature, lacked some important aspects:

- In the researched literature we have not found any attempt to find a generalized, albeit empirical, formula for the end-to-end jitter as a function of various network parameters. The papers we have found deal with particular cases or particular types of networks.
- The existence of background traffic on the jitter of the *tagged* or *reference* traffic is not always taken into consideration (the reference traffic stream is the traffic stream under study).
- No attempt to study two priority traffic streams has been found, although it seems important to study the effect of the reference and background low priority traffic flowing in the network on the jitter of the high priority traffic. In the two priority traffic streams case, the reference traffic is made up of a high priority traffic stream and a low priority traffic stream. Cells in the high priority traffic stream are always serviced before those in the low priority stream.
- In [LTWW94], the authors demonstrate that Ethernet local area network (LAN) traffic is statistically self-similar. None of the commonly used traffic models is able to capture this fractal behavior, however such behavior has serious implications for the design, control, and analysis of high-speed, cell-based (B-ISDN) networks, and that aggregating streams of such traffic

typically intensifies the self-similarity (burstiness). However, no simulation of the jitter of self-similar traffic has been found in the literature.

- Furthermore, while the literature in the domain of jitter control and analysis is quite important, no extensive simulation seems to be available for the two types of traffic that seem that be the most common in the current networks: self-similar and bursty traffic. As mentioned in [WMM97], single sources (single computer) exhibits bursty characteristics (certain types of traffic, e.g. voice/audio or MPEG video).
- No study takes into consideration the effect of multiple background sources connected to each intermediary network node (nodes between the reference traffic source and destination nodes).
- Many papers (e.g. [MSB94] and [MSB97]) provide an extensive analysis of low and heavy traffic. However, in it is also important to study the jitter under normal traffic conditions.

This thesis attempts to address all the aspects mentioned above.

Determining a means to calculate the end-to-end delay jitter between the source and destination node of a cell stream has a practical usage: for instance, it may allow data carrier companies to dimension their networks for optimal performance. It may also allow network equipment vendors to improve the performance of their devices.

A general case analytical approach to the problem seems to be quite difficult. Therefore, the approach taken in this thesis is to tackle the study of the end-to-end delay jitter using extensive simulations. Two types of traffic - self similar and bursty - have been used for our simulations. A twelve node network model using tandem queues has been designed and implemented using *OPNET* [MIL97], a network simulation package from *OPNET Technologies Inc.* The model will be described in detail in section 2. The simulation results have been processed (in the sense of obtaining best fit curves of the end-to-end jitter vs. different simulation parameters) using *Matlab,* a general mathematical package from *Mathworks* [MATL98]. *Matlab* allows us to obtain the coefficients of the polynomials that best approximate the empirical results obtained from the simulation. Hence, an empirical relationship of the end-to-end jitter as a function of various simulation parameters can be obtained.

1.3 Objectives and Contributions

The purpose of this study is to determine an empirical formula correlating the end-to-end delay jitter to intermediary nodes delay jitter. Since the delay jitter (or delay variance - notation σ^2) at each node can be obtained from direct calculation (in most cases), it is interesting to determine - albeit empirically - a relationship between the end-to-end delay jitter and the node delay jitter at intermediate nodes.

The contributions of this thesis are:

1. Modeling the end-to-end jitter by an empirical approach.
2. Implementing the model by an OPNET network simulator
3. Studying the performance of the network model
4. Obtaining a polynomial relationship, between the end-to-end jitter and the delay jitter at the intermediate nodes.
5. Investigating the relationship as a function of various simulation parameters.

1.4 Thesis Organization

This thesis is structured as follows. The first chapter - the introduction - deals with issues related to jitter in computer and telecommunication networks. The introduction also gives an overview of existing work in the domain of the end-to-end delay jitter (both analytical and empirical approaches) and presents the motivations for the current thesis. The approaches used in order to study the problem, objectives of this thesis and contributions (in the opinion of the author) to the study of jitter are also presented in the introduction. Finally, the first section introduces the symbols, notations and acronyms used throughout the thesis.

The second chapter presents the network simulation model and architecture used for the study of the jitter. It presents the model overview, assumptions and simulation model and parameters. It also gives a brief presentation of the types of network traffic used for the simulation. Chapters Three presents the simulation results, for all cases under study. In Chapter Four, empirical formulae are derived from the simulations. This chapter also presents the results of verifications of the formulae on a number of supplementary simulations: the values of the end-to-end jitter obtained experimentally are compared against those calculated using the derived formulae. Chapter Five presents the conclusion of the thesis. Chapter Six contains the list of references. Since we only discuss representative results in Chapters Two through Five, any extra results are presented in the Appendix for completeness purposes. The Appendix also contains a more detailed presentation of the self-similar and bursty traffic models, as well as an extensive description of the OPNET simulation model.

1.5 Symbols, Acronyms, Notations and Glossary

This section describes the terms and notations used in this thesis.

1.5.1 Glossary

Actual values - the numerical values of the parameter, output as results of a simulation.

Estimated values - values obtained by applying a certain function to the actual values of a simulation parameter.

Source node - the origin of the reference data traffic

Destination node - the destination of the reference data traffic

Intermediate node - a node that service both reference traffic and background traffic cells; an intermediate nodes implements a queuing model (it is characterized by a service rate and a finite queue capacity)

Cell or Packet - the basic unit of traffic; a cell has a fixed length (given in bits).

Delay jitter (or delay variance) - second moment of the delay random variable at an intermediate node (the definition of variance of a random variable can be found in [KLEI75])

Discard rate- Intermediate nodes servers can be programmed to discard a certain percentage of the background traffic; the discard rate shows the percentage of the traffic rate that is discarded. The actual effect of discarding background traffic is a variation of the background traffic rate, with respect to a maximum value; the maximum value is the traffic intensity for which no cells are discarded at the intermediate nodes.

End-to-end delay variance (or jitter) - second moment of the time interval calculated from the moment a cell leaves the source node to the moment it reaches the destination node.

Reference or tagged traffic - traffic under study; we are interested in the end-to-end jitter for the tagged traffic.

Background traffic - traffic that interferes with the tagged traffic; it simulates the effect of cells transmitted by sub-networks and taking the same path as the reference traffic.

Normalized bursty traffic intensity - the ratio of the average busy time to the average cycle time of a bursty traffic source (that is, the average percentage of the time when a bursty traffic source is emitting cells).

Normalized self-similar traffic intensity - the ratio of the intensity of the self-similar traffic (measured in cells/second) to the highest intensity of the traffic, for a given series of simulations for which the traffic is being varied.

Relative background traffic intensity - the relative value of the background traffic intensity, measured against the maximum value; used in conjunction with the ***discard rate***. The maximum traffic rate is the value of the background traffic obtained when no cells are discarded. Basically, the ***relative background traffic intensity*** is that fraction of the background traffic entering an intermediate node that is transmitted to the next intermediate node.

Utilization factor (ρ) - The ratio of the traffic intensity arriving at a server (node) to the service rate of a server ([KLEI75, pp18-19]).

1.5.2 Notations, Abbreviations and Acronyms

DR - discard rate

FIFO - first in first out

NRT - normalized reference traffic

NBT - normalized background traffic

E[X] - average (mean) of a random variable X

P_{loss} - end-to-end empirical cell loss probability

$P_{loss} = (N_E - N_A)/N_E$

N_E - Number of traffic cells emitted by the source node

N_A - Number of reference traffic cells that arrive at the destination node

$P_{loss(j)}$ - loss probability at intermediate node j

G/D/1/K - general (arbitrary) arrival process and determined service time queue with one server and K places in the input buffer.

σ^2_i - delay jitter or delay variance (at an intermediate node i)

Ξ^2 - end-to-end delay variance (or jitter)

Ω_n^2 - accumulated delay variance (at node n): $\Omega_n^2 = Sum\ \sigma_i^2$, for i=1,2, ... n

Δ - average end-to-end delay

Chapter 2
Network Operation, Modeling and Assumptions

In order to study the end-to-end jitter, a network simulation model has been developed. The model allows the study of the end-to-end jitter under a number of various scenarios. This chapter presents the reasoning that conducted us to the model used in this thesis, gives a model overview and describes how the network operates. This section also gives a description of the service model of the network nodes and the types of traffic we use for the simulation. A more formal definition of end-to-end jitter (or delay variance) is also introduced here.

2.1 Network Model

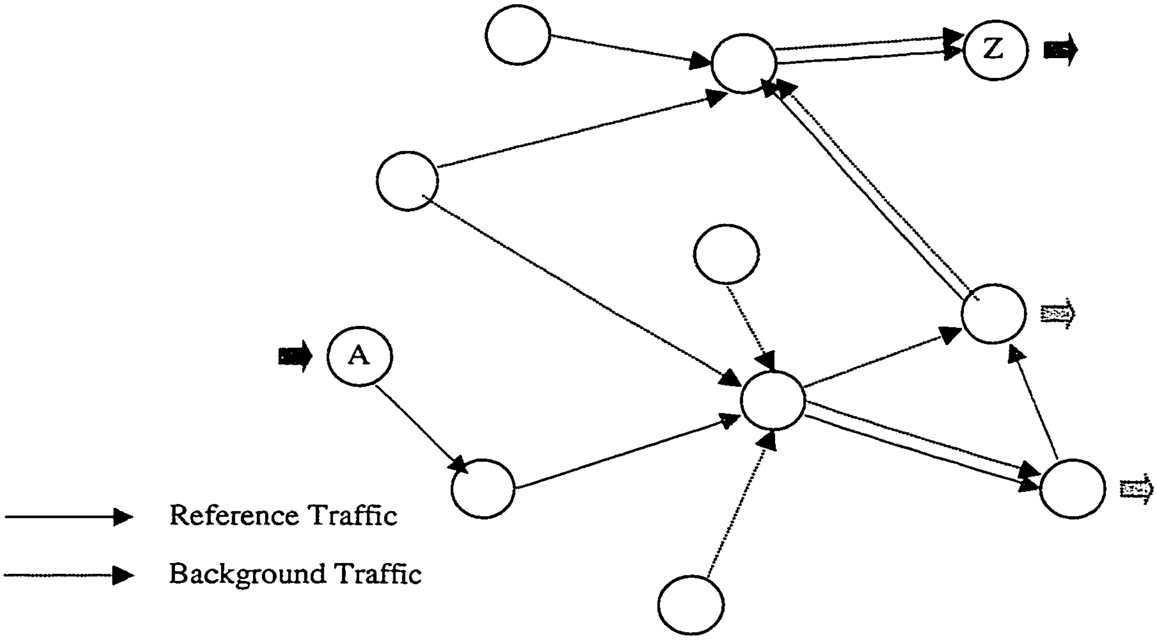


Figure 2 **Network traffic flow**

In order for a video stream to be transmitted from node *A* to *Z*, the stream must traverse the network as illustrated in Figure 2. *Background traffic* (traffic from other nodes in the network) may join the traffic of interest (also called *tagged* or *reference traffic* throughout this thesis) at each of the intermediate nodes along the path from *A* to *Z*. Background traffic cells may also be removed from the network (when they reach their own destination nodes) at different nodes along the path taken by the reference traffic. Since both the reference and background traffic compete for the same bandwidth capacity, the amount of background traffic will influence the performance of the reference traffic. For instance, the reference traffic may be delayed because the bandwidth for its timely delivery may be unavailable at a certain moment of time.

It would be quite difficult to simulate the traffic flow of the tagged traffic in a general network topology. In fact, it would not even be very useful, because the tagged traffic only follows a predetermined path through the network. Therefore, it is quite natural to consider for the simulation only the nodes that are actually traversed by this path. Actually, the only way the other nodes in the network affect the tagged traffic is by the means of the *background* traffic, the cumulated effect of the traffic emitted by all the other nodes in the network. The background traffic can quite easily be simulated, by associating one or multiple *background traffic sources* to every intermediate node in the traversed path.

We have built a linear network model, composed of a traffic *source node*, twelve *intermediate nodes* and a *destination* node, as shown in Figure 3. Although using only twelve intermediate nodes may seem at the first sight too small a number, it is quite appropriate to simulate the path that network traffic takes between the source and destination nodes. Take, for instance, the example of the Internet: we have randomly picked a number of Web sites and used *traceroute* (a Unix command) to obtain the number of hops to each site. For the given set, the average number of hops to these sites from the computer on which this thesis was written was fifteen. Also, each of the intermediate nodes can represent a network domain. It is quite reasonable to assume that a data packet will not traverse more that twelve network domains in its travel from the source to destination. Also, consider the case of voice traffic; if the average propagation delay at each intermediary node is 10 milliseconds, the end-to-end average delay will be 120 milliseconds. For comparison, the "satellite delay", i.e. the propagation delay when communicating over geo-stationary satellites, is about 240 milliseconds. The increase in propagation delay has adverse effects on the voice communication quality, hence the number of intermediary nodes cannot be set arbitrarily high. In summary, a twelve node model is a reasonable compromise.

The General Network Model is shown in Figure 3. Each intermediate node in the network receives background traffic from one or multiple background sources. The output of each node (with the exception of the destination node) is connected to the input of the next node. The input of the first intermediate node in the network is obtained from a traffic source; the last node output is connected to a sink process (where all traffic is discarded).

All nodes have an extra input line from one or multiple *background traffic* sources. Instead of complicating the model by creating an arbitrarily large number or extra nodes connected to the intermediate nodes traversed by the tagged traffic, the model uses background sources to simulate other sub-networks that may have been connected to the intermediate nodes of interest. It seems quite intuitive that a higher background traffic would have a larger impact on the end-to-end delay jitter; however, this remains to be established through simulations.

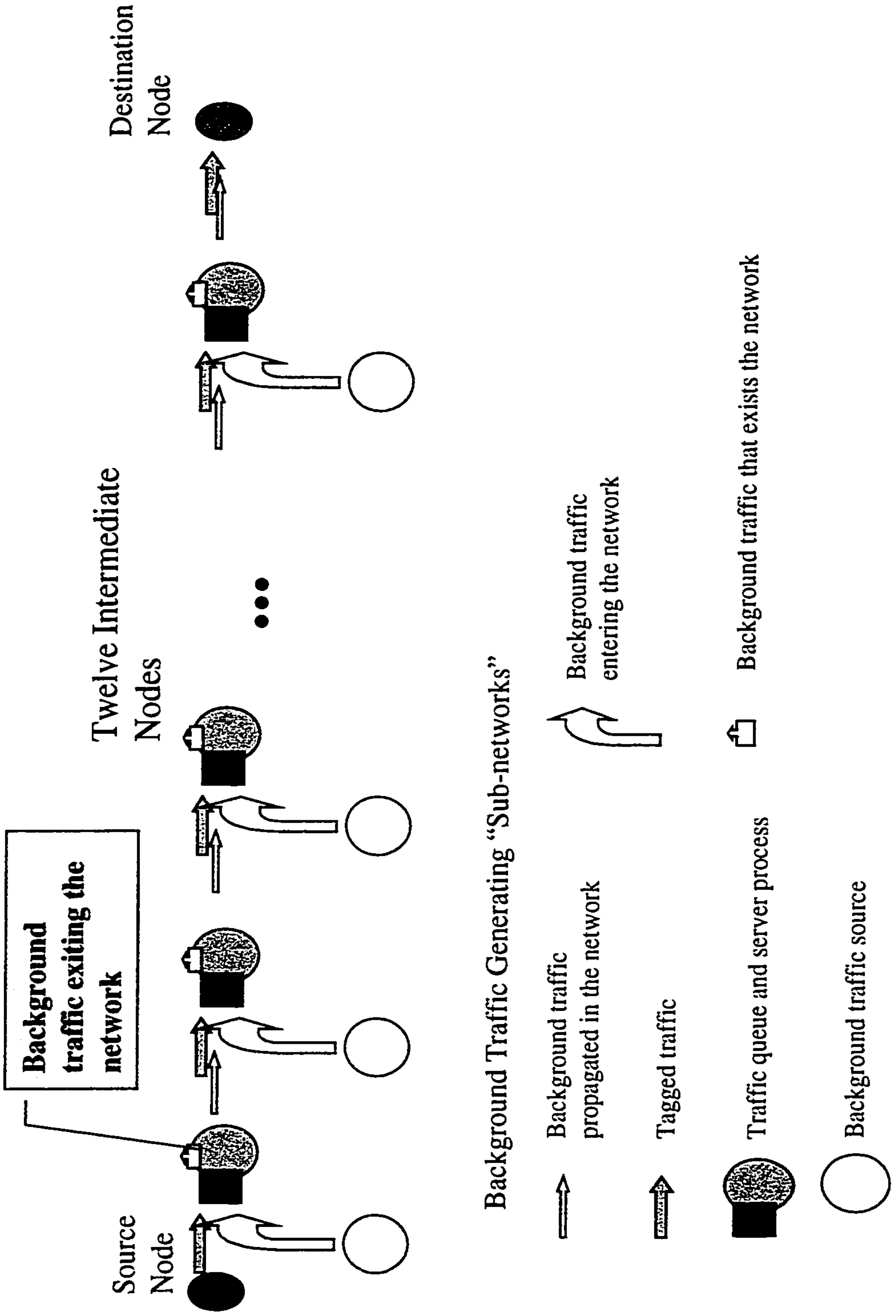


Figure 3 General network model

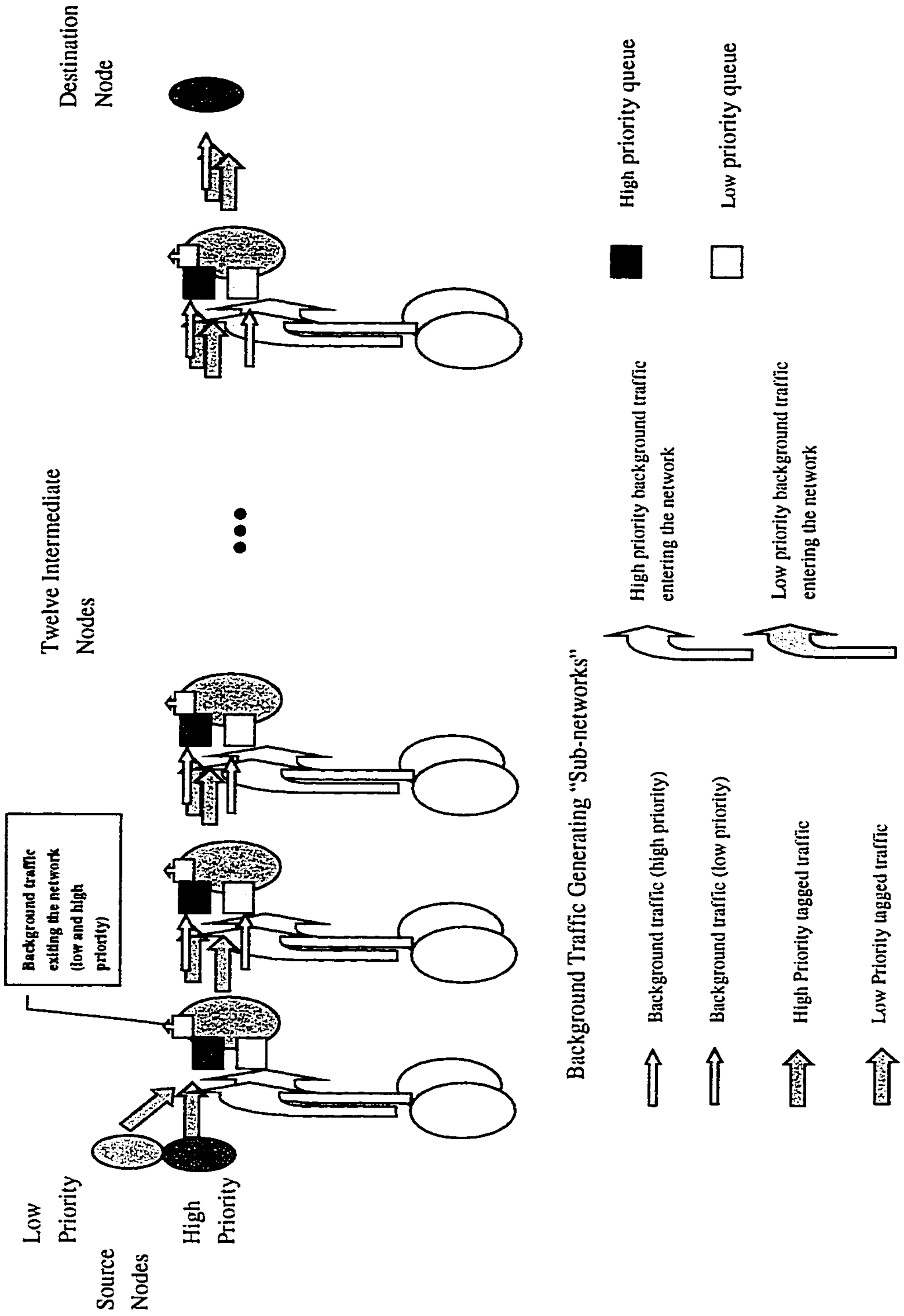


Figure 4 **Network model for prioritized traffic**

The general network model can be generalized for *prioritized* traffic, as shown in Figure 4. In this case, there are two source nodes; one generating low priority traffic and the other one high priority traffic. Similarly, there are two background sources associated to each intermediate node: one for low priority and the other for high priority traffic. For both the *no priority* and *two priorities* traffic, multiple background sources are also used. In this case, each of the background traffic generated sources is replaced with a number of traffic sources. This case is not depicted in Figure 3 and Figure 4.

The network described here has a fairly simple operation: the source node(s) generate the tagged traffic. The tagged data stream is input into the queue of the first intermediate node, if at least one input buffer is free. Also, each intermediate node receives background traffic from the background sources. The cells from the tagged traffic are intermixed with cells from the background traffic. Note that both tagged and background cells are of the same fixed length. In the case of the prioritized traffic, the high priority cells (both tagged and background traffic) are stored in the high priority queue and the low priority cells go the low priority queue. In this case, cells are labeled with their respective priority (low or high), such as that they can be recognized by the server of the intermediate node.

The server of the intermediate node services the background and tagged traffic cells in the order of arrival. In the case of the prioritized traffic, cells in the low priority queue are served only if the high priority queue is empty. More details regarding the service discipline are given in the section **Node Model.** Each intermediate node can be configured to service and then discard a certain percentage of the background traffic cells. That simulates the situation when some of the background traffic packets are sent to a specific network node, where it actually leaves the network. In this case, the packet is serviced and then is removed from the network. The amount (percentage) of the background traffic that may be discarded at each node is a simulation parameter; the exact number of removed packets is obtained using the normal distribution. Note that the intermediate nodes can distinguish a background cell from a tagged traffic cell.

The destination node does not play any special role, except for receiving all tagged cells and (remaining) background traffic cells. In fact, in the OPNET simulation model (described in the section **OPNET Simulation Model**), the destination node is also used to collect the end-to-end traffic statistics (e.g. average end-to-end delay, average end-to-end jitter).

The operation described here simulates quite closely the behaviour of the video traffic stream described in section 2.1; the traffic stream is generated at the source node and traverses a network of *N* nodes. Along its path, the reference traffic cells are joined by background traffic cells that are randomly discarded at the intermediate nodes (simulate a background cell reaching its destination). It can be seen from this scenario that there is no need to build a complicated network of a random topology, as long as we can effectively simulate the background traffic affecting the tagged stream.

2.2 Node Model

Figure 5 shows the model of one of the major node types in our open tandem queuing network [HAYE84, pp263-266]. The *intermediate nodes* are modeled as G/D/1/K queues. A G/D/1/K queue is a first in, first out (FIFO) queue with one server, for which the arrival process is arbitrary and the service time is deterministic. The deterministic service time is derived from the fact that all packets are of fixed length (measured in bits) and the service rate of each server is constant (N bits per second). There are "K" places in each queue buffer and there is only one server at each node. As the queue dimension is finite, any cells arriving when the queue is full are lost. Both background traffic cells and reference traffic cells can be lost.

Servers send both reference traffic and background cells to the queue of next server. The traffic arriving at the intermediate node does not obey any regular arrival distribution (e.g. Poisson), hence the model assumes a general arrival process.

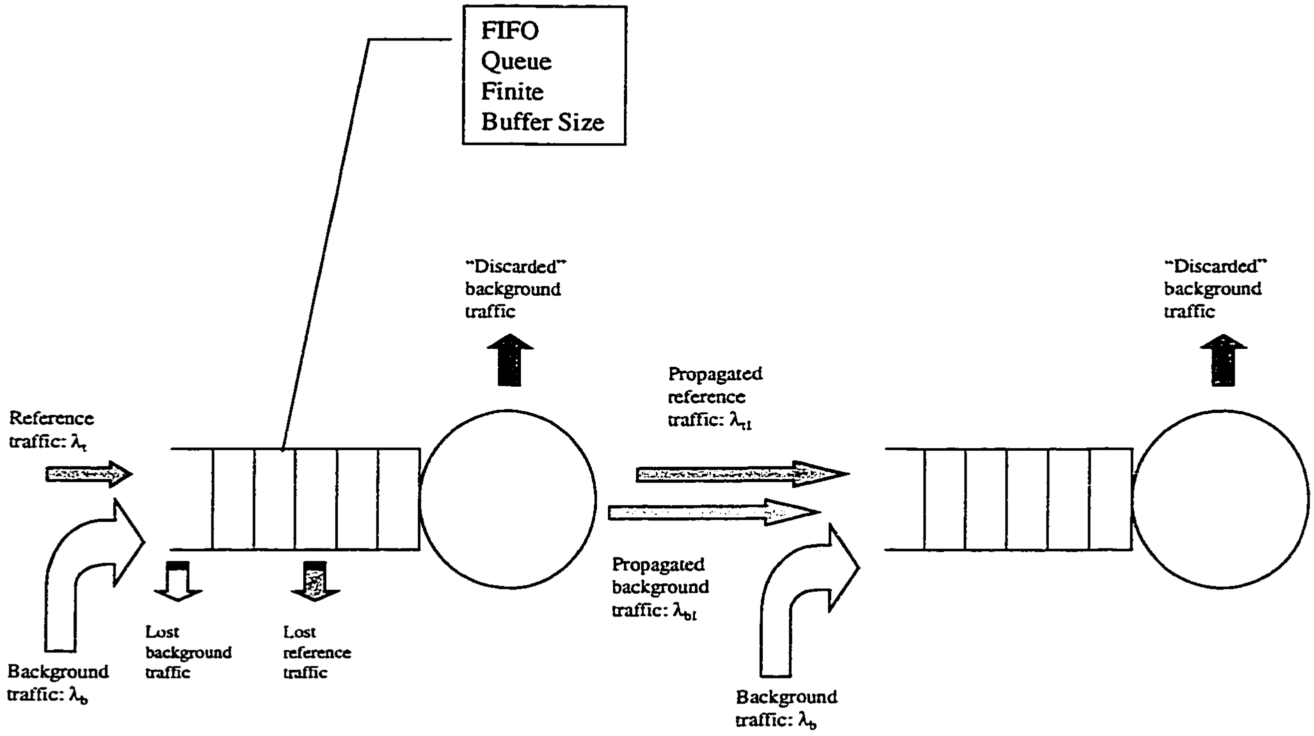


Figure 5 **Standard tandem queue model**

As will described in more detail in the OPNET Simulation Model, the OPNET processes that implement the servers can be configured to discard part of the background traffic even if the input buffers are not full.

The case of the prioritized tandem queue model is shown in **Figure 6**.

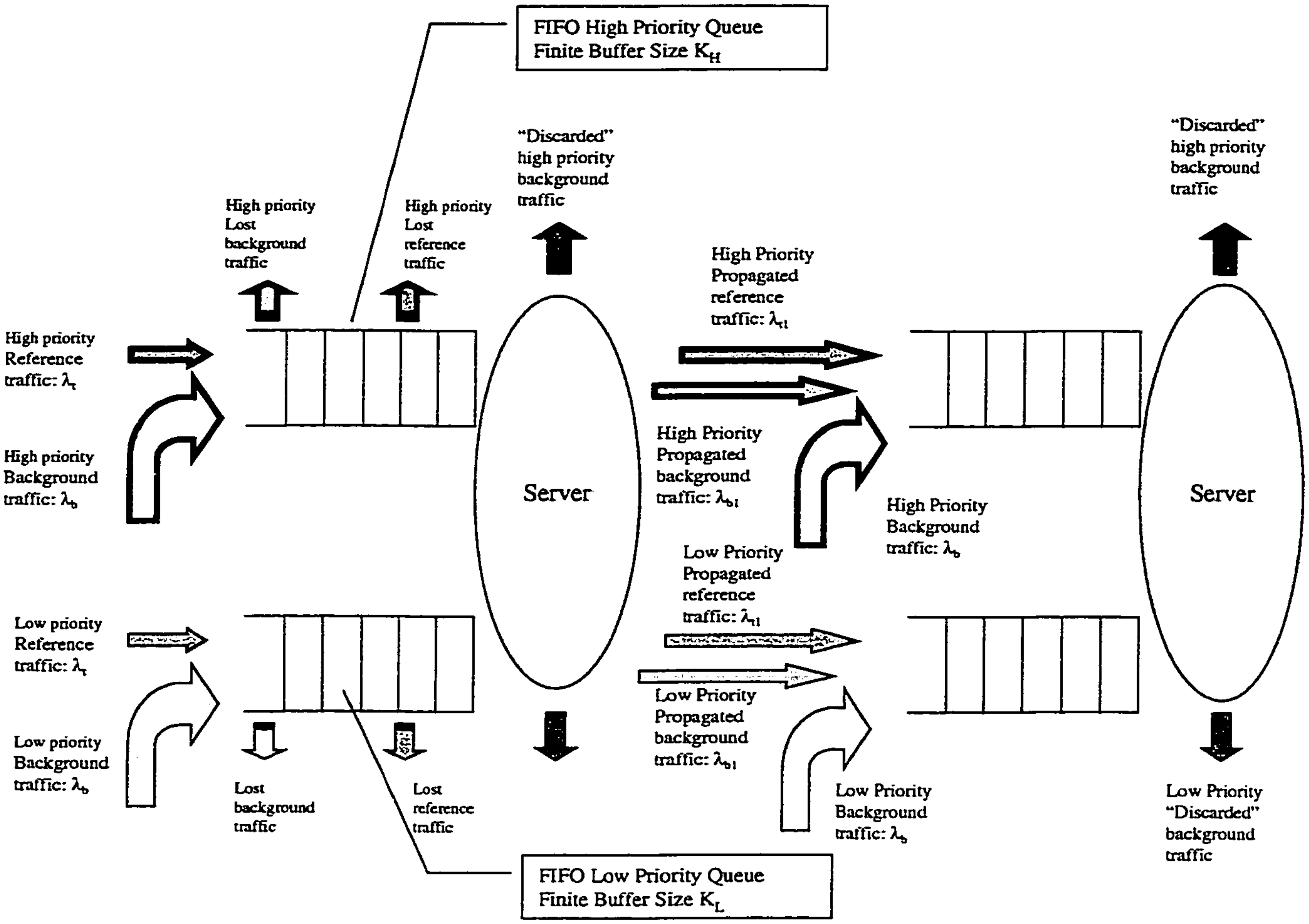


Figure 6 **Prioritized tandem queue model**

In this case, a single server serves both the high priority and low priority queue. Cells in the low priority queue are served only when the high priority queue is empty. However, the service is not pre-emptive: the service of a low priority cell is not interrupted by the arrival of high priority cell. This non-preemptive model is natural in the context of data networks: the cell size is quite small and cell contents cannot be intermixed, since cells are atomic data units.

Simulations are conducted for both non-prioritized traffic (one reference stream transmitted from the source to the destination node) and dual priority traffic. The dual-priority traffic models the case when two reference data streams (low and high priority) are transmitted from the source to destination.

Also, the background traffic can also be of two types: low and high priority. The rationale for using dual-priority traffic is to study the influence of the high priority traffic intensity on the low priority traffic end-to-end jitter and vice-versa (the influence of low priority traffic intensity on the high priority traffic end-to-end jitter).

2.3 General Assumptions

The modeled network operates under the following assumptions:

- Each traffic stream is independent of other traffic streams. Namely, the background traffic streams at different nodes in the network are independent and identically distributed with respect to each other. In the case of prioritized traffic, the high and low priority streams are also independent and identically distributed. The reference traffic stream is also independent of the background traffic streams.
- The overall probability loss for tagged the tagged traffic is low (below 5%). We consider that above this threshold voice transmission becomes noisy [HENN93]. All simulations for which the overall probability loss is above 5% are not taken into consideration for the study of jitter , their results being discarded.

2.4 Traffic Models

Our simulations use two types of traffic models: *self-similar* and *bursty* traffic. These types of traffic were chosen because they represent the typical traffic generally carried by integrated telecommunication networks nowadays.

In [LTWW94], the authors argue that self-similar traffic models describe the long range dependencies of modern network traffic. They show that Ethernet local area network (LAN) traffic is statistically self-similar. A very typical application of modern networks is to bridge LAN traffic between different locations of the same company. Since the LAN traffic is self-similar, it is natural to use self-similar traffic in our simulations.

On the other side, voice traffic is inherently bursty: when we speak, we always make pauses between words or phrases. Also, in a phone conversation, there are always longer pauses, when we listen to our counterpart at the other end of the line. Video traffic may also be bursty, its burstiness being determined by the type of encoding (e.g. MPEG). Hence, it also makes sense to use the bursty traffic model for the simulations done for this thesis.

The next two sections give a brief overview of the mathematical theory of self-similar and bursty traffic.

2.4.1 Bursty Traffic

Conceptually, the mathematical theory of the bursty traffic is very simple. A bursty source is active (emitting data packets) for a random interval of time (active period), then stops emitting for another random interval (idle period). Basically, it is an on/off type of traffic generator which produce packets at a constant rate *R* for random length active periods, intermixed with random idle periods.

The parameters of the bursty traffic source are:

- Average idle period: μ_i
- Average active period: μ_a
- Cycle time: $C = \mu_a + \mu_i$
- Average traffic intensity: $\lambda = \mathbf{R} \times \mu_a/(\mu_a + \mu_i)$

The active and idle period random variables can be generated by any probability distribution.

In this thesis we also use the term *normalized bursty traffic* to denote the ratio of the average busy time to the average cycle time of a bursty traffic source (that is, $\mu_a/(\mu_a+\mu_i)$).

2.4.2 Self-Similar Traffic

Intuitively, the critical characteristic of this self-similar traffic is that there is no natural length of a "burst". Rather, at every time scale ranging from a few milliseconds to minutes and hours, similar-looking traffic bursts are evident.

Figure 7 shows an example of self-similar traffic, which is Ethernet traffic measured over different time intervals. It can be seen that they all exhibit the same characteristics. That is, structural similarities exist across a wide range of time scales. The first plot at the top shows three seconds of the original trace where each point plotted represents the number of bytes of arrival traffic during a 10-millisecond interval. The second plot shows 30 seconds of the original trace where each point plotted represents the number of bytes of traffic during a 100-millisecond interval. The third and fourth plots correspond to a duration of 300 and 3,000 seconds respectively, and the corresponding traffic arrival during 1-second, respectively 10-second intervals. Even as the level of aggregation increases, the plots look the same.

In the following section we attempt to give a more formal mathematical definition of the topic. A more detailed description of the theory of self-similar traffic can be found in [PRIE81].

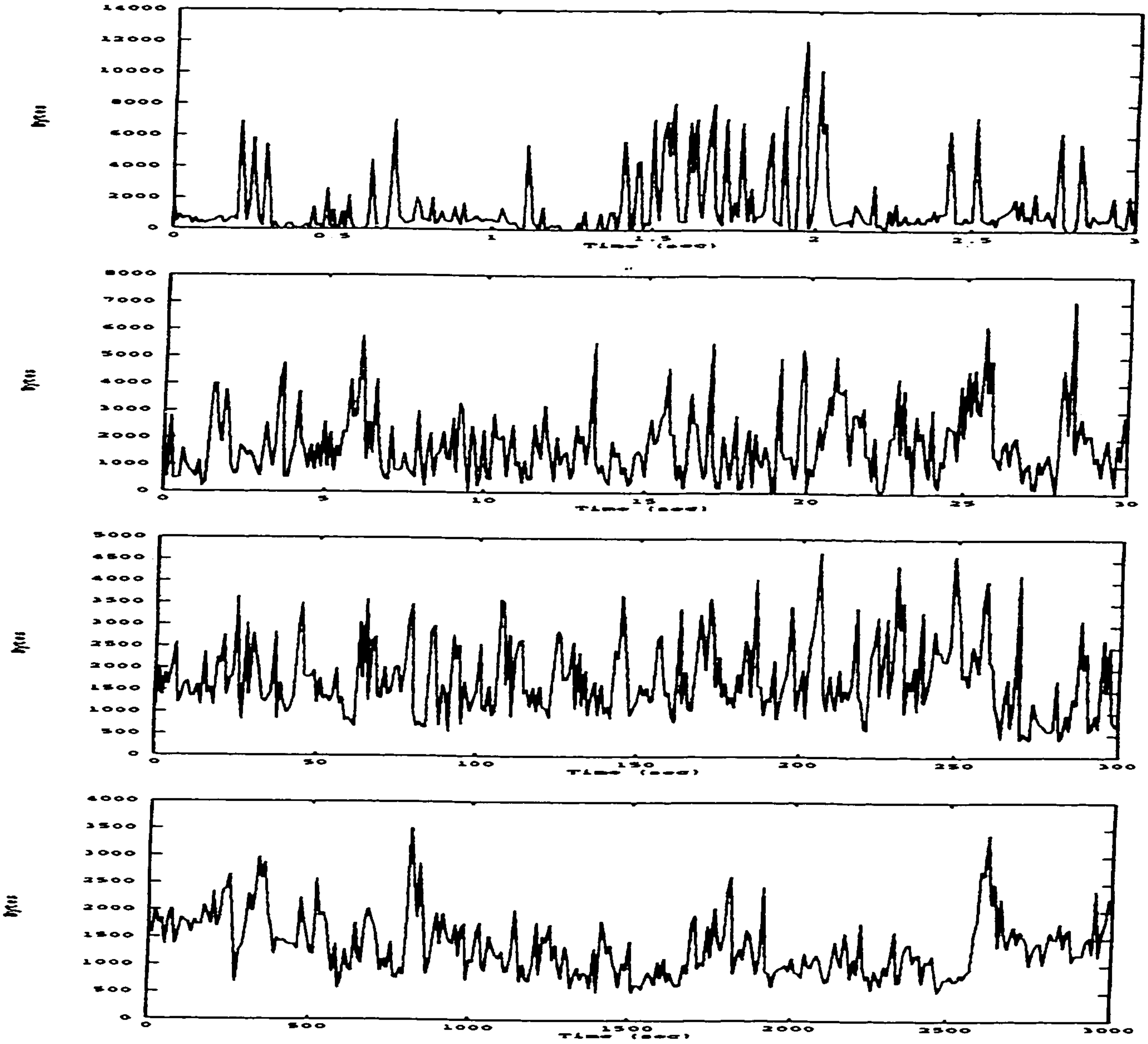


Figure 7 Ethernet traffic for different time intervals [MORI95].

2.4.2.1 Self-Similar Traffic Model

The self-similar traffic model described in this section has been used for the OPNET simulations. This model is described in [LTG97]. The theory of self-similar traffic is described in a large number of references, for instance [GIBB96].

Let us consider a number of M superimposed bursty traffic sources (similar to the traffic sources described in the section on bursty traffic). The burst time of each source is distributed with a "heavy tail", such that the mean burst time is finite but the variance of the burst time is infinite. An example of such distribution is the *Pareto* distribution:

$$\rho_j = Prob\{\tau = j\} = j^{-(2+\beta)} / c$$

where τ is the length of the active period.

If the number of sources approaches infinity but the aggregate traffic rate λ is held constant by allowing the active period of all sources to approach 0, the aggregate process will be self similar with $0.5 < H < 1$, where H is the Hurst parameter.

Note that this model reflects the physical situation where many users send varying lengths packets at widely inter-spaced time intervals.

While it is not possible to build an OPNET simulation model consisting of an infinite number of sources, [LTG97] argues that the number of sources S_t becoming active at the moment t is Poisson distributed with parameter λ, such that

$$Prob[S_t = k] = e^{-k}\lambda^k/k! \quad .$$

The burst length for each active source at any time t is Pareto distributed. Furthermore, if the traffic rate of a source that becomes active is R, the aggregate random process X_t has a mean and variance:

$$E[X_t] = R\lambda\eta_a$$

$$Var[X_t] = R^2\lambda\eta_a \quad ,$$

where η_a is the mean length of the active period.

2.4.3 Single versus Multiple Background Traffic Sources

A characteristic of the model is that both single and multiple background sources have been used. In the former case, only one background source generates the background traffic for each of intermediate nodes. In the latter case, four background sources are connected to each of the intermediate sources. In both cases, the background sources simulate the background traffic that flows through the network. The reason for conducting simulations with multiple background sources was to determine whether the superposition of multiple sources influences the end-to-end jitter or whether the only parameter that matters is the background traffic load.

2.5 OPNET Simulation Model

We have performed simulations using the OPNET 4.0 Modeler package from MIL3 (now called OPNET Technologies Inc.). The OPNET Modeler can be used for the modeling and simulation of communications networks, devices, and protocols. OPNET allows the development of hierarchical network models and complex network topologies with unlimited subnetwork nesting. Process modeling is done with finite state machines; processes can simulate arbitrary behavior with C/C++ logic in FSM's states and transitions. OPNET is probably one of the best, if not the best simulation package available, due to its capability to simulate a process down to any level of detail.

Figure 8 shows our generic OPNET simulation model (the implementation of the general model shown in Figure 3).

The building blocks of an OPNET simulation models are processes, nodes and sub-networks.

Processes

The basic unit of the OPNET model is the OPNET process. There are four general types of processes used for all simulation models:

- The **tandem queue** process; this process simulates the behaviour of servers at the intermediate nodes. There are two sub-types of tandem-queue processes:
  - The standard tandem queue process, with only one FIFO queue

  - The prioritized tandem queue process, with one FIFO queue for high priority cells and a FIFO queue for low priority cells. Cells in the low priority queue are transmitted only when the high priority queue is empty.

The tandem queue process can be programmed to discard a certain percentage of the cumulated background traffic, which is defined to be the background traffic arrived from the server at the previous stage and the new background traffic entering the network at the current intermediate node. Background cells are discarded only after they are processed (or serviced) by the local server and they represent traffic that is addressed to the local node. Obviously, no reference traffic cells are discarded at the intermediate nodes, since, by definition, the reference traffic is only addressed to the destination node.

- The **self-similar traffic** generating process. This process has two sub-types:
  - The self-similar background traffic generator process
  - The self-similar source traffic generator process

Here is the computer "algorithm" used for implementing a self-similar process OPNET simulation, as described in [TAYL98]:

1. Choose a time interval T for updating the traffic rate
2. Choose the desired mean and variance of the aggregate process X_t.
3. Choose H and calculate η_a, the mean length of the active period.
4. Solve for λ and R using the equations above (for $E[X_t]$ and $Var[X_t]$).
5. At the beginning of each time interval $t = nT$, compute the number of sources becoming active S_t by sampling a Poisson distribution with mean value λ.
6. Determine the burst length τ for each source becoming active by sampling the Pareto distribution for each source. Increment a circular buffer at index $t+\tau$ for each source becoming active at time t. The value stored in this buffer at index t corresponding to the current time indicates the number of sources K_t becoming inactive at time t. The length of the buffer minus one determines the maximum time that any source can be active.
7. At each time $t = nT$, update the packet generation rate of the aggregate source by the equation:

$$x_t = x_{t-1} + R(S_t - K_t)$$

- The **bursty traffic** generating process. This process has two sub-types:
  - The bursty background traffic generator process
  - The bursty source traffic generator process.

In the simulation, the active and idle periods random variables used for generating bursty traffic are obtained from a Poisson distribution. The traffic rate *R* of all bursty traffic sources is held constant (and equal to 1 cell/second) for all simulations, while the cycle time and average active period are variable parameters of the simulations.

- The **sink** process (implements the destination process).

All processes are described in a greater detail in the Appendix.

Note that bursty traffic can also be modeled using other probability distributions or methods.

Nodes (or sub-networks)

An OPNET simulation sub-network (or node, in the OPNET terminology, not to be confused with a network model node) comprises four tandem queue processes. There are three flavours of sub-networks:

- The source sub-network (***nd1***), which contains the reference traffic source process, background traffic processes and tandem queue processes ("intermediary nodes");
- The intermediary sub-network (***nd2***), which contains only tandem queue processes and background traffic processes
- The destination sub-network (***nd3***), which contains the sink process, tandem queue processes and background traffic processes.

Although the current model contains only one intermediary sub-network, in theory any number of such sub-networks could be connected together to provide for a larger number of stages.

In OPNET, inside the same sub-network, it is fairly straightforward to connect the output of a process to the input of the next one.

Network

In OPNET terminology, the OPNET simulation model is called a network. The network is composed of a number of sub-networks. Sub-networks are interconnected using a special OPNET construct called a *channel*. In our case, the communication channel is defined such that it **does not** introduce any simulated delay and it has an infinite capacity. This avoids any unwanted distortions of the simulation results. The bit rate of all channels are set to infinity, as otherwise each channel would introduce an extra delay to each cell's end-to-end propagation time (the time to transmit a cell of 424 bits at *m* bit/second).

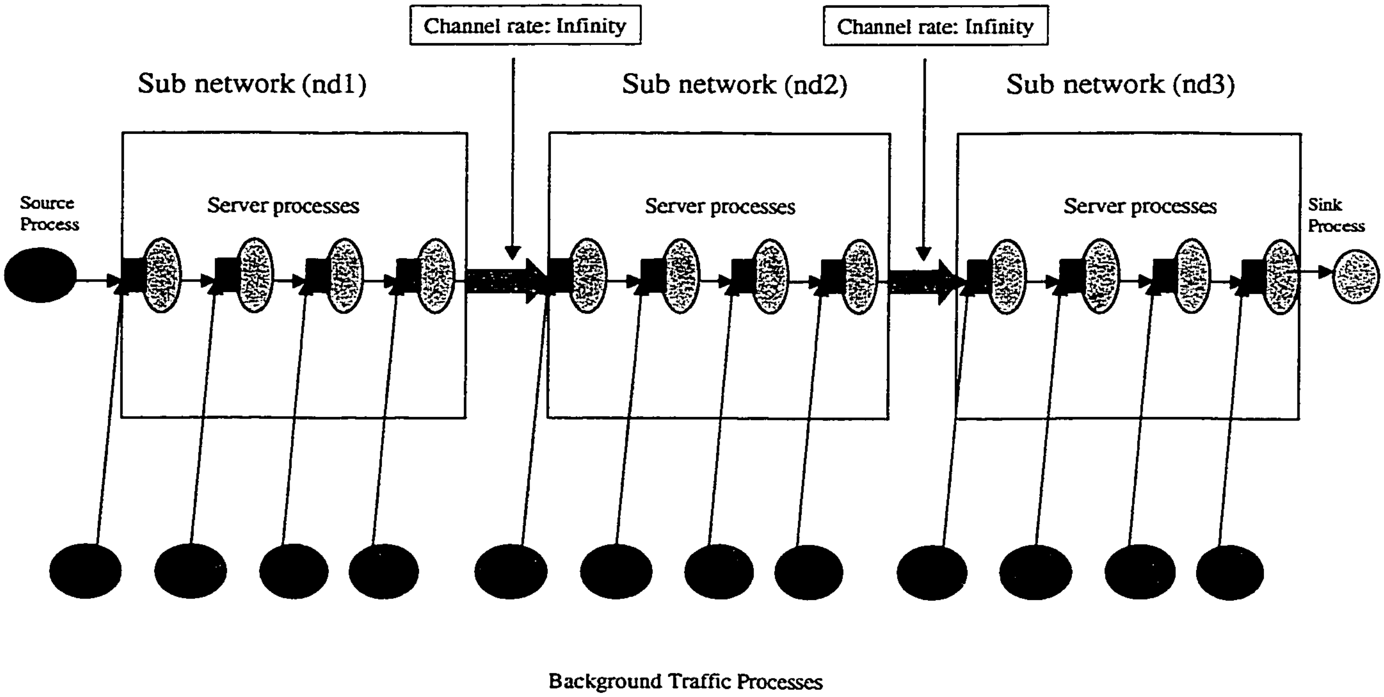


Figure 8 OPNET Model (regular traffic)

The self-similar traffic simulation network is built by instantiating the source process with a self-similar reference traffic source and the background traffic processes with background self-similar traffic generating processes. The bursty traffic model is generated in a similar way, but using bursty traffic sources.

Networks with Multiple Background Sources

Simulations with multiple (four) background traffic sources have also been conducted. In this case, the single background source is replaced with four background source processes, connected to the same intermediary tandem queue process.

Networks with Prioritized Traffic

A prioritized traffic simulation model can also be built from the OPNET model shown in **Figure 8**. In this case, the standard tandem queue process is replaced with a prioritized tandem queue process. Each traffic source (for both reference traffic and background traffic) is replaced with two identical source processes: one for low priority traffic and one for high priority traffic. The result is shown in **Figure 9**.

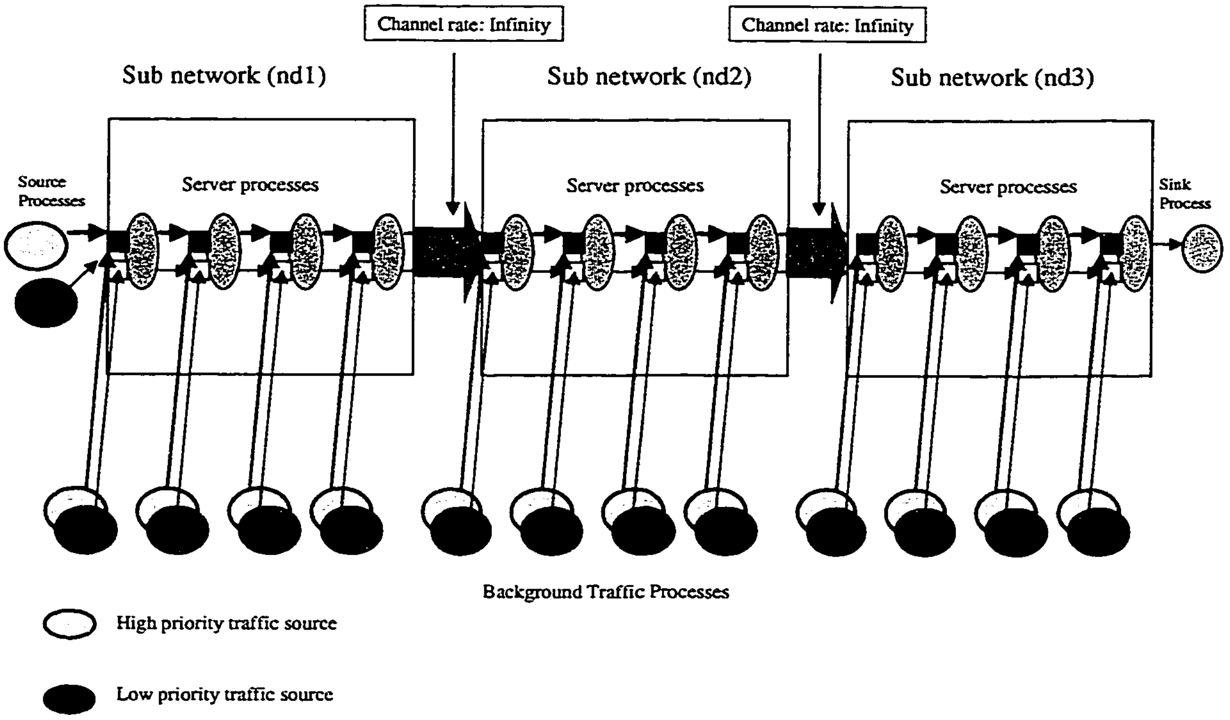


Figure 9 **OPNET Model (prioritized traffic)**

Statistics

Source processes generate simulation packets. A packet is an OPNET object that may have an arbitrary number of attributes, such as:

- Type of packet (reference traffic or background traffic)
- Priority (high or low).

The source processes fill in these attributes; the tandem queue process uses these attributes to determine how to operate on a certain packet. For instance, after being serviced, background cells may be discarded (with a certain probability). The OPNET processes also use the packet attributes to measure traffic statistics. It is worth mentioning here that during the simulation, all processes keep track of the traffic statistics, such as:

- Average delay
- Delay variance
- Number of lost cells (for each traffic type)
- Loss probability
- Average queue length
- End-to-end delay variance (sink node only)
- End-to-end delay average (sink node only).

2.5.1 Simulation Parameters

The following table summarizes the main simulation parameters:

Parameter	**Context**	**Note**
Traffic Intensity	Traffic source	Given by the average burst and cycle time in the case of bursty traffic and by the mean packet generation rate and packet generation rate variance for self-similar traffic.
Buffer Size	Intermediate node	Number of places in the server queue
Probability of discarding the background traffic	Intermediate node	-
Service rate	Intermediate node	Expressed in bits/second
Simulation Duration	Global	Expressed in simulated seconds
Simulation Seed	Global	Kept constant (29) in all cases.
Packet size	traffic source	Expressed in bits. Fixed at 424 bits.
Source Priority	traffic source	Used for prioritized traffic (low and high)
Service rate	Node	Constant rate at which cells are served at each intermediate node. Expressed in bits/second.
Number of reference traffic cells per simulation	Global	Determined by the source average traffic intensity (cells/second) and the simulation duration (in seconds). For accurate results, all simulations done for the same model should generate the same amount of reference cells.

Chapter 3
Performance Evaluation

The model described in the previous chapter has been used to conduct a fairly extensive series of simulations. This chapter presents the results of these simulations; the results are classified based on the type of traffic used in the simulations (bursty or self-similar) and whether single or multiple background traffic sources are connected to each of the intermediate nodes. A number of early results were presented at the Advanced Simulation Technologies Conference (ASTC 2000) and published in the conference proceedings [YOLM00].

The effects of the following variables on the end-to-end delay jitter are considered:

- background traffic intensity
- service rate of the intermediate nodes
- using two priority reference data streams (high/low priority traffic)
- end-to-end delay average on the *end-to-end jitter.*

The end-to-end jitter is defined in detail in section 3.1, while a discussion on the accuracy of the simulation is done in section 3.2.

Simulations are run long enough to ensure the results converge. Note, however, that there is no typical simulation duration; instead, the duration of all simulations are chosen such as the number of cells emitted by the traffic sources to be approximately 100,000. We have empirically determined that results do converge when the number of cells is approximately that number. This result was obtained by running a number of simulations with increasing duration (all other parameters being kept the same). It has been noticed that when the duration was such that the number of cells was about 100,000, the average queue size for the queue buffers stabilizes at the same value. We have also obtained the *confidence interval* for a number of simulations. A few representative results are given in section 3.2.

All simulations have been executed on a Sun Sparc Ultra-5 workstation with 128Mbytes RAM, running SunOS v5.6, using the OPNET 4.0 Modeler package. The typical effective CPU time is about 10-15 minutes.

The Other Investigation subsection also deals with the effects on the end-to-end delay jitter of the following parameters:

- Effect of the queue buffer size of the intermediate nodes
- Effect of the number of nodes (stages) in the network
- Effect of the end-to-end delay average

This subsection also presents other network performance related parameters: cell loss probability and end-to-end delay average.

3.1 End-to-end Jitter

Consider the time needed for a cell to travel from the source node to the destination node, in the network illustrated in Figure 2; depending on the traffic load, the duration may be longer or shorter. This duration is a random value and is called the *end-to-end delay*. For a random value, the probability theory defines certain associated measures. Two of the most important values are the *average* (or *mean* or *expectation*) and the *variance*.

Without going into details (a good and more formal introduction is given in [KLEI75 pp 377-381]), we can define the average of a random variable X as:

$$E[X] = (x_1+x_2 + \ldots x_N)/N \quad (3\text{-}1)$$

when $N \rightarrow \infty$ (or, stated otherwise, N is a very large number).

For the simulations executed for this thesis, N is of the order of 100,000 (for each simulation, the source node emits this number of cells).

The variance of a random variable X is defined as:

$$\sigma^2_X = E[X^2] - (E[X])^2 \qquad (3\text{-}2)$$

where $E[X^2]$ is the average of the random variable X^2.

The square root of the variance, $\sigma(X)$ is referred to as the *standard deviation*.

The ratio $C_X = \sigma_X/E[X]$ is known as the *coefficient of the variation*.

For the purpose of this thesis, we use the term *end-to-end jitter* for the *variance of the end-to-end delay* random variable.

The *end-to-end delay standard deviation* is an important parameter for network traffic. The statistics theory shows that if a random variable X has average $E[X]$ and standard deviation σ_X, then most of the values x_i of the random variable X are within the interval $(E[X] - \sigma_X, E[X] + \sigma_X)$. Particularizing this result to end-to-end delay random variable, that means that most cells travel from the source to the destination with an end-to-end delay in the interval $(\Delta - \sigma, \Delta + \sigma)$, where Δ is the end-to-end delay average and σ is the standard deviation of the end-to-end delay.

Given the delay average at each intermediate node (i.e. the time a cell spends at the intermediate node, in the input buffer or being transmitted), the end-to-end delay average can be calculated quite easily, as the sum of the delay averages (e.g. [HAYE84]). However, there is no known relationship for the calculation of the end-to-end jitter (or standard deviation, for the matter). A number of papers (for instance [MSB94], [MSB97], [KETKB92]) provide estimations of the end-to-end jitter for a number of particular cases, but none of them provides a general formula. As mentioned in the introduction, though, the end-to-end jitter is an important network parameter since real time traffic (e.g. voice) have very little tolerance for large variations of the inter-arrival time. It would be ideal that σ be as small as possible, to ensure that the inter-cell time is the same both at the source and destination. Clearly, this condition can be met if σ is very small.

For the rest of this thesis, the notation Ξ^2 will be used for the end-to-end delay variance (or jitter).

3.2 Confidence Interval

The *confidence interval* allows us to determine with a certain degree of certainty whether the simulation results are "correct" (or, more accurately, they are close to a mean value).

A confidence interval is defined as a range of values that has a specified probability of containing the parameter or random variable being estimated. The 95% and 99% confidence intervals, which have 0.95 and 0.99 probabilities of containing the parameter respectively, are most commonly used. If the random variable being estimated were ***m***, the 95% confidence interval might look like the following:

$$\mathbf{A} < m < \mathbf{B}$$

The interval between **A** and **B** has a 0.95 probability of containing ***m*** (also called *level of confidence*).

We have used the 95% confidence interval and chosen the *end-to-end delay* between the source and destination nodes as the random variable of choice for which we calculate the confidence interval. Note that similar results have been obtained for other random variables (e.g. the average queue length at the intermediate nodes). We have performed a number of simulations with exactly the same parameters, but with different *simulation seeds*. The seed value is used by OPNET to randomize the results of the simulations. Note that all seed values are set to prime numbers. Furthermore, we have assumed that the end-to-end delay is normally distributed with respect to the simulation seed.

We use ***m*** do denote the end-to-end delay random variable, ***M*** its sample mean and σ_M the standard error of the mean.

The sample mean ***M*** of the end-to-end delay is defined as:

$$M = \left(\sum_{i=1}^{N} m_i \right) / N$$

where N is the number of performed simulations (i.e. the sample size)

The standard error of the mean is defined as:

$$\sigma_M = \sigma / (N)^{1/2}$$

where is the σ standard deviation.

The confidence interval has ***M*** for its center and the formula for a confidence interval is:

$$M - z\sigma_M < m < M + z\sigma_M$$

where the value of *z* depends on the level of confidence.

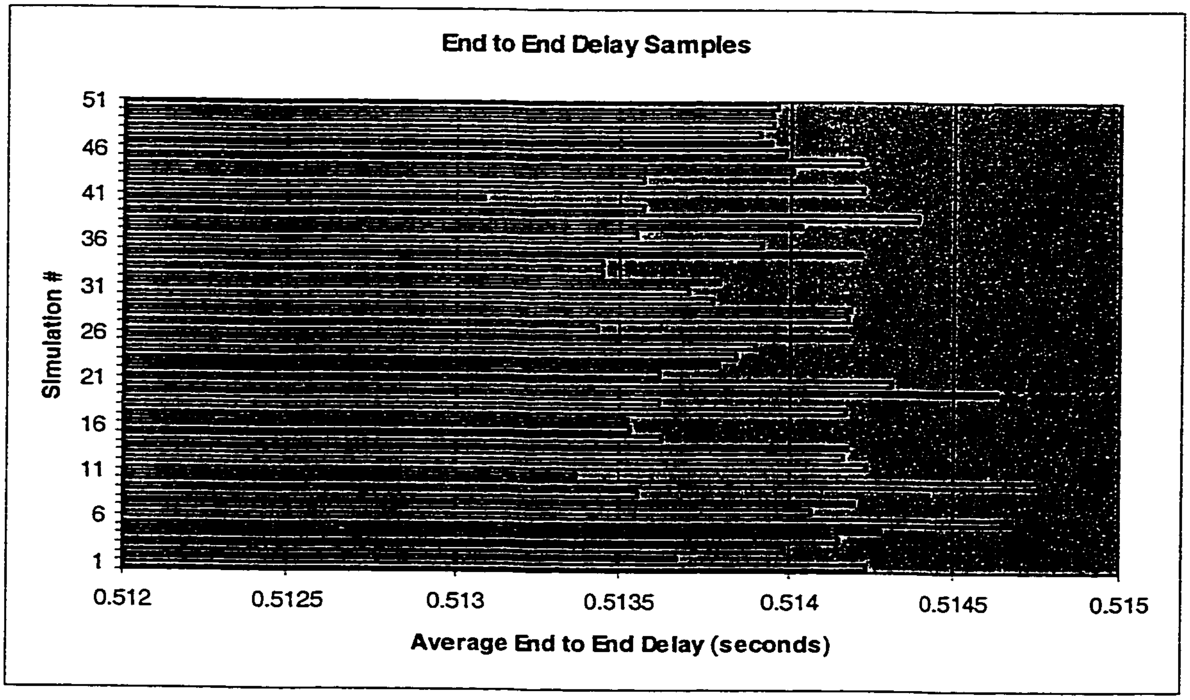


Figure 10 End-to-end delay Samples, for Bursty Traffic, Single Background Sources

Figure 10 shows a sample population for the end-to-end delay which has been obtained by performing simulations with the service rate at intermediate nodes set to 25 cells/second, normalized background traffic intensity kept at 0.20 and normalized reference traffic intensity kept at 0.5. All simulations have been run for the same duration. In this case, we have:

$\sigma_M = 4.9677E\text{-}05$

$M = 0.513934$

and the 95% confidence interval is: $0.513837 < m < 0.514032$

This shows that the accuracy is fairly good, since in 95% of the cases the result for the end-to-end delay is within very close range of the mean value.

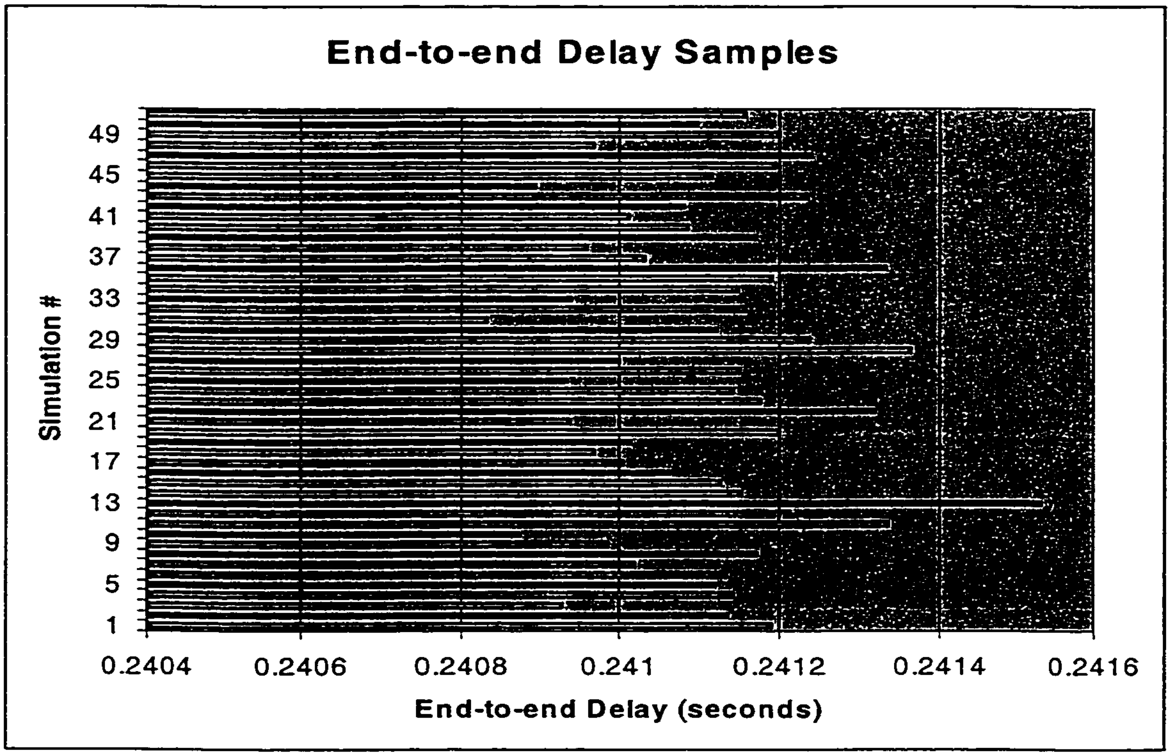


Figure 11 End-to-end Delay Samples, for Self-Similar Traffic, Single Background Sources

Figure 11 shows a similar result, obtained for self-similar traffic. In this case, the sample population for the end-to-end delay has been obtained by performing simulations with the service rate at the intermediate nodes set to 100 cells/second, the background traffic intensity kept at 10 cells/second and reference traffic intensity kept at 5 cells/second. All simulations have been run for the same duration. In this case, we have:

σ_M = *1.92875E-05*

***M* = 0.241110**

and the 95% confidence interval is: ***0.241073< m < 0.241148***, showing again a fairly good accuracy. Other simulations have yielded similar results, both for self-similar and bursty traffic.

3.3 Simulation Assumptions

In addition to the general assumptions made in Chapter 2, we also assume the following in our simulations:

We have assumed that the overall (end-to-end) cell loss is no more than 5%. This threshold has been arbitrarily set; it is considered that above 5% loss, the quality of a voice stream would be intolerably low, as shown in [HENN93]. No retransmission protocol is implemented. Essentially, the results of all simulations for which the overall cell loss was above 5% have not been taken into consideration.

All nodes have the same buffer capacity. The size of the buffer is a parameter of the simulation. Unless otherwise specified, a buffer of finite capacity (5 cells) is used.

The communication channels between the OPNET processes do not introduce any extra delay, nor does it have any losses.

The simulated time is measured in seconds.

3.4 Simulation Results

We present here the most relevant and representative results of simulations for different scenarios. The Appendix contains the complete list of simulation results.

All simulations have two varying parameters, among the following three:

- Background traffic rate
- Reference traffic rate
- Service Rate

The third parameter is always kept constant, for any given simulation.

Series of simulations are usually conducted (*N* series of *M* simulations each). One of the two varying parameters is kept constant for each of the series, while the other one is varied. The first parameter is also varied, from one series of simulations to the next. This procedure allows us to obtain families of curves (e.g. end-to-end jitter vs. accumulated delay variance).

The results, in the form of graphical plots produced by ***Matlab,*** are grouped based on:

- Type of traffic
- Number of background sources
- Number of data streams (single reference stream or high/low priority streams).

For both the single and multiple background traffic source cases, simulations have been done for no priority and high/low priority data streams. In the case of the high/low priority reference data streams, the effect of the low priority traffic on the jitter of the high priority traffic is also studied.

Although the main purpose of this thesis is to evaluate the end-to-end jitter, a number of other parameters are also studied:

- Average end-to-end delay
- Loss probability

Recall that the purpose of this thesis is to find an empirical relationship between the end-to-end jitter (denoted by Ξ^2) and certain parameters of the simulation that can be easily determined by analytical means. For this purpose, we introduce the *accumulated delay variance* at node n (notation Ω_n^2). The accumulated delay variance at node n is defined as:

$$\Omega_j^2 = \sum_{i=1}^{j} \sigma_i^2$$

where σ_i^2 is the delay variance at node i.

Since in many cases the quantities σ_i^2 can be determined fairly easily, for instance by numerical means, an empirical relationship of the end-to-end jitter vs. the accumulated delay variance (which is a sum of the quantities σ_i^2) could be used to calculate the end-to-end jitter with no need for running further simulations.

In the following section, we plot the end-to-end jitter (that is Ξ^2) as a function of the accumulated delay variance at the intermediate and destination nodes (Ω^2), that is

$$\Xi^2_j = f(\Omega_j^2)$$, for j from 1 to n.

3.4.1 Bursty Traffic

The most relevant results for the bursty traffic simulations are presented in this section, both for single and multiple background traffic sources. The complete simulation results are given in Appendix A.4.1. In this section, the term **normalized traffic intensity** (background or reference) is defined as the ratio of the average busy time to the average cycle time of a bursty traffic source (that is, the average percentage of the time when a bursty traffic source is emitting cells).

3.4.1.1 Single Background Traffic Sources

In this section we make use of the single background traffic model discussed in section 2.5. All traffic sources emit bursty traffic. We study a network model that has twelve intermediate nodes and one or two background traffic sources connected to each intermediate node. The latter case is only used to study the effect of two-priority traffic on the end-to-end jitter: one of the background sources emits low priority traffic, the other one high priority traffic. Similarly, the model may use one or two reference traffic sources, connected to the first intermediate node.

(a) Effect of the Background Traffic on the End-to-end Jitter

In order to study the effect of background traffic on the end to end jitter we have conducted several series of simulations for which the background traffic is varied. Five series of 20 simulations each have been conducted. The normalized background traffic intensity varies from 0.05 to 1 in steps of 0.05. The reference traffic intensity is constant for all simulations of a given series. The average burst cycle is kept constant at 201 seconds, while the average burst time varies from 5 seconds to 200 seconds, in steps of 5 seconds. The average burst cycle is kept constant at 29 seconds, while the average burst time varies from 5 to 25 seconds, step 5. The normalized reference traffic intensity is increased from one series of simulations to the other, from 0.17 to 0.85 (with a step of 0.17).

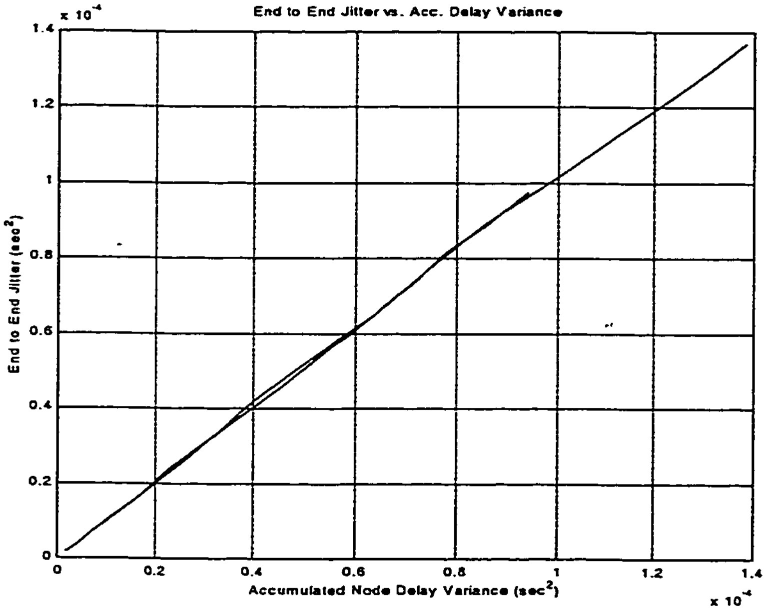


Figure 12 **End-to-end Jitter vs. Accumulated Delay Variance for Varying Background Traffic with Single Priority Bursty Stream**

Figure 12 shows the end-to-end jitter vs. the accumulated node delay variance for all nodes in the network. The figure displays the end-to-end jitter (Ξ^2) vs. the accumulated delay variance (Ω^2) for three values of the normalized background traffic (0.17, 0.34 and 0.51). It can be seen that:

- The three graphics overlap (that means, the relation $\Xi^2 = f(\Omega^2)$ is the same, independent of the background traffic rate).
- The relationship $\Xi^2_i = f(\Omega^2_i)$ for i =1,...12 seems to be linear.

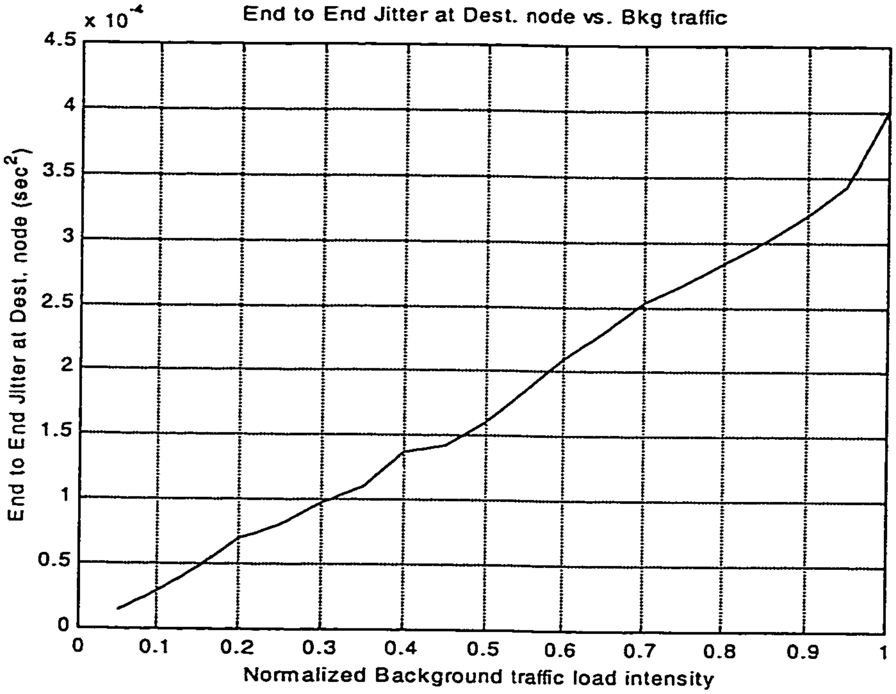
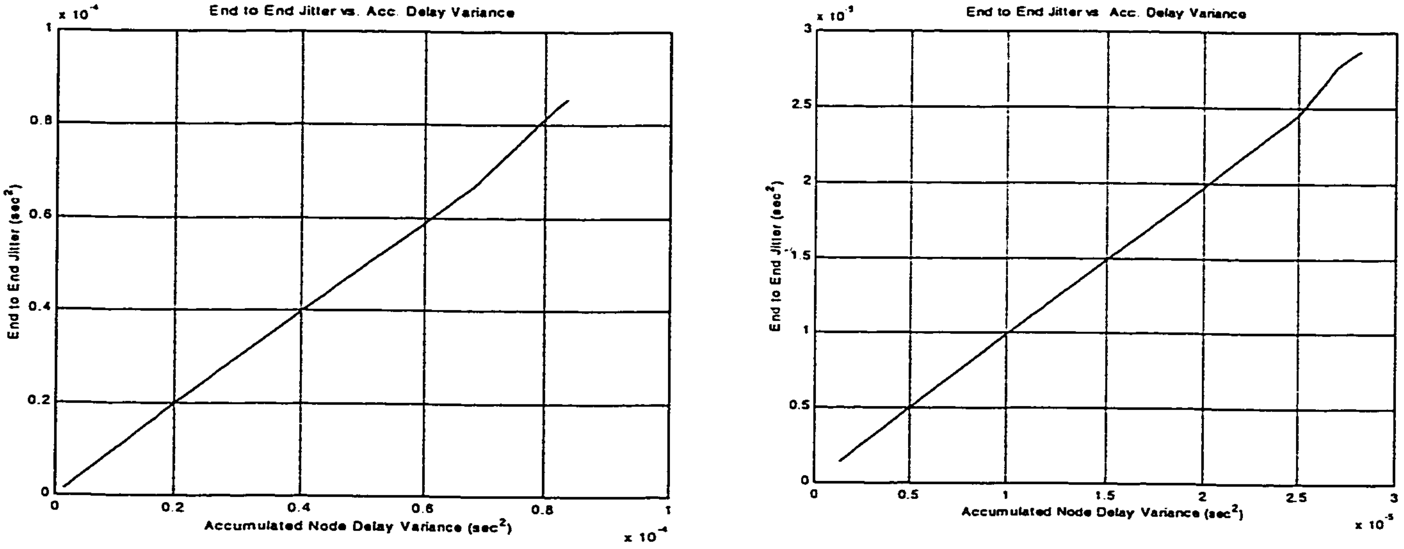


Figure 13 **End-to-end Jitter at Destination Nodes vs. the Normalized Background Traffic Intensity**

Figure 13 shows the variation of the end-to-end jitter at the destination node when the background traffic increases (the intermediate node service rate being set at 5 cells/second). It can be seen that the end-to-end jitter increases with the increase of the background traffic.

Intuitively, this type of relation is quite normal: the more background traffic we inject in the network, the more it affects the behaviour of the reference traffic, both in terms of average end-to-end delay and end-to-end jitter.

(b) Effect of the Intermediate Node Service Rate on the End-to-end Jitter



(A) **(B)**

Figure 14 Comparison of the End-to-end Jitter vs. Accumulated Delay Variance for Different Service Rates: (A) 12 cells/second and (B) 20 cells/second

In order to study the effect of service rate on the end to end jitter we have conducted series of simulations for which the service rate is varied.

Five series of 10 simulations each have been conducted. The normalized background traffic intensity is set to 0.05 by keeping the average burst cycle constant at 201 seconds and average burst time at 5 seconds. The service rate at all intermediary nodes is varied from 12 cells/second to 36 cells/second, with a step of 2.4 cells/second, for each of the 10 simulations in a series. The normalized reference traffic intensity of the five simulation series varies from 0.17 to 0.85 in steps of 0.17.

Figure 14 shows the relation between the end-to-end jitter and the accumulated delay variance for two different service rates at the intermediate nodes. The same linear type of relationship exists in both cases; this is supported by many other simulation results presented in the Appendix. As can be inferred from Figure 14 (A) and (B), the end-to-end jitter is smaller when the service time is larger.

This relationship seems fairly natural, as can be seen from Figure 15, which shows the relationship of the end-to-end jitter at the destination node to the service rate at the intermediate nodes:

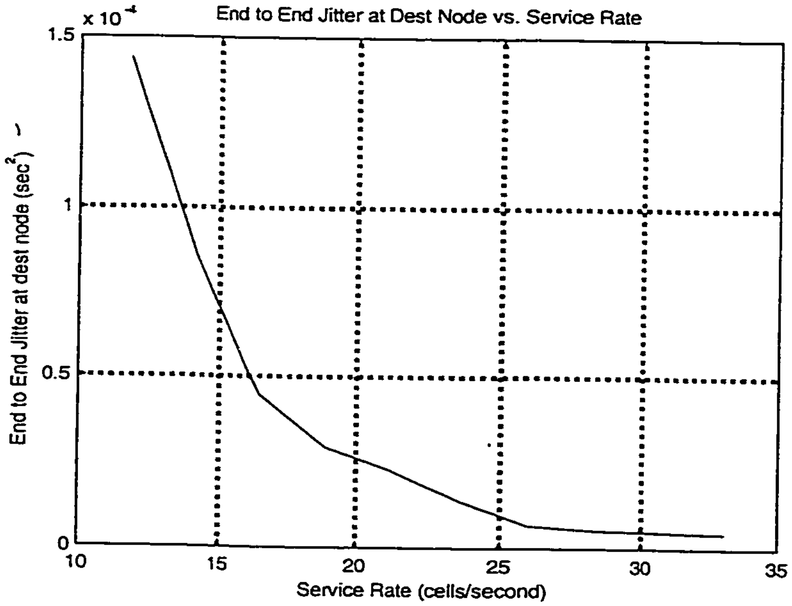


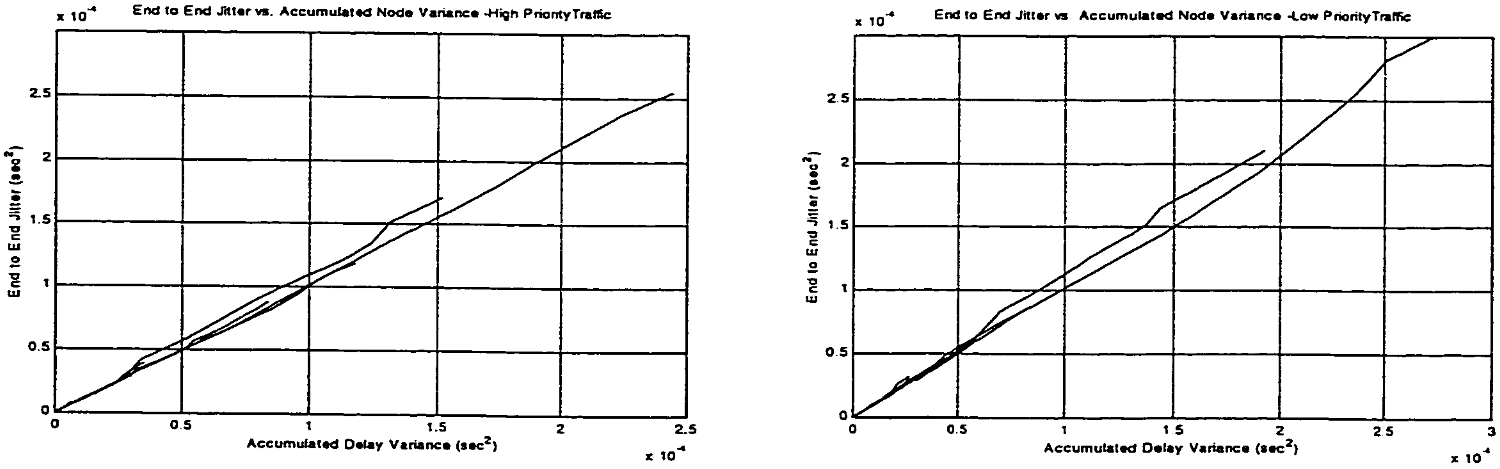
Figure 15 End-to-end Jitter at Destination Nodes vs. Service Rate

(c) Effect of Two Priority Data Streams

The network model for studying two priority data streams is shown in Figure 4. Two background traffic sources are connected to each intermediate node: one source emits low priority cells and one source emits high priority cells. Similarly, there are two reference traffic sources, one for low and one for high priority cells. In this case, all sources emit bursty traffic.

For all simulations conducted in this case, the service rate (all intermediary nodes) is kept constant at 24 cells/second, and the normalized intensity of the low priority reference traffic is kept at 0.45.

Five series of 20 simulations each are conducted. The normalized background traffic intensity (both low and high priority) is varied from 0.05 to 1 with a step of 0.05, for each of the 20 simulations in a series. The normalized intensity of high and low priority reference traffic of the five simulation series varies from 0.17 to 0.85 in steps of 0.17.



(A) (B)

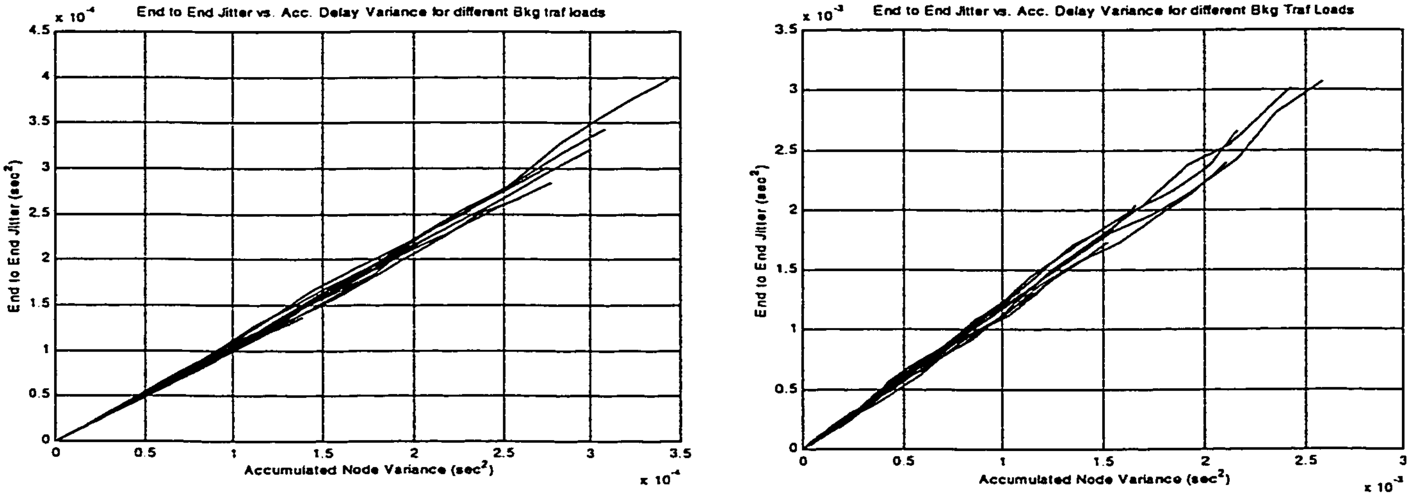
Figure 16 **Comparison Between High and Low Priority Reference Traffic Streams: (A) High Priority Traffic (B) Low Priority Traffic**

In the case when two priority streams are used, the relationship of the end-to-end jitter to the accumulated delay variance stays quasi-linear; however the low priority stream has a higher jitter than the high priority stream, as can be observed from Figure 16 (A) and (B).

3.4.1.2 Multiple Background Traffic Sources

In this section we make use of the multiple background traffic model discussed in section 2.5. All traffic sources emit bursty traffic. We study a network model that has twelve intermediate nodes and four background traffic sources connected to each intermediate node. The simulation parameters are the same as those described in section 3.4.1.1(a), except that four background sources are connected to each intermediate node.

Using multiple background sources does not affect the quasi-linearity of the relationship of the end-to-end jitter to the accumulated delay jitter, given that no cell loss occurs. This can be supported by the complete simulation results shown in the Appendix, for both the single and multiple background sources. In Figure 17, for instance, we compare the results for the effect of the background traffic for single and multiple background sources:



(A) **(B)**

Figure 17 Comparison of Single and Multiple Background Traffic Sources Results for End-to-end Jitter: (A) Single Background Sources and (B) Multiple Background Sources

The maximum end-to-end jitter (at the destination node) is about 4×10^{-4} in the case of single background sources and 3×10^{-3} in the case of multiple background sources, but, as can be observed from Figure 17, the relationship stays linear. The differences in the maximum values of the end-to-end jitter are explained by the higher background intensity in the case of the multiple sources, a result essentially similar to the one described in 3.4.1.1(a).

3.4.2 Self-Similar Traffic

This section presents the most relevant results for the self-similar traffic simulations, both for single and multiple background traffic sources. The complete simulation results are given in the Appendix, section Figure 78.

3.4.2.1 Single Background Traffic Sources

The single background traffic model discussed in section 2.5 is used for studying self-similar traffic as well. All traffic sources emit self-similar traffic. We study a network model that has twelve intermediate nodes and one or two background traffic sources connected to each intermediate node. The latter case is only used to study the effect of two-priority traffic on the end-to-end jitter: one of the background sources emits low priority traffic, the other one high priority traffic. Similarly, the model may use one or two reference traffic sources, connected to the first intermediate node.

(a) Effect of the Background Traffic on the End-to-end Jitter

Ten series of ten simulations each have been conducted in order to study the effect of the background traffic on the end-to-end jitter for self-similar traffic. For each series of simulations, the reference traffic intensity is kept constant, while the background traffic intensity is varied. The reference traffic is varied, however, from one series to the other (from 5 cells/second for the first series to 14 cells/second for the last series, with a step of 1). The background traffic is varied within simulations in the same series by changing the probability of discarding the background traffic (i.e. discard rate) at all intermediary nodes. The discard rate is decreased, with a step 10%, from 100% (all background traffic dropped after being serviced) for the first simulation in a series to 10% for the last simulation. The service rate at all intermediary nodes is kept constant for all simulations (at 120 cells/second).

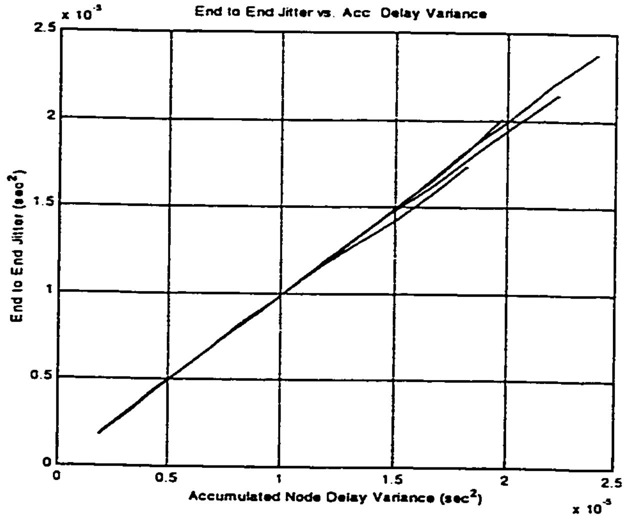


Figure 18 End-to-end Jitter vs. Accumulated Delay Variance for Varying Background Traffic with Single Background Sources and a Single Priority Self-Similar Stream

Figure 18 shows the end-to-end jitter vs. the accumulated node delay variance for all nodes in the network, in the case of self-similar traffic. The figure actually displays the end-to-end jitter vs. the accumulated delay variance for four values of the background traffic. It can be seen that:

- All four graphics are almost overlapping, meaning that the relation $\Xi^2 = f(\Omega^2)$ is the same, independent of the background traffic rate.
- The relationship $\Xi^2_i = f(\Omega^2_i)$ for i =1,...12 seems to be linear.

This is very similar to the relationship in the case before.

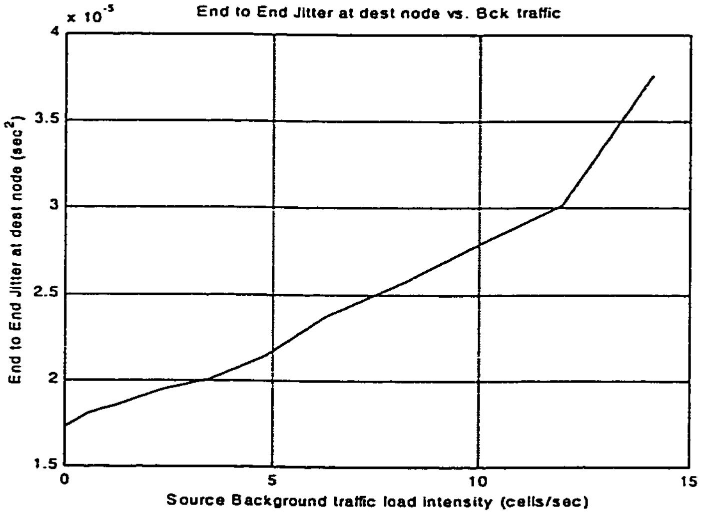


Figure 19 **End-to-end Jitter at Destination Node vs. Background Traffic with Single Background Sources and Single Priority Self-Similar Traffic**

Figure 19 shows the effect that the increase of the self-similar traffic has on the end-to-end jitter at the destination node, namely, the end-to-end jitter monotonously increases when the background traffic increases.

(b) Effect of the Intermediate Node Service Rate on the End-to-end Jitter

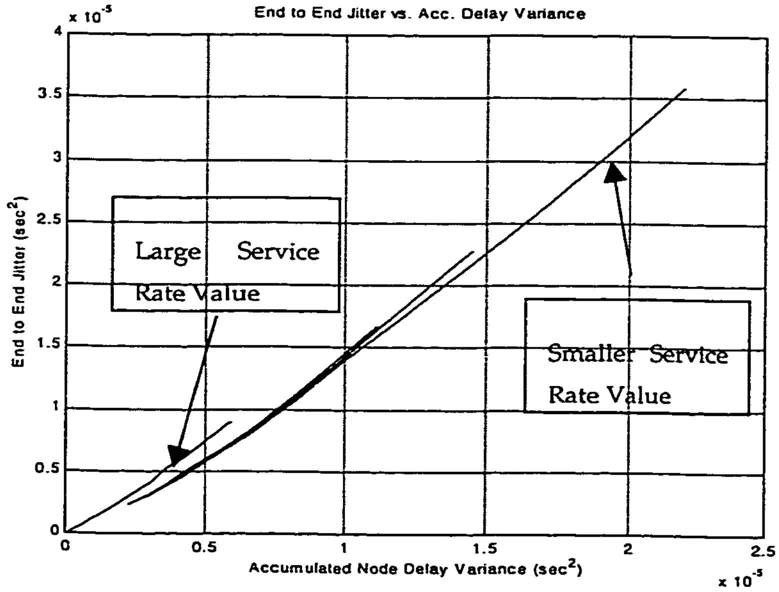


Figure 20 End-to-end Jitter vs. Accumulated Delay Variance for Varying the Service Rate with Single Background Sources and Single Priority Self-Similar Stream

For studying the effect of the service rate on the end to end jitter, ten series of ten simulations have been conducted. The reference traffic and background traffic are kept constant within each series of simulations (each traffic source emits 14 cells/second). The service rate at all intermediate nodes is varied from 120 cells/second for the first simulation in a series to 360 cells/second for the last one, with a step of 24 cells/second. The background traffic is varied from one series to the next, by varying the discard rates at intermediate nodes, from 10% for the first series to 100% for the last series, with a step of 10%.

Figure 20 displays the relationship of the end-to-end jitter to the accumulated node delay for different values of the service rate. The figure shows a linear relationship between the end-to-end jitter vs. the accumulated delay variance.

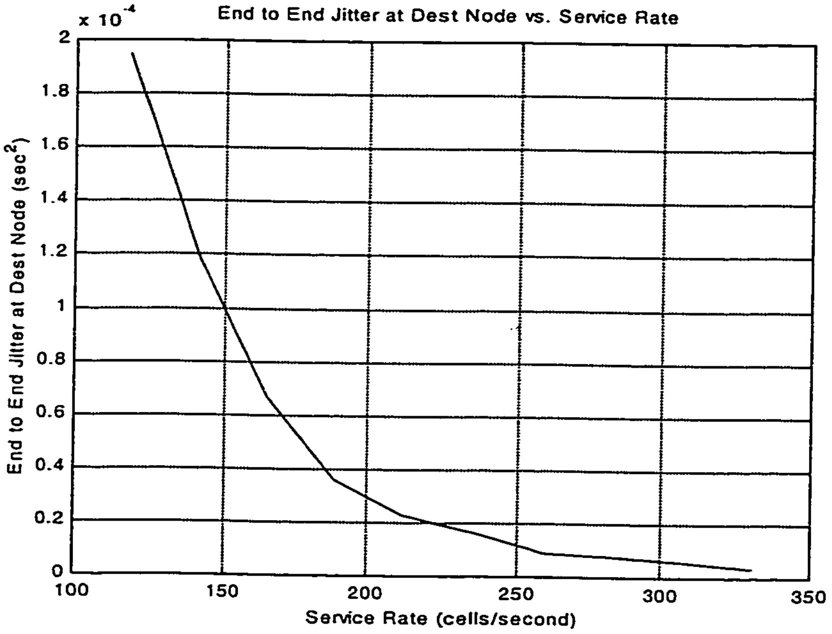


Figure 21 End-to-end Jitter at Destination Nodes vs. Service Rate

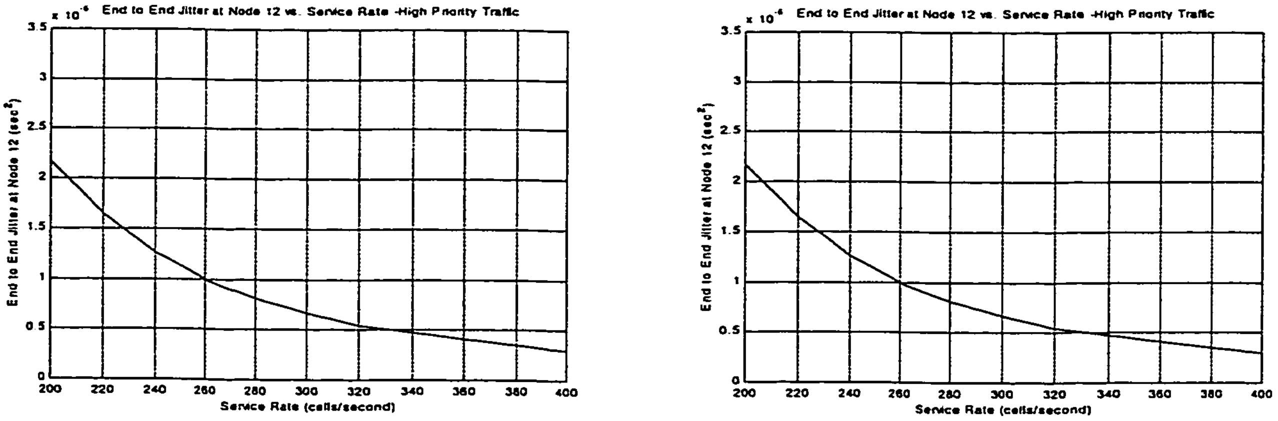
Figure 21 shows that the end-to-end jitter at the destination nodes decreases when the service rate of the intermediate nodes increases. This effect is expected, since the server utilization decreases in this case, hence the delay variance of each node decreases. Since the end-to-end jitter at the destination node is a linear function of the sum of the delay variances at the intermediate nodes, it will decrease as well.

(c) Effect of Two Priority Data Streams

The network model for studying two priority data streams is shown in Figure 4. Two background traffic sources are connected to each intermediate node: one source emits low priority cells and one source emits high priority cells. Similarly, there are two reference traffic sources, one for low and one for high priority cells. In this case, all sources emit self-similar traffic.

Ten series of ten simulation simulations each have been conducted. For each series of simulations, the reference traffic intensity is kept constant, while the effective background traffic intensity is varied, by varying the discard rate at all intermediate nodes (decreased from 100% to 10%, with a step of 10%). The background and reference traffic sources generate 14 cells/second for all simulations.

The service rate (at all intermediary nodes) is varied from 200 cells/second for the first simulation in a series to 400 cells/second for the last simulation, with a step of 20cells/second.



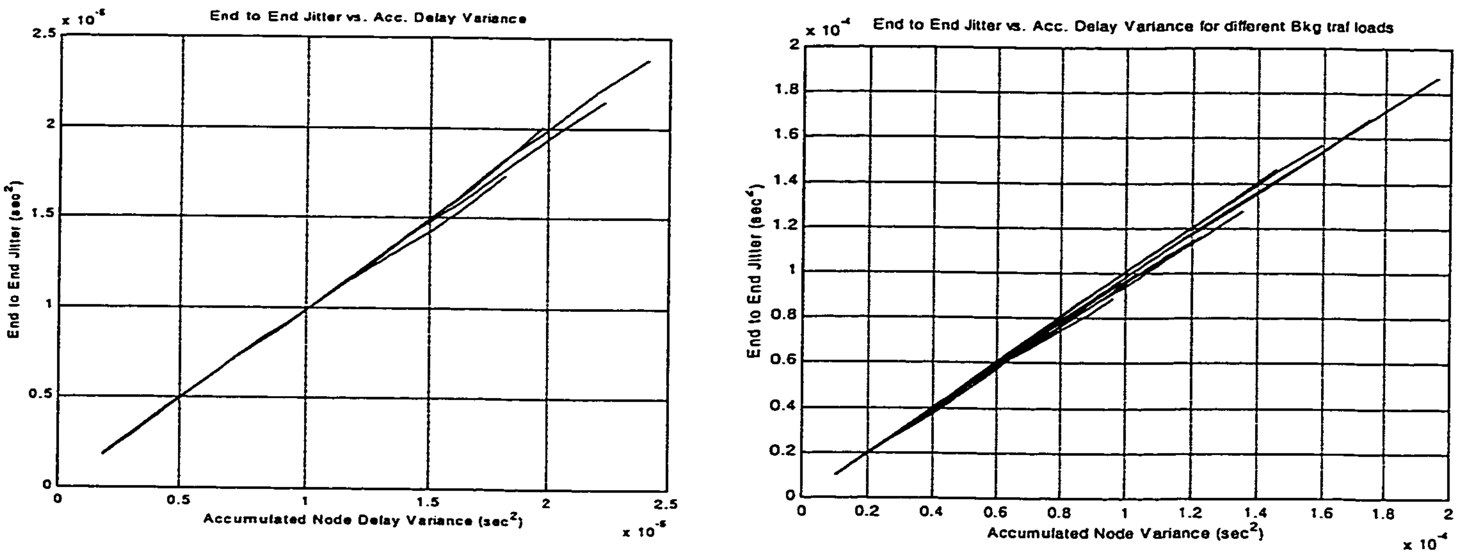
(A) (B)

Figure 22 **Comparison of the End-to-end Jitter for (A) High and (B) Low Priority Traffic for Varying Service Rate**

As for the bursty traffic, in the case when two priority streams are used for the simulation, the low priority stream has a higher jitter than the high priority stream, as can be noticed from Figure 22. In both cases, the relationship of the end-to-end jitter to the accumulated delay variance stays quasi-linear as well.

3.4.2.2 Multiple Background Traffic Sources

In this section we make use of the multiple background traffic model discussed in section 2.5. All traffic sources emit bursty traffic. We study a network model that has twelve intermediate nodes and four background traffic sources connected to each intermediate node. The simulation parameters are the same as those described in section 3.4.2.1(a).



(A) (B)

Figure 23 Comparison of (A) Single and (B) Multiple Background Traffic Sources Results for End-to-end Jitter for Self-Similar Traffic

As in the case of the bursty traffic, the linearity of the relationship of the end-to-end jitter to the accumulated delay is not changed. Figure 23 (B) shows the case of multiple background sources, while Figure 23 (A) shows the case of single background sources. The smaller end-to-end jitter (2.5×10^{-6}) for the case of single background sources versus 2.5×10^{-4} for multiple background sources can be explained by the fact that multiple sources generated more background traffic than a single one. The previous results showed that the end-to-end jitter increases when the background traffic increases.

3.5 Other Investigation

In the current section we study the influence of the end-to-end delay average, the number of intermediate nodes between the source and destination nodes and the input buffer size on the end-to-end jitter.

3.5.1 Dependency of the End-to-end Jitter vs. the Average End-to-end Delay

The effect of the average end-to-end delay of reference traffic cells on the end-to-end jitter is studied in this subsection. We define the average end-to-end as:

$$E[D] = (\sum_{j=1}^{n} D_j) / n,$$

where n is a large number of reference traffic cells (for instance, 100,000 cells) and D_j is the measured end-to-end delay for cell j of the simulation.

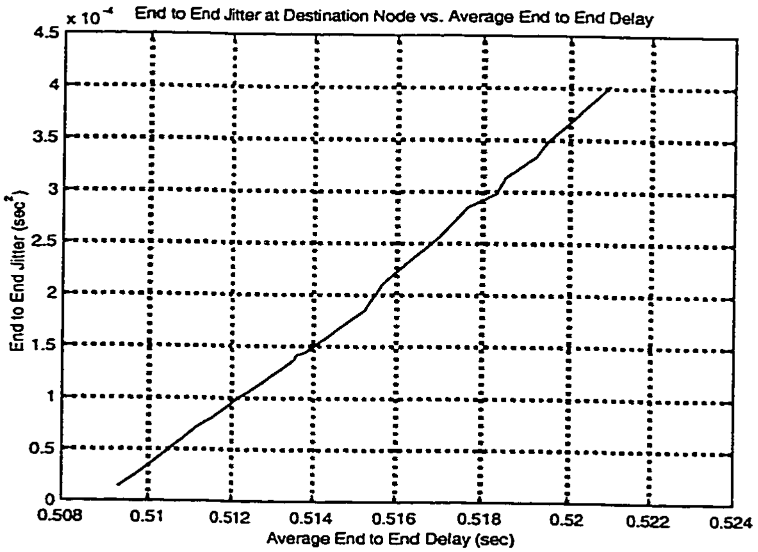


Figure 24 End-to-end Jitter at the Destination Node vs. the End-to-end Delay Average for Bursty Traffic with Single Background Sources and Single Data Stream. Parameter: Increasing Background Traffic Rate

Figure 24 shows the dependency of the end-to-end jitter at the destination node on the end-to-end delay average in the case of bursty traffic. The increase of the average end-to-end delay (represented on the X-axis) is caused by an increase of the normalized background traffic load (from 0.1 to 0.9, with a step of 0.05), for a series of simulations for which the intermediate node service rate is kept constant at 25 cells/second. It can be seen that the end-to-end jitter (represented on the Y-axis) increases (almost) linearly with the increase of average end-to-end delay.

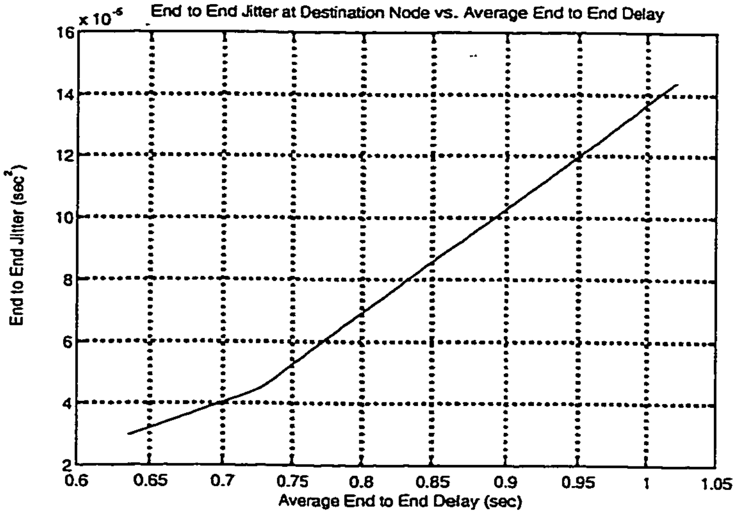


Figure 25 **End-to-end Jitter at the Destination Node vs. End-to-end Delay Average for Bursty Traffic and Single Background Source for a Single Data Stream. Parameter: Decreasing Service Rate**

Figure 25 shows the same type of dependency, but in this case the increase of the average end-to-end delay represented on the X-axis is due to decreasing the intermediate node service rate (from 80 cells/second to 60 cells/second, with a step of 1 cell/second). The normalized background traffic is kept constant at 0.30.

From Figure 24 and Figure 25 we actually notice an expected relationship between the end-to-end jitter and end-to-end delay average. In fact, when the average end-to-end delay is low, this is because either the background traffic is low or the service rate is high (that is, the server utilization is low). The same type of relationship also exists between the end-to-end delay jitter and the intermediate node service rate or background traffic intensity. A similar relationship between the end-to-end jitter and delay average has been obtained for self-similar traffic (illustrated in Figure 26), as well as for multiple background sources simulations, for both bursty and self-similar traffic. These results support the previous findings of this chapter, showing that the end-to-end jitter increases when the overall traffic load increases or the intermediate node service rate decreases. This section also shows that a linear relationship exists between the average end-to-end delay and the end-to-end jitter.

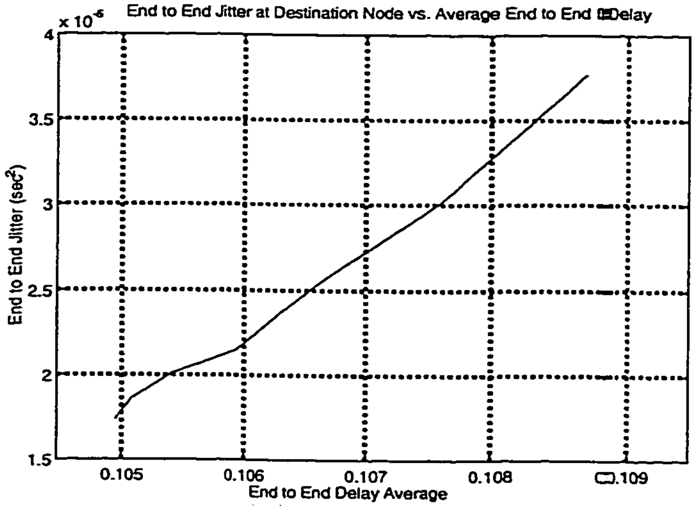
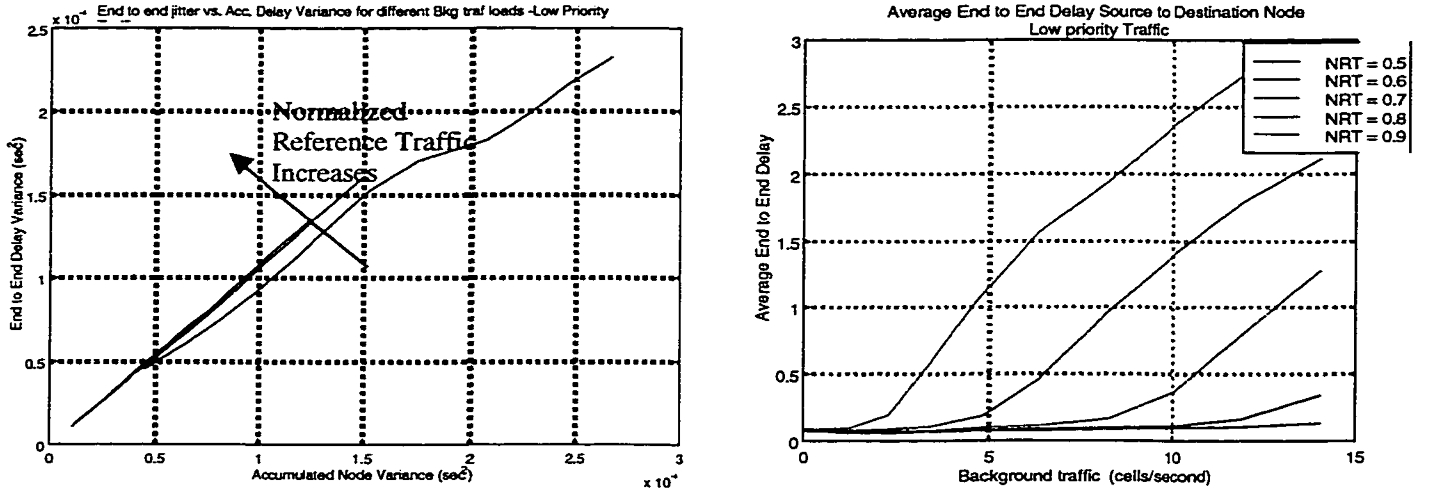


Figure 26 End-to-end Jitter at the Destination Node vs. Average End-to-end Delay for Self-Similar Traffic with Single Background Sources and a Single Data Stream; Parameter: Increasing Background Traffic Rate

3.5.1.1 Effect of Large Average End-to-end Delay on the End-to-end Jitter

A large average end-to-end delay can be considered an indicator of the traffic load in the network.



A **B**

Figure 27 **Effect of Large Average End-to-end Delay on the End-to-end Jitter A. End-to-end Jitter vs. Accumulated Delay Variance and B. Average End-to-end Delay vs. Background Traffic**

Figure 27 shows that the linear relationship between the end-to-end delay jitter and the accumulated delay variance is lost when the average end-to-end delay grows due to increased network traffic. These figures are obtained for the simulation described in section A.4.2.2.3.1, for the low priority traffic stream. In contrast with the results presented in the previous sections of this chapter, this figure illustrates the case of heavy traffic, with all intermediate nodes having large input buffers (10 cells). Since the buffer size is large enough, only a little amount of cells are lost; instead, the average end-to-end delay increases very significantly (as shown in Figure 27.B), while the relationship of the end-to-end to the accumulated delay variance is no longer linear (Figure 27.A).

3.5.2 Cell Loss Probability

In this thesis, the cell loss probability has been studied with respect of the:

- Service rate
- Background traffic load

We are concerned only with loss in the reference traffic, hence for the purposes of this paper, the end-to-end "empirical cell loss probability" is defined as:

$$P_{loss} = (N_E - N_A)/N_E \qquad (3\text{-}3),$$

where

N_E - Number of reference traffic cells emitted by the source node

N_A - Number of reference traffic cells that arrive at the destination node

The same formula can be written as

$$P_{loss} = N_{loss\ total} / N_E \qquad (3\text{-}4)$$

where

$N_{loss\ total}$- Total number of reference traffic cells discarded between the source and destination node due to full input buffers at the intermediate nodes.

It can be easily demonstrated (by induction) that:

$$P_{loss} = 1 - \Pi^{M}_{j=1} (1 - p_j) \qquad (3\text{-}5)$$

where p_j is the loss probability at each of the intermediate nodes and

$p_j = N_{lost(j)}/N_{j-1}$ (by definition)

$N_{lost(j)}$ -number of lost reference traffic cells at node *j*

N_{j-1} -number of reference traffic cells entering node *j*

The simulations determine the cell loss probability at all intermediate nodes. Relation (3-5) is used to generate the end-to-end cell loss probability.

Here is a brief demonstration (by induction) for (3-5). Let P_n be the loss probability between the source node and node n (note that $P_{loss} = P_{n=12}$). Formula (3-5) can be generalized for node *n* as:

$$P_n = 1 - \Pi^{n}_{j=1} (1 - p_j) \qquad (3\text{-}6)$$

For P_1, we clearly have $P_1 = p_1$.

We must now show that if we assume (3-7) as true:

$$P_{n-1} = 1 - \Pi^{n-1}_{j=1} (1-p_j) \qquad (3\text{-}7)$$

then (3-6) can be inferred from (3-7).

We start with the definition of the end-to-end loss probability at node n:

$$P_n = (N_E - N_{(n)})/N_E \qquad (3\text{-}8)$$

where N_E is the number cells emitted for the source node and N_n the number of cells propagated from node n.

We can write $N_{(n)}$ as

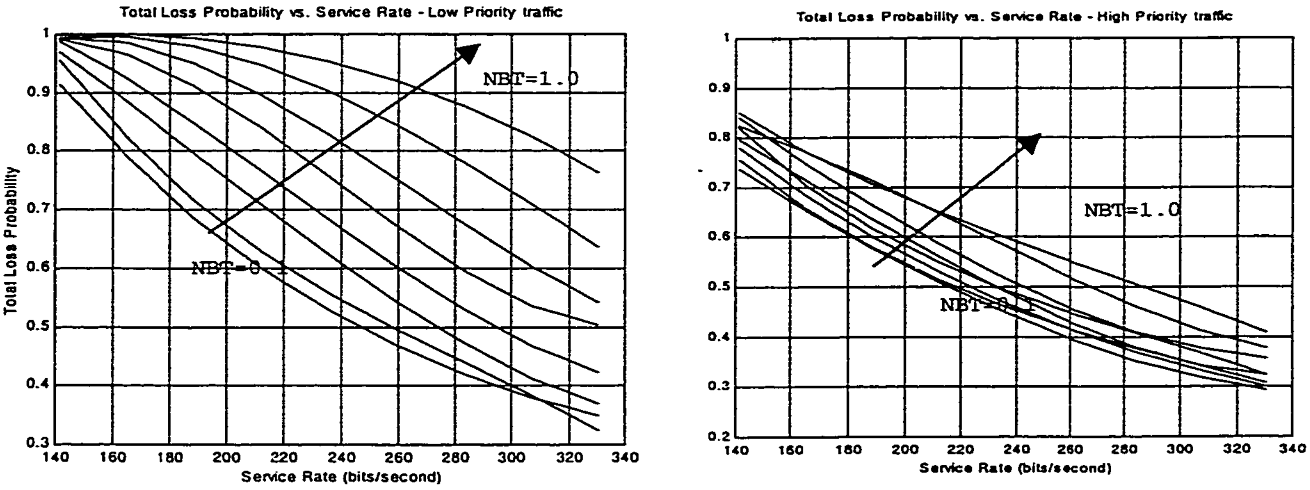
$$N_{(n)} = (1 - p_n) \times N_{(n-1)} = (1 - p_n) \times (1 - P_{n-1}) \times N_E \qquad (3\text{-}9)$$

By replacing $N_{(n)}$ in (3-8) with the last formula from (3-9) and P_{n-1} with (3-7) and after some elementary algebraic computations, we obtain for P_n the formula given in (3-6), which completes the induction.

Note that since data loss above 5% is not acceptable, separate simulations where used to determine the dependency of the loss probability to the background traffic rate and service rate. For all these special separate simulations, the queue buffer has been fixed at two cells, in order to cause a cell loss greater than 5%.

3.5.2.1 Total Loss Probability as a Function of Service Rate

The graphics from Figure 28 are obtained for self-similar dual-priority traffic. They show a family of loss probability curves vs. service rate. The cell loss probability increases when the normalized background traffic increases from 0.1 to 1.0. The arrow direction shows an increase in the normalized background traffic (NBT).



(A) (B)

Figure 28 Comparison of Cell Loss Probability as a Function of Service Rate, for Self Similar, Two Priority Traffic. (A) Low Priority and (B) High Priority Traffic

3.5.2.2 Loss Probability as a Function of Background Traffic

Figure 29 has been obtained for self-similar traffic, with the service rate fixed at 120 cells/second, for varying reference traffic rates.

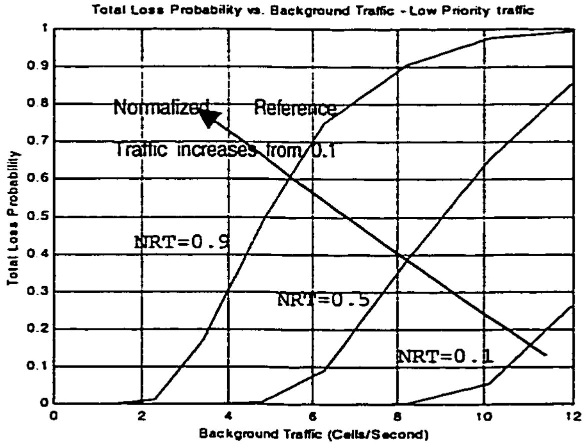


Figure 29 Cell Loss Probability as Function of Background Traffic, for Self Similar Traffic

The loss probability dramatically increases when the normalized reference traffic (NRT) increases from 0.1 to 0.9.

3.5.3 Effect of Intermediate Node Input Buffer Size on the End-to-end Jitter

The input buffer size does not directly influence the end-to-end jitter. However, a finite input buffer causes cell loss, which in its turn affects the end-to-end jitter.

For instance, as shown in the Figure 30 (from section A.4.1.1.3.1), in the case of high cell loss probability, the linear relationship of the end-to-end jitter to the accumulated delay variance at the destination node is "degraded" (is no longer linear).

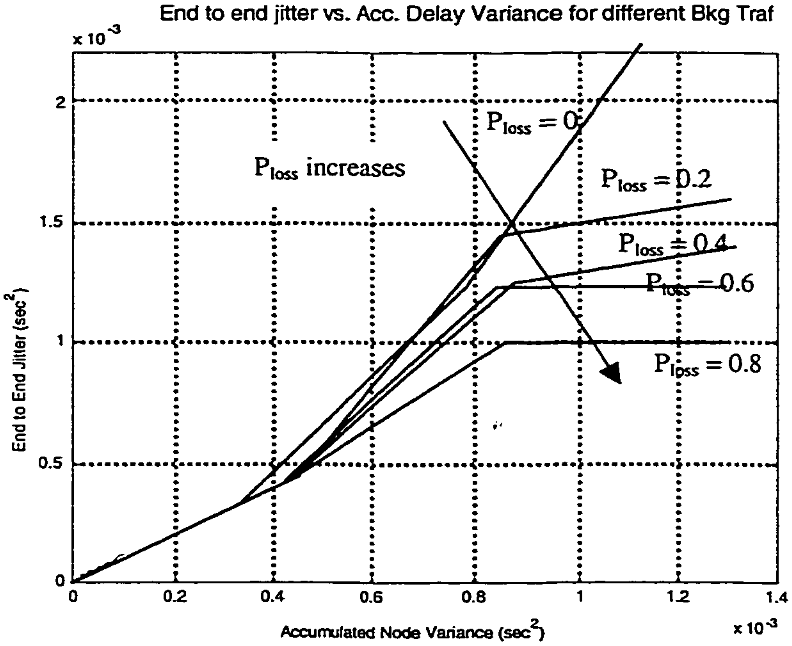


Figure 30 **Effect of Cell Loss/Finite Input Buffer Size on the End-to-end Jitter**

Since a number of reference traffic cells are lost at the intermediate nodes closer to the reference traffic source, the reference traffic intensity at nodes closer to the destination source decreases, hence the overall end-to-end jitter decreases. This effect can be noticed in the figure: although the accumulated delay variance (on the X-axis) is larger at node (N) than at node (N-1), the end-to-end jitter at node N remains the same as the node (N-1), that is, when the accumulated delay variance increases. Note that by definition, the accumulated delay variance increases from node (N-1) to node (N).

3.5.4 Effect of Queue Length on the End-to-end Jitter

The buffer size has been set to five for all simulations. Generally, the average queue length has been varied between 0.5 and 1.5; also, the total cell loss probability for these cases has been zero or very close to zero. No effect of the average queue length on the end-to-end jitter has been noticed.

However, in the case when the buffer size is set to "infinite" and for high background traffic loads, the average queue size increases as expected to very large values (100-1000); the network becomes congested. In those cases, the average end-to-end delay also increases, with the effects on the end-to-end jitter described in the previous section.

3.5.5 Effect on the Number of Stages on the End-to-End Jitter

The same linear relationship seems to apply between the end-to-end jitter and the accumulated delay variance irrespective of the node (or stage) at which the relationship is plotted.

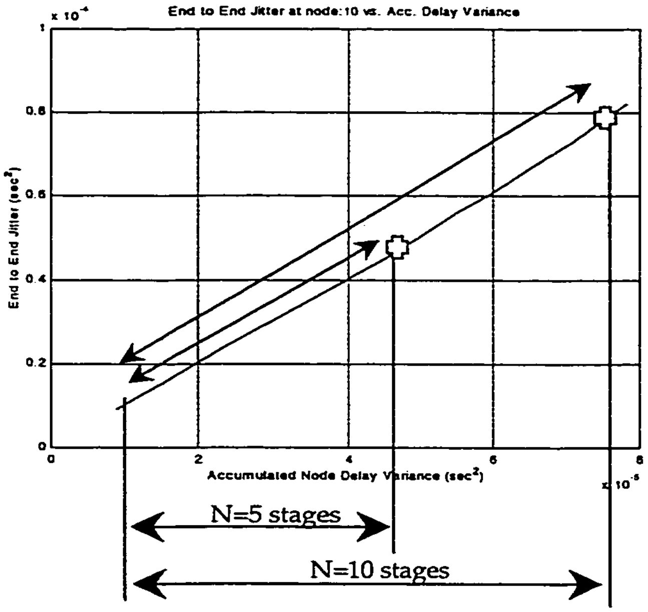


Figure 31 End-to-End Jitter vs. Accumulated Delay Variance at Two Different Stages.

Figure 31 has been obtained for the simulations described in A.4.1.1. As can be observed from the figure, the relationship between the end-to-end jitter and accumulated node delay variance is linear irrespective of whether the end-to-end jitter is plotted for a 5-stage or 10-stage network. In the general case the results for nodes 1, 2, 3, up to the total number of nodes in a network are always overlapped on the same line.

The same type of behaviour has been noticed for all the other simulations.

3.5.6 Effect of Priority Traffic on the End-to-End Jitter

As already illustrated in the Simulation Results section, low priority and high priority traffic display the same type of behaviour with respect to the end-to-end jitter, that is, there exist a linear first order polynomial relation between the end-to-end jitter and the accumulated delay variance at the destination node. The end-to-end jitter for the low priority traffic is higher than the jitter for the high priority traffic.

In conclusion, under heavy traffic circumstances, it is more likely that low priority traffic will be lost (since high priority traffic is serviced first). Under such circumstances, the linear polynomial relationship of the end-to-end jitter to the accumulated delay variance at the destination node is degraded.

As expected, the average end-to-end delay is also larger in the case of the low priority traffic. While the increase or decrease of high priority traffic clearly impacts the behaviour of the low priority, the low priority traffic only has a negligible impact on the end-to-end jitter of the high priority traffic, impact due to the effect of non-preemptive queuing.

3.6 Concluding Remarks

In this section we have presented a few representative simulation results for bursty and self-similar traffic. In both cases, we have discovered a linear relationship between the end-to-end jitter and the accumulated node delay variance. In both cases, the end-to-end jitter at the destination node decreases with an increase of the background traffic increases and decreases with an increase of the service rate at the intermediate nodes. This seems to suggest that the end-to-end jitter is in fact influenced by the *utilization factor* of the servers (nodes) on the path from the source to the destination nodes. This assumption shall be further investigated in the next section.

Furthermore, using multiple background traffic sources does not seem to have any noticeable effect on the linearity of the relationship between the end-to-end jitter and the accumulated node delay variance.

Based on our simulation results, in the next chapter we shall investigate the mathematical relationship between the end-to-end delay jitter and the accumulated node delay variance.

Chapter 4
Empirical Formulation

An empirical formula for the relationship between the end-to-end jitter and the accumulated delay variation is presented in this section. The polynomial coefficients are shown to depend on the different network parameters (e.g. service rate or background traffic intensity). The empirical formula is then verified against the actual simulation results and the relative error of the empirical formula is calculated.

4.1 Polynomial Expression

The examination of the simulation results has shown that a polynomial relation seems to exist between the end-to-end delay jitter (Ξ^2) and the accumulated node delay variance at the destination node (Ω^2). For simplicity, we introduce the notation: $\omega = \Omega^2$.

The general polynomial relationship between the end-to-end delay jitter and the accumulated delay variance is of the form: $\Xi^2 = \Sigma a_i \times \omega^i$, for i =0, 1, 2... n

However, the simulation results presented in Chapter 3 show that the polynomial relation between the end-to-end delay jitter and the accumulated delay variation is actually linear (a first order polynomial, in many cases). Therefore, we will attempt to find a relationship of the form:

$$\Xi^2 = p_1 \times \omega + p_2 \qquad (4\text{-}1)$$

using the curve fitting feature from *Matlab* to determine the coefficients p_1 and p_2.

The next two subsections will determine the values of p_1 and p_2 as functions of the background traffic intensity and service rate, for both the bursty and self-similar types of traffic, using the presentation in Chapter 3, as well as the complete set of results in the Appendix.

This section also investigates the relationship of the end-to-end jitter to the intermediate nodes server utilization factor ρ. To this purpose, we shall attempt to find a relationship of the polynomial coefficients p_1 and p_2 to the utilization factor ρ.

All figures representing the polynomial coefficients p_1 and p_2 are presented as a family of curves. Each curve is a function of a certain parameter x (e.g. background traffic intensity), while curves within a family vary according to a second parameter q (e.g. reference traffic intensity).

4.2 Relation of the Polynomial Coefficients to the Background Traffic Intensity

We present here the relationship of the coefficient p_1 to the intensity of the background traffic, for both bursty and similar traffic. The intention is to show that general behaviour of the coefficient is about the same among all simulations, as evidenced from the results in section 3.4.1. In fact, the p_2 coefficient of formula *(4-1)* above is always 0, therefore its analysis is not presented in the following. That means that relation *(4-1)* actually becomes

$$\Xi^2 = p_1 \times \omega \qquad (4\text{-}2).$$

4.2.1 Bursty Traffic

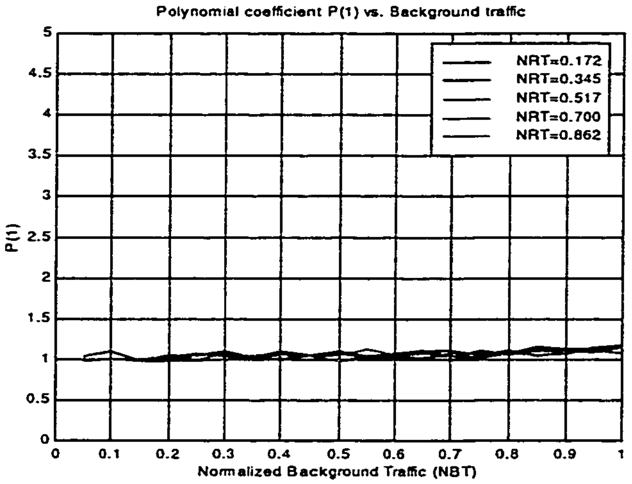


Figure 32 **Polynomial Coefficient p_1 for Bursty Traffic, Single Background Sources, No Priority Traffic Stream**

Figure 32 and Figure 33 show p_1 as a function of the normalized background traffic (NBT), for various normalized regference traffic (NRT) values. The family of polynomial coefficients depicted in the two figures have been obtained by curve fitting for the simulations described in 3.4.1.1(a) and

A.4.1.1.3.1, respectively, for normalized background traffic (NBT) varying from 0.05 to 1 (step 0.05) and normalized reference traffic (NRT) varying from 0.17 to 0.85 (step 0.17).

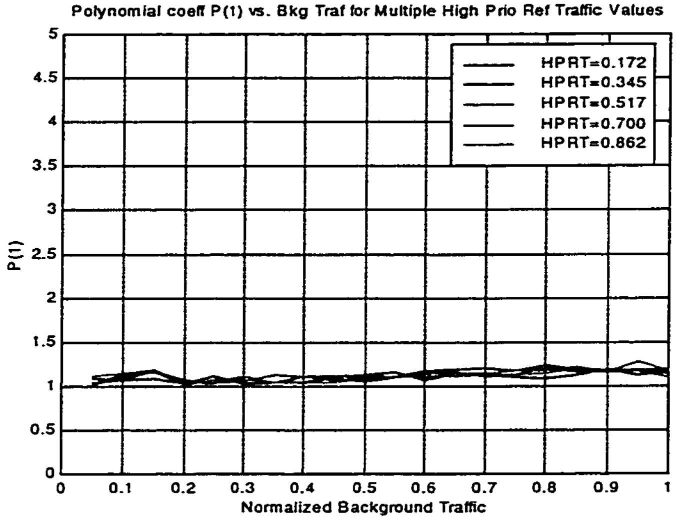


Figure 33 **Polynomial Coefficient p_1 for Bursty Traffic, Single Background Sources, Two Priority Traffic Streams**

Figure 32 illustrates the case of no priority traffic, while Figure 33 illustrates the case of high priority reference traffic (HPRT) for a two priority traffic simulation. In both cases, the polynomial is quasi-constant (it slowly grows when the background traffic increases, though) and very close to 1.0. The value of p_1 slowly increases when the reference traffic increases. Therefore, we have: $\Xi^2 = p_1(t) \times \omega$, where t is a variable simulation parameter (the reference traffic, in this case). The coefficient p_1 behaves similarly for other simulations of bursty traffic, as can be observed from the Appendix (sections A.4.1.1.1, A.4.1.1.3.1, A.4.1.2.1 and A.4.1.2.3.1). The actual form of the function $p_1(t)$ will be determined in section 4.4.

4.2.2 Self Similar Traffic

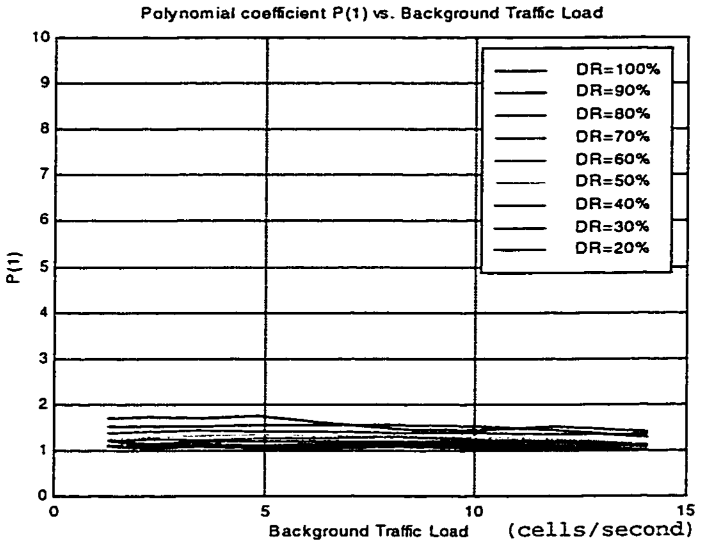


Figure 34 **Polynomial Coefficient p_1 for Self Similar Traffic, Single Background Traffic Source, No Priority Data Streams**

Figure 34 shows the coefficient p_1 for self similar traffic. The p_1 coefficient has been obtained by curve fitting for the simulation described in 3.4.2.1(a). The propagated background traffic load is changed from one series of simulations to the other by varying the discard rate (DR) at the intermediate nodes, from 20% to 100%, while the traffic emitted by the background sources is a variable parameter of each series of simulations. As for the case of the bursty traffic, the p_1 coefficient is quasi constant. Also, as for the bursty traffic, the value of p_1 slowly increases when the background reference traffic is changed (increased) from one series of simulations to the next. However, the value of p_1 varies within a larger range (from 1 to 1.7, approximately). Therefore, we have:

$$\Xi^2 = p_1(t) \times \omega$$

where t is the background traffic load intensity. The actual form of the function $p_1(t)$ is obtained in section 4.4.

The results obtained in the case of high-priority traffic are very similar to those presented in Figure 34 and are not shown separately.

4.3 Relation of the Polynomial Coefficients to the Service Rate

The current subsection shows the relationship of the coefficient p_1 to the intensity of the service rate, for both bursty and self-similar traffic. By repeating the same technique as in 4.2.1, we obtain the same simplified relation for *(4-1)*, namely:

$$\Xi^2 = p_1 x \omega$$

4.3.1 Bursty Traffic

Figure 35 presents p_1 as a function of the service rate. As in the case of the background traffic, the coefficient is quasi-constant and close to 1. The coefficient p_1 has been obtained by curve fitting for the simulations described in 3.4.1.1(b). The service rate varies from 12 cells/second to 34 cells/second. The value of p_1 slowly changes changes when the background traffic rate changes. Each p_1 curve is obtained for a given discard rate (DR) of the background traffic rate. The actual form of p_1 as a function of service rate is obtained in 4.4.

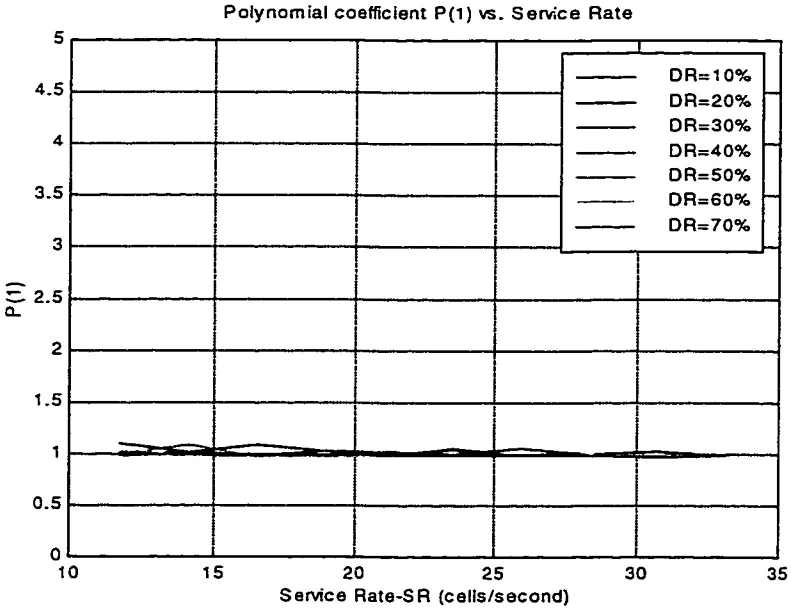


Figure 35 **Polynomial Coefficient p_1 vs. Service Rate for No Priority Bursty Traffic, Single Background Traffic Sources**

4.3.2 Self Similar Traffic

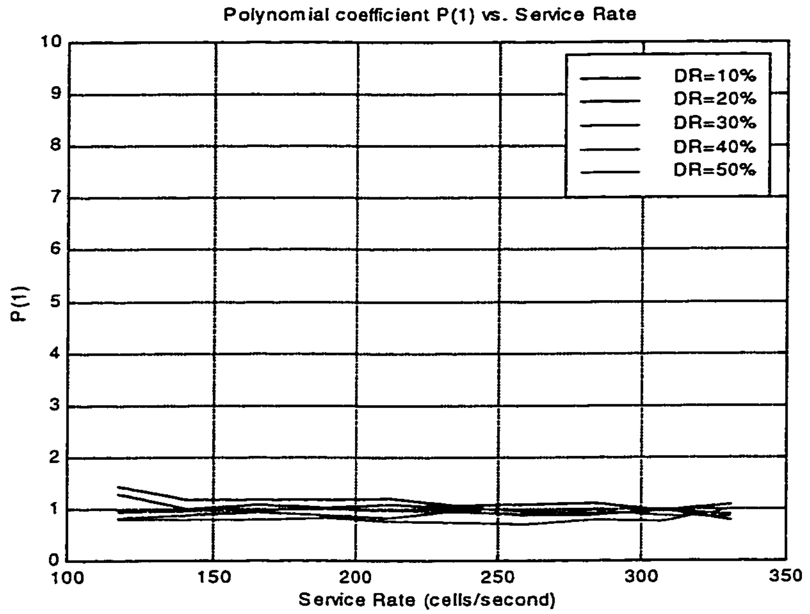


Figure 36 **Polynomial coefficient p_1 vs. service rate, self-similar no priority traffic, multiple background traffic sources**

The coefficient p_1 presented in Figure 36 was obtained by curve fitting for the self-similar traffic simulations described in A.4.2.2.2, as a function of the service rate. The service rate varies from 80 cells/second to 340 cells/second. The coefficient p_1 decreases very slowly when the service rate increases, each p_1 curve being obtained for a given discard rate (DR) of the background traffic rate. The actual form of p_1 as a function of the service rate (and background traffic) is found in 4.4.

4.4 Dependency of Polynomial Coefficient on the Simulation Parameters

In the previous sections of this chapter, we have shown that the end-to-end jitter linearly depends on the end-to-end accumulated delay variance: $\Xi^2 = p_1 \times \omega$.

In this section we determine that although p_1 *appears* quasi-constant with respect to the service rate and background traffic, a closer look at the results shows that actually p_1 slowly increases when the background traffic is increased and the service rate decreased. In order to find the relationship of p_1 to the background traffic and service rate, we make use of the fact that two simulation parameters are varied for each series of simulations (e.g. the intermediate node service rate and the background traffic load). Using the curve fitting capability of *Matlab,* we find a polynomial relationship of p_1 with respect to the simulation parameter that varies from one series of simulation to the next. Note that for simplicity, we consider that p_1 is "constant" with respect to the other varying simulation parameter (in fact, the actual variation is very small).

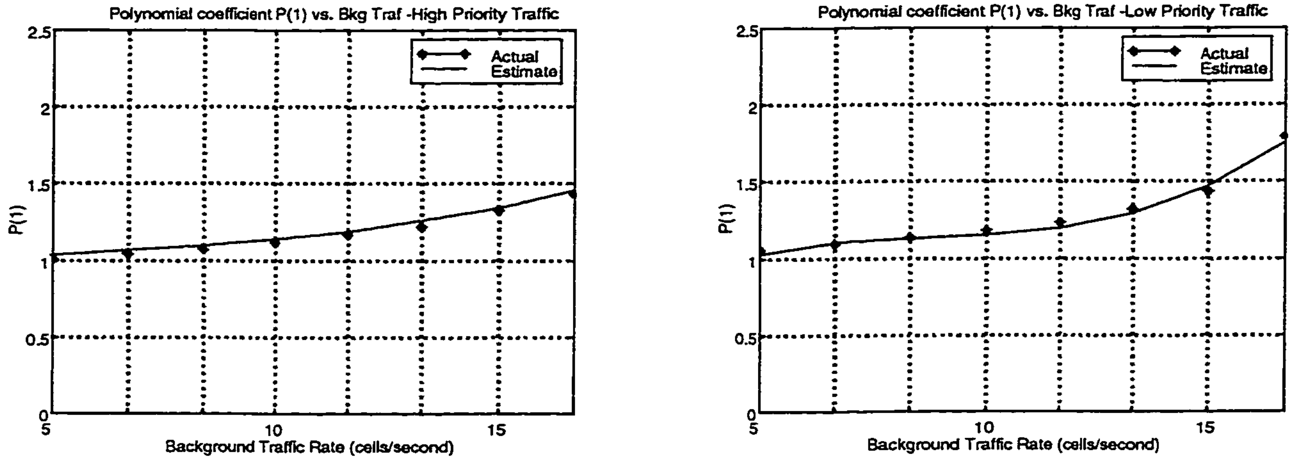
The procedure for finding the ***estimated*** values of p_1 from the ***actual*** values of p_1 is described in the following. First, we designate ***actual*** values of p_1 to be those values of p_1 that are obtained from the simulation results for the end-to-end jitter and accumulated delay variance, for particular points of a parameter t (where t is either the service rate or the background traffic): $t_1, t_2, \ldots t_n$. The actual values are then used to obtain an empirical formula for p_1. For instance, recall the five series of ten simulations each that we have performed. For some of these series, the background traffic is kept constant for all simulations in a series, while the service rate is increased from 5 cells/second to 15 cells/second, and the normalized background traffic rate of each series is increased from 0.17 to 0.85 with a step of 0.17. Correspondingly, we obtain 5 series of p_1 values. As shown in section 4.3, the values of p_1 are quasi-constant with respect to the service rate for a fixed background traffic rate, i.e. their variation with respect to the service rate is very small.

In order to obtain a representative ***actual value*** of p_1 corresponding to a series, we calculate the mean value of p_1 for each of the five series. Thus, we obtain five mean values for p_1, one for each background traffic intensity: $p_1(0.17)$, $p_1(0.34)$, $p_1(0.51)$, $p_1(0.68)$ and $p_1(0.85)$. We then use Matlab to fit a least-mean-square curve through the five points of p_1 (for 0.17, 0.34, 0.51. 0.68 and 0.85) and obtain a polynomial formula ***p_1(t=background traffic).*** Using a similar procedure, we also obtain a formula ***p_1(t=service rate).*** The ***estimated*** values of p_1 are obtained using the empirical formula ***p_1(t),*** where t can be an arbitrary value of either the background traffic intensity or the service rate.

For the simulations described in sections A.4.2.2.3.1 and A.5.1.2.3.2 (self-similar, multiple background sources), a linear polynomial formula is obtained for the relationship of p_1 to the background traffic rate, as shown in Figure 37.

Both the ***actual*** and ***estimated*** values of p_1 as a function of background rate are plotted. The figure also compares the coefficient p_1 obtained for high and low priority traffic.

It is interesting to observe from Figure 37 and Figure 38 that the increase of p_1 with respect to the background rate for the low priority traffic is steeper than for the high priority traffic. This is due to the fact that the end-to-end jitter of the low priority reference traffic is affected by both the high and low priority traffic in the network, while the end-to-end jitter of the high priority reference traffic is only affected by the high priority traffic itself.



(A) **(B)**

Figure 37 Comparison of actual and estimated values of p_1, for varying background traffic rate for self-similar traffic, multiple background sources. (A) High Priority Traffic and (B) Low Priority Traffic

For high priority traffic, we obtain the following formula for the estimated $p_1(t)$

$p_1(t) = 0.00003 \times t^3 + 0.0002 \times t^2 + 0.0621 \times t + 0.5783$ (4-3),

while for low priority traffic the formula is

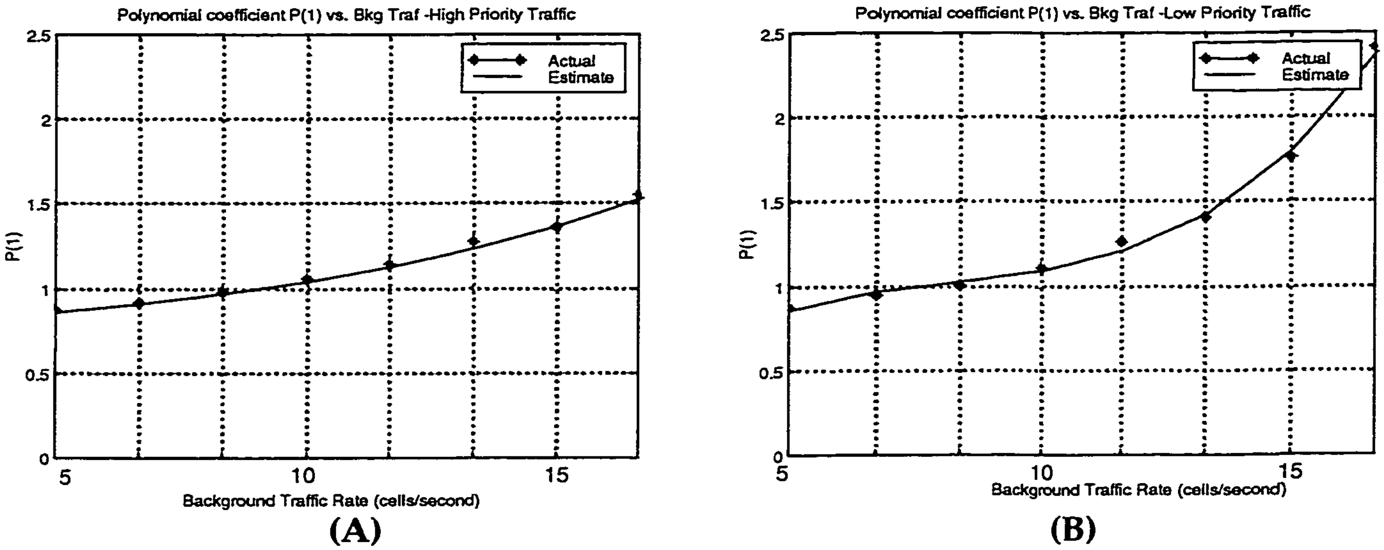
$p_1(t) = 0.0008 \times t^3 - 0.0081 \times t^2 + 0.0671 \times t + 0.7015$ (4-4).

where ***t*** is the background traffic rate measured in cells/second.

It is interesting to note that the coefficients of t^3 and t^2 in formula (4-3) are small and can be ignored. The more pronounced effect of t^3 and t^2 in formula

(4-4) is due to the effect that the high priority has on the low priority traffic jitter.

A similar relationship can be found for self-similar traffic with single background traffic sources, as shown in Figure 38.



(A) (B)

Figure 38 **Comparison of actual and estimated values of p_1, for varying background traffic rate for self-similar traffic and single background sources. (A) High Priority and (B) Low Priority Traffic**

In this case, the formula for the estimated $p_1(t)$ for high priority traffic is

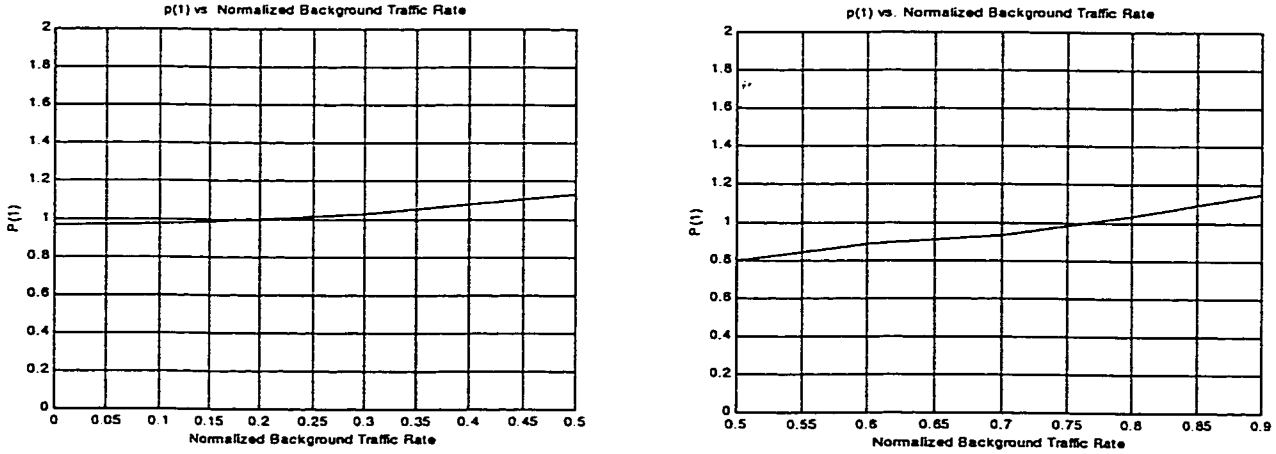
$$p_1(t) = 0.00002 \times t^3 - 0.00011 \times t^2 + 0.0510 \times t + 0.7316 \qquad (4\text{-}5),$$

and for low priority traffic

$$p_1(t) = 0.0005 \times t^3 - 0.0073 \times t^2 + 0.0512 \times t + 0.8523 \quad (4\text{-}6).$$

Similarly, the coefficients of t^3 and t^2 in formula (4-5) are fairly small and can be ignored, showing a quasi-linear formula of p_1 with respect to the background traffic.

For bursty traffic, the coefficient p_1 also varies quasi-linearly with the increase of the background traffic. In this case, p_1 is obtained for the simulations described in section A.5.1.1.1.1, the case of a single background traffic source per intermediate node and A.5.1.1.2.1, for multiple sources per intermediate nodes. The results are displayed in Figure 39.



(A) **(B)**

Figure 39 Comparison of the p_1 variation with the background bursty traffic. (A) Single Background Sources and (B) Multiple Background Sources

For the case of the single background sources (Figure 39.A), the empirical formula for the estimated p_1 is:

$$p_1(t) = 0.42 \times t + 0.962 \qquad (4\text{-}7)$$

while for the case of multiple background sources (Figure 39.B), we obtain the formula:

$$p_1(t) = 1.05 \times t + 0.381 \qquad (4\text{-}8)$$

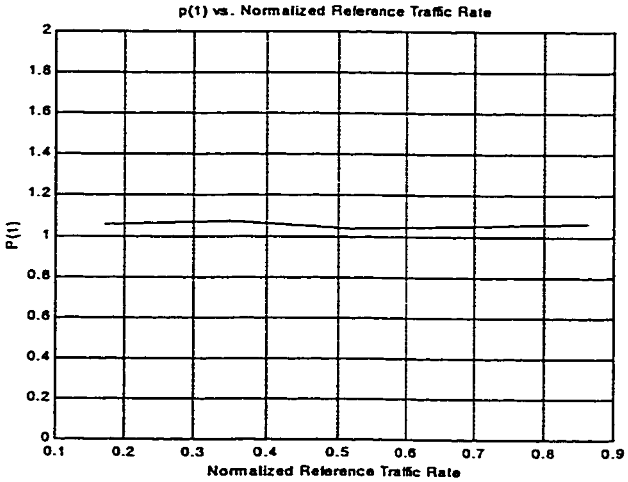


Figure 40 **Polynomial Coefficient Relationship to the Reference Traffic Rate for Bursty Traffic**

Our results have also shown that p_1 is quasi-constant with respect to the reference traffic rate (as illustrated in Figure 40, which displays a result obtained for bursty traffic). A similar type of result is obtained for all simulations that we have conducted, irrespective the type of traffic (bursty or self-similar) or whether no priority or two priority traffic is used.

4.5 Relation of the Polynomial Coefficients to the Intermediate Node Utilization Factor

In sub-sections 4.2, 4.3 and 4.4 we have studied the dependency of the polynomial coefficient on the service rate of the intermediate nodes and the background traffic intensity. Although important, these results do not represent a generalized formula for p_1, and hence for the end-to-end jitter vs. the accumulated delay variance. It would be more useful to obtain a formula for p_1 as a function of the intermediary node ***utilization factor*** (ρ).

Intuitively, the server utilization factor ρ is a measure of how busy the server is servicing incoming cells. The utilization factor ρ is defined as the aggregate arrival rate normalized with respect to the service time. By definition, $\rho = \lambda/\mu$, where λ is the arriving traffic intensity and is the μ service rate of the server. The utilization factor ρ is a dimensionless figure, hence it is an appropriate and generalized formula for the end-to-end jitter. It needs not refer to a particular service rate or background traffic rate; only their ratio matters. For an extensive discussion of the utilization factor, please refer to [KLEI75, pp 18-19].

The previous results for the influence of the background traffic intensity and service rate on the end-to-end jitter seem to indicate that a similar relationship should exist with respect to the effect of the utilization factor on the end-to-end jitter. The reasoning is simple: when we increase the background traffic intensity (hence the utilization factor) and keep the service rate constant, the end-to-end jitter increases, while when we increase the service rate (hence decrease the utilization factor) and keep the background traffic intensity constant, the end-to-end jitter decreases. Therefore, we can infer that the end-to-end jitter increases when the utilization factor increases.

It is important to notice that in most simulations that we have conducted, the intermediate node server utilization factors are not identical. This is due to the fact that only a fraction of the background traffic that joins the network at node ***n*** leaves the network at the same node; a fraction of it continues along the way to the destination node. In order to have the same background traffic intensity at all nodes (and hence the same utilization factor), the discard rate must be set to 100%, that is, all background traffic entering the network at an intermediate node is discarded at the same node, after being serviced.

Therefore, we have conducted a number of simulations for which the background traffic discard rate at all nodes is set to 100% and the background traffic rate is increased from one simulation to the other, for both bursty and self-similar traffic. We have used the results of these simulations to plot the curve of the p_1 polynomial coefficient against the utilization factor. The results of these simulations show the same type of linear relation between the end-to-end jitter and the accumulated delay variance that we have noticed in Chapter 3.

Figure 41 presents the polynomial coefficient vs. the utilization factor for bursty traffic. The polynomial coefficient in Figure 41 has been obtained from a simulation using bursty, no priority traffic for which the discard rate has been set to 100% at all intermediate nodes. The reference traffic rate intensity has been fixed at 1 cell/second (very small compared to the service rate) and the service rate has been fixed at 100 cells/second. The background traffic intensity has been varied from 10 cells/second to 80 cells/second (hence obtaining a range of the utilization factor from 0.1 to 0.8).

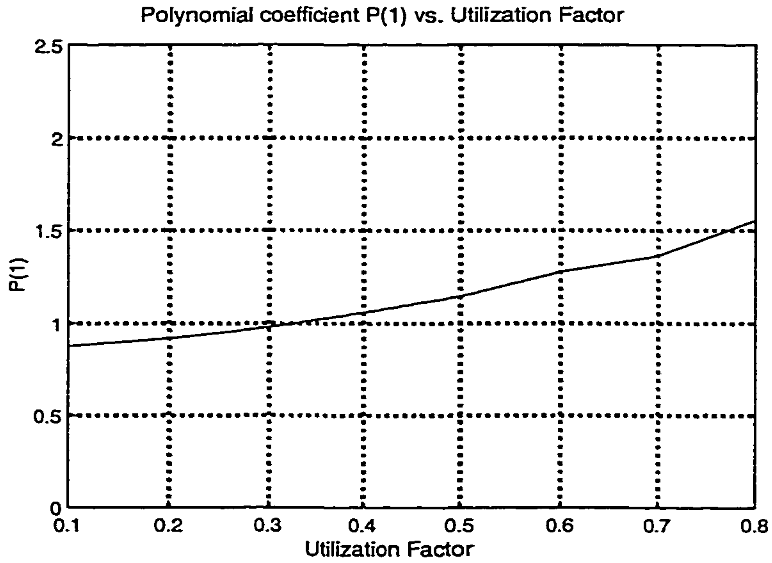


Figure 41 **Polynomial Coefficient vs. Intermediate Node Utilization Factor for Bursty Traffic**

As can be observed from Figure 41, a quasi-linear relationship exists between p_1 and the utilization factor ρ:

$$p_1(\rho) = 1.15\,\rho + 0.9\,. \qquad (4\text{-}9)$$

Other bursty traffic simulations indicate that the same type of relationship exists between the polynomial coefficient for the end-to-end and the server utilization factor, namely:

$$p_1(\rho) = a_1\,\rho + a_0 \quad . \qquad (4\text{-}10)$$

The same type of relationship $p_1(\rho)$ also exists in the case of self-similar traffic. In that case, however, a_1 is about 1.4, while a_0 is 1.

The results obtained in equations (4-9) and (4-10) do not apply for situations when the utilization factor is not the same at all nodes. Although more difficult to study, this case is more interesting, since in a real life network it is likely that the different sub-networks connected to the intermediate nodes may generate different traffic intensities. We can argue that the upper bound for the end-to-end jitter is given by the coefficient p_1 corresponding to highest utilization factor among all intermediate nodes. Also, we suggest that the formula

$$p_1(\rho_{mean}) = a_1 \rho_{mean} + a_0 \qquad (4\text{-}11),$$

where $\rho_{mean} = \sum_{i=1}^{N} \rho_i / N$, with N being the total number of nodes

may be used as a good approximation for the case when the intermediate nodes do not have the same utilization factor. We have found that the coefficient a_1 can be chosen to be *1.1* for bursty traffic and *1.3* for self-similar traffic, while a_0 is chosen to be 1.0 in both cases. Note that formula (4-11) is identical to the formulae (4-9) and (4-10) if all nodes have the same utilization factor. A verification of the representative results obtained using this formula is presented in section 4.6.2.

4.6 Verification

This section uses the following terminology:

Measured values: the numerical values of a parameter, output as results of a simulation. Among others, simulations output numerical values for the end-to-end jitter and the delay variance.

Estimated values: the values Q_E of a parameter (generically named Q), obtained by applying a generic function **F** (e.g. a formula obtained empirically) to the measured values P_M of another simulation parameter (generically named P): $Q_E = \mathbf{F}(P_M)$. Note that one can also obtain the measured values Q_M for the parameter Q.

The results obtained through simulations have been verified using two methods:

- **Estimation Accuracy**. The **measured end-to-end jitter** obtained in a simulation is compared to the **estimated end-to-end jitter** for the same simulation.

  In the previous sections we have obtained, by curve fitting, the values of the polynomial coefficient p_1 for a number of simulations. The ***estimated*** value of the end-to-end jitter for those simulations is given by:

$$Estimated(\Xi^2) = p_1(t) \times \omega \quad (4\text{—}12),$$

where t is either the service rate, the background traffic intensity or the mean utilization factor ρ_{mean}(used in formula 4-11), and the ***measured*** values of the end-to-end jitter Ξ^2 are values obtained from the simulations.

In order to estimate the accuracy of our method, we obtain the ***estimate*** of the end-to-end jitter by applying the empirical formulae (4-12) to the ***measured*** accumulated delay variation ($\omega \overset{notation}{=} \Omega^2$) obtained from the simulations. We then compare the estimated and measured values of the end-to-end jitter.

As a measure of the estimated accuracy we introduce the relative end-to-end jitter error $E_{r\text{-}estimate}$, defined as:

$$E_{r\text{-}estimate} = |\ Estimated(\Xi^2)\ -\ \Xi^2\ |\ /\ \Xi^2 \qquad (4\text{-}13)$$

As another measure of the estimation accuracy, we have also used the mean square error to gauge how fit the polynomial $p_1(t)$ is to approximate (estimate) the measured values.

- **Prediction Accuracy.** The prediction accuracy is obtained by comparing the ***calculated*** end-to-end jitter obtained from the formula

$$Calc(\Xi^2) = p_1(t) \times \omega \qquad (4\text{-}14)$$

to the ***measured*** end-to-end jitter obtained from a *supplementary simulation*. In formula (4-14), $p_1(t)$ is one of the empirical formulae obtained in sub-section 4.4 and ω is obtained from the results of the simulation. The *supplementary simulations* use modified simulation parameters with respect to the original simulations that we have used for obtaining p_1. For instance, for an original simulation for which the service rate has been set to vary from 10 to 100 cells/seconds with a step of 10 cells/second, the service rate of the supplementary simulation is set to 85 cells/second. The ***calculated value*** of the end-to-end jitter is fairly similar to the ***estimated value,*** except that the p_1 coefficient used for the ***calculated end-to-end jitter*** is itself obtained through estimation, instead of being the immediate result of curve fitting. This is done, for instance, by setting *t=85 cells/second* in formula 4-14. The procedure verifies the accuracy of predicting the values of the end-to-end delay jitter for new simulation parameters.

Similarly, we introduce a measure of the prediction accuracy defined as $E_{r\text{-}calculated}$:

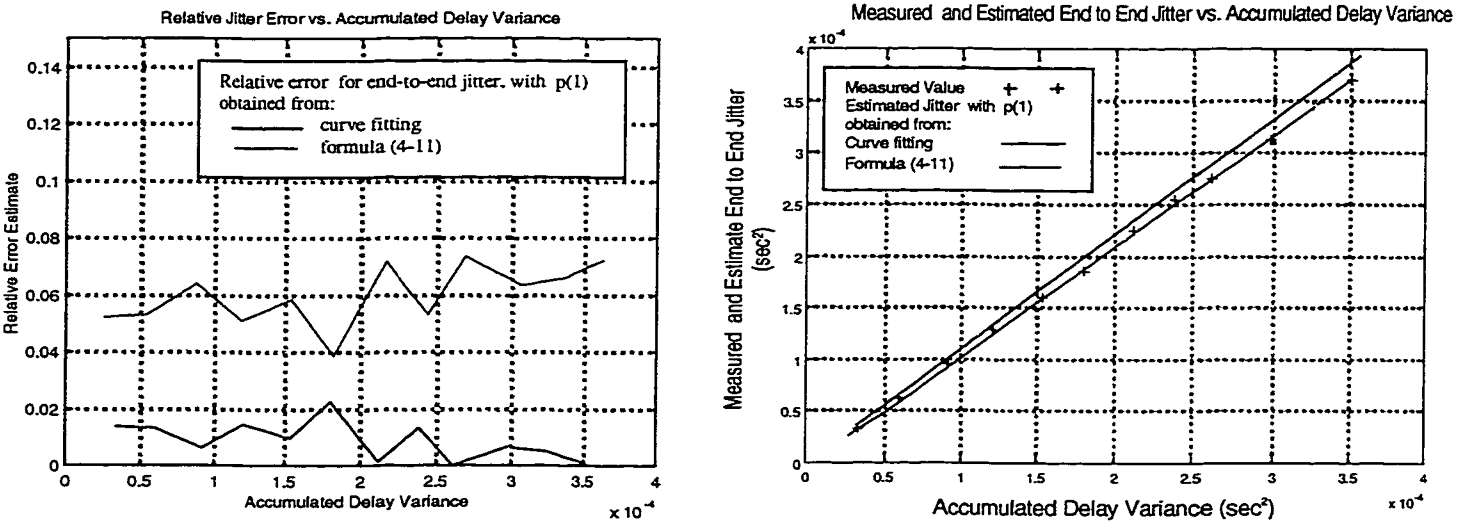
$$E_{r\text{-calculated}} = |\ Calc(\Xi^2)\ - \Xi^2\ |\ /\ \Xi^2 \qquad (4\text{-}15)$$

We also determine the prediction accuracy using formula (4-11) from section 4.5, for p_1 as a function of the utilization factor, $Calc(\Xi^2) = p_1(\rho_{mean}) \times \omega$, in order to calculate the end-to-end jitter.

4.6.1 Estimation Accuracy

In order to demonstrate the estimation accuracy, we have obtained and plotted the relative end-to-end jitter error $E_{r\text{-estimate}}$ against the accumulated delay variance. Our purpose is to show that the relative error is fairly small in all cases, thus the measured value and polynomial estimate of the end-to-end jitter are quite close.

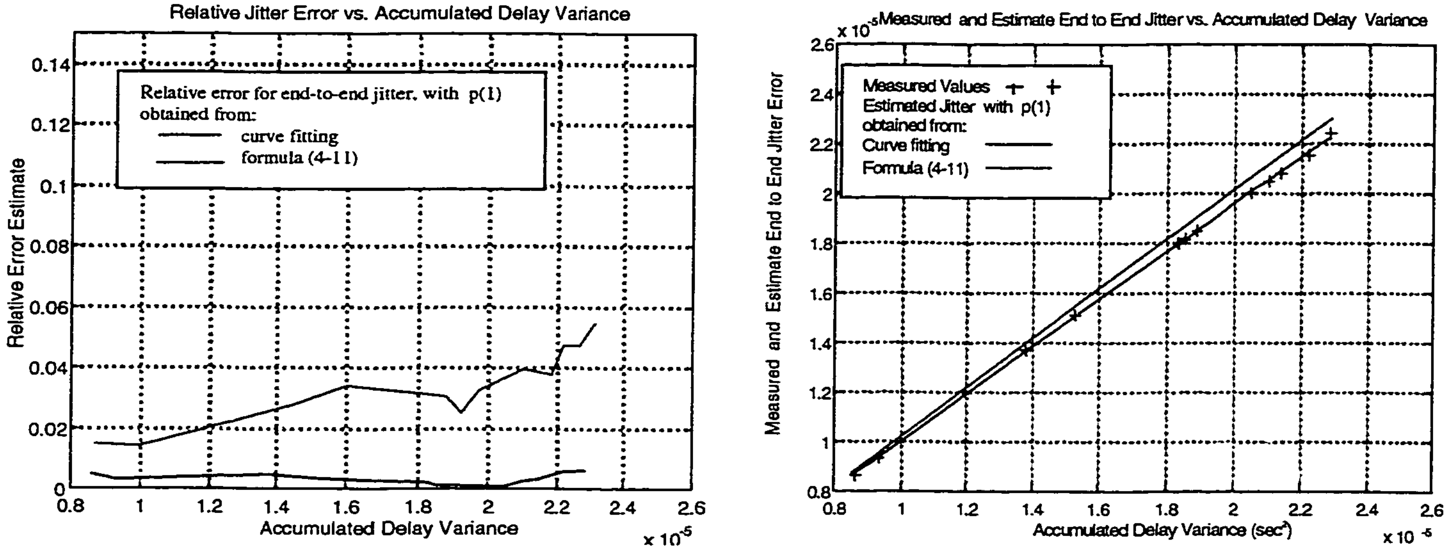
This subsection shows a few examples of the relative estimation errors for the end-to-end jitter. The estimated end-to-end jitter is obtained for the p_1 values obtained in sections 4.2 and 4.3, as a result of curve fitting, as well as for the values obtained using formula (4-11) from section 4.5, that gives p_1 as a function of the mean utilization factor ρ_{mean}. These two ***estimated*** results are then compared against the ***measured*** results for the end-to-end jitter.



(A) **(B)**

Figure 42 Estimation Accuracy for Varying Background Bursty Traffic, Single Reference Stream and Single Background Traffic Sources. (A) Relative Estimation Error and (B) Measured vs. Estimated End-to-end Jitter

Using the results of the simulations described in section A.4.1.1.1 (conducted to study the effect of bursty background traffic on the end-to-end delay jitter), the relative end-to-end jitter error and the comparison of the measured to estimated end-to-end jitter are obtained in Figure 42. These results are obtained for a normalized background traffic intensity of 0.7, while the service rate for all intermediate nodes is 24 cells/seconds. The coefficient p_1 obtained from formula (4-11) is $p_1(\rho_{mean}) = 1.19$, and the coefficient p_1 obtained as a result of the curve fitting is $p_1= 1.12$. As expected, the relative error (from 2 to 6%) obtained when using p_1 from formula (4-11) is larger than the relative end-to-end jitter error obtained when using p_1 resulted from curve fitting (below 2%). The results obtained for the other simulations conducted in order to study the *effect of the background traffic* on the end-to-end jitter (for both bursty and self-similar traffic), are very similar.



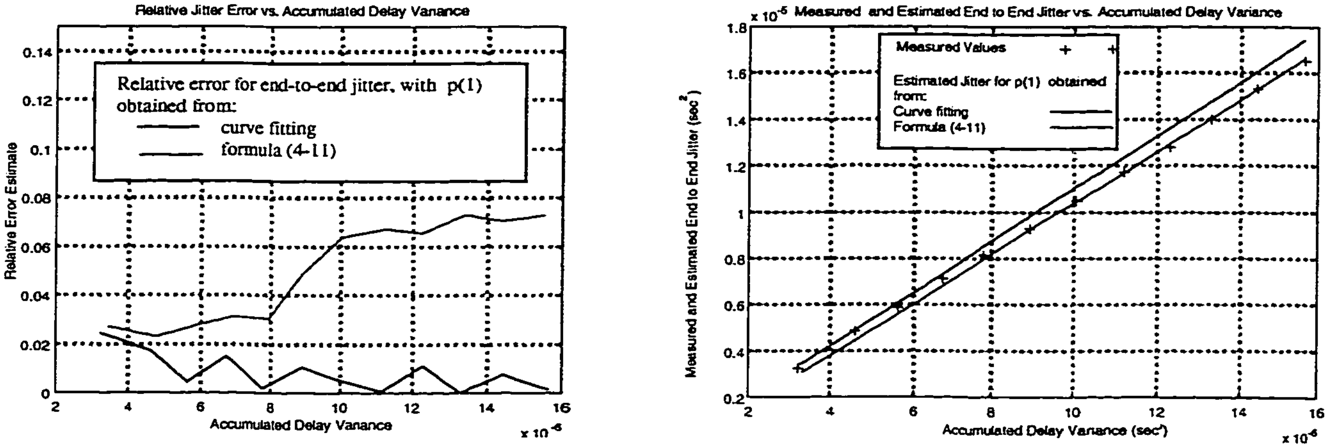
(A) **(B)**

Figure 43 Rate **Estimation Accuracy for Single Bursty Traffic Stream and Varying Service**

(A) Relative Estimation Error and (B) Measured and Estimated End-to-end Jitter vs. Accumulated Delay Variance

Figure 43 shows the relative error and measured vs. estimated end-to-end jitter for the simulation described in section A.4.1.1.2, conducted to study the effect of *varying the service rate* on the end-to-end jitter, in the case of bursty traffic. The results represented here are obtained for a service rate of 12 cells/second at all intermediary nodes and a normalized background traffic intensity of 0.05. The relative error corresponding to the estimated end-to-end jitter resulted for the coefficient p_1 = ***1.01*** obtained by curve fitting is even smaller here (practically below 0.005, and even 0 in certain points). The relative error corresponding to $p_1(\rho_{mean})$ = ***1.104*** obtained from formula (4-11) is higher (between 2 and 6%). This is reflected in the results presented in Figure 43.B, for the measured end-to-end jitter and the two variants of the estimated end-to-end jitter.

Similar results have been obtained for the other simulations conducted in order to study the effect of the *service rate* on the end-to-end jitter, for both bursty and self-similar traffic.
The accuracy is comparable in the case of self-similar traffic (simulations described in section A.4.2.2.2) as illustrated in Figure 44.



(A) **(B)**

Figure 44 Estimate Relative Error for End-to-end Jitter Varying Service Rate for Self Similar Traffic.
(A) Relative Error (B) Measured and Estimate End-to-end Jitter

For these simulations, conducted to study *the effect of the service rate* on the end-to end jitter of self-similar traffic, the background traffic and reference traffic emitted by all sources have been kept constant at 14 cells/second. The results presented in Figure 44 have been obtained for a service rate value of 144 cells/second. In this case, the relative error is also below 0.02 (2%), in the case of p_1=***1.1*** obtained from curve fitting, and higher (up to 6-7%) for the $p_1(\rho_{mean})$=***1.06*** value obtained using formula (4-11).

Mean Square Errors. *Matlab* uses the *least square errors* method for the operation of curve fitting. The coefficients of the best-fitting linear polynomial obtained for a set of empirical results are chosen such as the sum: $MSE = \Sigma^{N}_{i=1} e^{2}_{i} / N$, is minimal. N is the total number of points and e_i is the *estimation error*, i.e. the difference between the estimated and measured values of the end-to-end jitter at a point i. We have used a normalized value of MSE as another measure of the estimation accuracy, namely

$$Norm[MSE] = \sqrt{MSE} \; / \; J_R \,,$$

where J_R is the range of the end-to-end jitter for the particular set of simulation results for which MSE was calculated, that is:

J_R = ***<Maximum Value of End-to-end Jitter> - <Minimum Value of End-to-end Jitter>***

This formula allows us to compare the estimation accuracy of different simulations. Our results have shown that in general, *Norm[MSE]* is between 3.5×10^{-4} and 2×10^{-3}.

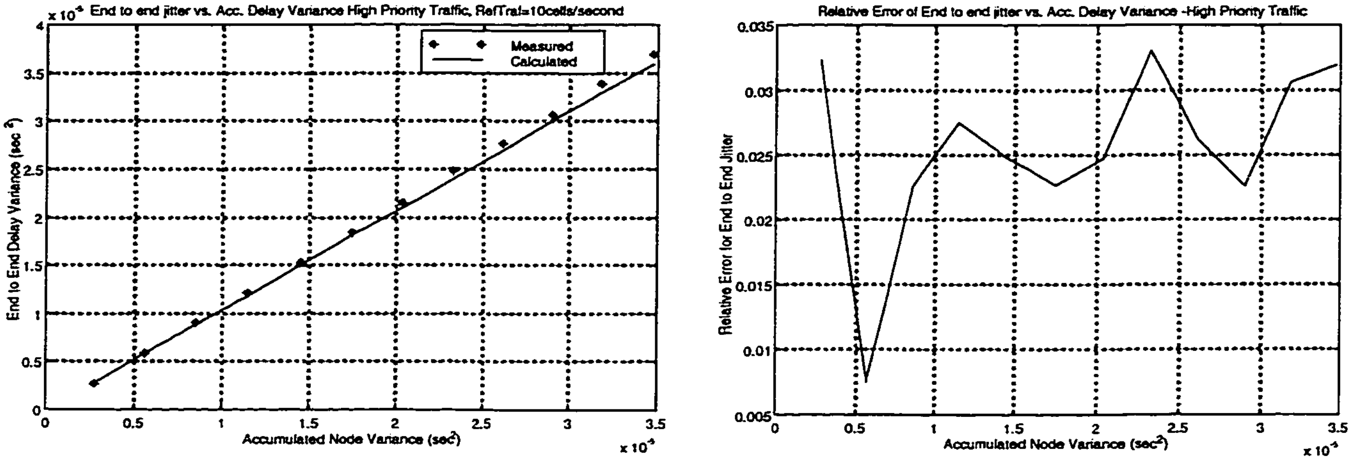
Conclusion. We have investigated all normal simulations (no network congestion and cell loss probability below 5%) and found the end-to-end jitter relative error to be below 5%. In fact, in most cases the error is around 2% or lower. It is also interesting to note that for certain points the estimation using p_1 obtained from curve fitting error is zero (as illustrated in Figure 44.A).

4.6.2 Prediction Accuracy

For the self-similar, two priority traffic simulations described in section A.4.2.2.3.1, the simulation parameters have been modified, in order to conduct a supplementary simulation, as follows:

- The discard rate for background traffic has been set at 85%
- The service rate for the intermediate nodes is set to 120 cells/second.
- The average background traffic rate of each of the background sources has been set at 12 cells/second.
- The average reference traffic rate is set at 10 cells/second.

Under these assumptions, and using formula (4-3) from section 4.4 for $p_1(t)$, where $t=12$ (the background traffic rate measured in cells/second), we obtain the results presented in Figure 45:



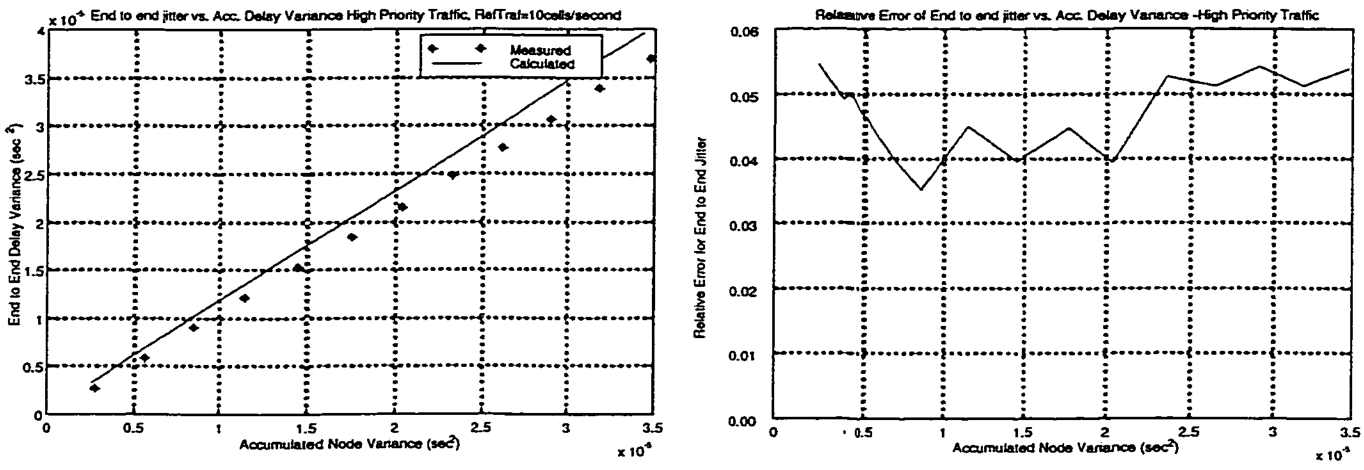
(A) **(B)**

Figure 45 Verification of Prediction Accuracy for Self-Similar, Two Priority Traffic. (A) Measured and Calculated End-to-end Jitter and (B) Relative Error of End-to-End Jitter

As can be observed from Figure 45, the relative prediction error is below 3.5%, while the ***measured*** and ***calculated*** end to end jitter match quite closely. The definitions for the measured and calculated end-to-end jitter are those from the beginning of section 4.6. That is, the ***calculated end-to-end*** jitter is obtained by applying the ***estimated*** formula for p_1***(t=120 cells/second)*** to the ***measured values*** for the accumulated delay variance, while the ***measured end-to-end jitter*** is a simulation result and corresponds to the same measured values of the accumulated delay variance.

For the same set of simulations, the mean utilization factor is ρ_{mean} = ***0.11***. By applying formula *4-11* to calculate p_1 (with a_1 = ***1.3*** and a_0 = ***1.0***), we obtain $p_1(\rho_{mean})$= ***1.14***.

Figure 46 is the counterpart of Figure 45, when using this latter value $p_1(\rho_{mean})$ instead of the value obtained from (4-3). In this case, it can be noticed that the relative error is larger.



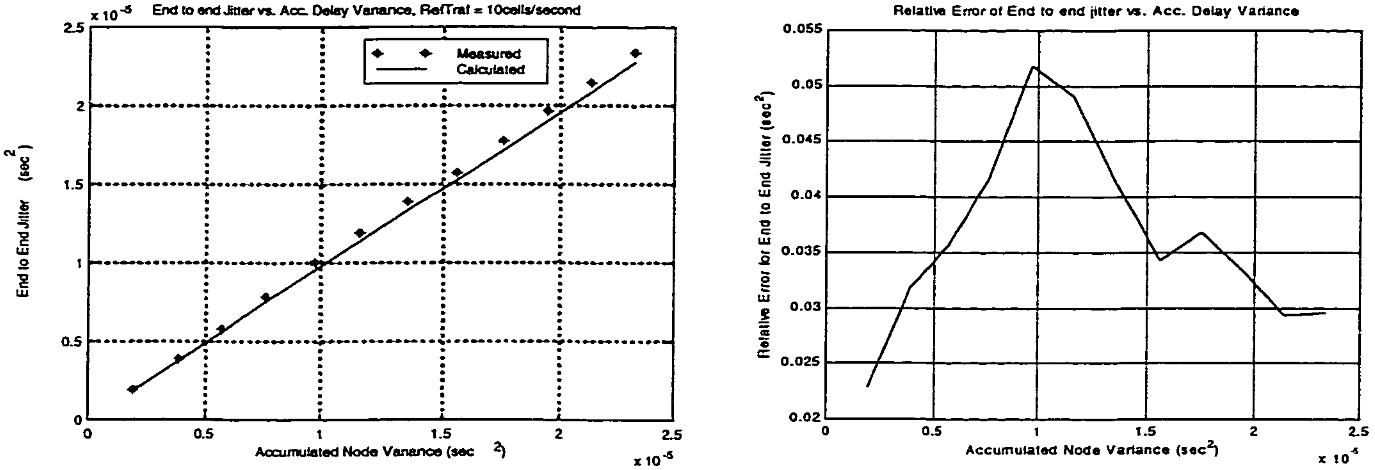
(A) (B)

Figure 46 Verification of Prediction Accuracy for Self--Similar, Two Priority Traffic with p_1 calculated as a function of ρ_{mean}. (A) Measured and Calculated End-to-end Jitter and (B) Relative Error of End-to-End Jitter

For the single priority self-similar traffic simulations described in section A.4.2.2.3.1, the following simulation parameters have been modified, in order to conduct a supplementary simulation:

- The discard rate for background traffic has been set at 95%
- The average background traffic rate of each of the background sources has been set at 12 cells/second.
- The average reference traffic rate is set at 10 cells/second.

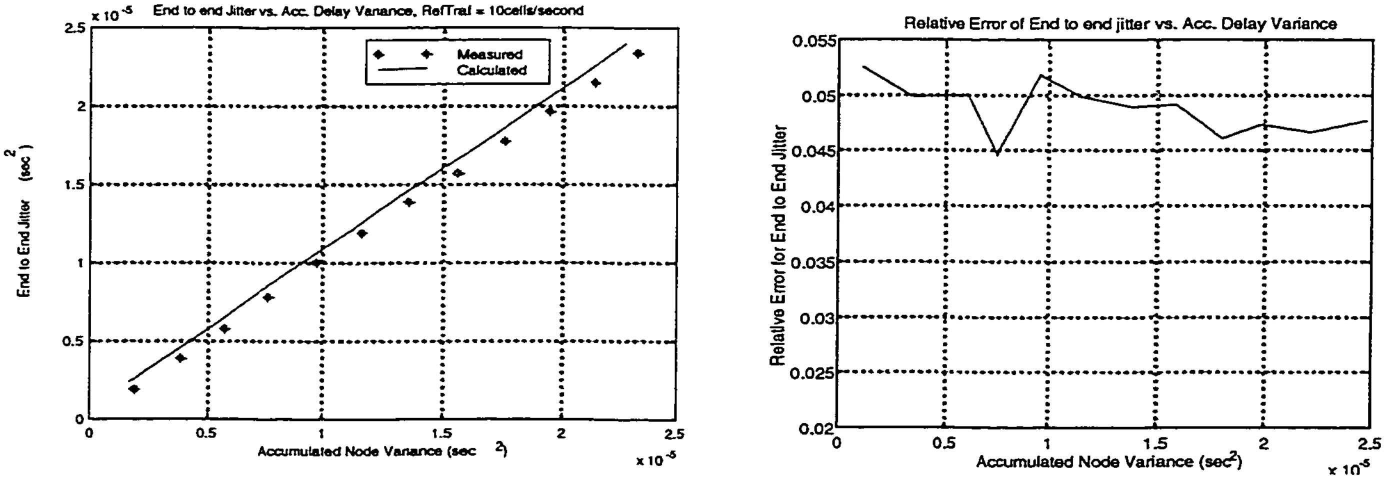
With these new parameters, and using formula (4-5) from section 4.4 for $p_1(t)$, where t is the background traffic rate (in cells/seconds), we have obtained the results illustrated in Figure 47:



(A) **(B)**

Figure 47 Verification of Prediction Accuracy for Self Similar, No Priority Traffic. (A) Measured and Calculated End-to-end Jitter and (B) Relative Error for the End-to-end Jitter

As it can be seen from Figure 47, the ***calculated*** end-to-end jitter matches quite well (with a relative error of at most 5%) the ***measured*** jitter obtained from the simulation.



(A) **(B)**

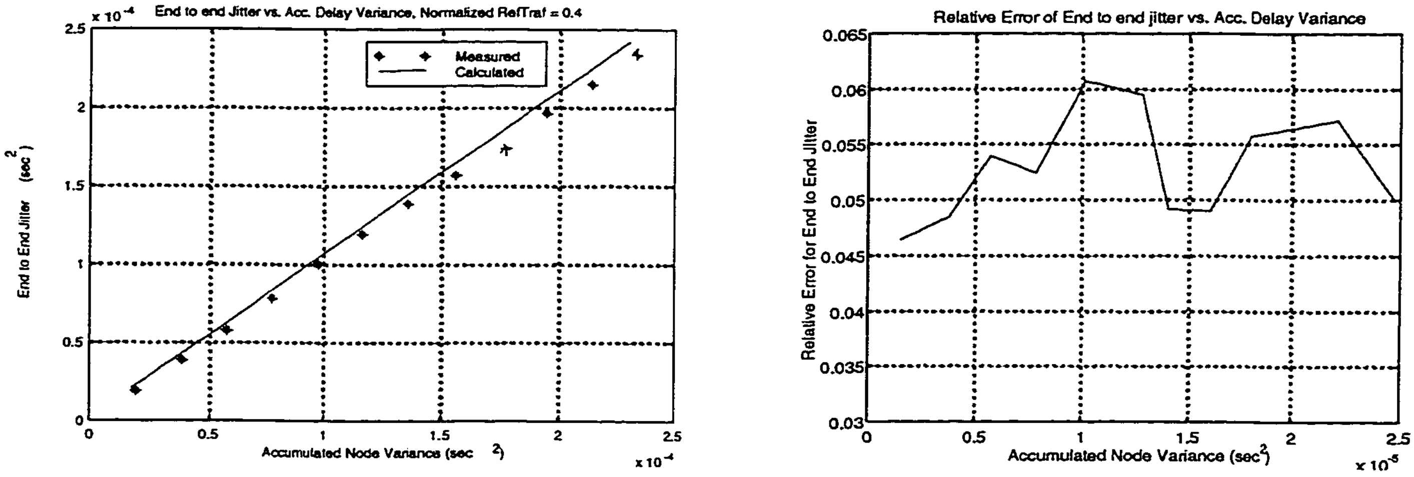
Figure 48 Verification of Prediction Accuracy for Self Similar, No Priority Traffic, with p_1 calculated as a function of ρ_{mem}. (A) Measured and Calculated End-to-end Jitter and (B) Relative Error for the End-to-end Jitter

By applying again formula *4-11* to calculate p_1 (with $a_1 = 1.3$, $a_0 = 1.0$ and $\rho_{mean} = 0.1$), we obtain $p_1(\rho_{mean}) = 1.13$. Figure 48 corresponds to Figure 47, when using this latter value of $p_1(\rho_{mean})$ instead of the value obtained by using formula *(4-3)*. Again, the relative error is larger in this case.

The same procedure has been be applied to the bursty traffic simulations described in A.4.1.1.1. The following parameters were used for the supplementary simulation:

- The service rate for all the intermediate nodes is set to 24 cells/second, and the discard rate to 50%.
- The normalized background traffic rate of each of the background sources is set at 0.5.
- The normalized reference traffic rate (NRT) is set at 0.4.

In this case, $\rho_{mean} = 0.04$. By applying formula 4-11 to calculate p_1 for bursty traffic (for $a_1 = 1.1$ and $a_0 = 1.0$), we obtain $p_1(\rho_{mean}) = 1.044$. The results are presented in Figure 49.



(A) **(B)**

Figure 49 Verification of Prediction Accuracy for Bursty, No Priority Traffic, with p_1 calculated as a function of ρ_{mean}. (A) Measured and Calculated End-to-end Jitter and (B) Relative Error for the End-to-end Jitter

For the case of bursty traffic, the relative error for the end-to-end jitter calculated with formula (4-11), is larger than the corresponding relative error for the end-to-end jitter calculated using the p_1 coefficient obtained in sections 4.2 and 4.3. This is similar to results obtained for self-similar traffic. In general, the relative error obtained when using formula (4-11) for p_1 is between 5% and

7%, which is fairly acceptable for an approximation. Note that the end-to-end jitter calculated using formula (4-11) seems to be always larger than the measured value of the jitter.

4.7 Chapter Summary

This section has shown the influence of different simulation parameters on the end-to-end delay jitter. Generally, we have determined that the end-to-end jitter linearly depends on the accumulated node delay variance:

$$\Xi^2 = p_1 \times \Omega^2 \qquad (4\text{-}16),$$

where p_1 slowly increases with an increase of the background traffic and decreases with an increase of the service rate. This suggests that the server utilization of intermediate nodes plays an important role in the overall end-to-end jitter.

We also have found a generalized quasi-linear relationship between p_1 and the intermediate node utilization factor, in the case that all nodes have the same utilization factor

$$p_1(\rho) = a_1\,\rho + a_0 \qquad (4\text{–}17),$$

or the mean of the utilization factors of all intermediate nodes, if the intermediate nodes have different utilization factors

$$p_1(\rho) = a_1\,\rho_{mean} + a_0 \qquad (4\text{–}18).$$

We could have found a second or third order approximation for the dependency of the p_1 coefficient and the utilization factor ρ (as we did in sub-section 4.4, for the service rate and background traffic), but we have considered more convenient to use a quasi-linear relationship. The gain in accuracy by using a second or third order approximation seems to be minimal in this case.

Also note that formula *(4-17)* provides an upper bound for the end-to-end jitter in case each node has a different utilization factor; the upper bound can be calculated by setting the value of ρ in formula *(4-17)* to the largest utilization factor of the nodes from the source to the destination. A general approximation is given by formula *(4-18)*. However, this formula is less accurate (the relative error for this formula is 5 to 7%, versus 2 to 3% for the other formulae).

Chapter 5
Conclusion

This thesis has undertaken an empirical study of the end-to-end jitter in computer and data networks, under realistic traffic assumptions. The effect of background traffic load, intermediate nodes service rate, cell loss and intermediate node buffer size on the end-to-end jitter has been studied. A simple linear polynomial relationship (first order polynomial) between the end-to-end jitter and the accumulated delay variance at the destination node has been found. Simple relationships of the first order polynomial coefficient (p_1) to the background and reference traffic intensities have also been determined. The relative jitter error using the polynomial estimate of the end-to-end jitter as a function of the accumulated delay variance is about 5%.

The current study has also shown that:

- the linear polynomial relationship is degraded under heavy traffic (high cell loss above 20% and/or high average end-to-end delay).
- the polynomial relationship between the end-to-end jitter and accumulated node delay is similar (first order polynomial) in the case of self-similar and burst traffic. The type of traffic (bursty or self-similar) does not seem to have any influence of the form of the polynomial relationship.
- under normal circumstances (no network congestion) the intensity of the reference or background traffic does not have any impact on the linearity of the relationship between the end-to-end jitter and the accumulated delay variance at the destination node.
- the low priority background and reference traffic have a very small impact on the high priority reference traffic.
- the use of multiple background sources at each intermediate node has no impact on the polynomial relationship; in other words, the effect of multiple background sources on the end-to-end jitter can be obtained with one source that emits the combined traffic of all the multiple sources.
- we have found a general, although approximate linear relationship between the polynomial coefficient p_1 and the server utilization factors of the intermediate nodes.

Obtaining a simple empirical relationship of the end-to-end jitter to the sum of the intermediate node delay variance is of practical importance for network planers. Since the node delay variance can be simply determined through either analytical or numerical methods, a simple empirical formula of the end-to-end delay jitter can help in dimensioning new communication networks with a low amount of jitter, suited for voice and video transmissions. Conversely, such a formula can also be used to determine how much traffic an existing network can support before voice or video streams become adversely affected by the end-to-end jitter.

A thorough understanding of end-to-end jitter is fairly important. As further work, the most interesting step would be to use the results of the simulations in order to obtain a theoretical formula for the end-to-end jitter.

Chapter 6
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Appendix A.

The Appendix contains more details regarding the theory of self-similar traffic, the complete simulation results and polynomial coefficient graphics. It also contains a detailed description of the OPNET simulation model.

A.1 Theory of Self-Similar Traffic

A.1.2 Stationary Random Processes

Assume X is a ***random variable*** that varies over time. We can denote X (t) as the quantity at time t. Furthermore, at each point in time t, $X(t)$ is a random variable, and the complete form of $X(t)$ as t varies over time is called a ***random process***. A random process X is said to be ***stationary*** if the statistical properties of the process do not change over time (i.e. they are the same at all time points).

A random process is said to be ***wide-sense stationary*** or stationary up to order 2 if the first and second order statistical properties, namely the mean and variance, do not change over time.

Given a wide-sense stationary process X, the ***auto-covariance*** function is defined as:

$$R(\tau) = E[(X(t) - \mu)(X(t+\tau) - \mu)]$$

and the ***auto-correlation*** function:

$$\rho(\tau) = R(\tau)/R(0) = R(\tau)/\sigma^2$$

For each τ, $R(\tau)$ measures the covariance between elements of X separated by an interval τ, while $\rho(\tau)$ measures the correlation between elements of X separated by the same interval τ.

A.1.3 Self-Similar Processes

Given a wide-sense stationary random process with the ***auto-correlation*** function $\rho(\tau)$ of the form:

$$\rho(\tau) \rightarrow\propto \tau^{-\beta}L(\tau), \text{ as } \tau \rightarrow\propto$$

where L(t) is slowly varying at infinity, namely:

$$\lim_{t \to \infty} L(tx)/L(t) = 1$$

Let $X^{(m)}$ be the new process obtained by averaging the original X series in non-overlapping sub-blocks of size m:

$$X^{(m)}(t) = (X_{tm-m+1} + X_{tm-m+2} + \ldots X_{tm})/m$$

Note that $X^{(m)}$ actually defines a wide-sense stationary random process for a each m.

Definition of self-similarity

Assume $\rho^{(m)}(\tau)$ is the auto-correlation function of $X^{(m)}$.

The process X is ***exactly second-order self-similar*** with self-similarity parameter $H = 1 - \beta/2$ (Hurst parameter) if the aggregated processes $X^{(m)}$ have the same auto-correlation structure as X, that is:

$$\rho^{(m)}(\tau) = \rho(\tau), \text{ for all } m = 1, 2 \ldots$$

The process X is ***asymptotically second-order self-similar*** with self-similarity parameter $H = 1 - \beta/2$ if for all aggregated processes $X^{(m)}$:

$$\rho^{(m)}(\tau) \to 2^{1-\beta}, \text{ as } m \to \infty$$

$$\rho^{(m)}(\tau) \to \delta^2[\tau^{2-\beta}], \text{ as } m \to \infty$$

where δ^2 is the central difference operator defined as:

$$\delta^2[f(x)] = f(x+1) - 2f(x) + f(x-1)$$

and $0 < \beta < 1$.

Note that in the case of self-similarity the correlation structures of the aggregated processes do not degenerate as $m \to \infty$. This is in contrast to traditional models, which have the property that the correlation structure of their aggregated processes degenerate as $m \to \infty$.

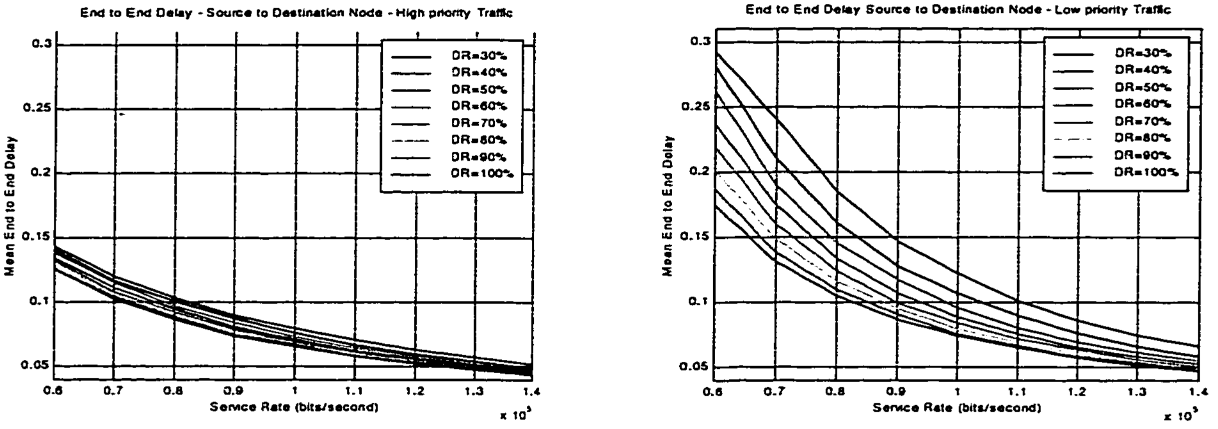
$$\rho^{(m)}(\tau) \to 0 \text{ as } m \to \infty$$

In other words, for self-similar processes the aggregated process $X^{(m)}(t)$ is indistinguishable from the original process in terms of the auto-correlation function.

A.2 Average End-to-end Delay

This subsection presents simulation results for the end-to-end delay of the reference traffic. The study of the average end-to-end delay is important in the case of two-way communication. For instance, a normal phone conversation cannot take place if the end-to-end delay is larger than a certain threshold. Also, a very large end-to-end delay indicates a congested network.

A.2.1 Average End-to-end Delay as a Function of Service Rate

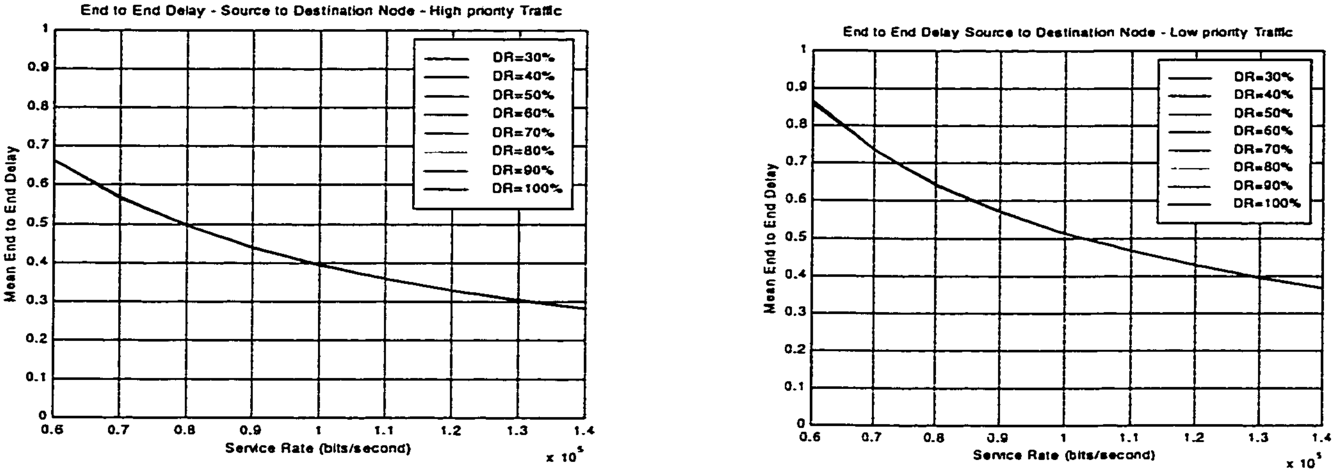


(A) (B)

Figure 50 Comparison of Average End-to-end Delay as a Function of Service Rate for Self-Similar Traffic. (A) High Priority Traffic and (B) Low Priority Traffic

The graphics in Figure 50 represent the average end-to-end delay as a function of the service rate, for two priority, self-similar traffic (for the simulation parameters given in A.4.2.2.3.2). As expected, the average delay for the high priority traffic is lower than the average delay for the low priority traffic.

The same type of relationship between the average end-to-end delay is obtained for bursty traffic.



(A) (B)

Figure 51 Comparison of Average End-to-end Delay as a Function of Service Rate for Self Similar Traffic. (A) High Priority and (B) Low Priority Traffic

A.2.2 Average End-to-end Delay as a Function of the Background Traffic

The graphics in Figure 52 shows the variation of the average end-to-end delay as a function of the background traffic, for the simulation described in section A.4.2.2.1 (single reference stream self-similar traffic). As it can be seen, the end-to-end delay increases when the normalized background traffic rate (NBT) increases.

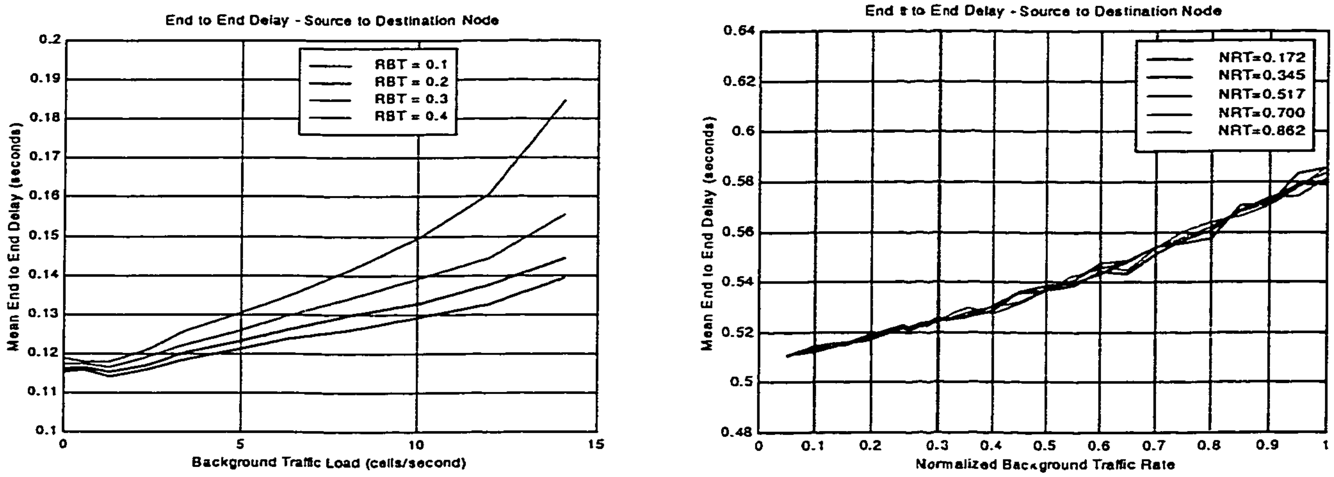


Figure 52 Average End-to-end Delay as a Function of the Background Traffic

A.3 Effect of Cell Loss on End-to-end Jitter

In small amounts, the cell loss does not seem to have any effect on the type of relationship of the end-to-end jitter to the accumulated delay variance at the destination node; that is, the relationship is kept first order polynomial. A two priority (low/high priority) reference traffic simulation for which a fairly low reference cell loss (below 5%) has been noticed demonstrated no effect on the dependency of the end-to-end jitter to the accumulated delay variance at the destination node, as shown for the simulation described below. When the cell loss probability increases, though, the linear relationship of the end-to-end jitter vs. the accumulated delay variance is distorted.

Constant parameters

Background traffic: 14 cells/second (approximately).

Reference traffic: 14 cells/second (approximately).

Variable parameters

Simulation duration: variable, such as to generate the same number of reference traffic cells for all simulations.

Probability of discarding the background traffic - discard rate (at all intermediary nodes): The discard rate is decreased from 100% to 10%(all background traffic dropped ***after*** being serviced), with a step of 10%. Note that the effective intensity of the background traffic varies (increases) due to the varying discard rate.

Service rate (all intermediary nodes): from 50 kbits/second to 150 kbits/second, with a step of 10 kbits/second.

Simulation Series

For each series of simulations, the reference traffic intensity is kept constant, while the effective background traffic intensity is varied within the range described above (one simulation for each value of the background traffic intensity, for a total of 10 simulations per series).

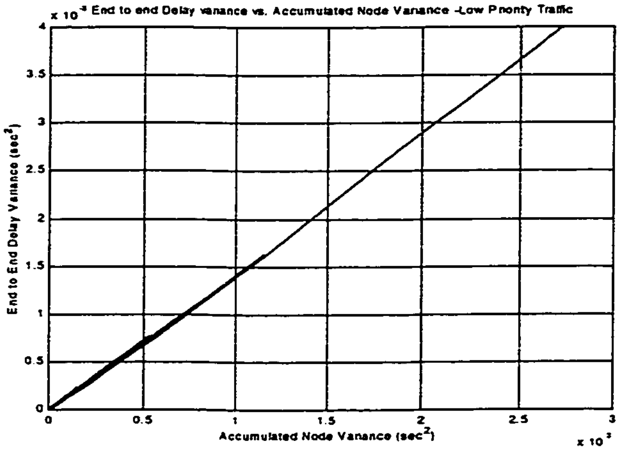


Figure 53 End-to-end Jitter vs. Accumulated Delay Variance for variable Background Traffic Intensity with Bursty Traffic and Single Background Sources. Study of Cell Loss

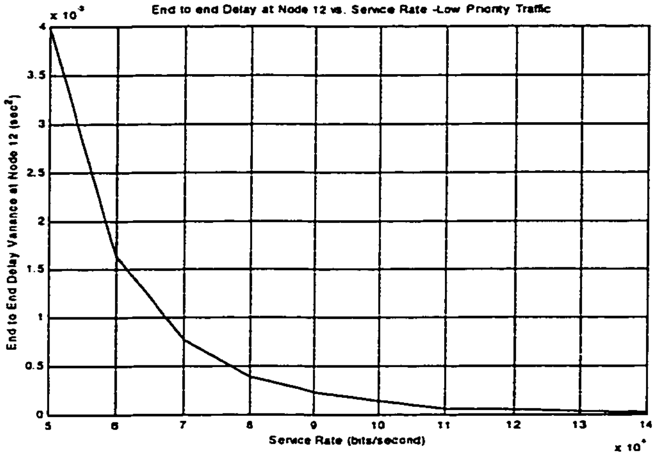


Figure 54 End-to-end Jitter at Destination Node vs. Background Traffic for Bursty Traffic and Single Background Sources

As can be seen from Figure 53, the relation of the accumulated end-to-end jitter to the accumulated (destination) node delay variance is linear. However, the cell loss probability is very high for the lower service rates of the simulation and high priority normalized background traffic rates. Note, however, the cases where the polynomial coefficient is no longer quasi-constant. They correspond to increases in the cell loss probability.

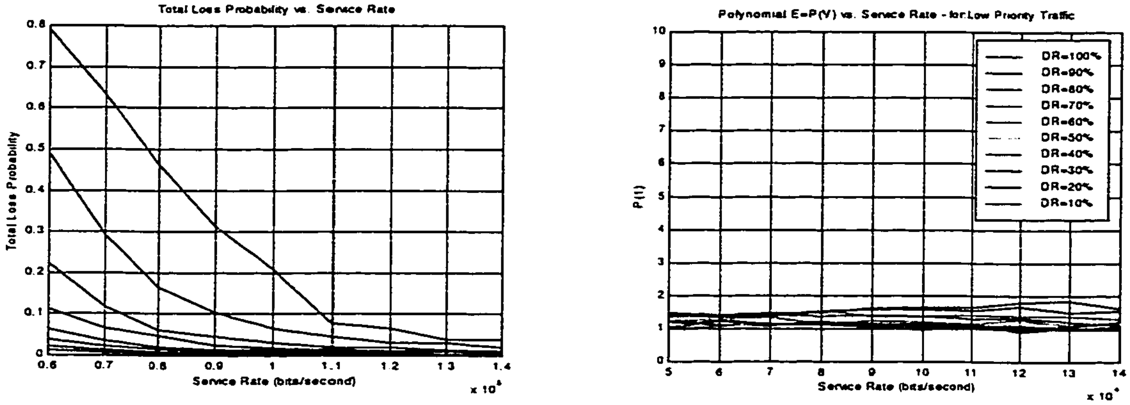


Figure 55 **Effect of Cell Loss Probability on the End-to-end Jitter Polynomial Coefficient**

A.4 Complete Simulation Results

This section presents the complete simulation results, for both the bursty and self-similar types of traffic. The results are grouped by the following criteria:

- type of traffic
- whether a single or multiple background sources are connected to the intermediate nodes
- parameters that affect the end-to-end jitter (intermediate node service rate, background traffic service rate, traffic priority).

The results are grouped by series of simulations; in each series, two simulation parameters are varied (e.g. intermediate node service rate and background traffic rate) and one is kept constant (e.g. reference traffic rate). This allows us to plot families of curves for the parameter of which effect on jitter we study. For instance, if we study the effect of the background traffic on the end-to-end jitter, we vary the background traffic rate and the service rate at the intermediate nodes. The different service rates allow us to obtain a family of curves of the end-to-end jitter vs. the background traffic rate for different values of the service rate. To clarify the ideas, say we want to study the effect of the service rate on the end-to-end jitter. We may conduct five series of ten simulations each. A different value of the background traffic rate will be used for each of the five series, while the service rate will vary for the ten simulations of the same series. The range for the service rate variation will be the same for each of the series (say, from 10 cells/second to 110 cells/second , with a step of 10 cells/second). That allows us to obtain a family of curves, of the form $f(p,x)$, where p is the curve family parameter (the background traffic rate, in our case) and x is the variable of which effect on the end-to-end jitter we want to study (the service rate, in our case).

Two graphics are shown for each series of simulations: the *end-to-end jitter vs. accumulated delay variance* and the *end-to-end jitter and node 12* (destination node) *vs. a variable simulation parameter* (the parameter of which effect on the jitter is being studied, e.g. background traffic rate). All curves in a family of curves are shown on all *end-to-end jitter vs. accumulated delay variance* figures.

A.4.1 Bursty Traffic

As mentioned in the **Glossary** section, by ***Normalized bursty traffic*** we understand ratio of the average busy time to the average cycle time of a bursty traffic source (that is, the average percentage of the time when a bursty traffic source is emitting cells).

A.4.1.1 Single Background Traffic Sources

A.4.1.1.1 Effect of Background Traffic on the End-to-end Jitter

Constant parameters

Service rate (all intermediary nodes): 24 cells/second.

Probability of discarding the background traffic (all intermediary nodes): 50%.

Variable parameters

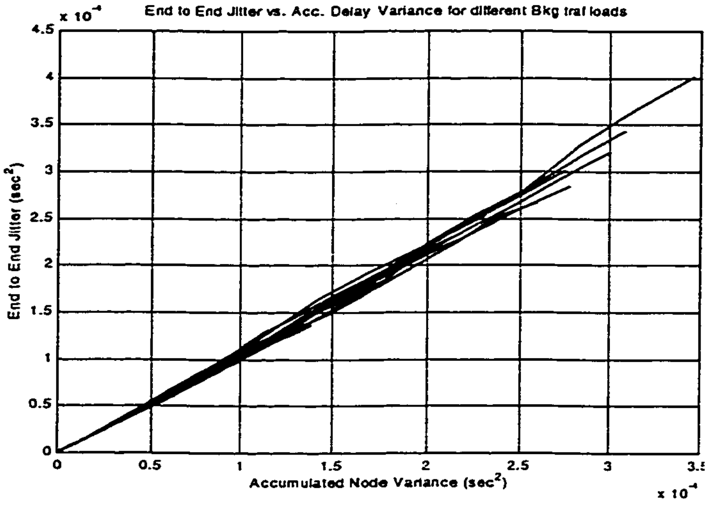
Simulation duration: variable, such as to generate the same number of reference traffic cells for all simulations.

Background traffic. The normalized intensity varies from 0.05 to 1 (using a step of 0.05). The average burst cycle is kept constant (at 201 simulated seconds), while the average burst time varies from 5 seconds to 200 seconds (step 5 seconds).

Reference traffic. The normalized intensity varies from 0.17 to 0.86 (step 0.17). The average burst cycle is kept constant (29 simulated seconds) while the average burst time varies (from 5 to 25 seconds, step 5).

Simulation Series.

Five series of 20 simulations each have been conducted. The reference traffic is constant for all simulations from a given series. The background traffic intensity is varied for each of the simulations within a series (as described above). The reference traffic is increased from one series of simulations to the other.



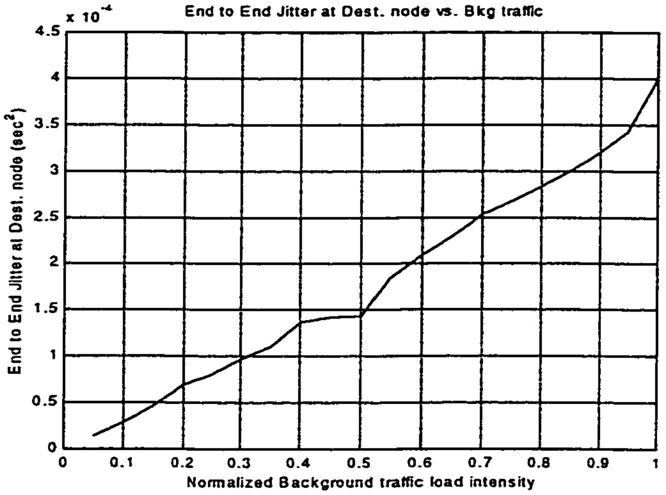


Figure 56 End-to-end Jitter vs. Accumulated Delay Variance for variable Background Traffic Intensity with Bursty Traffic and Single Background Sources

Figure 57 End-to-end Jitter at Destination Node vs. Background Traffic for Bursty Traffic and Single Background Sources

A.4.1.1.2 Effect of Service Rate on the End-to-end Jitter

Constant parameters

Background traffic. The normalized intensity is 0.05. The average burst cycle is kept constant (at 201 seconds), while the average burst time is set to 5 seconds.

Reference traffic. The normalized intensity varies from 0.17 to 0.86 (step 0.17). The average burst cycle is kept constant (29 simulated seconds) while the average burst time varies (from 5 to 25 seconds, step 5).

Variable parameters

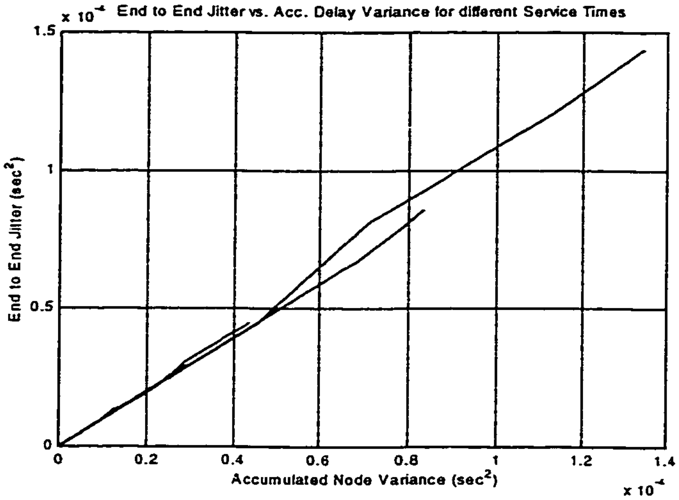
Simulation duration: variable, such as to generate the same number of reference traffic cells for all simulations.

Service rate (all intermediary nodes): from 12 cells/second to 36 cells/second, with a step of 2.4 cells/second.

Probability of discarding the background traffic-discard rate (all intermediary nodes): from 10% to 100%, step 10%. As the rate increases, the effective background traffic load decreases.

Simulation Series

For the simulations in a series of simulations, the service rate is varied from 12 cells/second to 36 cells/second, with a step of 2.4 cells/second, while the background traffic is kept constant. The background traffic rate is decreased from a series of simulations to the other. Ten series of simulations are executed, one for each of the background traffic discarding probabilities.



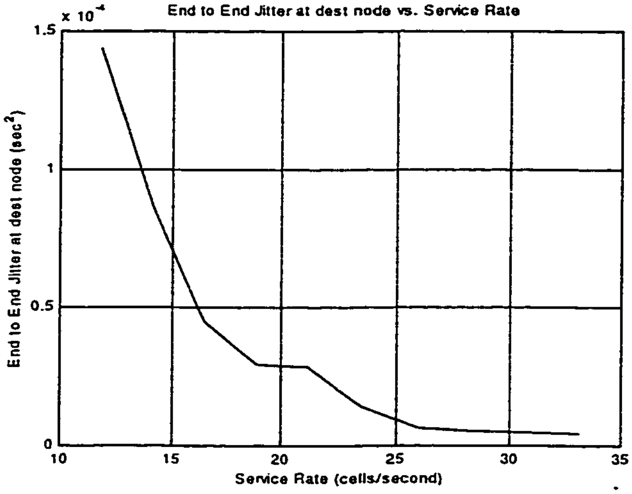


Figure 58 End-to-end Jitter vs. Accumulated Delay Variance when varying the Service Rate, for Bursty Traffic and Single Background Sources

Figure 59 End-to-end Jitter at Destination Node vs. Service Rate, for Bursty Traffic and Single Background Sources

A.4.1.1.3 Effect of Two Priorities Traffic

A.4.1.1.3.1 Effect of Background Traffic on the End-to-end Jitter

Constant parameters

Service rate (all intermediary nodes): 24 cells/second.
Probability of discarding the background traffic (all intermediary nodes): 50%.
Low Priority Reference traffic: Normalized intensity at 0.45.

Variable parameters

Simulation duration: variable, such as to generate the same number of high priority reference traffic cells for all simulations.

High/Low Priority Background traffic. The normalized intensity varies from 0.05 to 1 (using a step of 0.05). The average burst cycle is kept constant (at 201 simulated seconds), while the average burst time varies from 5 seconds to 200 seconds (step 5 seconds). Variable within each series of simulations.

High/Low Priority Reference traffic. The normalized intensity varies from 0.17 to 0.86 (step 0.17). The average burst cycle is kept constant (29 simulated seconds) while the average burst time varies (from 5 to 25 seconds, step 5). Different values for different series of simulations, but constant within each series.

Simulation Series

The reference traffic intensity is kept constant for each series of simulations, while the background traffic intensity (both low and high priority) is varied as described above. Five series of such simulations are conducted (one series for each value of the reference traffic defined above).

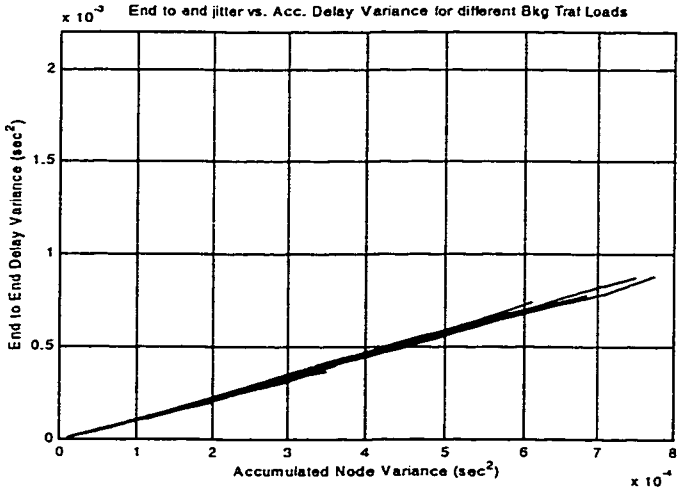


Figure 60 End-to-end Jitter vs. Accumulated Delay Variance with variable Background Traffic Intensity, for Bursty High Priority Traffic and Single Background Sources

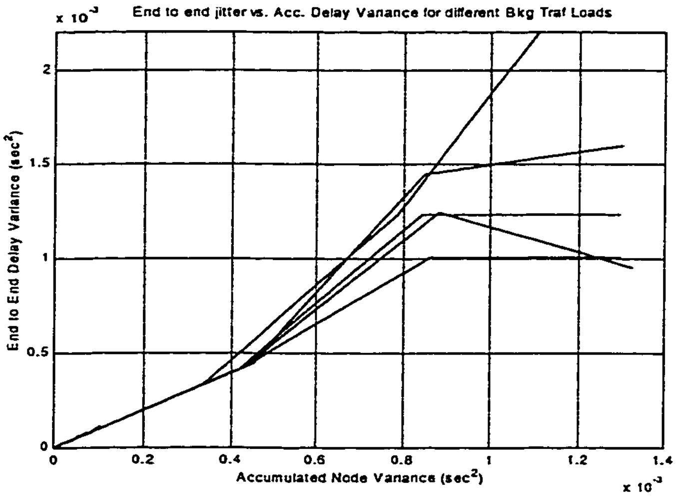


Figure 61 End-to-end Jitter vs. Accumulated Delay Variance with variable Background Traffic Intensity, for Bursty Low Priority Traffic and Single Background Sources

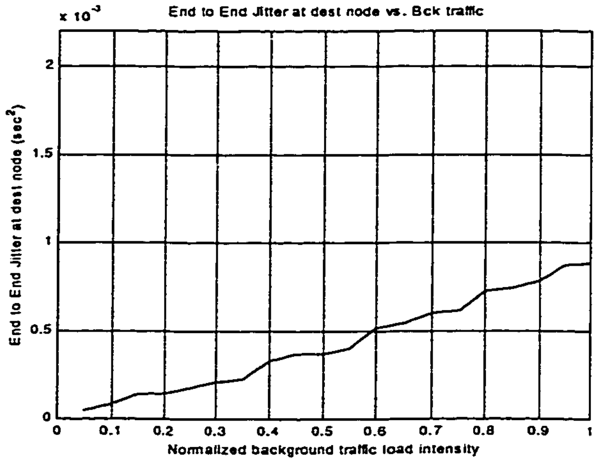


Figure 62 End-to-end Jitter at Destination Node vs. Background Traffic, for Bursty High Priority Traffic and Single Background Sources

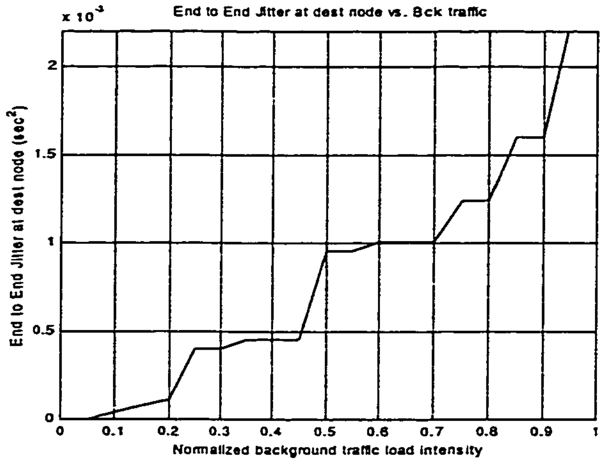


Figure 63 End-to-end Jitter at Destination Node vs. Background Traffic, for Bursty Low Priority Traffic and Single Background Sources

A.4.1.1.3.2 Effect of Service Rate on the End-to-end Jitter

Constant parameters

Background traffic. The normalized intensity is 0.05. The average burst cycle is kept constant (at 201 seconds), while the average burst time is set to 5 seconds.

Reference traffic. The normalized intensity varies from 0.17 to 0.86 (step 0.17). The average burst cycle is kept constant (29 simulated seconds) while the average burst time varies (from 5 to 25 seconds, step 5).

Variable parameters

Simulation duration: variable, such as to generate the same number of reference traffic cells for all simulations.

Service rate (all intermediary nodes): from 12 cells/second to 36 cells/second, with a step of 2.4 cells/second.

Probability of discarding the background traffic (all intermediary nodes): from 10% to 100%, step 10%.

Simulation Series

For each series of simulations, the service rate is varied in the range described above, while the probability of discarding the background traffic is kept constant.

Ten series of simulations are executed, one for each of the background traffic discarding probabilities.

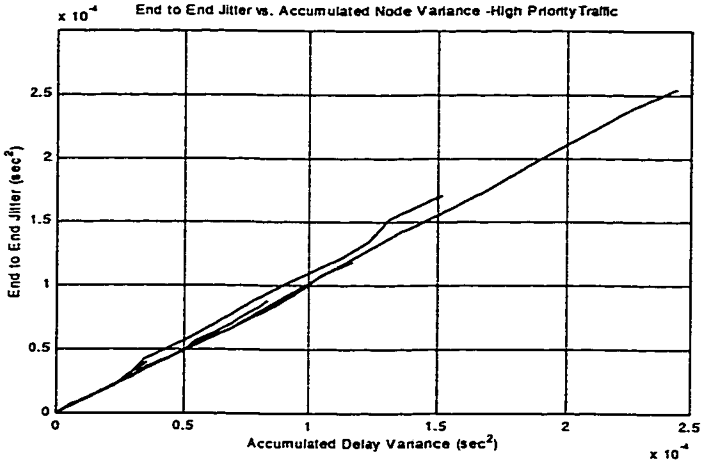


Figure 64 End-to-end Jitter vs. Accumulated Delay Variance with varying Service Rate for Bursty High Priority Traffic and Single Background Sources

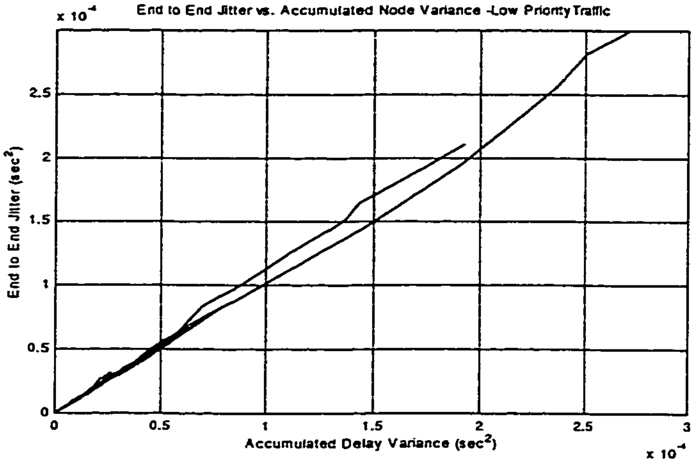


Figure 65 End-to-end Jitter vs. Accumulated Delay Variance when varying the Service Rate, for Bursty Low Priority Traffic and Single Background Sources

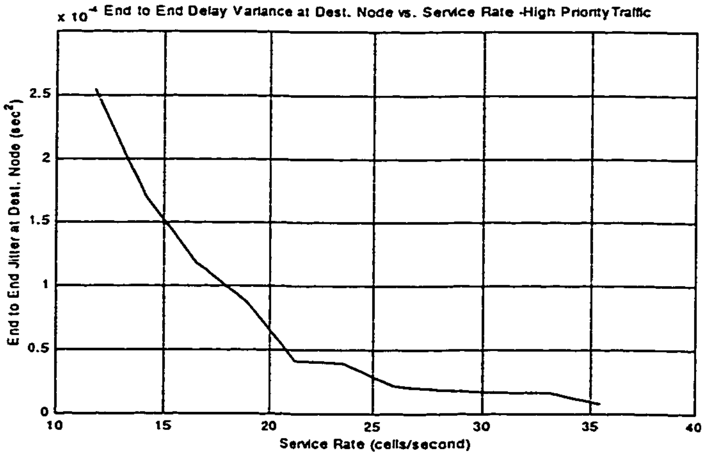


Figure 66 End-to-end Jitter at Destination Node vs. Service Rate for Bursty High Priority Traffic and Single Background Sources

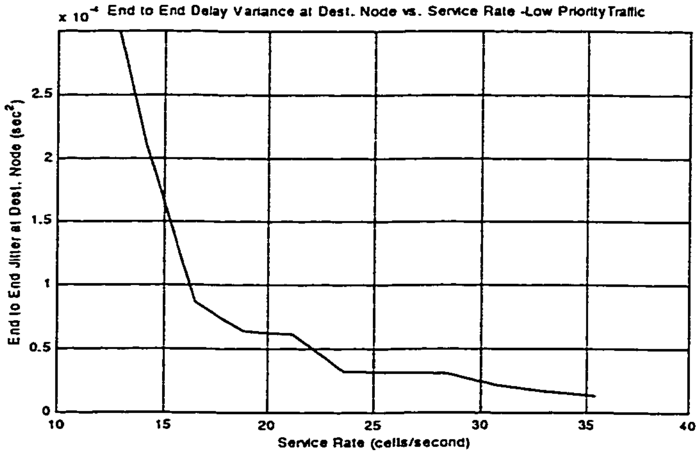


Figure 67 End-to-end Jitter at Destination Node vs. Service Rate for Bursty Low Priority Traffic and Single Background Sources

A.4.1.2 Multiple Background Traffic Sources

A.4.1.2.1 Effect of Background Traffic on the End-to-end Jitter

Constant parameters

Service rate (all intermediary nodes): 24 cells/second.

Probability of discarding the background traffic (all intermediary nodes): 50%.

Variable parameters

Simulation duration: variable, such as to generate the same number of reference traffic cells for all simulations.

Background traffic. The normalized intensity varies from 0.05 to 1 (using a step of 0.05). The average burst cycle is kept constant (at 201 simulated seconds), while the average burst time varies from 5 seconds to 200 seconds (step 5 seconds). Varied from simulation to simulation, within the same series.

Reference traffic. The normalized intensity varies from 0.17 to 0.86 (step 0.17). The average burst cycle is kept constant (29 simulated seconds) while the average burst time varies (from 5 to 25 seconds, step 5). Varied for different series of simulations; kept constant for simulations within the same series.

Simulation Series

The reference traffic intensity is kept constant for simulations within a series. The background traffic intensity is varied within the range described above. Five simulations series are conducted; the reference traffic is varied from one series to the other.

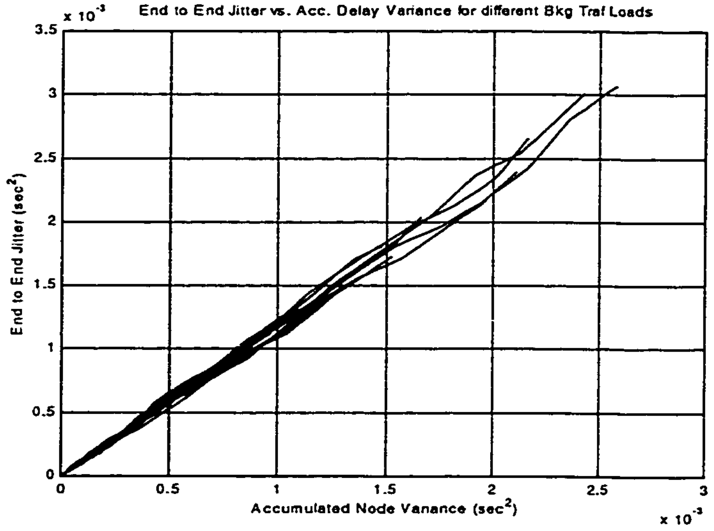


Figure 68 End-to-end Jitter vs. Accumulated Delay Variance for variable Background Traffic Intensity, for Bursty Traffic and Multiple Background Sources

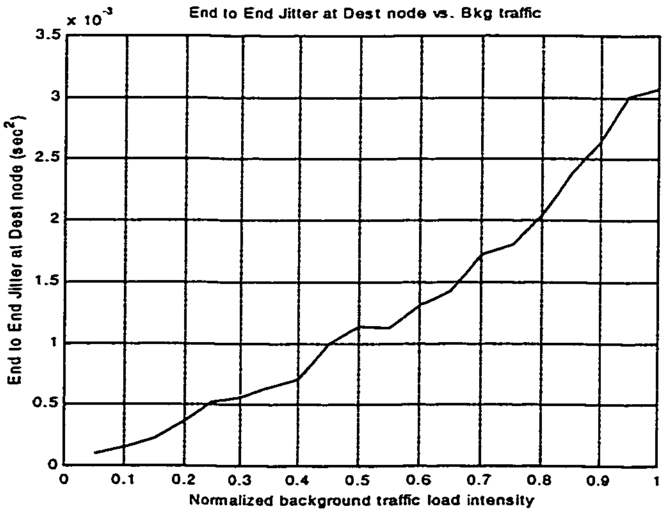


Figure 69 End-to-end Jitter at Destination Node vs. Background Traffic, for Bursty Traffic and Multiple Background Sources

A.4.1.2.2 Effect of Service Rate on the End-to-end Jitter

Constant parameters

Background traffic. The normalized intensity is 0.05. The average burst cycle is kept constant (at 201 seconds), while the average burst time is set to 5 seconds.

Reference traffic. The normalized intensity varies from 0.17 to 0.86 (step 0.17). The average burst cycle is kept constant (29 simulated seconds) while the average burst time varies (from 5 to 25 seconds, step 5).

Variable parameters

Simulation duration: variable, such as to generate the same number of reference traffic cells for all simulations.

Service rate (all intermediary nodes): from 12 cells/second to 36 cells/second, with a step of 2.4 cells/second.

Probability of discarding the background traffic-discard rate (all intermediary nodes): from 10% to 100%, step 10%. As the rate increases, the effective background traffic load decreases. Kept constant within the same series of simulations; varies from one series of simulations to the other.

Simulation Series

Ten series of simulations are executed, one for each of the background traffic discarding probabilities.

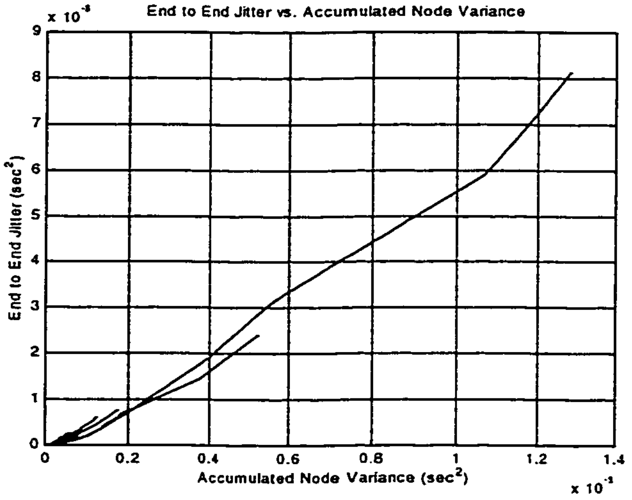


Figure 70 End-to-end Jitter vs. Accumulated Delay Variance when varying the Service Rate, for Bursty Traffic and Multiple Background Sources

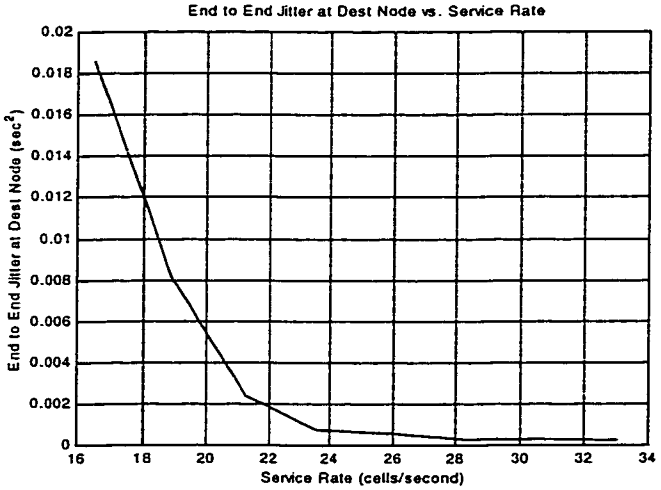


Figure 71 End-to-end Jitter at Destination Node vs. Service Rate, for Bursty Traffic and Multiple Background Sources

A.4.1.2.3 Effect of Two Priorities Traffic

A.4.1.2.3.1 Effect of Background Traffic on the End-to-end Jitter

Constant parameters

Service rate (all intermediary nodes): 24 cells/second.

Probability of discarding the background traffic (all intermediary nodes): 50%.

Variable parameters

Simulation duration: variable, such as to generate the same number of reference traffic cells for all simulations.

Background traffic (both low and high priority). The normalized intensity varies from 0.05 to 1 (using a step of 0.05). The average burst cycle is kept constant (at 201 simulated seconds), while the average burst time varies from 5 seconds to 200 seconds (step 5 seconds).

Reference traffic. The normalized intensity varies from 0.17 to 0.86 (step 0.17). The average burst cycle is kept constant (29 simulated seconds) while the average burst time varies (from 5 to 25 seconds, step 5).

Simulation Series

For each series of simulations, the reference traffic intensity is kept constant, while the background traffic intensity is varied within the range described above (one simulation for each value of the background traffic intensity, for a total of 20 simulations per series).

Five such series of such simulations are conducted (one series for each value of the reference traffic defined above).

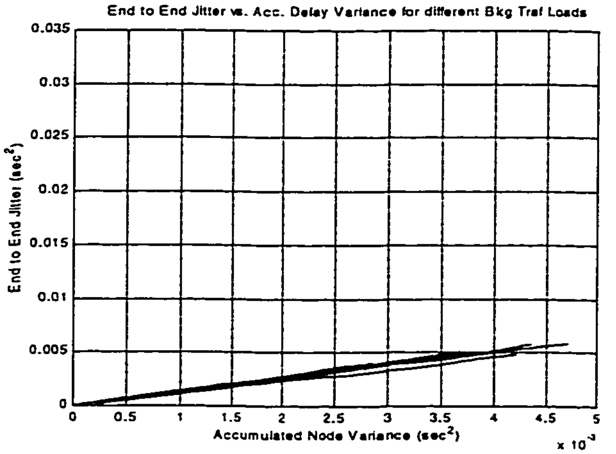


Figure 72 End-to-end Jitter vs. Accumulated Delay Variance when varying the Background Traffic Intensity, for High Priority Bursty Traffic and Multiple Background Sources

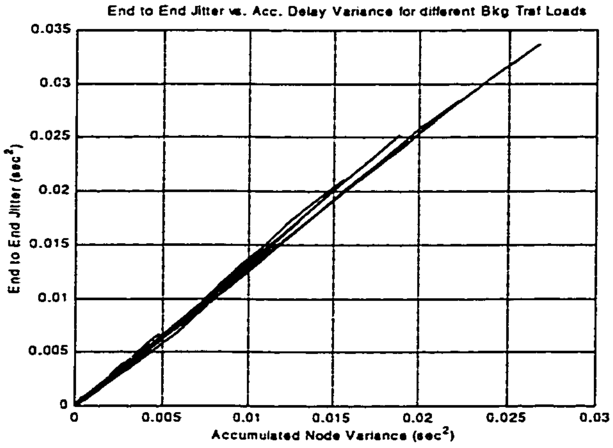


Figure 73 End-to-end Jitter vs. Accumulated Delay Variance when varying the Background Traffic Intensity, for Low Priority Bursty Traffic and Multiple Background Sources

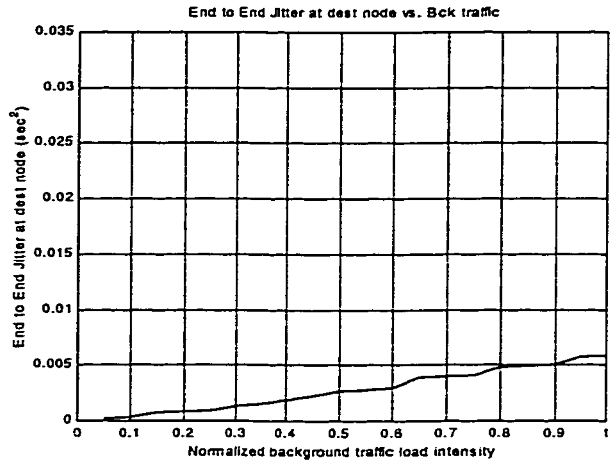


Figure 74 End-to-end Jitter at Destination Node vs. Background Traffic, for High Priority Bursty Traffic and Multiple Background Sources

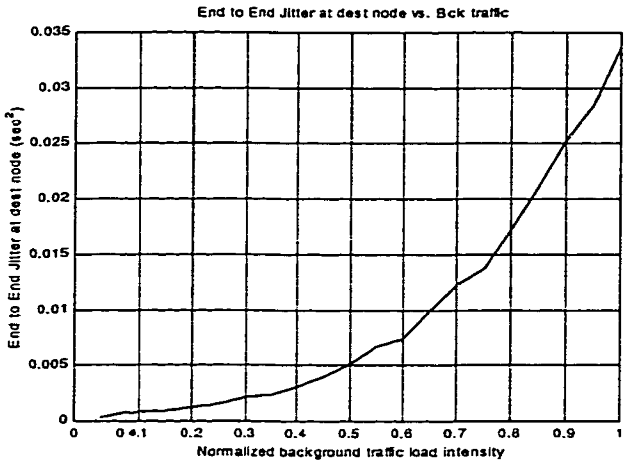


Figure 75 End-to-end Jitter at Destination Node vs. Background Traffic, for Low Priority Bursty Traffic and Multiple Background Sources

A.4.1.2.3.2 Effect of Service Rate on the End-to-end Jitter

Constant parameters

Background traffic. The normalized intensity is 0.05. The average burst cycle is kept constant (at 201 seconds), while the average burst time is set to 5 seconds.

Reference traffic. The normalized intensity varies from 0.17 to 0.86 (step 0.17). The average burst cycle is kept constant (29 simulated seconds) while the average burst time varies (from 5 to 25 seconds, step 5).

Variable parameters

Simulation duration: variable, such as to generate the same number of reference traffic cells for all simulations.

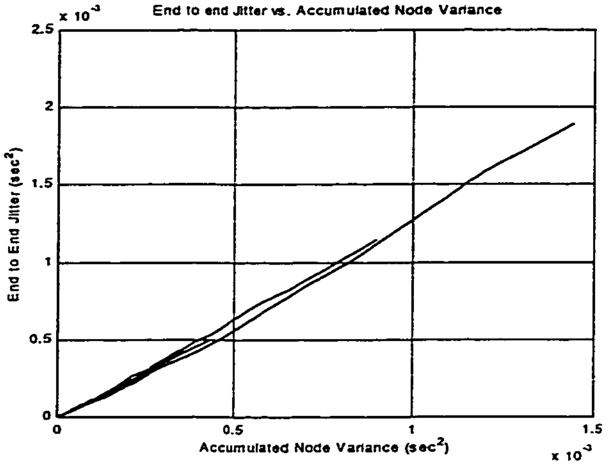
Service rate (all intermediary nodes): from 12 cells/second to 36 cells/second, with a step of 2.4 cells/second.

Probability of discarding the background traffic-discard rate (all intermediary nodes): from 10% to 100%, step 10%. As the rate increases, the effective background traffic load decreases.

Simulation Series

For each series of simulations, the service rate is varied in the range described above, while the probability of discarding the background traffic is kept constant.

Ten series of simulations are executed, one for each of the background traffic discarding probabilities.



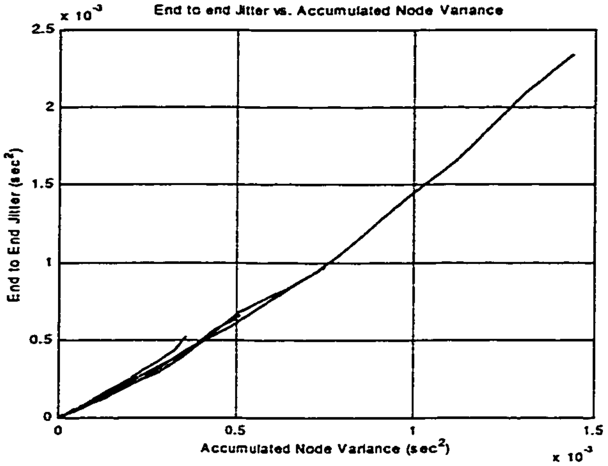
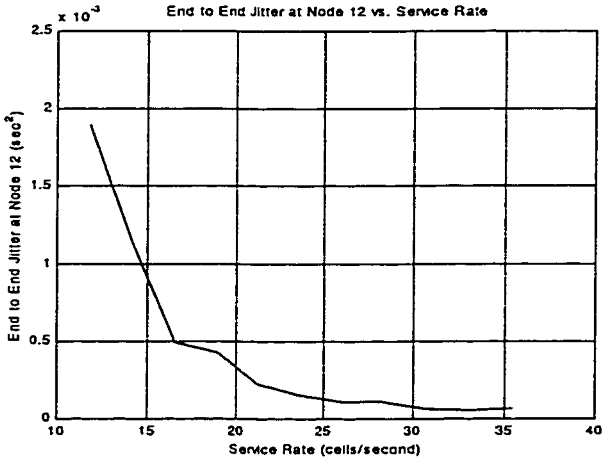


Figure 76 End-to-end Jitter vs. Accumulated Delay Variance when varying the Service Rate, for High Priority Bursty Traffic and Multiple Background Sources

Figure 77 End-to-end Jitter vs. Accumulated Delay Variance when the Service Rate, for Low Priority Bursty Traffic and Multiple Background Sources



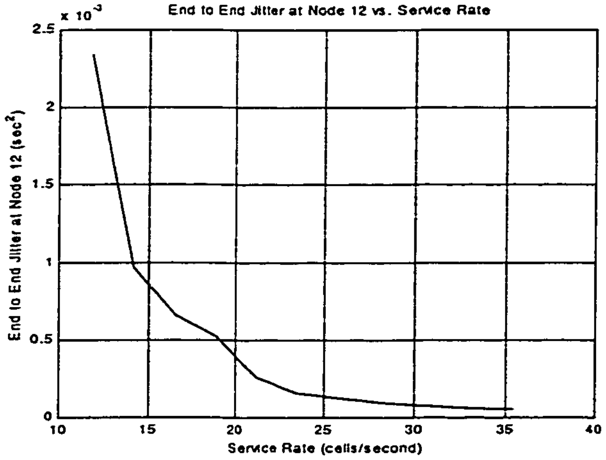


Figure 78 End-to-end Jitter at Destination Node vs. Service Rate, for High Priority Bursty Traffic and Multiple Background Sources

Figure 79 End-to-end Jitter at Destination Node vs. Rate for Low Priority Bursty Traffic and Multiple Background Sources

A.4.2 Self Similar Traffic

A.4.2.1 Single Background Traffic Sources

A.4.2.1.1 Effect of Background Traffic

Constant parameters

Service rate (all intermediary nodes): 120 cells/second.

Variable parameters

Simulation duration: variable, such as to generate the same number of reference traffic cells for all simulations.
Probability of discarding the background traffic - discard rate (at all intermediary nodes): The discard rate is decreased from 100% (all background traffic dropped ***after*** being serviced) to 10%, with a step 10%.
Background traffic. The effective intensity of the background traffic varies due to the varying discard rate.
Reference traffic. From 5 cells/second to 14 cells/second, step 1 (approximately).

Simulation Series

For each series of simulations, the reference traffic intensity is kept constant, while the background traffic intensity is varied within the range described above (one simulation for each value of the background traffic intensity, for a total of 10 simulations per series). Ten such series of such simulations are conducted (one series for each value of the reference traffic defined above).

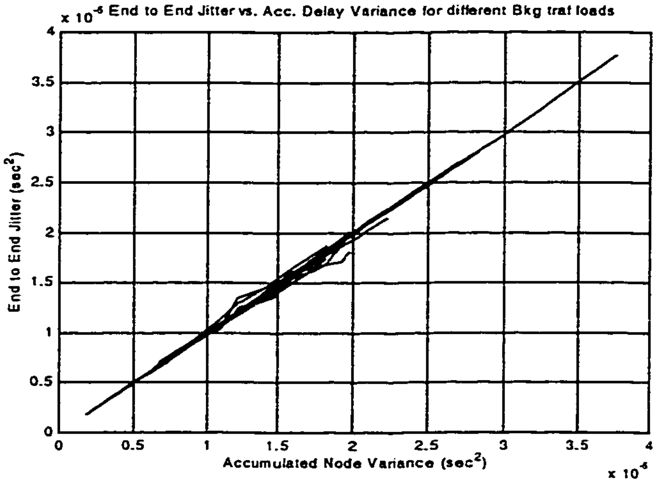


Figure 80 End-to-end Jitter vs. Accumulated Delay Variance when varying the Background Traffic Intensity, for Self-Similar Traffic and Single Background Sources

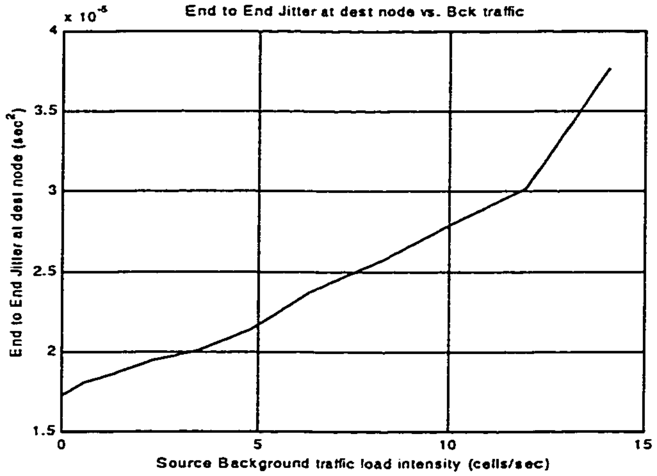


Figure 81 End-to-end Jitter at Destination Node vs. Background Traffic, for Self-Similar Traffic and Single Background Sources

A.4.2.1.2 Effect of Service Rate

Constant parameters

Background traffic: 14 cells/second (approximately).

Reference traffic: 14 cells/second (approximately).

Variable parameters

Simulation duration: variable, such as to generate the same number of reference traffic cells for all simulations.

Probability of discarding the background traffic - discard rate (at all intermediary nodes): The discard rate is increased from 10% to 100%(all background traffic dropped ***after*** being serviced), with a step of 10%. Note that the effective intensity of the background traffic varies due to the varying discard rate.

Service rate (all intermediary nodes): from 120 cells/second to 360 cells/second, with a step of 24 cells/second.

Simulation Series

For each series of simulations, the reference traffic intensity is kept constant, while the effective background traffic intensity is varied within the range described above (one simulation for each value of the background traffic intensity, for a total of 10 simulations per series). Ten series of such simulations are conducted (one series for each value of the reference traffic defined above).

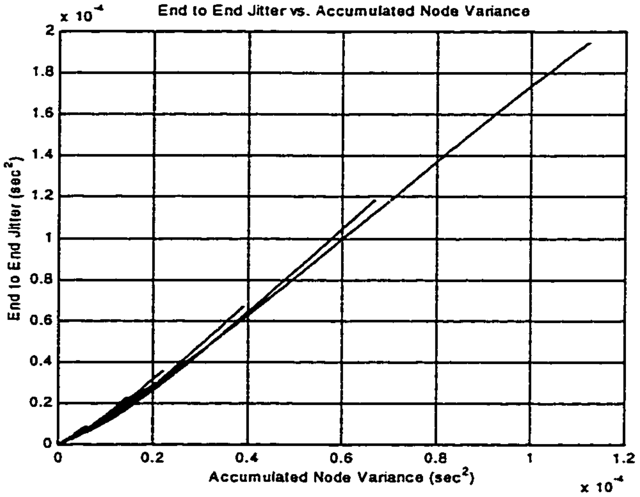


Figure 82 **End-to-end Jitter vs. Accumulated Delay Variance when varying the Service Rate, for Self-Similar Traffic and Single Background Source**

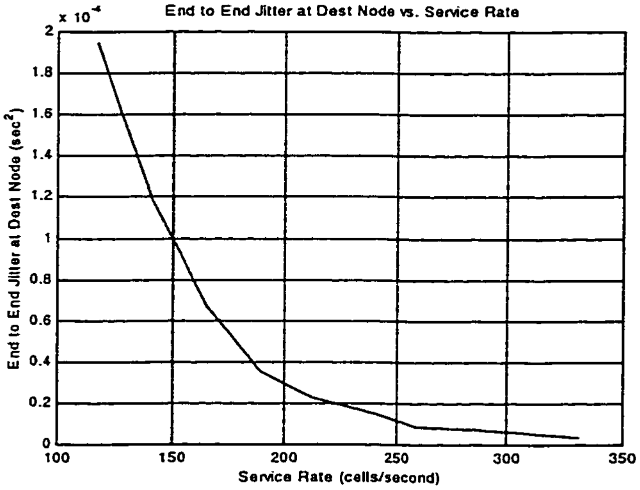


Figure 83 **End-to-end Jitter at Destination Node vs. Service Rate, for Self-Similar Traffic and Single Background Source**

A.4.2.1.3 Effect of Two Priorities Traffic

A.4.2.1.3.1 Effect of Background Traffic

Constant parameters

Service rate (all intermediary nodes): 120 cells/second.

Variable parameters

Simulation duration: variable, such as to generate the same number of reference traffic cells for all simulations.

Probability of discarding the background traffic - discard rate (at all intermediary nodes): The discard rate is decreased from 100% (all background traffic dropped *after* being serviced) to 10%, with a step 10%.

Background traffic. The effective intensity of the background traffic varies due to the varying discard rate.

Reference traffic. From 5 cells/second to 14 cells/second, step 1 (approximately).

Simulation Series

For each series of simulations, the reference traffic intensity is kept constant, while the background traffic intensity is varied within the range described above (one simulation for each value of the background traffic intensity, for a total of 10 simulations per series). Ten such series of such simulations are conducted (one series for each value of the reference traffic defined above).

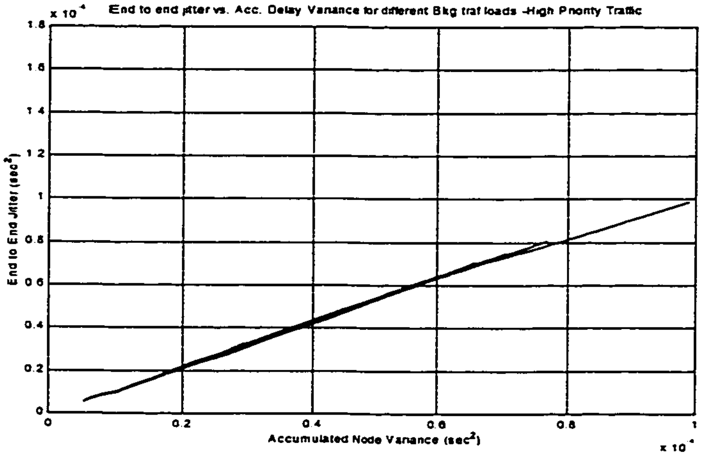


Figure 84 **End-to-end Jitter vs. Accumulated Delay Variance when varying the Background Traffic Intensity, for High Priority Self-Similar Traffic and Single Background Sources**

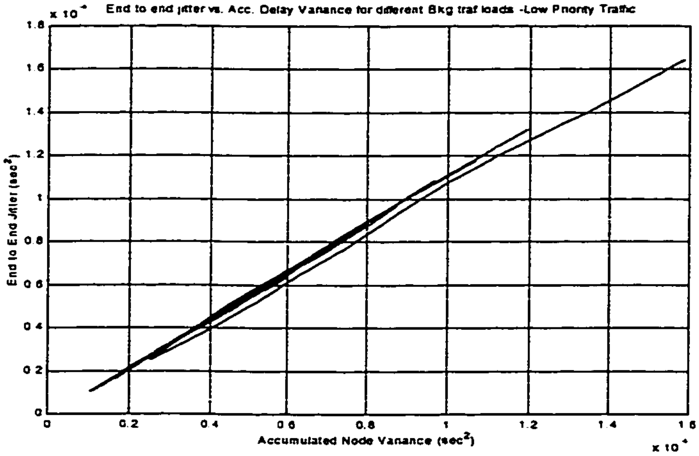


Figure 85 **End-to-end Jitter vs. Accumulated Delay Variance when varying the Background Traffic Intensity, for Low Priority Self-Similar Traffic and Single Background Sources**

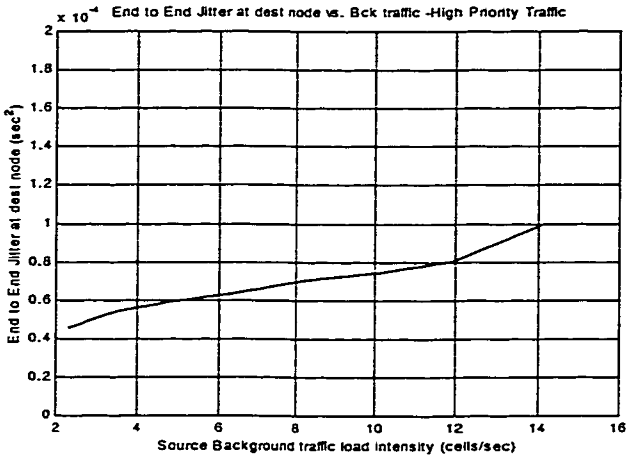


Figure 86 End-to-end Jitter at Destination Node vs. Background Traffic, for High Priority Self-Similar Traffic and Single Background Sources

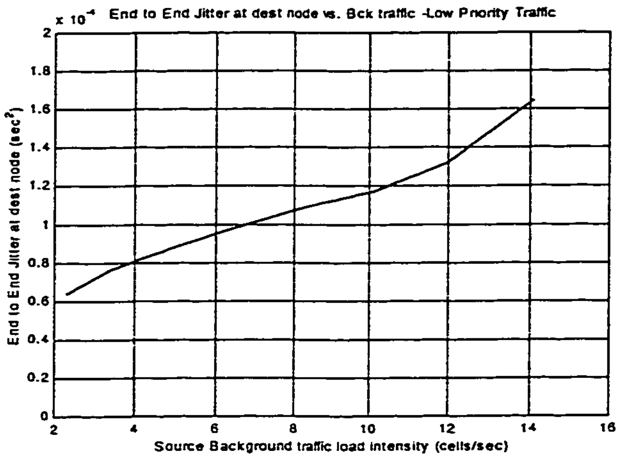


Figure 87 End-to-end Jitter at Destination Node vs. Background Traffic, for Low Priority Self-Similar Traffic and Single Background Sources

A.4.2.1.3.2 Effect of Service Rate

Constant parameters

Background traffic: 14 cells/second (approximately).

Reference traffic: 14 cells/second (approximately).

Variable parameters

Simulation duration: variable, such as to generate the same number of reference traffic cells for all simulations.

Probability of discarding the background traffic - discard rate (at all intermediary nodes): The discard rate is decreased from 100% to 10%(all background traffic dropped ***after*** being serviced), with a step of 10%. Note that the effective intensity of the background traffic varies (increases) due to the varying discard rate.

Service rate (all intermediary nodes): from 84.8 kbits/second (200 cells/second) to 169.6 kbits/second (400 cells/second), with a step of 8.480 kbits/second (20cells/second).

Simulation Series

For each series of simulations, the reference traffic intensity is kept constant, while the effective background traffic intensity is varied within the range described above (one simulation for each value of the background traffic intensity, for a total of 10 simulations per series). Ten such series of such simulations are conducted (one series for each value of the reference traffic defined above).

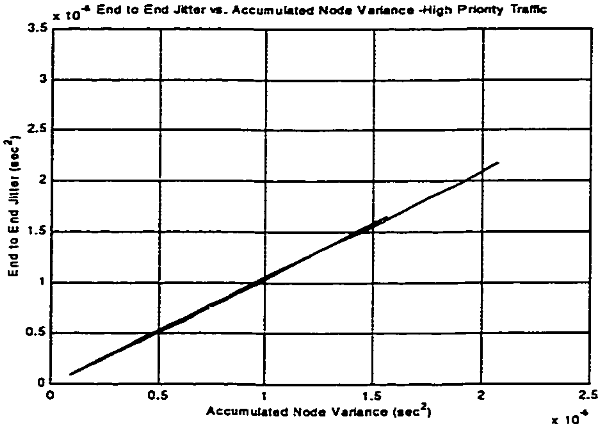


Figure 88 End-to-end Jitter vs. Accumulated Delay Variance when varying the Service Rate, for High Priority Self-Similar Traffic and Single Background Sources

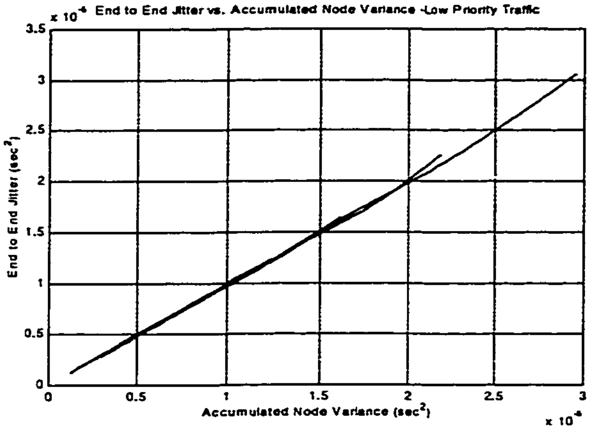


Figure 89 End-to-end Jitter vs. Accumulated Delay Variance when varying the Service Rate, for Low Priority Self-Similar Traffic and Single Background Sources

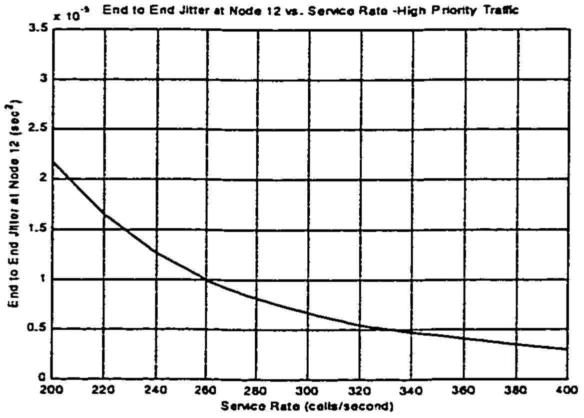


Figure 90 End-to-end Jitter at Destination Node vs. Service Rate, for High Priority Self-Similar Traffic and Single Background Sources

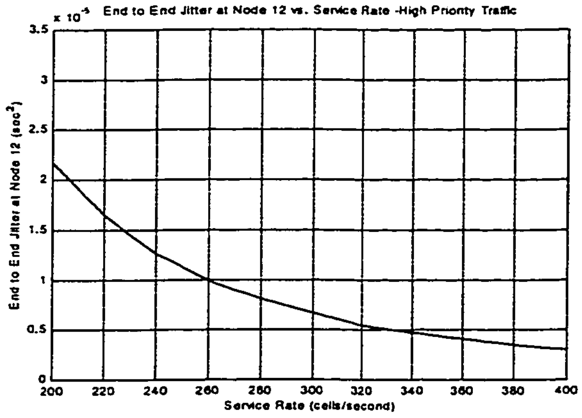


Figure 91 End-to-end Jitter at Destination Node vs. Service Rate, for Low Priority Self-Similar Traffic and Single Background Sources

A.4.2.2 Multiple Background Traffic Sources

A.4.2.2.1 Effect of Background Traffic on the End-to-end Jitter

Constant parameters

Service rate (all intermediary nodes): 120 cells/second.

Variable parameters

Simulation duration: variable, such as to generate the same number of reference traffic cells for all simulations.
Probability of discarding the background traffic - discard rate (at all intermediary nodes): The discard rate is decreased from 100% (all background traffic dropped ***after*** being serviced) to 10%, with a step 10%.
Background traffic. The effective intensity of the background traffic varies due to the varying discard rate.
Reference traffic. From 5 cells/second to 14 cells/second, step 1 (approximately).

Simulation Series

For each series of simulations, the reference traffic intensity is kept constant, while the background traffic intensity is varied within the range described above (one simulation for each value of the background traffic intensity, for a total of 10 simulations per series). Ten such series of such simulations are conducted (one series for each value of the reference traffic defined above).

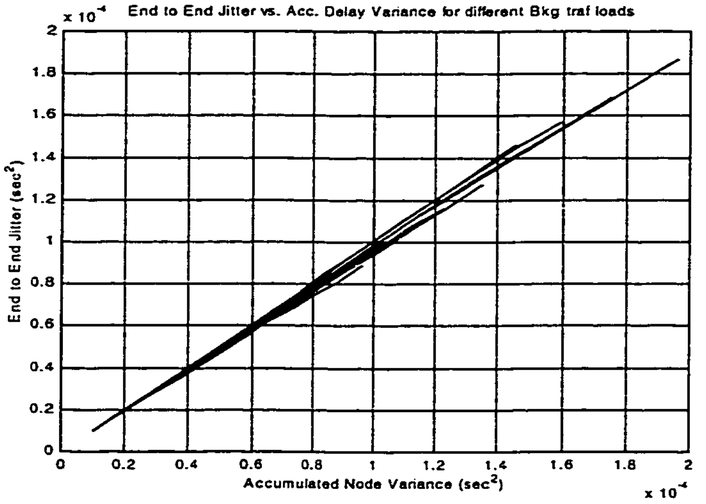


Figure 92 End-to-end Jitter vs. Accumulated Delay Variance when varying the Background Traffic Intensity, for Self-Similar Traffic and Multiple Background Sources

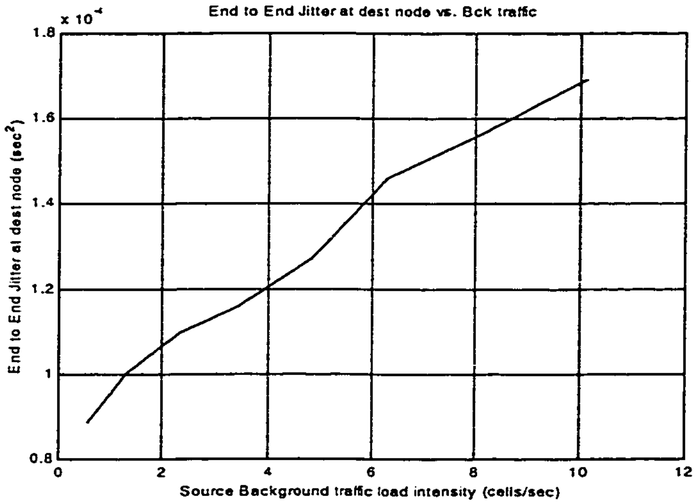


Figure 93 End-to-end Jitter at Destination Node vs. Background Traffic, for Self-Similar Traffic and Multiple Background Sources

A.4.2.2.2 Effect of Service Rate on the End-to-end Jitter

Constant parameters

Background traffic: 14 cells/second (approximately).

Reference traffic: 14 cells/second (approximately).

Variable parameters

Simulation duration: variable, such as to generate the same number of reference traffic cells for all simulations.

Probability of discarding the background traffic - discard rate (at all intermediary nodes): The discard rate is increased from 10% to 50%(all background traffic dropped ***after*** being serviced), with a step of 10%. Note that the effective intensity of the background traffic varies due to the varying discard rate.

Service rate (all intermediary nodes): from 120 cells/second to 336 cells/second, with a step of 24 cells/second.

Simulation Series

For each series of simulations, the reference traffic intensity is kept constant, while the effective background traffic intensity is varied within the range described above (one simulation for each value of the background traffic intensity, for a total of 10 simulations per series). Ten such series of such simulations are conducted (one series for each value of the reference traffic defined above).

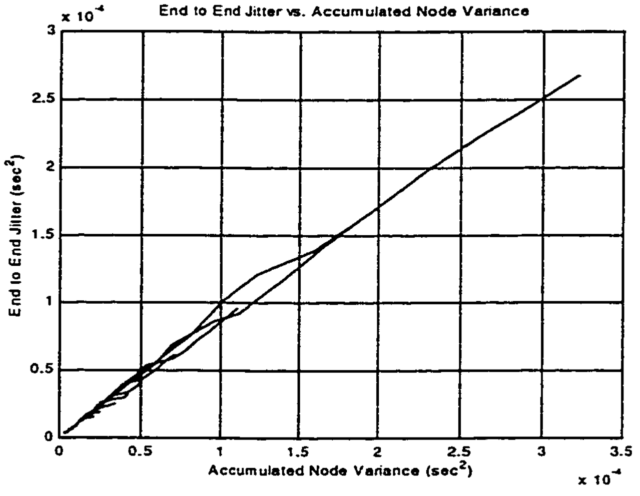


Figure 94 **End-to-end Jitter vs. Accumulated Delay Variance when varying the Service Rate, for Self-Similar Traffic and Multiple Background Sources**

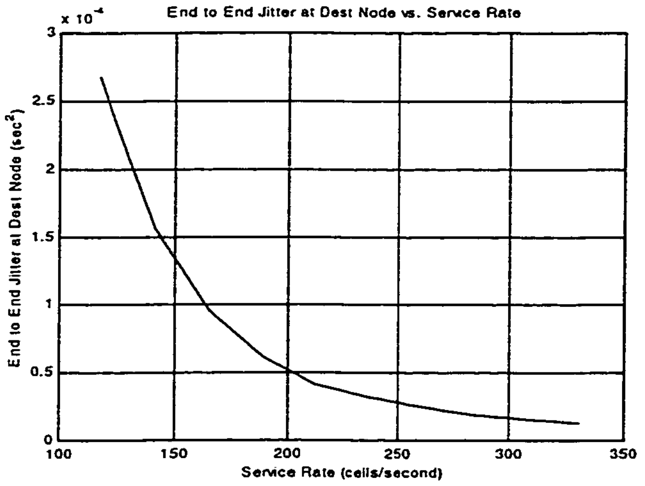


Figure 95 **End-to-end Jitter at Destination Node vs. Service Rate, for Self-Similar Traffic and Multiple Background Sources**

A.4.2.2.3 Effect of Two Priorities Traffic

A.4.2.2.3.1 Effect of Background Traffic on the End-to-end Jitter

Constant parameters

Service rate (all intermediary nodes): 120 cells/second.

Variable parameters

Simulation duration: variable, such as to generate the same number of reference traffic cells for all simulations.

Probability of discarding the background traffic - discard rate (at all intermediary nodes): The discard rate is decreased from 100% (all background traffic dropped *after* being serviced) to 10%, with a step 10%.

Background traffic. The effective intensity of the background traffic varies due to the varying discard rate.

Reference traffic. From 5 cells/second to 14 cells/second, step 1 (approximately).

Simulation Series

For each series of simulations, the reference traffic intensity is kept constant, while the background traffic intensity is varied within the range described above (one simulation for each value of the background traffic intensity, for a total of 10 simulations per series). Ten such series of such simulations are conducted (one series for each value of the reference traffic defined above).

Note. The buffer size for the low priority traffic queues has been set to 10.

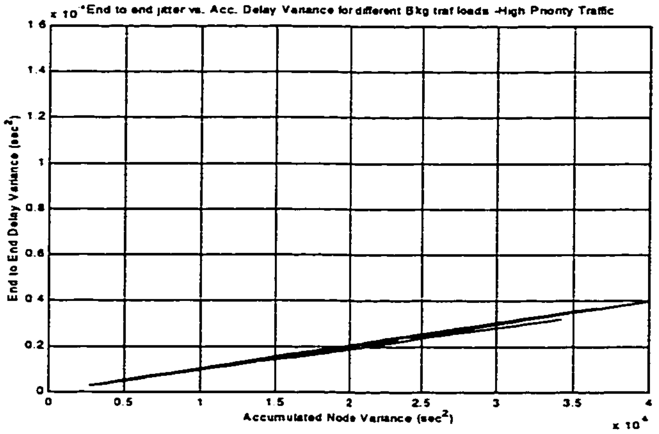


Figure 96 **End-to-end Jitter vs. Accumulated Delay Variance when varying the Background Traffic Intensity, for High Priority Self-Similar Traffic and Multiple Background Sources**

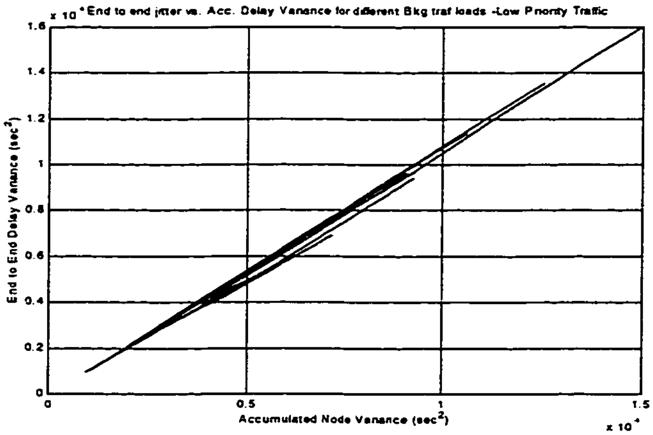


Figure 97 **End-to-end Jitter vs. Accumulated Delay Variance when varying the Background Traffic Intensity, for Low Priority Self-Similar Traffic and Multiple Background Sources**

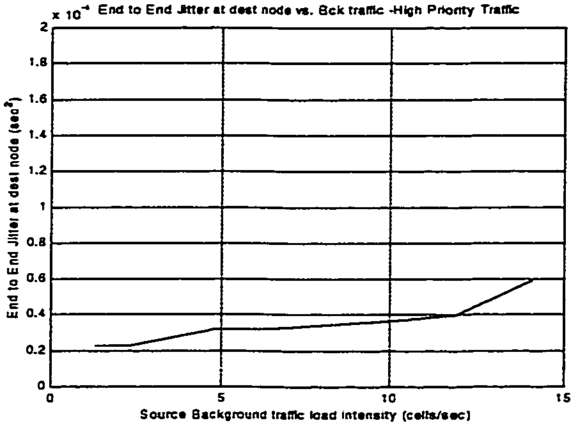


Figure 98 End-to-end Jitter at Destination Node vs. Background Traffic, for High Priority Self-Similar Traffic and Multiple Background Sources

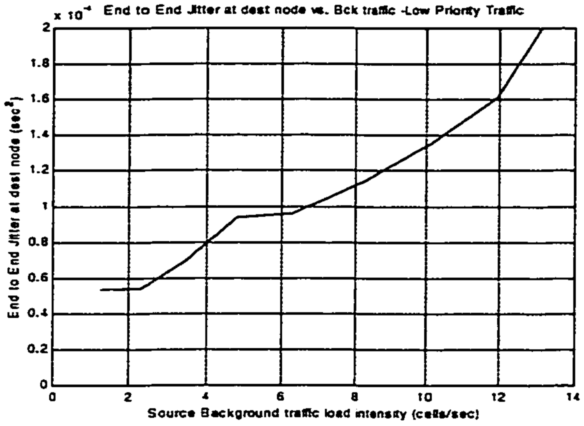


Figure 99 End-to-end Jitter at Destination Node vs. Background Traffic, for Low Priority Self-Similar Traffic and Multiple Background Sources

A.4.2.2.3.2 Effect of Service Rate on the End-to-end Jitter

Constant parameters

Background traffic: 14 cells/second (approximately).

Reference traffic: 14 cells/second (approximately).

Variable parameters

Simulation duration: variable, such as to generate the same number of reference traffic cells for all simulations.

Probability of discarding the background traffic - discard rate (at all intermediary nodes): The discard rate is decreased from 100% to 10% (all background traffic dropped ***after*** being serviced), with a step of 10%. Note that the effective intensity of the background traffic varies due to the varying discard rate (it increases when the discard rate decreases).

Service rate (all intermediary nodes): from 394.32 kbits/second (930 cells/second) to 521.52 kbits/second (1230 cells/second), with a step of 12.72 kbits/second (30 cells/second).

Simulation Series

For each series of simulations, the reference traffic intensity is kept constant, while the effective background traffic intensity is varied within the range described above (one simulation for each value of the background traffic intensity, for a total of 10 simulations per series). Ten such series of such simulations are conducted.

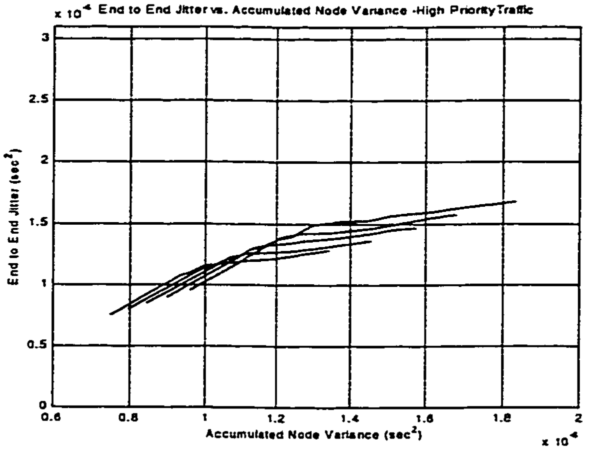


Figure 100 End-to-end Jitter vs. Accumulated Delay Variance when varying the Service Rate, for High Priority Self-Similar Traffic and Multiple Background Sources

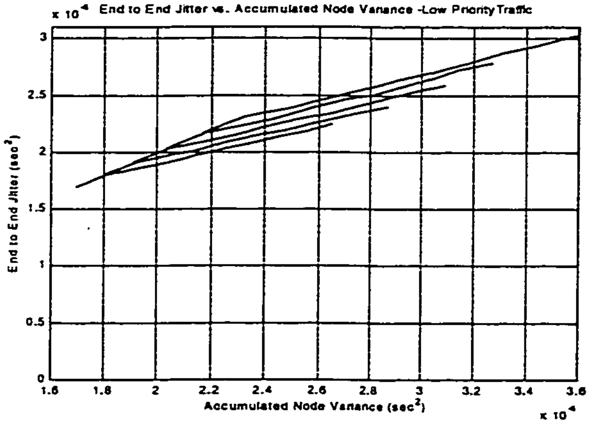


Figure 101 End-to-end Jitter vs. Accumulated Delay Variance when varying the Service Rate, for Low Priority Self-Similar Traffic and Multiple Background Sources

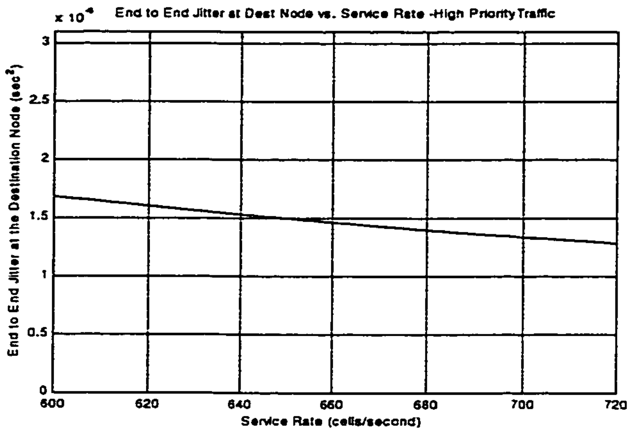


Figure 102 End-to-end Jitter at Destination Node vs. Service Rate, for High Priority Self-Similar Traffic and Multiple Background Sources

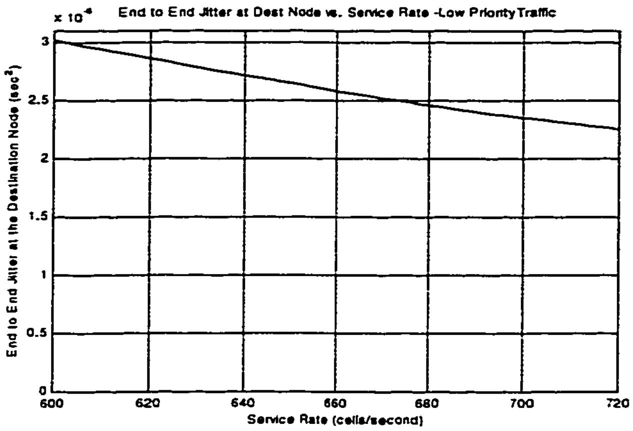


Figure 103 End-to-end Jitter at Destination Node vs. Service Rate, for Low Priority Self-Similar Traffic and Multiple Background Sources

A.5 Polynomial Coefficient for the End-to-end Jitter Empirical Formula

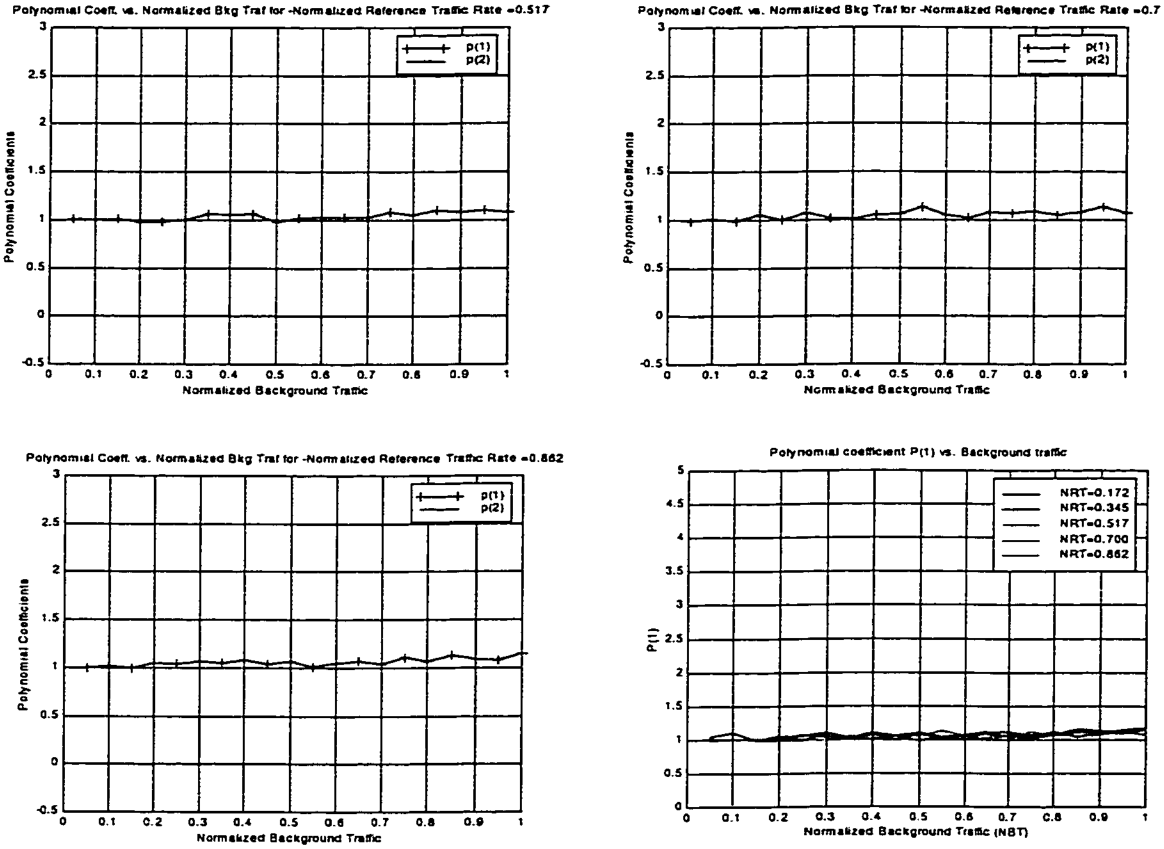
A.5.1 Relation of the polynomial coefficients to the background traffic

A.5.1.1 Bursty Traffic

A.5.1.1.1 Single Background Node Simulations

A.5.1.1.1.1 No Priority Traffic

The polynomial coefficients in Figure 104 are quasi-constant and very close to

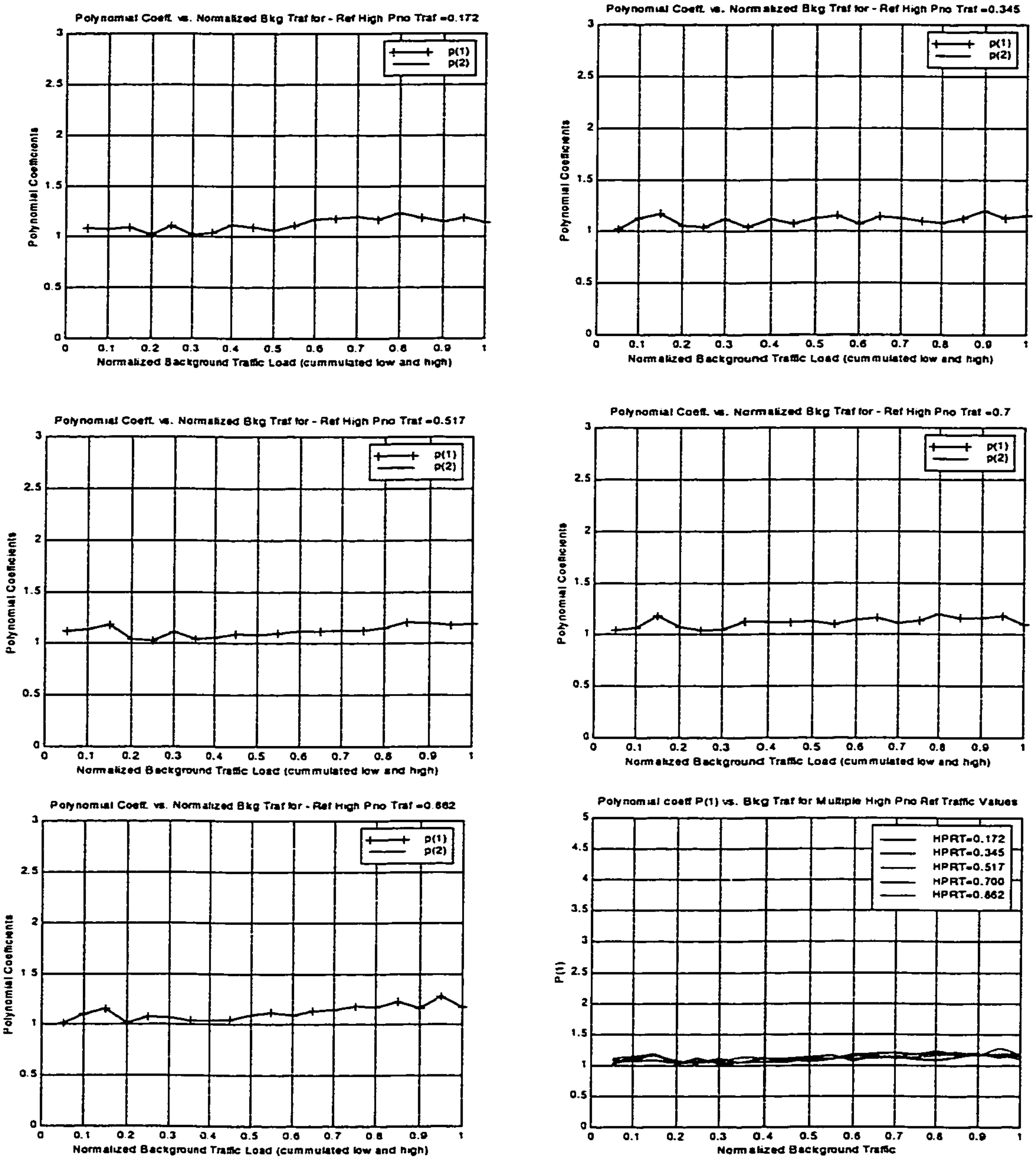


1.

Figure 104 Polynomial Coefficients for Bursty Traffic, Single Background Sources, Single Stream Traffic

A.5.1.1.1.2 Two Priorities Traffic

The polynomial coefficients are quasi-constant and close to 1.


Polynomial Coeff. vs. Normalized Bkg Traf for - Ref High Prio Traf =0.172

Polynomial Coeff. vs. Normalized Bkg Traf for - Ref High Prio Traf =0.345

Polynomial Coeff. vs. Normalized Bkg Traf for - Ref High Prio Traf =0.517

Polynomial Coeff. vs. Normalized Bkg Traf for - Ref High Prio Traf =0.7

Polynomial Coeff. vs. Normalized Bkg Traf for - Ref High Prio Traf =0.862

Polynomial coeff P(1) vs. Bkg Traf for Multiple High Prio Ref Traffic Values

Figure 105 Polynomial Coefficients for Bursty Traffic, Single Background Sources, Dual Stream Traffic

A.5.1.1.2 Multiple Background Nodes

A.5.1.1.2.1 No Priority Traffic

In the case of the single reference traffic, the polynomial coefficients are obtained for the series of simulations described in section A.4.1.2.1. The reference high priority background traffic varies from 0.17 to 0.86, for the figures from left to right, top to bottom.

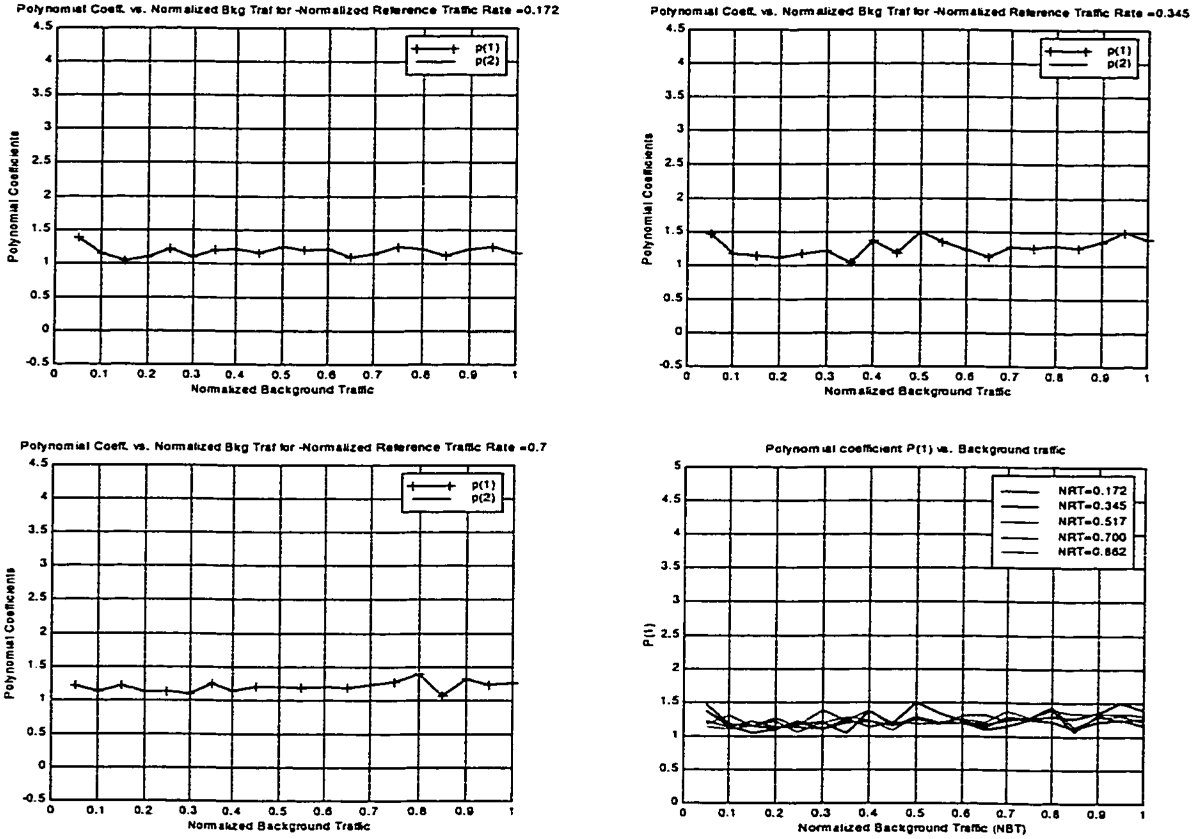


Figure 106 Polynomial Coefficients for Bursty Traffic, Multiple Background Sources, No Priority Traffic

A.5.1.1.2.2 Two Priorities Traffic

In the case of the single reference traffic, the polynomial coefficients are obtained for the series of simulations described in section A.4.1.2.3.1. The reference high priority background traffic varies from 0.17 to 0.86, for the figures from left to right, top to bottom.

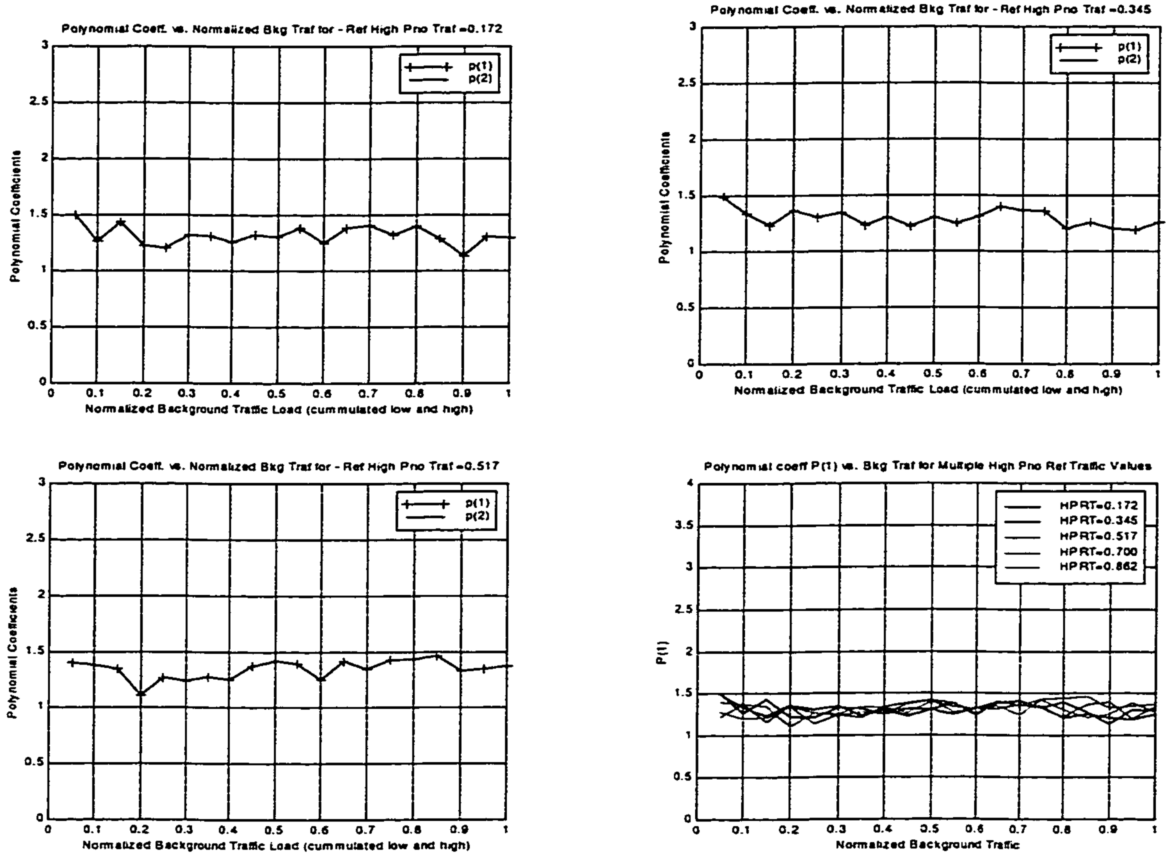


Figure 107 Polynomial Coefficients for Bursty Traffic, Multiple Background Sources, Two Priorities Streams Traffic

A.5.1.2Self Similar Traffic

A.5.1.2.1 Single Background Node Simulations

A.5.1.2.2 No Priority Traffic

In the case of the single reference traffic, the polynomial coefficients are obtained for the series of simulations described in section A.4.2.1.1.

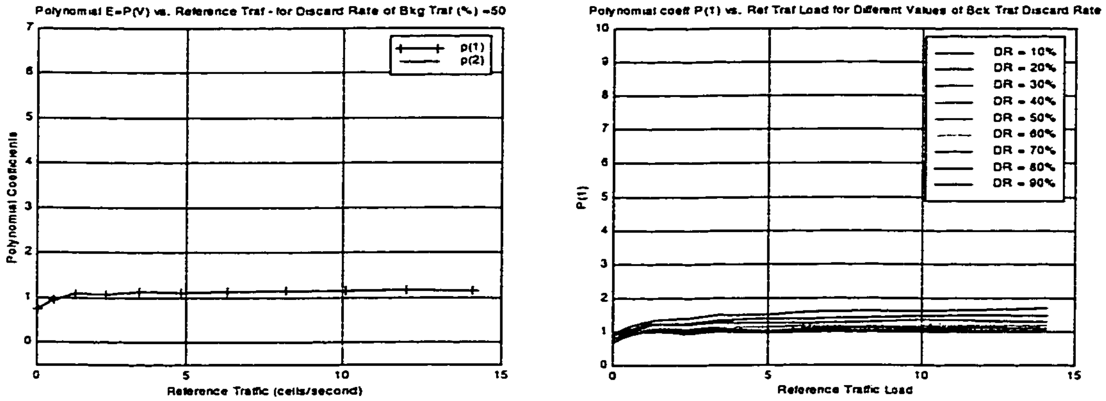


Figure 108 **Polynomial Coefficients for Self-Similar Traffic, No Priority Traffic, Single Background Traffic Sources**

A.5.1.2.2.1 Two Priorities Traffic

In the case of the single reference traffic, the normalized background traffic varies from 0.1 to 0.8, for the figures from left to right, top to bottom.

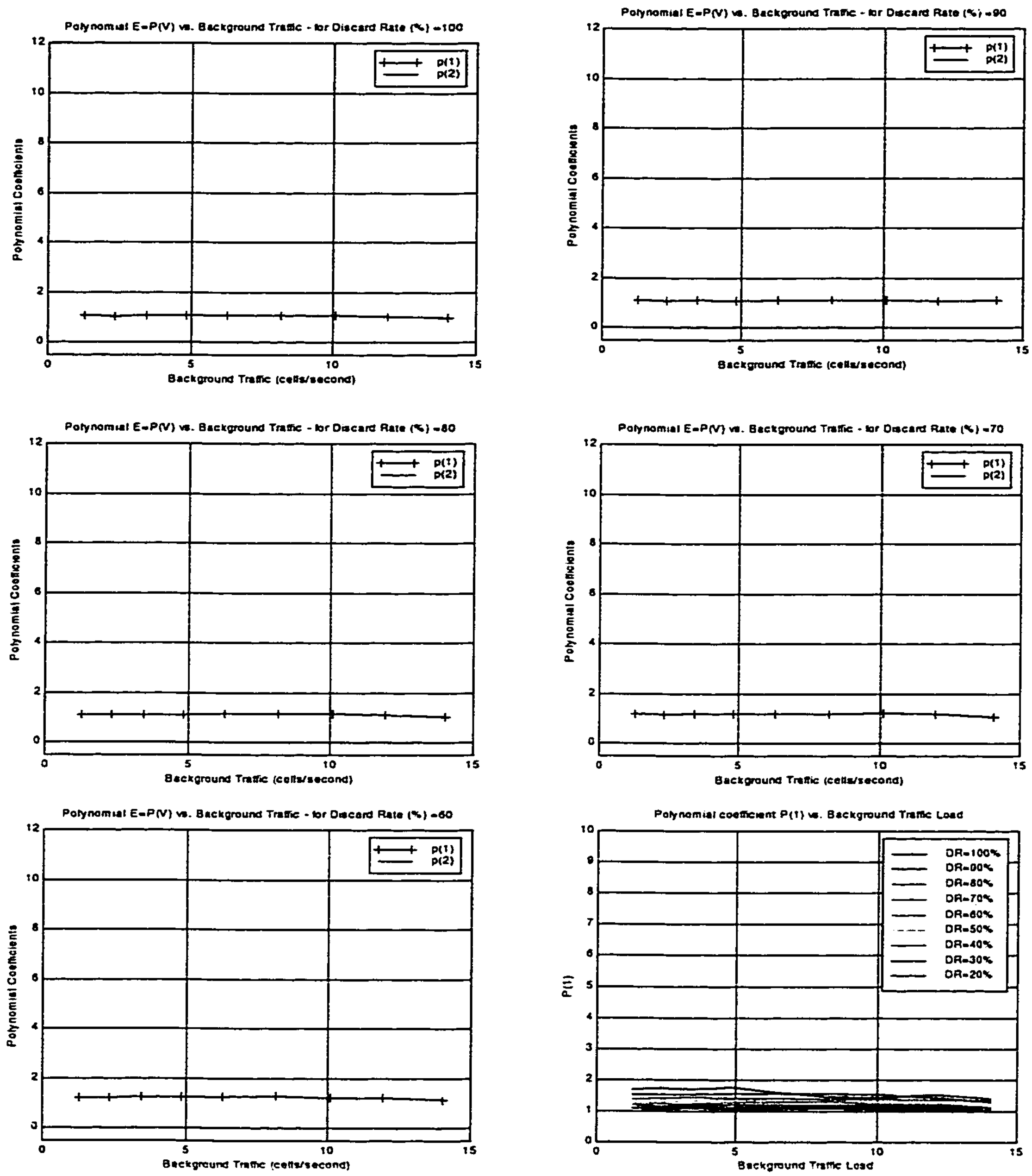


Figure 109 **Polynomial Coefficients for Self-Similar Traffic, Single Background Nodes, Two Priority Traffic**

A.5.1.2.3 Multiple Background Nodes

A.5.1.2.3.1 No Priority Traffic

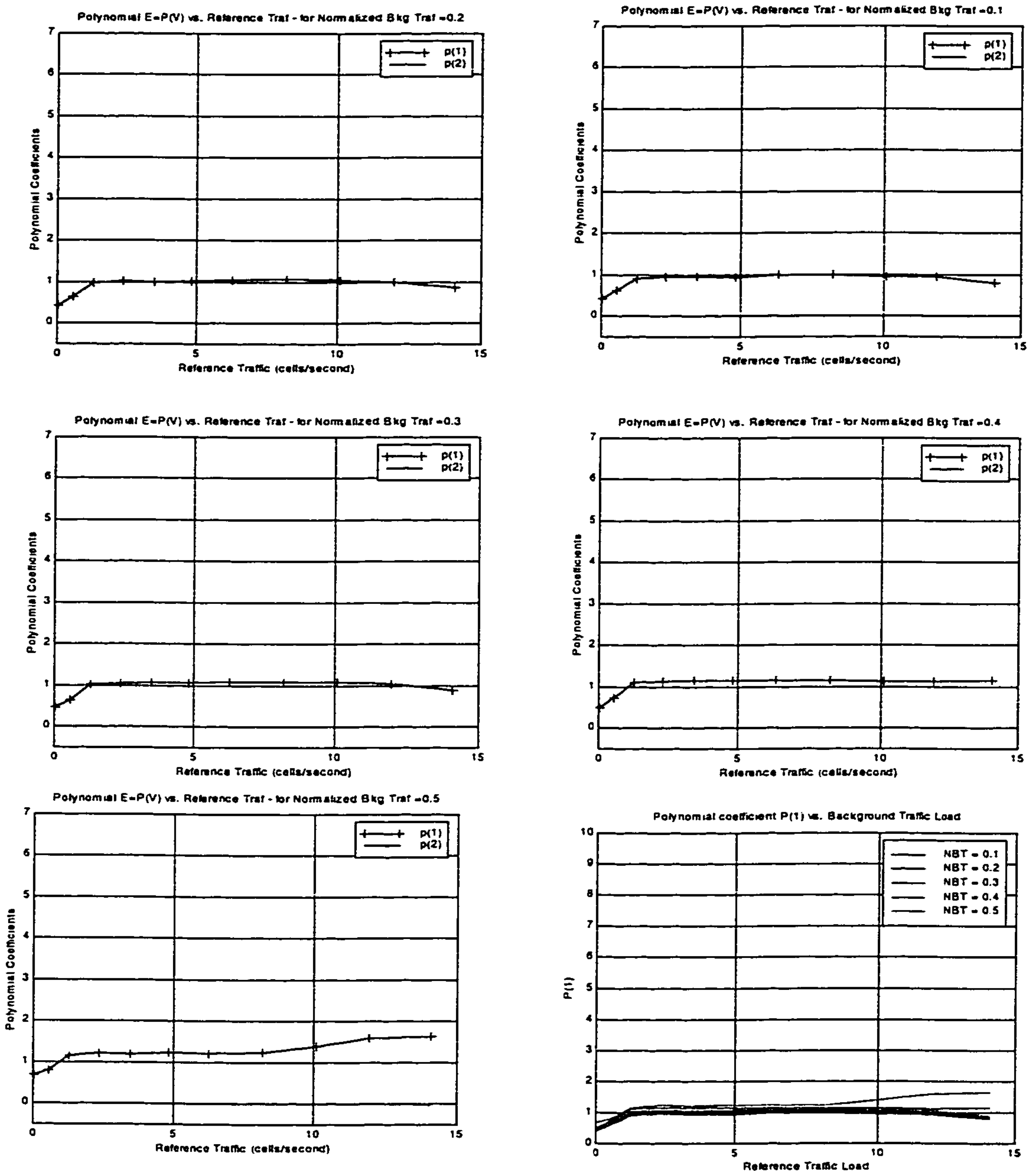


Figure 110 Polynomial Coefficients for Self-Similar Traffic, Single Background Traffic Sources, No Priority Traffic

A.5.1.2.3.2 Two Priorities Traffic

In the case of the single reference traffic, the polynomial coefficients are obtained for the series of simulations described in section A.4.2.2.3.1. The normalized background traffic varies from 0.1 to 0.8, for the figures from left to right, top to bottom.

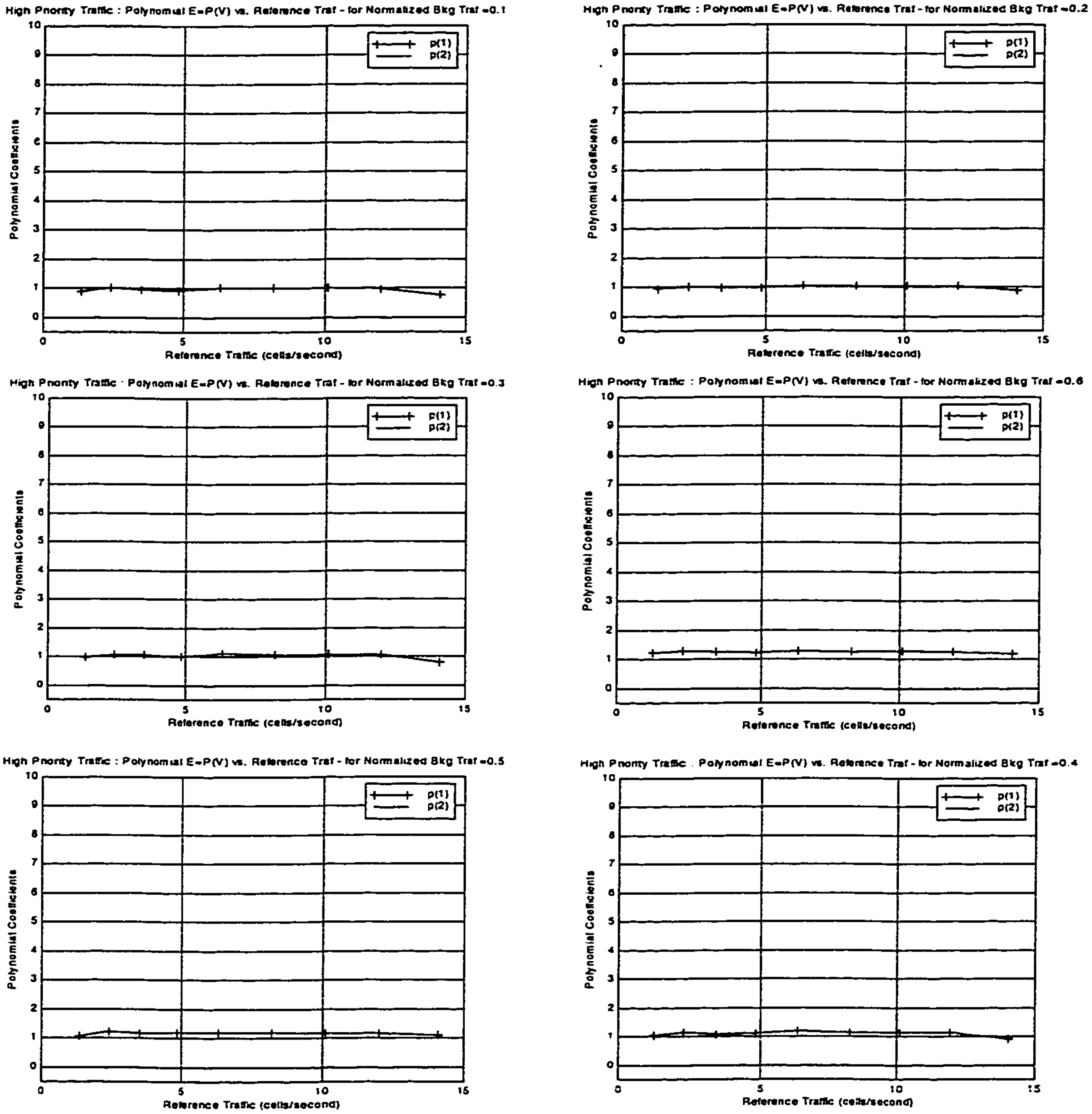
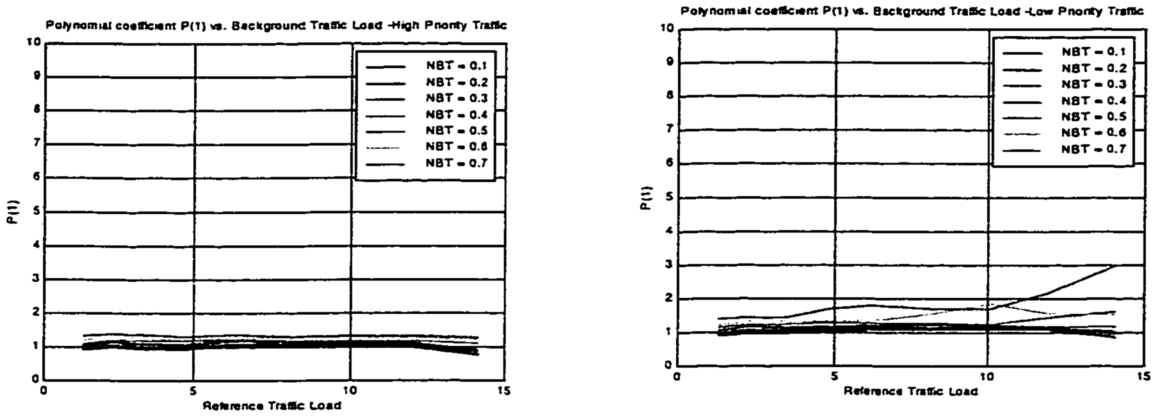


Figure 111 Polynomial Coefficients for Self-Similar Traffic, Multiple Background Sources, Two Priorities Traffic



(A) (B)

Figure 112 **Comparison of Polynomial Coefficients for (A) High Priority Traffic and (B) Low Priority Traffic**

The two figures above compare the p_1 coefficient for the case of high and low priority traffic. It can be seen that the coefficient for the low priority traffic is degraded, when the normalized background traffic increases (NBT = 0.5, 0.6 and 0.7). This is due to the increased end-to-end delay and probability loss for the low priority traffic.

A.5.2 Relation of the polynomial coefficients to the service rate

A.5.2.1 Self Similar Traffic

A.5.2.1.1 Single Background Node Simulations

A.5.2.1.1.1 No Priority Traffic

Figure 113 represents p_1 and p_2 - left to right, top to bottom, for discard rates varying from 10% to 60% (step 10%).

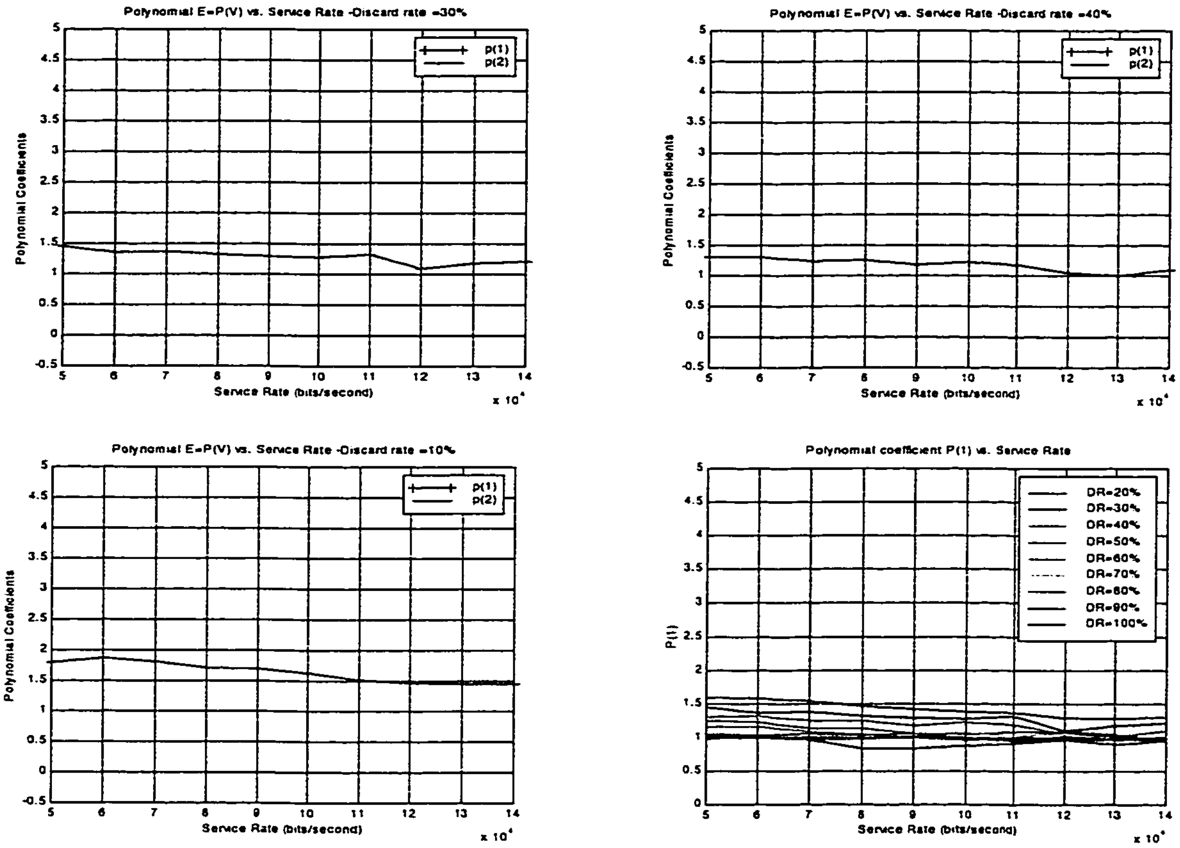


Figure 113 Polynomial Coefficients for Self-Similar, Single Background Sources, No Priority Traffic

A.5.2.1.1.2 Priority Traffic

In the case of the single reference traffic, the polynomial coefficients are obtained for the series of simulations described in the section A.4.2.2.3.1.

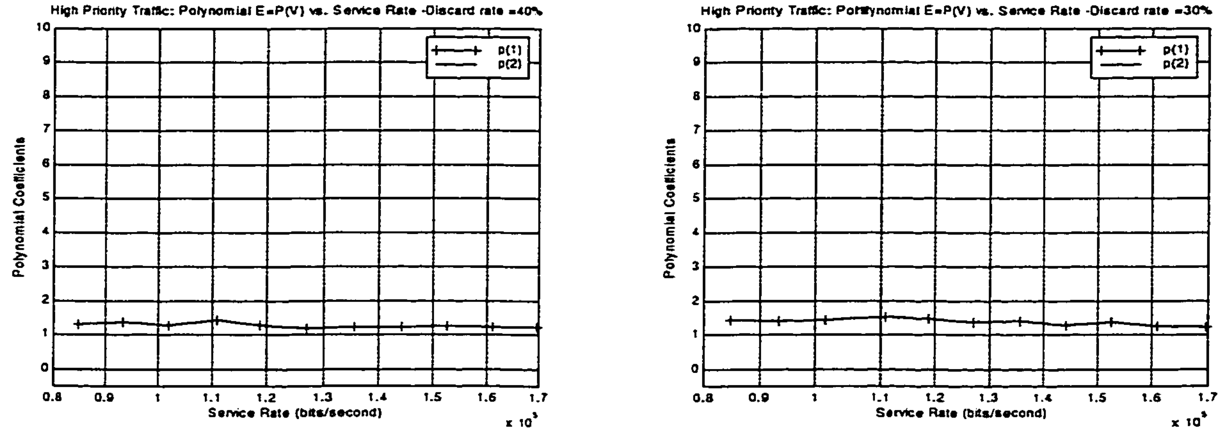


Figure 114 Polynomial Coefficients for Self-Similar, Two Priority Traffic with Single Background Sources (High Priority Traffic)

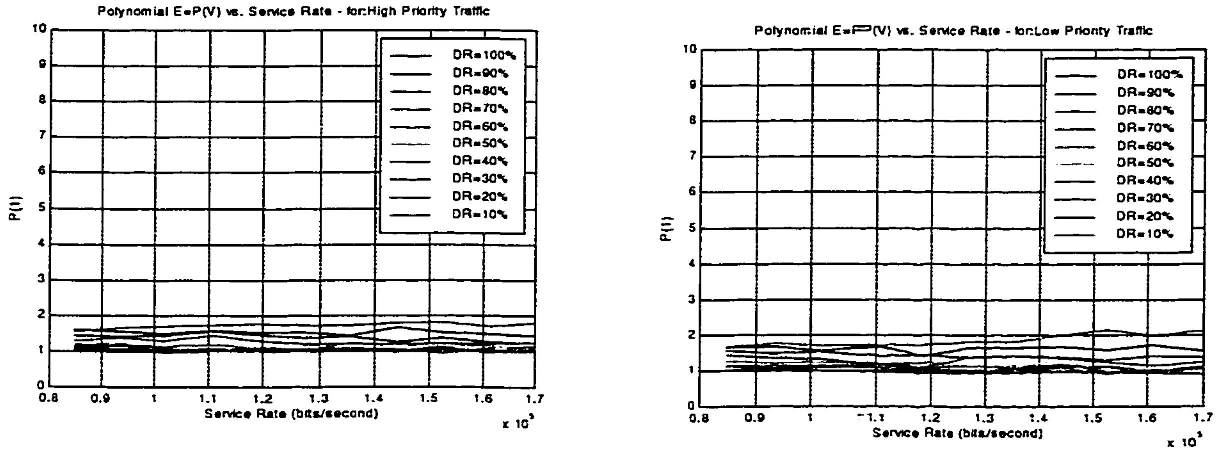


Figure 115 Comparison of Polynomial Coefficients for Self-Similar with Single Background Sources: High and Low Priority Traffic

A.5.2.1.2 Multiple Background Sources

A.5.2.1.2.1 No Priority Traffic

In the case of the no priority traffic, the polynomial coefficients are obtained for the series of simulations described in the section A.4.2.2.2.

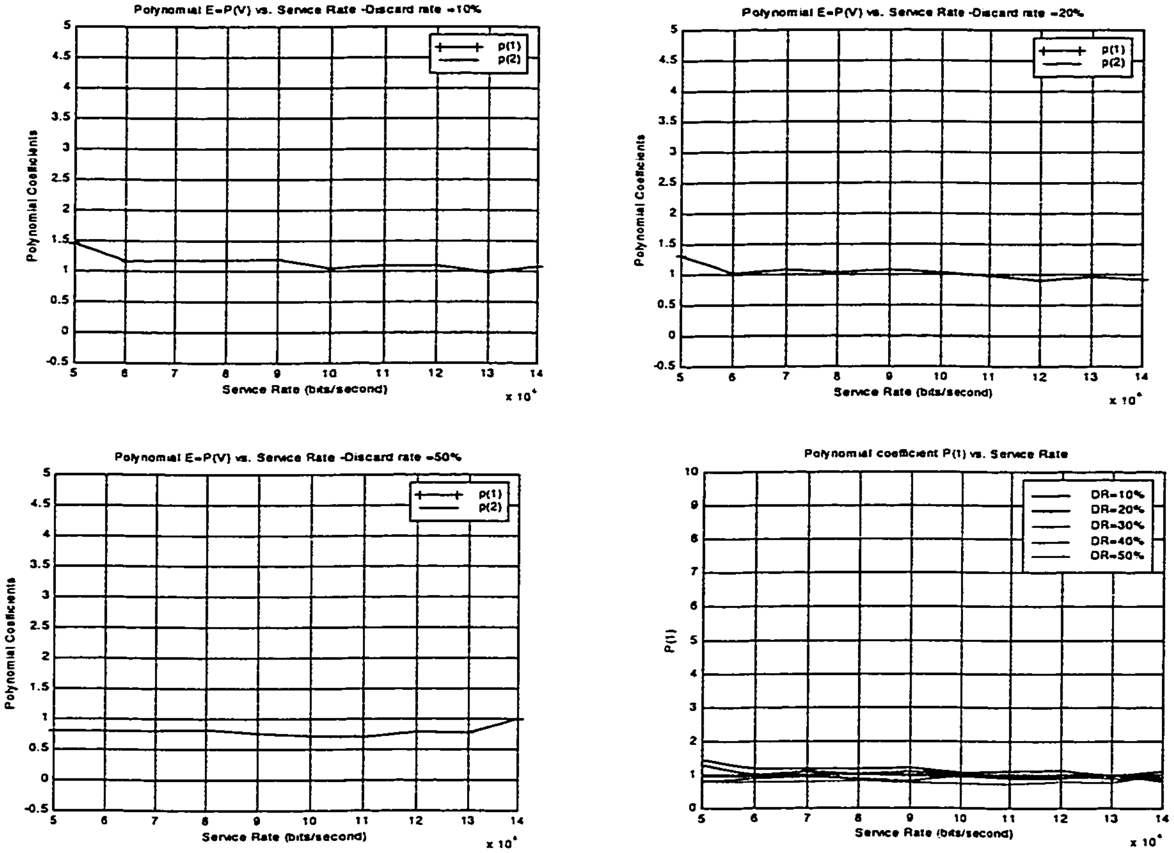


Figure 116 Polynomial Coefficients for Self-Similar, No Priority Traffic with Multiple Background Sources

A.5.2.2 Bursty Traffic

A.5.2.2.1 Single Background Node Simulations

A.5.2.2.1.1 No Priority Traffic

In the case of the single reference traffic, the polynomial coefficients are obtained for the series of simulations described in the section A.4.1.1.2.

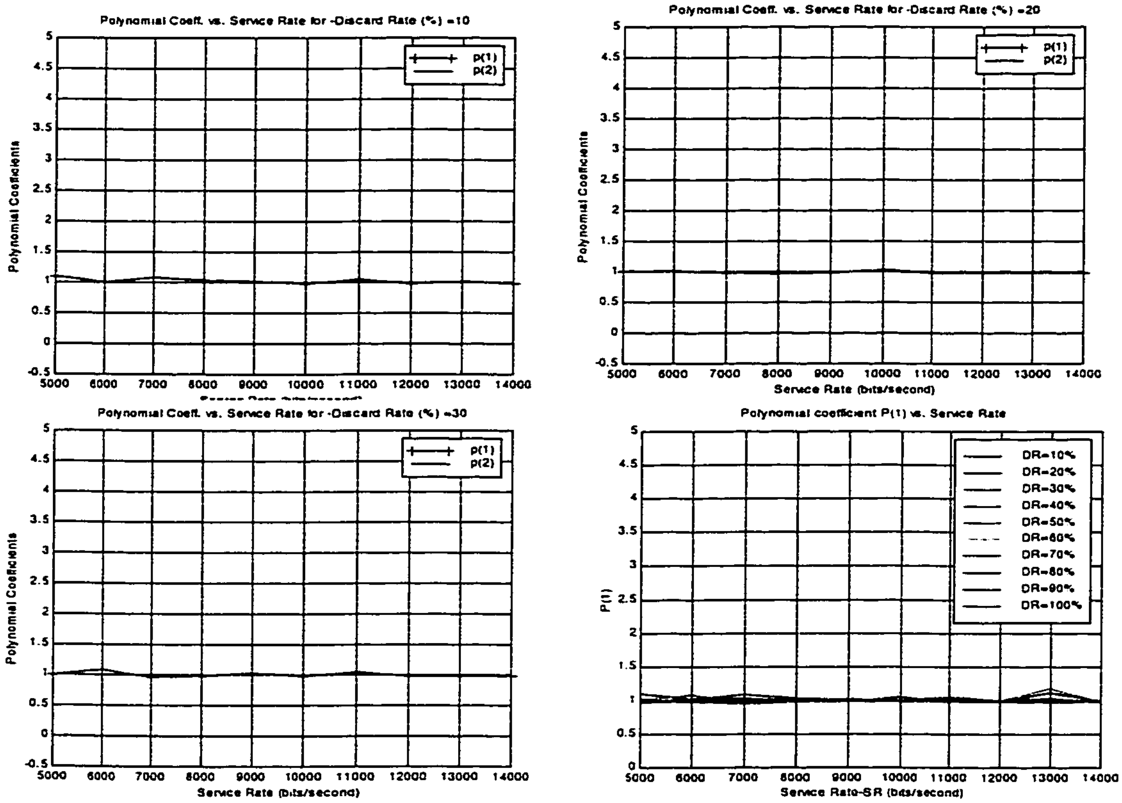
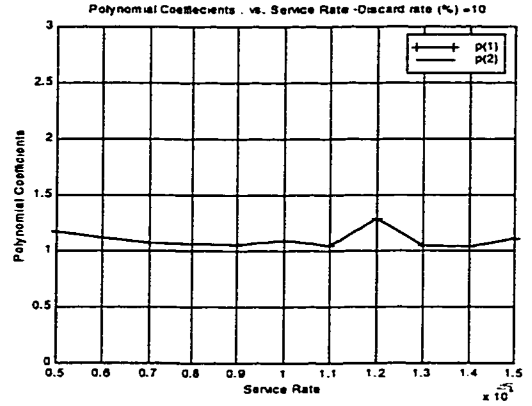


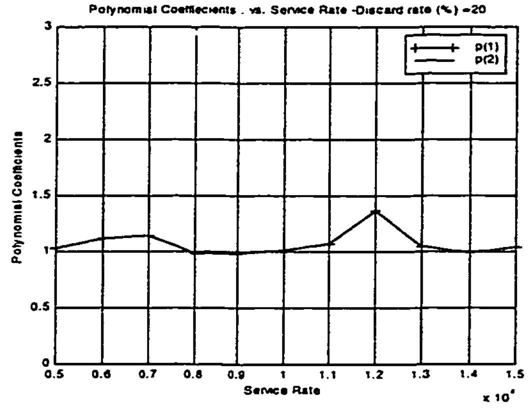
Figure 117 Polynomial Coefficients for Bursty, No Priority Traffic, Single Background Sources

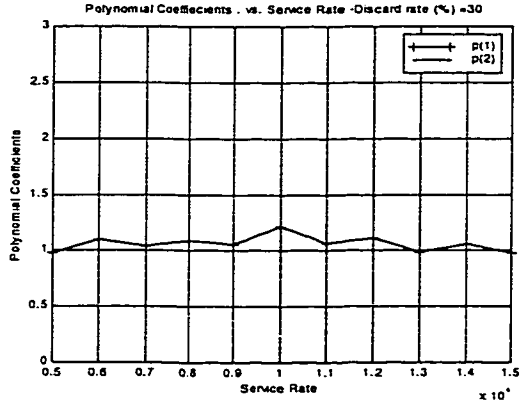
A.5.2.2.1.2 Two Priority Traffic

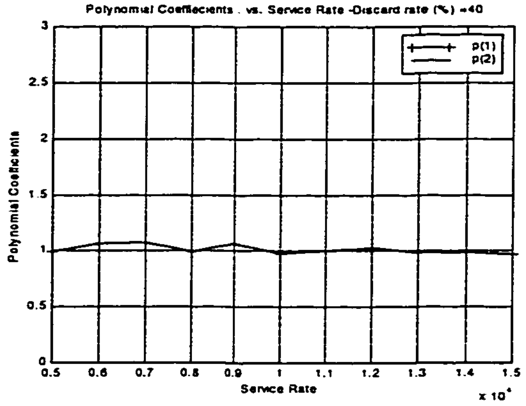
In the case of the single reference traffic, the polynomial coefficients are obtained for the series of simulations described in the section Figure 62.

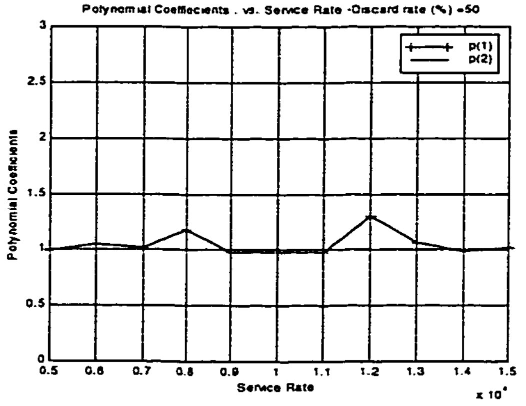
The following ten figures represents p_1 and p_2 - left to right, top to bottom, for discard rates varying from 10% to 100% (step 10%). At 100% discard rate, all background traffic arriving to a node is discarded, after it is serviced.

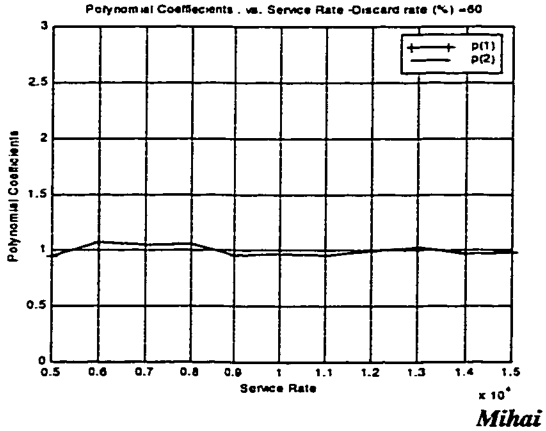












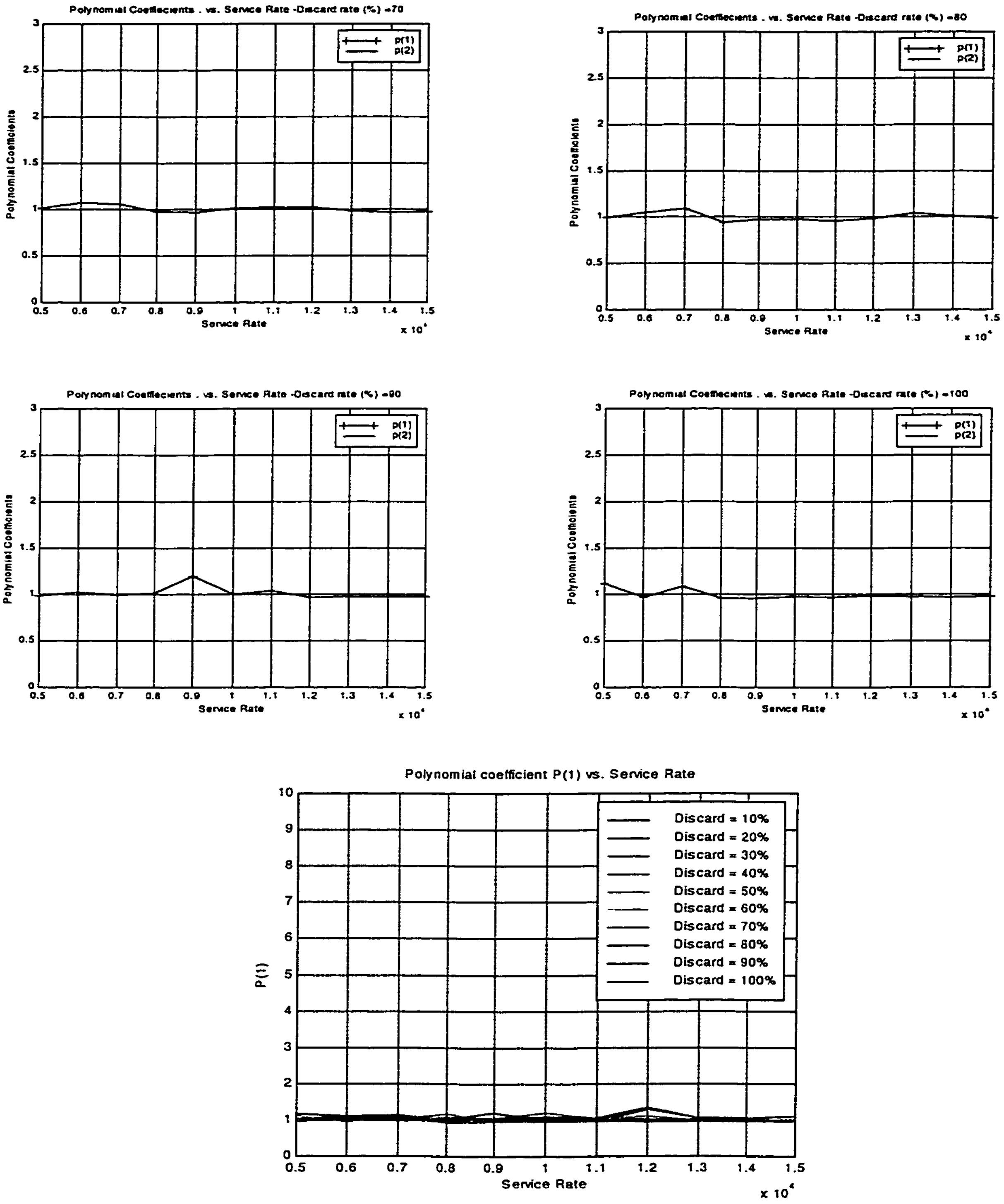


Figure 118 Polynomial Coefficients for Bursty, Two Priority Traffic, Single Background Sources

A.5.2.2.2 Multiple Background Sources

A.5.2.2.2.1 No Priority Traffic

In the case of the single reference traffic, the polynomial coefficients are obtained for the series of simulations described in the section A.4.1.2.2.

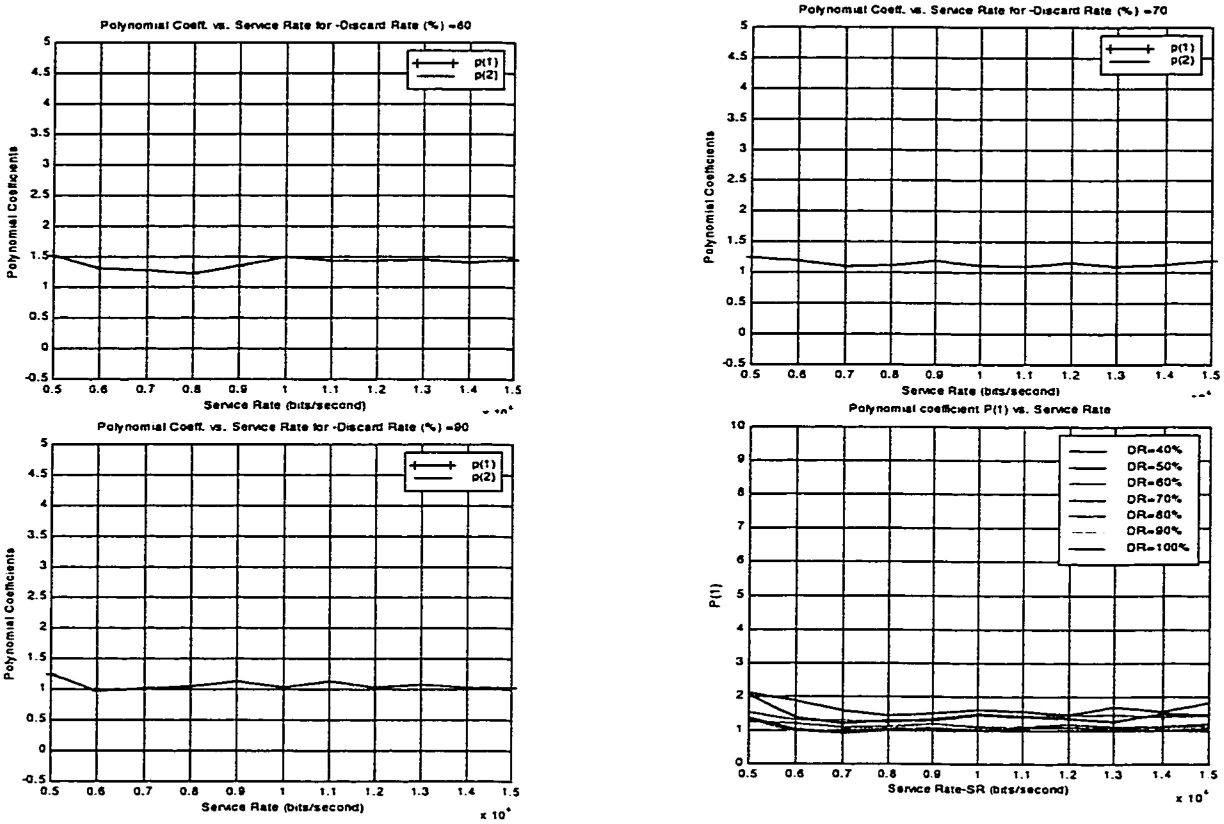
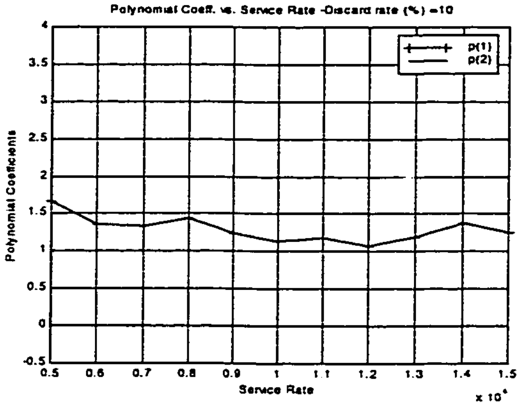


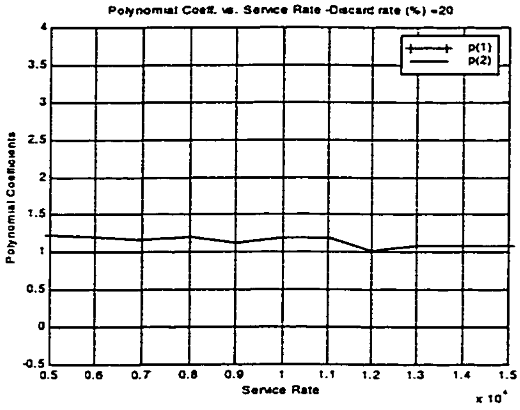
Figure 119 Polynomial Coefficients for Bursty, No Priority Traffic with Multiple Background Sources

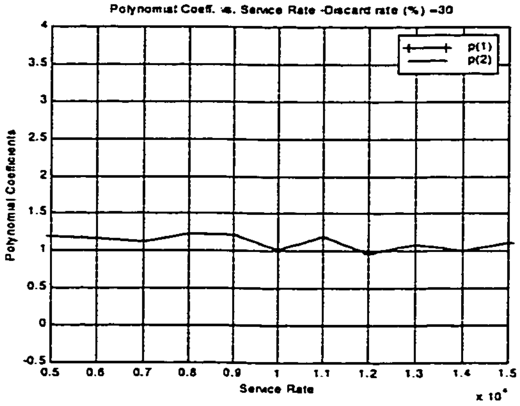
A.5.2.2.2.2 Two Priority Traffic

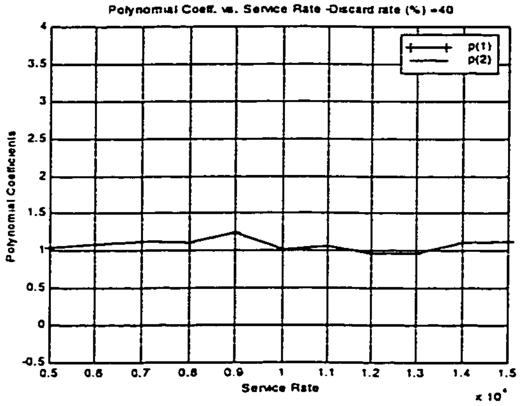
In the case of the single reference traffic, the polynomial coefficients are obtained for the series of simulations described in the section A.4.1.2.3.2.

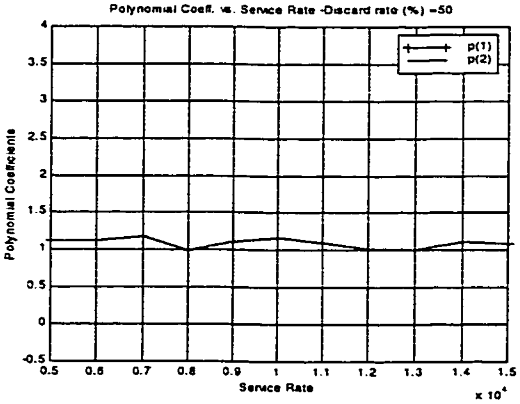
The following ten figures represent p(1) and p(2) - left to right, top to bottom, for discard rates varying from 10% to 100% (step 10%). At 100% discard rate, all background traffic arriving to a node is discarded, after it is serviced.

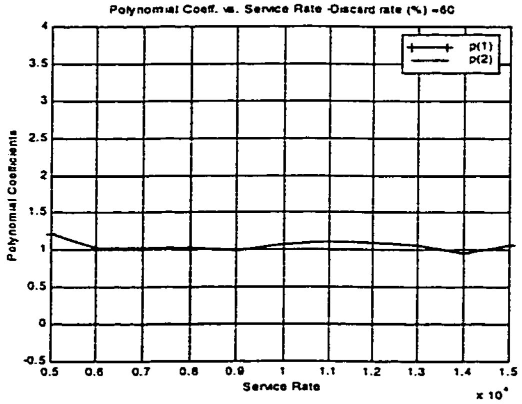












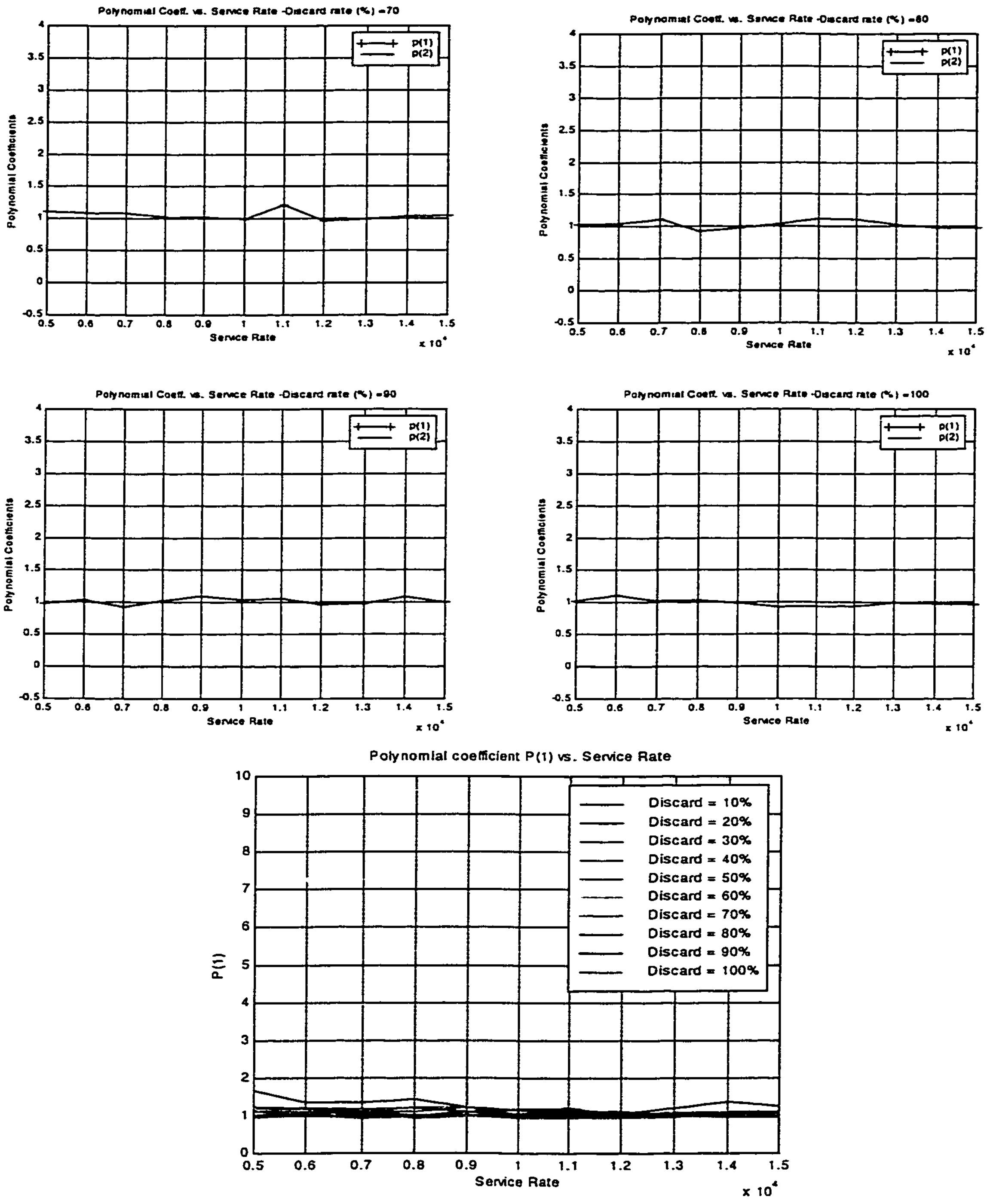


Figure 120 Polynomial Coefficients for Bursty, Two Priority Traffic with Multiple Background Sources

A.6 OPNET Simulation Models

All OPNET simulation models are derived from the generic model described in Figure 8. The OPNET representation of the three sub-networks (source, intermediary and destination) comprising the model is given below:

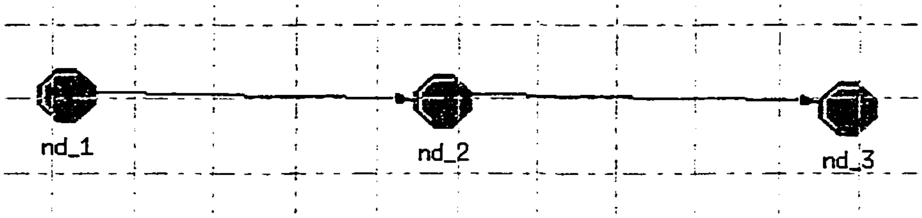


Figure 121 General OPNET Simulation Model

The following section describes the OPNET model used for two priority streams (high and low priority) simulations. The models for single stream simulations are very similar, with two exceptions:

- The low priority traffic generators are not present.
- Queue processes accept only one type of traffic (versus high and low priority traffic).

The OPNET model uses three types of processes:

- Server ("queue") processes
- Traffic generators (for bursty and self-similar traffic, respectively).

These processes are described in the section **A.6.2 Process Models.**

A.6.1 Sub-networks

In the case of a "two-priority" data stream traffic, the *source network* ***nd_1*** is an instantiation of the following sub-network node (*source* node):

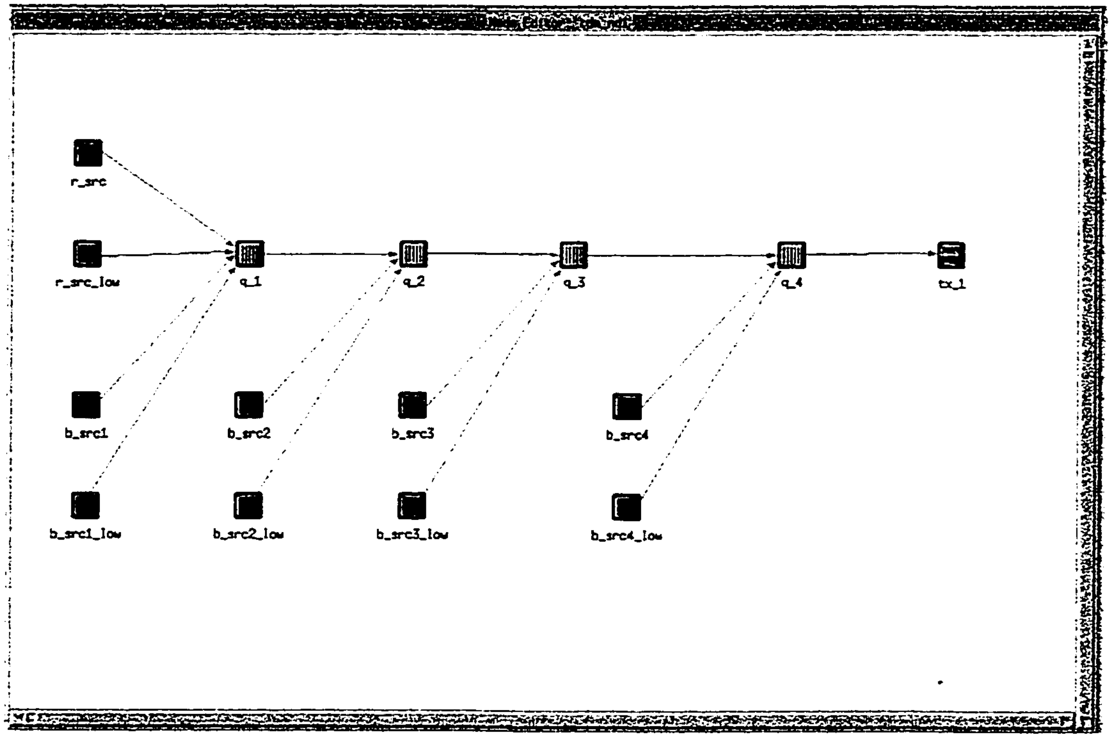


Figure 122 **OPNET Source Network nd_1**

Where:

- *r_src* is the high priority reference traffic data stream generator
- *r_src_low* is the low priority reference traffic data stream generator
- *q_1, q_2, q_3* and *q_4* are implementation of server processes ("tandem queue"), as described in section 2.2.
- *b_src1, b_src2, b_src3* and *b_src4* are high priority background traffic generators.
- *b_src1_low, b_src2_low, b_src3_low* and *b_src4_low* are low priority background traffic generators.
- *tx_1* is a predefined OPNET "point to point transmitter", used to transfer all network traffic to the next simulation node (stage).

The *intermediary network* ***nd_2*** is an instantiation of the following sub-network node (*intermdediary* node):

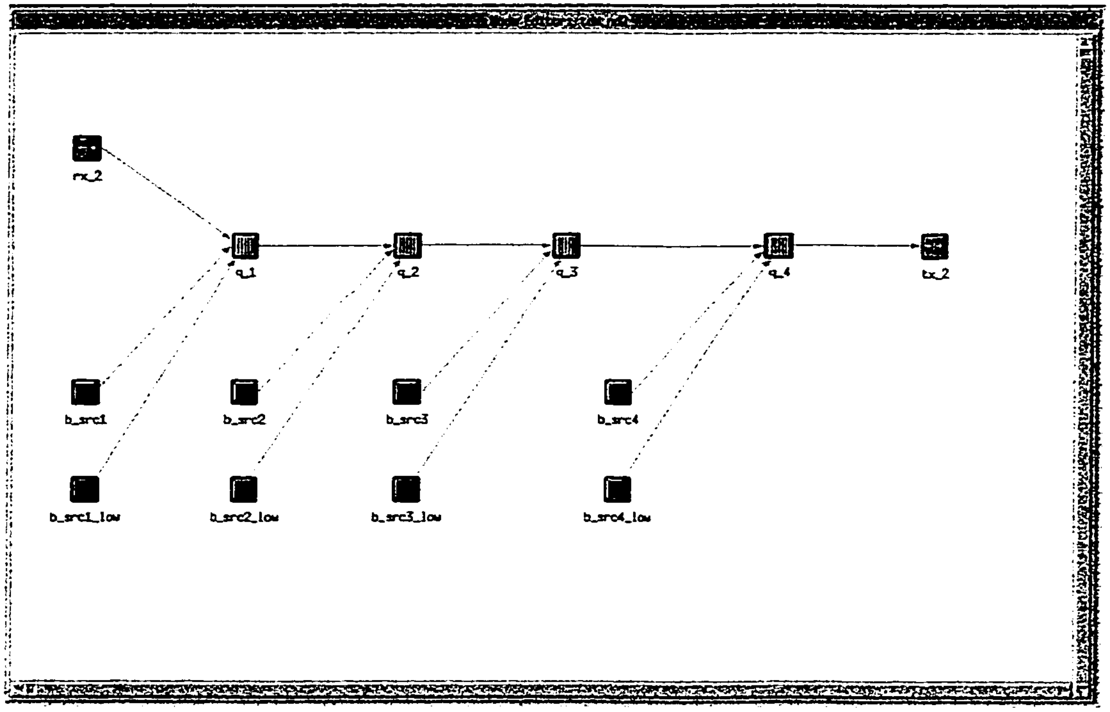


Figure 123 OPNET Intermediary Network nd_2

- *rx_2* is a predefined OPNET "point to point receiver"
- *b_src1, b_src2, b_src3* and *b_src4* are high priority background traffic generators.
- *b_src1_low, b_src2_low, b_src3_low* and *b_src4_low* are low priority background traffic generators.
- *tx_2* is a predefined OPNET "point to point transmitter", used to transfer all network traffic to the next simulation node (stage).

The *destination network* ***nd_3*** is an instantiation of the following sub-network node:

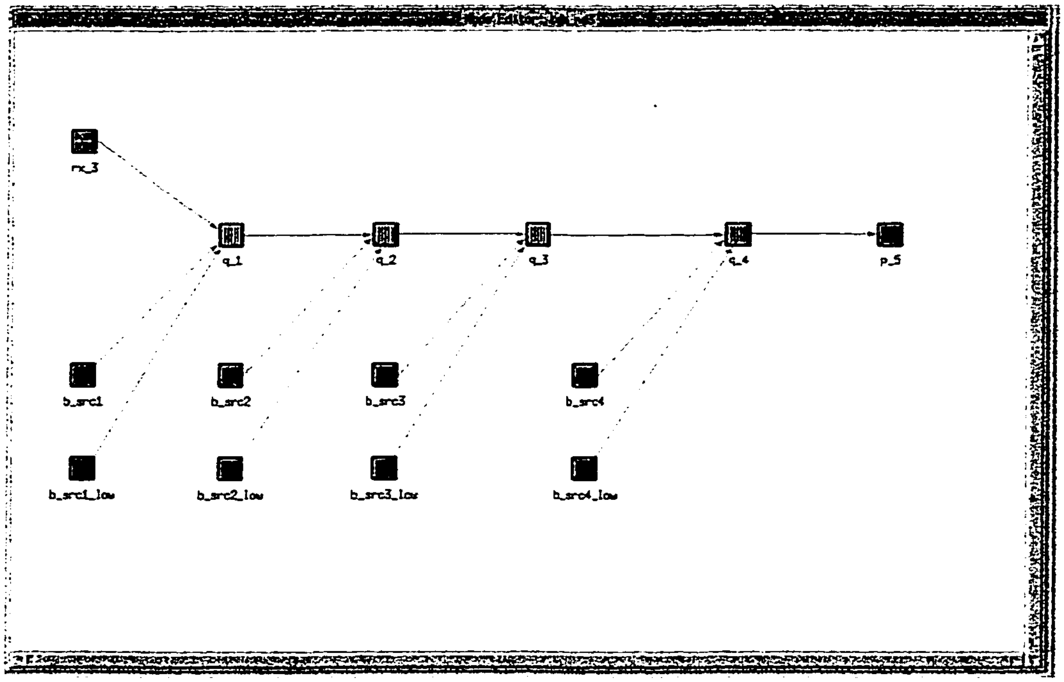


Figure 124 OPNET Destination Network nd_3

- *rx_3* is a predefined OPNET "point to point receiver"
- *b_src1, b_src2, b_src3* and *b_src4* are high priority background traffic generators.
- *b_src1_low, b_src2_low, b_src3_low* and *b_src4_low* are low priority background traffic generators.
- *p5* is a "sink" process; it destroys all data packets it receives and calculates end-to-end traffic parameters (e.g. end-to-end delay variation).

A.6.2 OPNET Process Models

A.6.2.1 Bursty Traffic Generator

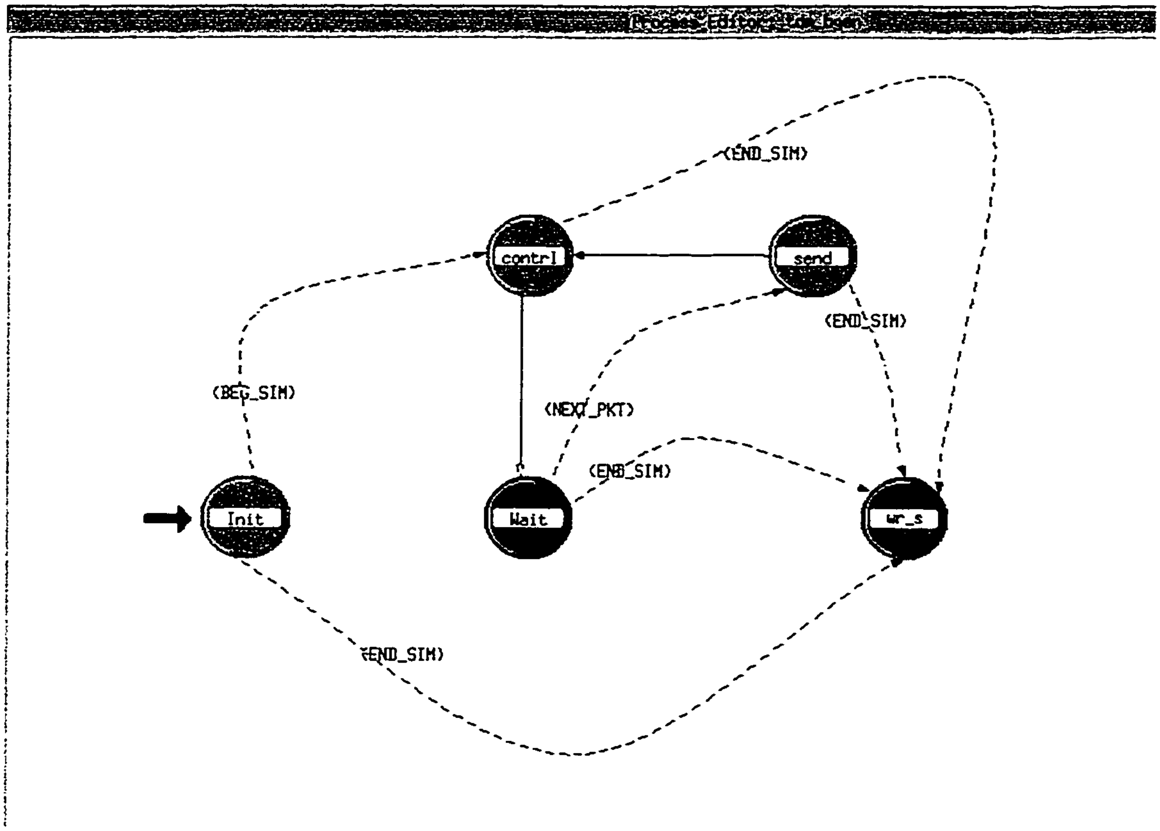


Figure 125 **OPNET Bursty Traffic Generator Finite State Machine**

The process has five states: ***Init, contrl, wr_s, send*** and ***Wait.***

Init, contrl and ***send*** are *forced* OPNET states (the execution of the process finite state machine cannot be interrupted while in this states).

The state machine illustrated in this picture is used for bursty traffic generators, used both as reference and background sources. All sub-networks (***nd_1, nd_2*** and ***nd_3***) use this process, but only for network models that use bursty traffic.

The following table gives a brief description of these states:

State	Forced	Description
Init	Yes	Read simulation variables and initialize simulation parameters.
contrl	Yes	Schedule the next time when a packet is sent, by sampling the distributions for the active and idle periods.
wr_s	No	Write simulation statistics (when the simulation ends).
send	Yes	Send a packet.
Wait	No	Wait for an event to happen (*next_pkt*, which forces a packet be sent).

A.6.2.2 Self-Similar Traffic Generator

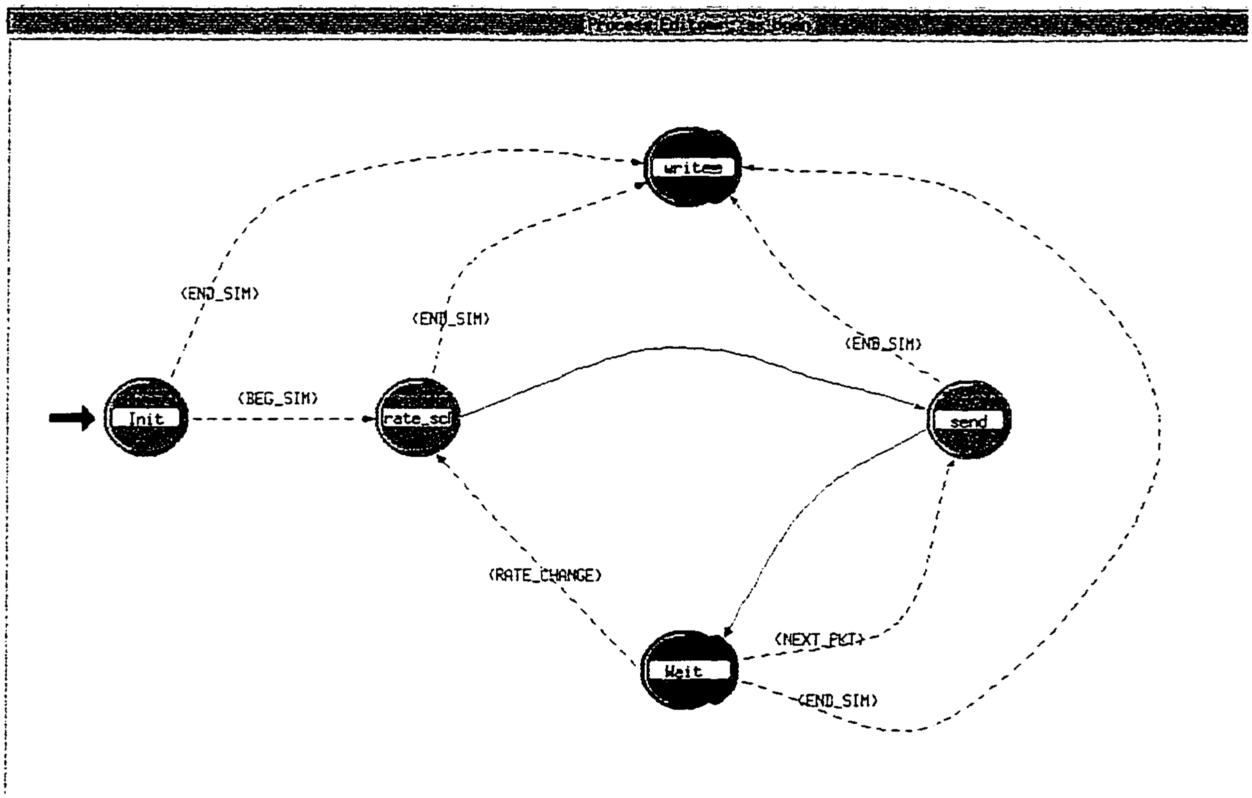


Figure 126 **OPNET Self-Similar Traffic Generator Finite State Machine**

The process has five states: ***Init, rate_sch, write, send*** and ***Wait.***

Init, rate_sch and ***send*** are *forced* OPNET states (the execution of the process finite state machine cannot be interrupted while in this states).

The state machine illustrated in this picture is used for self-similar traffic generators, used both as reference and background sources. All sub-networks (***nd_1, nd_2*** and ***nd_3***) use this process, but only for network models that use self-similar traffic.

The following table gives a brief description of these states:

State	**Forced**	**Description**
Init	Yes	Read simulation variables and initialize simulation parameters
rate_sch	Yes	The number of new generators is sampled from a Poisson distribution with parameter λ. For each generator becoming active, determine the duration of the active state by sampling the Pareto distribution Calculate the new aggregate rate Schedule a new "rate_sch" interrupt Send the generated packet (by going to the "send" state).
write	No	Write simulation statistics (when the simulation ends).
send	Yes	Send a packet.
Wait	No	Wait for an event to happen (either *send* or *rate_schedule*).

A.6.2.3Tandem Queue Process

The queue process has two variants: one of single data traffic and one for two priority (high and low priority) traffic.

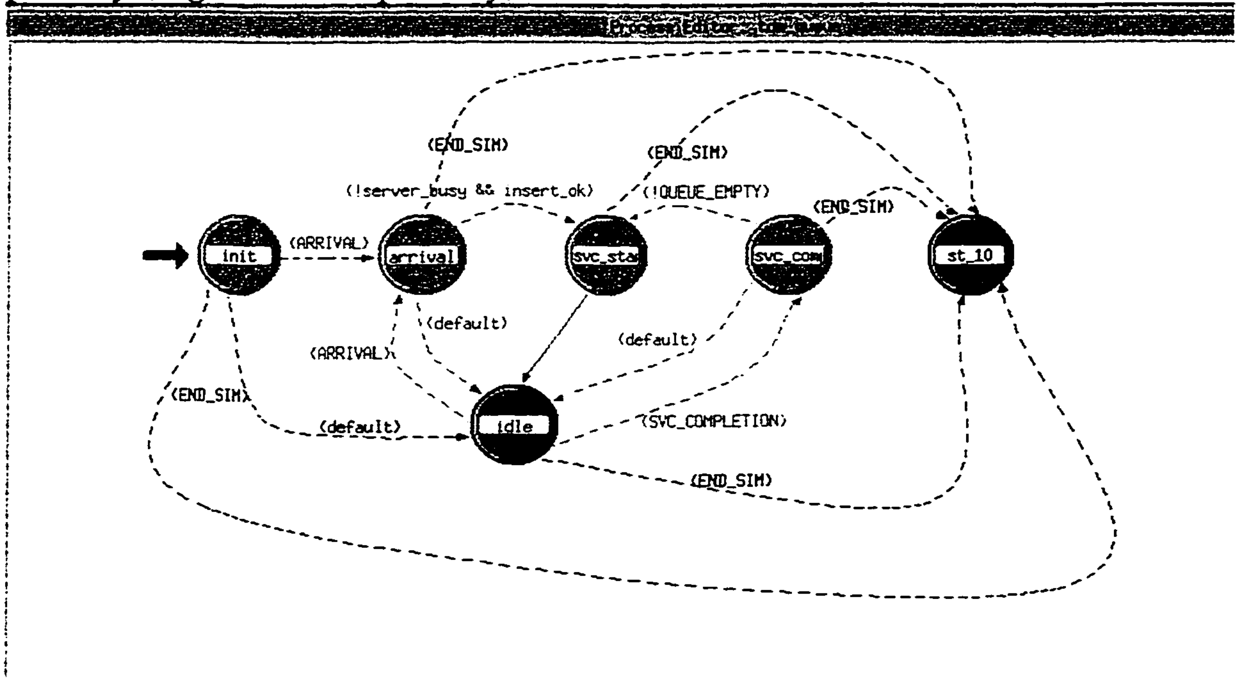


Figure 127 OPNET Tandem Queue Process Finite State Machine

The process has six states: ***init, arrival, svc_start, svc_completed, st_10*** and ***idle.***

Init, arrival, svc_start and ***svc_completed,*** are *forced* OPNET states (the execution of the process finite state machine cannot be interrupted while in this states).

Note that in the case of the dual traffic, the tandem queue process maintains two separate waiting queues: one of high priority traffic and another for low priority traffic. The low priority traffic is serviced only if the high priority queue is empty. However, the service discipline is non-preemptive (i.e., an arriving high priority packet does not preempt a low priority packet already being serviced).

The state diagram is the same for the two cases; however, the executable code is different. The tandem queue process is used by all sub-networks (***nd_1, nd_2*** and *nd_3*), for both types of traffic. The two priority traffic network models use the two priority variant of the tandem queue process.

The following table gives a brief description of these states:

State	**Forced**	**Description**
init	Yes	Read simulation variables and initialize simulation parameters.
arrival	Yes	Arrival of a new packet. If the server was idle, the new packet starts being serviced immediately. Otherwise, the packet is deposited in the queue (assuming enough place is available; otherwise the packet is discarded).
st_10	No	Write simulation statistics (when the simulation ends).
svc_start	Yes	Start of service for the new packet
svc_completed	Yes	Service of a packet is completed. The packet is either further transmitted or discarded (only if the packet is of type "background traffic" and the "discard probability" indicates that the packet should be discarded).
idle	No	Wait for an event to happen (arrival or end of service time).