

SCHEDULING AND MANAGEMENT OF REAL-TIME
COMMUNICATION IN POINT-TO-POINT WIDE AREA
NETWORKS

By
Cheryl Lynn Pope
2002

A THESIS SUBMITTED FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
IN THE DEPARTMENT OF COMPUTER SCIENCE
UNIVERSITY OF ADELAIDE

2002

© Copyright 2003

by

Cheryl Lynn Pope

Abstract

Applications with timing requirements, such as multimedia and live multi-user interaction, are becoming more prevalent in wide area networks. The desire to provide more predictable performance for such applications in packet switched wide area networks is evident in the channel management provided by Asynchronous Transfer Mode (ATM) networks and in the extensions to the Internet protocols proposed by the Internet Engineering Task Force (IETF) working groups on integrated and differentiated service. The ability to provide guarantees on the performance of traffic flows, such as packet delay and loss characteristics, relies on an accurate model of the traffic arrival and service at each node in the network.

This thesis surveys the work in bounding packet delay based on various proposed queuing disciplines and proposes a method for more accurately defining the traffic arrival and worst case backlog experienced by packets. The methods are applied to the first in first out (FIFO) queuing discipline to define equations for determining the worst case backlog and queuing delay in multihop networks. Simulation results show a significant improvement in the accuracy of the delay bounds over existing bounds published in the literature. An improvement of two orders of magnitude can be realised for a ten hop path and the improvement increases exponentially with the length of the path for variable rate network traffic. The equations derived in the thesis also take into consideration the effect of jitter on delay, thereby removing the requirement for rate controllers or traffic shaping within the network.

In addition to providing more accurate delay bounds, the problem of providing fault tolerance to channels with guaranteed quality of service (QoS) is also explored. This

thesis introduces a method for interleaving resource requirements of backup channels to reduce the overall resource reservations that are required to provide guaranteed fault recovery with the same QoS as the original failed channel. An algorithm for selecting recovery paths that can meet a channel's QoS requirements during recovery is also introduced.

Declaration

This is to certify that this thesis contains no material which has previously been accepted for the award of any degree or diploma in any University. To the best of my knowledge and belief it contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

If this thesis is accepted for the award of the degree, permission is granted for it to be made available for loan and photocopying.

Cheryl Pope

2002

Acknowledgements

I may never have undertaken this PhD without the enthusiastic encouragement of the person who became my advisor, Dr. Jay Yantchev. He often steered me in the right direction when I wasn't certain which path to investigate and I acknowledge his significant contribution to my PhD studies.

Prof. Chris Barter deserves special mention, not only for providing excellent facilities as Head of the Computer Science department; but also for providing the opportunity for me to spend part of my early candidature at Oxford University. It was during this time that I was able to visit the University of York's real-time computing group and define my research problem.

Spouses are often acknowledged for their significant support and tolerance during PhDs. Few people are as fortunate as I am, however, to have a spouse who has offered not only emotional support but intellectual support as well. For his infinite patience, system administration and LaTeX skills, giving me priority on our home computer, being a sounding board for my ideas, not being afraid to actually read and understand the "hairy equations", as well as giving me encouragement when I needed it, I acknowledge my husband, Dr. Michael Pope. I'm very lucky to have him.

Finally I would like to acknowledge my parents for encouraging my interest in maths and science and for the many sacrifices they have made for my studies. I would also like to thank Erika for having some long naps while I was making amendments to this thesis. This thesis is dedicated to her. May she find the world a peaceful place full of discoveries to be made.

Contents

Abstract	iii
Declaration	v
Acknowledgements	vi
1 Introduction	2
1.1 Differentiated and Integrated Service	5
1.2 Managing QoS Agreements	7
1.3 Building End-to-End QoS	10
1.4 Contributions of Thesis	12
1.5 Outline of Thesis	13
2 Requirements and Goals for Real-Time Communication in WANs	15
2.1 Network Architecture	16
2.2 Relevance of Scaling Real-Time LAN Techniques	20
2.3 Survey	24
2.3.1 Best Effort Approaches	25
2.3.2 Bandwidth Reservation Approaches	28
2.3.3 Schedulability Analysis	30
2.4 End-to-End Requirements	32
2.4.1 Specification of per Flow Performance Requirements	32
2.4.2 Flow Traffic Specification	35

2.4.3	Mapping Applications to Flow Specification	38
2.4.4	Routing	40
2.4.5	Connection Admission Control	43
2.4.6	Traffic Policing and Shaping	46
2.5	Conclusion	48
3	Router Scheduling Policies for Real-Time Communication	49
3.1	Introduction	49
3.2	Traffic Arrival, Service Policy and QoS Bounds	50
3.3	Current Service Disciplines for Real-Time Networks	56
3.3.1	FIFO	56
3.3.2	Priority Queues	58
3.3.2.1	Rotating Priority Queues	59
3.3.3	Earliest Deadline First	61
3.3.3.1	Delay Earliest Due Date	62
3.3.3.2	Jitter Earliest Due Date	64
3.3.4	Stop and Go	65
3.3.5	Virtual Clock	68
3.3.6	Leave-in-Time	70
3.3.7	Fair Queuing	70
3.3.7.1	Packet by Packet Generalised Processor Sharing	71
3.4	Taxonomy	72
3.5	Comparing the Service Discipline Bounds	77
3.5.1	Switch Complexity	82
3.5.2	Over-Reservation of Resources	84
3.6	Conclusions	86
4	FIFO Schedulability Analysis for Non-Rate Controlled Traffic Flows	89
4.1	Introduction	89
4.2	Traffic Serialization	90

4.3	Idle Periods on Input Links	92
4.3.1	Finding a Node's Maximum Delay, Jitter and Buffer Use	99
4.4	Per Node Schedulability Analysis	99
4.4.1	Service Analysis for Combined Peak Channel Rates Less Than or Equal to the Output Link Rate	100
4.4.1.1	Sum of Input Link Rates Less Than or Equal To the Output Link Rate	100
4.4.1.2	Sum of the Input Link Rates Greater Than the Output Link Rate	101
4.4.2	Service Analysis for Combined Peak Channel Rates Greater Than the Output Rate	104
4.5	Limiting Search Space	107
4.6	Traffic Distortion in a Multi-hop Network	109
4.7	Multi-hop Bounds for Non-Rate Controlled Traffic	111
4.7.1	Service Analysis for Combined Peak Channel Rates Less than or equal to Output Link Rate	112
4.7.1.1	Sum of Input Link Rates less than or equal to Output Link Rate	112
4.7.1.2	Sum of the Input Link Rates Greater Than the Output Link Rate	112
4.8	Combined Peak Channel Rates $>$ Output Link Rate	120
4.9	Summary	122
5	Connection Admission Control	123
5.1	Introduction	123
5.2	Connection Admission Control	124
5.3	Avoiding Deadlock and Livelock	132
5.4	Conclusions	134
6	Simulation Results	135

6.1	Introduction	135
6.2	Single Hop Simulation Results	137
6.2.1	Combined Peak Channel Rates Less Than or Equal to the Output Link Rate	139
6.2.2	Combined Peak Channel Rates Greater Than the Output Link Rate	146
6.2.3	Packet Backlog versus Load	148
6.2.4	Packet Backlog versus Time	153
6.2.5	Backlog Under Non-Worst Case Conditions	156
6.3	Simulation of a Multihop Flow	157
6.3.1	Continuous Bit Rate Traffic	161
6.3.2	Bursty Traffic	164
6.3.3	Variable Rate Traffic	166
6.4	Discussion	168
7	Fault Tolerance in Real-Time Packet Switched Networks	173
7.1	Introduction	173
7.2	Methods of Fault Tolerance	174
7.3	Efficient Proactive Fault Recovery	175
7.3.1	Establishing Real-Time Channels	176
7.3.1.1	Minimum Guaranteed Delay Bound	178
7.3.2	Fault Tolerant Real-Time Channels	180
7.3.2.1	Single Failure Immune (SFI) Real-Time Channels	181
7.3.2.2	Using Network Characteristics to Reduce Resources for Back Up Channels	184
7.4	IBR vs SFI: an example	188
7.4.1	Summary of the Cost and Benefits of IBR	190
7.5	Timing Effects	191
7.5.1	Recovery Timing Effects on End to End Delay	192
7.5.2	Local Fault Recovery	193

7.5.3	Source Fault Recovery	194
7.5.4	Recursive Nearest Node Recovery	195
7.5.5	Management of Channel Recovery	199
7.5.6	Summary	202
7.6	Conclusions	203
8	Conclusions	205
A	Additional Equations and Proofs for Chapter 4	213
B	Algorithm for Calculating Maximum Delay	223
C	Resource Overhead of IBR in a Mesh	225

List of Tables

1	Behaviour Taxonomy	75
2	Implementation	76
3	Delay and Jitter Bounds	78
4	Parameters	78
5	Delay and Jitter Bounds (Packet Based Model)	80
6	Buffer Bounds	82
7	Design Trade-offs	84

List of Figures

2-1	Network Architecture	17
2-2	Network Router Node Architecture	18
2-3	Distortion of a Flow	29
2-4	Unique Aperiodic Flows with Identical Specification	38
2-5	Link Sharing in Receiver Initiated Reservations	45
3-1	Backlog and QoS at a Node	51
3-2	Individual Flow Arrivals	54
3-3	Service Curve	54
3-4	FIFO	57
3-5	Priority Queues	58
3-6	Rotating Priority Queues	60
3-7	Scheduler Saturation	62
3-8	Jitter-EDD node	64
3-9	Stop and Go	66
3-10	Incoming and Outgoing Frames	66
3-11	The General Real-Time Node	76
4-1	Serialization of Channel Traffic	91
4-2	Idle Link Periods	94
4-3	Determining the Start of a Busy Period	96
4-4	Backlog vs. Time	107
4-5	Traffic Generated by Links L_0 and L_1	107
4-6	Traffic Distortion within a Network	110

5-1	3-phase connection establishment	125
6-1	Single Hop Simulation	138
6-2	Simulation Configuration - Total Channel Rate and Total Input Link Rate Less than Output Link Rate	140
6-3	Total Channel Rate and Total Input Link Rate no Greater than Output Link Rate	141
6-4	Simulation Configuration - Total Channel Rate no Greater than Output Link Rate, Total Input Link Rate Greater than Output Link Rate . . .	143
6-5	Simulation Output -Total Channel Rate Less than Output Link Rate - 10% load	145
6-6	Simulation Output - Total Channel Rate Less than Output Link Rate - 99% load	146
6-7	Packet Backlog vs Load	149
6-8	Packet Backlog vs Load - Closer View	150
6-9	Backlog and Channel Bursts	150
6-10	Arrivals From Channels with Different Averaging Intervals	152
6-11	Backlog vs Time at 99% load	154
6-12	Backlog vs Time at 20% Load	155
6-13	Channels with Different Averaging Intervals	156
6-14	Backlog under Non-worst case traffic	157
6-15	Multiple Hop Simulation	158
6-16	Continuous Bit Rate Traffic - End-to-End Delay by Path Length	161
6-17	Comparison of Models - Continuous Traffic - 99% Load	163
6-18	Bursty Traffic - Total Delay at each Hop	165
6-19	Comparison of Models - Bursty Traffic - 99% Load	166
6-20	Comparison of Models - Bursty Traffic - 99% Load - Closer View	167
6-21	Variable Rate Traffic - Total Delay at each Hop	168
6-22	Comparison of Models - Variable Rate Traffic - 99% Load	169
7-1	Determining d^t	179

7-2 Routing Fault Recovery	194
--------------------------------------	-----