

Differentiated Service Support in Optical Burst Switching
WDM Networks

DISSERTATION

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By

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ABSTRACT

The explosive growth of Internet traffic provides strong incentives to exploit the huge bandwidth of (dense) wavelength division multiplexing fiber optical networks. Real-time applications, such as videoconferencing, and telemedicine, require higher Quality of Service than the current best-effort IP service. Differentiated Service (Diff-Serv) architecture has been proposed recently by the Internet Engineering Task Force as a scalable and manageable architecture for service differentiation in IP networks and the Internet. Compared with other optical switching technologies such as wavelength routing and optical packet switching, Optical Burst Switching (OBS) takes advantage of both mature electronic control processing and high-speed optical data transmission technologies. It is very important to provide DiffServ support in OBS WDM networks in order to meet future Internet bandwidth and QoS demands.

This research proposes a Differentiated Optical Burst Service (DOBS) model and its network architecture. The OBS resource reservation and scheduling process is modeled as a queueing network. The burst loss probability conservation law is proved for the M/M/K/K priority loss system when all bursts of various priority classes have the same service rate. Two burst scheduling schemes are designed to support DiffServ in OBS WDM networks. The priority-based burst scheduling (PBS) scheme processes control packets based on their priority classes and preempts one or more lower priority bursts if necessary. The Differentiated Burst Scheduling (DS) scheme schedules high

priority bursts earlier than lower priority bursts only if the high priority bursts arrive with a certain period of time after the lower priority bursts. Both the PBS and DS schemes guarantee the multimedia data synchronization. DS also allows each core node to dynamically support differentiated services according to its resource and capacity. The performances of PBS and DS are evaluated in terms of burst loss probability by extensive simulations for a single link in a core node as well as for the ABILENE network with two wavelengths per link and two priority classes. Both exponential and Pareto distributions are considered for the control packet inter-arrival times and burst lengths.

This is dedicated to my parents.

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TABLE OF CONTENTS

	Page
Abstract	ii
Dedication	iv
Acknowledgments	v
Vita	vi
List of Tables	xiii
List of Figures	xiv
Chapters:	
1. INTRODUCTION	1
1.1 Motivation	1
1.2 Related Work	3
1.2.1 Differentiated Optical Services Model	3
1.2.2 Reservation Process Modeling and Performance Analysis	6
1.2.3 Differentiated Service Support with OBS Scheduling	6
1.3 Major Contributions	8
1.4 Organization of the Dissertation	10
2. BACKGROUND	12
2.1 Introoduction	12
2.2 Differentiated Services	12
2.3 Optical Network and WDM	15
2.4 Optical Switching	16
2.5 Optical Burst Switching Mechanism	17

2.6	OBS Network Architecture	20
2.7	OBS Router Architecture	20
2.8	Data Burst Assembly Mechanism	22
2.9	OBS Data Burst Scheduling Schemes	25
2.10	QoS Support Mechanisms	26
2.11	Chapter Summary	27
3.	DIFFERENTIATED OPTICAL BURST SERVICES	29
3.1	Introduction	29
3.2	DOBS Framework	30
3.3	DOBS Architectural Model	31
3.4	DOBS Parameters and Functional Capabilities	32
3.5	DOBS Burst Assembly and Class Mapping	34
3.6	Chapter Summary	35
4.	RESERVATION PROCESS MODELING AND PERFORMANCE ANALYSIS	37
4.1	Introduction	37
4.2	OBS Reservation Process and Parameters	38
4.2.1	Reservation Process	38
4.2.2	Reservation Process Parameters	39
4.3	OBS Reservation Process Modeling	42
4.3.1	Scheduling Wait Process	42
4.3.2	Control Packet Process	42
4.3.3	Burst Offset Process	43
4.3.4	Switch Setup Process	44
4.3.5	Burst Transmission Process	44
4.4	Burst Loss Probability Conservation	44
4.4.1	Loss Probability Conservation	45
4.4.2	M/M/1 Two Priority Preemption	46
4.5	OBS Reservation Performance Analysis	48
4.5.1	Achievable Burst Loss Probability	48
4.6	Burst Loss Probability Analysis	49
4.7	Chapter Summary	50
5.	PRIORITY-BASED SCHEDULING	52
5.1	Introduction	52
5.2	Burst Scheduling Framework	53
5.3	Priority-based Scheme	54

5.4	Simulation Results and Discussion	56
5.4.1	Simulation Model and Parameters	56
5.4.2	Single Traffic Flow	60
5.4.3	Multiple Traffic Flows	92
5.5	Chapter Summary	124
6.	DIFFERENTIATED SCHEDULING	126
6.1	Introduction	126
6.2	Differentiated Service Scheduling	127
6.2.1	Scheduling Scheme	127
6.2.2	Base Offset Time	130
6.2.3	Differentiated Processing Delay	131
6.2.4	Priority Offset Time	131
6.2.5	Burst Offset Time	132
6.2.6	Support of Different Number of Priority Classes	132
6.2.7	Priority Class Isolation	133
6.3	Performance Evaluation	135
6.3.1	Single Traffic Flow	136
6.3.2	Multiple Traffic Flows	149
6.3.3	Control of Service Differentiation	164
6.4	Conclusion	169
7.	END-TO-END DIFFERENTIATED SERVICES	170
7.1	Introduction	170
7.2	Scheduling Queue Policies	171
7.3	Simulation Model	173
7.4	Simulation Results and Performance Analysis	175
7.4.1	Burst Loss Probability of High Priority Class	175
7.4.2	Burst Loss Probability over Flow	180
7.4.3	Performance Comparison of Burst Scheduling Schemes	184
7.5	Chapter Summary	189
8.	CONTRIBUTIONS AND FUTURE WORK	191
8.1	Key Results	191
8.2	Future Work	193
Appendices:		
A.	ABBREVIATION AND ACRONYMS	195

B.	SIMULATION MODELS	197
B.1	CSIM Simulation Package	197
B.2	General Simulation Run Times and Data Variances	198
B.3	Basic Process and Data Structures for Simulation	199
B.3.1	Input of the simulation Program	201
B.3.2	Time Control of the Simulation	205
B.3.3	Simulation of Basic Processes	205
B.3.4	Data Structures	207
B.3.5	Data Collection and Processing of the Simulation Program .	208
B.3.6	Simulation Results: An Example	209
B.4	Summary	218
	Bibliography	219

LIST OF TABLES

Table	Page
5.1 SBS, PBS, and pJET system and flow variables	59
6.1 SBS, PBS, pJET, and DS system and flow variables	136
7.1 Traffic Route Description	174
7.2 System and flow variables	175

LIST OF FIGURES

Figure	Page
2.1 Optical Burst Switching Mechanism	19
2.2 Optical Burst Switched Network Architecture	21
2.3 Optical Burst Switched Core Router Architecture	22
2.4 Optical Burst Switched Edge Router Architecture	23
3.1 The Differentiated Optical Burst Services (DOBS)	30
3.2 The Differentiated Optical Burst Services (DOBS) Model	32
3.3 The Optical Transport Network Architectures of G.872, DoS, and DOBS	35
3.4 DOBS functionalities	36
4.1 OBS reservation process and its time parameters	40
4.2 Queueing network model of OBS reservation process	43
4.3 State transition diagram of M/M/1/ with priority	47
5.1 Scheduling Qos Data Bursts	57
5.2 Scheduling Qos Data Bursts	58
5.3 Burst loss probability as a function of the traffic load for 4 priority classes using SBS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.	61

5.4	Burst loss probability as a function of the traffic load for 4 priority classes using the SBS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths	62
5.5	Burst loss probability as a function of the traffic load for 4 priority classes using the SBS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, Pareto distributed inter-arrival time, and exponentially distributed burst lengths	63
5.6	Burst loss probability as a function of the traffic load for 4 priority classes using the SBS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, Pareto distributed inter-arrival time, and Pareto distributed burst lengths	64
5.7	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.	65
5.8	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths	66
5.9	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths	67
5.10	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, Pareto distributed inter-arrival time, and Pareto distributed burst lengths	68
5.11	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-WP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.	70

5.12	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-WP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths	71
5.13	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-WP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths	72
5.14	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-WP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, Pareto distributed inter-arrival time, and Pareto distributed burst lengths	73
5.15	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.	74
5.16	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths	75
5.17	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths	76
5.18	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, Pareto distributed inter-arrival time, and Pareto distributed burst lengths	77
5.19	Burst loss probability as a function of the traffic load for priority class 0 for schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.	79

5.20	Burst loss probability as a function of the traffic load for priority class 3 for schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.	80
5.21	Burst loss probability as a function of the traffic load for priority class 0 for schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, $n = 4$, exponentially distributed control packet inter-arrival times, and Pareto distributed burst lengths.	81
5.22	Burst loss probability as a function of the traffic load for priority class 3 for schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, $n = 4$, exponentially distributed control packet inter-arrival times, and Pareto distributed burst lengths.	82
5.23	Burst loss probability as a function of the traffic load for priority class 0 for schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, $n = 4$, Pareto distributed control packet inter-arrival times, and exponentially distributed burst lengths.	84
5.24	Burst loss probability as a function of the traffic load for priority class 3 for schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, $n = 4$, Pareto distributed control packet inter-arrival times, and exponentially distributed burst lengths.	85
5.25	Burst loss probability as a function of the traffic load for priority class 0 for schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, $n = 4$, Pareto distributed control packet inter-arrival times, and Pareto distributed burst lengths.	86
5.26	Burst loss probability as a function of the traffic load for priority class 3 for schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, $n = 4$, Pareto distributed control packet inter-arrival times, and Pareto distributed burst lengths.	87

5.27	Burst loss probability of class 0 as a function of the traffic load using burst scheduling scheme PRI for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, $t_{ou} = 20\mu$, $t_{du} = 40\mu$, the burst traffic has an Pareto inter-arrival time distribution and an exponential burst length distribution.	88
5.28	Burst loss probability of class 3 as a function of the traffic load using burst scheduling scheme PRI for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, $t_{ou} = 20\mu$, $t_{du} = 40\mu$, the burst traffic has an Pareto inter-arrival time distribution and an exponential burst length distribution.	89
5.29	Burst loss probability as a function of the maximum number of the number of priority classes for $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 40\mu s$, and $\rho = 0.8$	90
5.30	Burst loss probability as a function of the maximum number of the number of wavelengths for $n = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 40\mu s$, and $\rho = 0.8$	91
5.31	Burst loss probability as a function of the offset time unit for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, and $\rho = 0.8$	92
5.32	Burst loss probability as a function of the traffic load for 4 priority classes using the SBS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.	94
5.33	Burst loss probability as a function of the traffic load for 4 priority classes using the SBS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $srv_a = 1.5$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths	95
5.34	Burst loss probability as a function of the traffic load for 4 priority classes using the SBS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $iar_a = 1.5$, Pareto distributed inter-arrival time, and exponentially distributed burst lengths	96
5.35	Burst loss probability as a function of the traffic load for 4 priority classes using the SBS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $iar_a = 1.5$, $srv_a = 1.5$, Pareto distributed inter-arrival time, and Pareto distributed burst lengths	97

5.36	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.	98
5.37	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $srv_a = 1.5$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths	99
5.38	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $iar_a = 1.5$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths	100
5.39	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $iar_a = 1.5$, and $srv_a = 1.5$, Pareto distributed inter-arrival time, and Pareto distributed burst lengths	101
5.40	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-WP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.	102
5.41	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-WP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $srv_a = 1.5$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths	103
5.42	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-WP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $iar_a = 1.5$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths	104
5.43	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-WP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $iar_a = 1.5$, $srv_a = 1.5$, Pareto distributed inter-arrival time, and Pareto distributed burst lengths	105

5.44	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.	106
5.45	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $srv_a = 1.5$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths	107
5.46	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $iar_a = 1.5$, Pareto distributed inter-arrival time, and Pareto distributed burst lengths	108
5.47	Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $iar_a = 1.5$, $srv_a = 1.5$, Pareto distributed inter-arrival time, and Pareto distributed burst lengths	109
5.48	Burst loss probability as a function of the traffic load for priority class 0 for the schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.	111
5.49	Burst loss probability as a function of the traffic load for priority class 3 for the schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.	112
5.50	Burst loss probability as a function of the traffic load for priority class 0 for the schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, $n = 4$, $srv_a = 1.5$, exponentially distributed control packet inter-arrival times, and Pareto distributed burst lengths.	113

5.51	Burst loss probability as a function of the traffic load for priority class 3 for the schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, $n = 4$, $srv_a = 1.5$, exponentially distributed control packet inter-arrival times, and Pareto distributed burst lengths.	114
5.52	Burst loss probability as a function of the traffic load for priority class 0 for schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, $n = 4$, Pareto distributed control packet inter-arrival times, and exponentially distributed burst lengths.	115
5.53	Burst loss probability as a function of the traffic load for priority class 3 for the schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, $n = 4$, $iar_a = 1.5$, Pareto distributed control packet inter-arrival times, and Pareto distributed burst lengths.	116
5.54	Burst loss probability as a function of the traffic load for priority class 0 for the schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, $n = 4$, $iar_a = 1.5$, $srv_a = 1.5$, Pareto distributed control packet inter-arrival times, and Pareto distributed burst lengths.	117
5.55	Burst loss probability as a function of the traffic load for priority class 3 for the schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, $n = 4$, $iar_a = 1.5$, and $srv_a = 1.5$, Pareto distributed control packet inter-arrival times, and Pareto distributed burst lengths.	118
5.56	Burst loss probability of class 0 as a function of the traffic load using the burst scheduling scheme PBS-SP for $n = 4$, $k = 4$, $h = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, $t_{ou} = 20\mu$, $t_{du} = 40\mu$, $iar_a = 1.5$, and $srv_a = 1.5$	119
5.57	Burst loss probability of class 3 as a function of the traffic load using the burst scheduling scheme PBS-SP for $n = 4$, $k = 4$, $h = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, $t_{ou} = 20\mu$, $t_{du} = 40\mu$, $iar_a = 1.5$, and $srv_a = 1.5$	120
5.58	Burst loss probability as a function of the maximum number of the number of priority classes for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_p = 10\mu s$ and $t_{ou} = 20\mu s$	121

5.59	Burst loss probability as a function of the maximum number of the number of wavelengths per link for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$	122
5.60	Burst loss probability as a function of the maximum number of the remaining hops for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, and $\rho = 0.8$.	123
5.61	Burst loss probability as a function of the maximum number of the remaining hops for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, and $\rho = 0.8$.	124
6.1	Differentiated Scheduling	130
6.2	Burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_b = 40\mu s$, $t_{du} = 40\mu s$, $h = 1$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.	138
6.3	Burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_b = 40\mu s$, $t_b = 40\mu s$, $t_{du} = 40\mu s$, $h = 1$, $n = 4$, $srv_ \alpha = 1.5$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths	139
6.4	Burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_b = 40\mu s$, $t_{du} = 40\mu s$, $h = 1$, $n = 4$, and $iar_ \alpha = 1.5$, Pareto distributed inter-arrival time, and exponentially distributed burst lengths	140
6.5	Burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_b = 40\mu s$, $t_{du} = 40\mu s$, $h = 1$, $n = 4$, $iar_ \alpha = 1.5$, $srv_ \alpha = 1.6$, Pareto distributed inter-arrival time, and Pareto distributed burst lengths.	141
6.6	Burst loss probability of class 0 as a function of the traffic load varying burst scheduling schemes for SBS, PBS-SP, PBS-WP, PBS-MP, PJET, and DS for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, exponentially distributed inter-arrival time, and exponentially distributed burst lengths, and PJET uses priority offset unit $40\mu s$	142

6.7	Burst loss probability of class 0 as a function of the traffic load varying burst scheduling schemes for SBS, PBS-SP, PBS-WP, PBS-MP, PJET, and DS for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, exponentially distributed inter-arrival times, and exponentially distributed burst lengths, and PJET uses priority offset unit $40\mu s$	143
6.8	Burst loss probability of class 0 as a function of the traffic load using burst scheduling scheme DS for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, $t_{ou} = 20\mu$, $t_{du} = 40\mu$, the burst traffic has an exponentially or Pareto distributed inter-arrival times and burst lengths.	144
6.9	Burst loss probability of class 3 as a function of the traffic load using burst scheduling scheme DS for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, $t_{ou} = 20\mu$, $t_{du} = 40\mu$, the burst traffic has an exponentially or Pareto distributed inter-arrival times and burst lengths.	145
6.10	Burst loss probability as a function of the maximum number of the remaining hops for $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{du} = 40\mu s$, $\rho = 0.8$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths	146
6.11	Burst loss probability as a function of the maximum number of the number of wavelengths for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{du} = 40\mu s$, $\rho = 0.8$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.	147
6.12	Burst loss probability as a function of the maximum number of the offset time unit for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{du} = 40\mu s$, $\rho = 0.8$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.	148
6.13	Burst loss probability as a function of the differentiated processing delay unit for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, and $\rho = 0.8$.exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths	149
6.14	Burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme for $k = 4$, $t_p = 10\mu s$, $t_b = 40mus$, $t_{ou} = 20\mu s$, $t_{du} = 40\mu s$, $h = 4$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.	151

6.15	Burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{du} = 40\mu s$, $h = 4$, $n = 4$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths	152
6.16	Burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{du} = 40\mu s$, $h = 4$, $n = 4$, Pareto distributed inter-arrival time, and exponentially distributed burst lengths	153
6.17	Burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{du} = 40\mu s$, $h = 4$, $n = 4$, Pareto distributed inter-arrival time, and Pareto distributed burst lengths	154
6.18	Burst loss probability of class 0 as a function of the traffic load varying burst scheduling schemes for SBS, PBS-SP, PBS-WP, PBS-MP, PJET, and DS for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, exponentially distributed inter-arrival time, and exponentially distributed burst lengths, and PJET uses priority offset unit $40\mu s$	155
6.19	Burst loss probability of class 0 as a function of the traffic load varying burst scheduling schemes for SBS, PBS-SP, PBS-WP, PBS-MP, PJET, and DS for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, exponentially distributed inter-arrival time, and exponentially distributed burst lengths, and PJET uses priority offset unit $40\mu s$	156
6.20	Burst loss probability of class 0 as a function of the traffic load using burst scheduling scheme DS for $n = 4$, $k = 4$, $h = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, $t_{ou} = 20\mu$, $t_{du} = 40\mu$, the burst traffic has an Pareto inter-arrival time distribution and an exponential burst length distribution.	157
6.21	Burst loss probability of class 3 as a function of the traffic load using burst scheduling scheme DS for $n = 4$, $k = 4$, $h = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, $t_{ou} = 20\mu$, $t_{du} = 40\mu$, the burst traffic has an Pareto inter-arrival time distribution and an exponential burst length distribution.	158
6.22	Burst loss probability as a function of the maximum number of the remaining hops for $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{du} = 40\mu s$, $\rho = 0.8$, exponentially distributed control inter-arrival times, and exponentially distributed burst lengths.	160

6.23	Burst loss probability as a function of the maximum number of the remaining hops for $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{du} = 40ms$, $\rho = 0.8$, exponentially distributed control inter-arrival times, and exponentially distributed burst lengths.	161
6.24	Burst loss probability as a function of the maximum number of the remaining hops for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{du} = 40ms$, $\rho = 0.8$, exponentially distributed control inter-arrival times, and exponentially distributed burst lengths.	162
6.25	Burst loss probability as a function of the maximum number of the remaining hops for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$	163
6.26	Burst loss probability as a function of the maximum number of the remaining hops for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $\rho = 0.8$, exponentially distributed control inter-arrival times, and exponentially distributed burst lengths	164
6.27	Burst loss probability of class 0 as a function of the traffic load when $DPD_0 = 0\mu s$, DPD_1 ranges from $0\mu s$ to $80\mu s$, $DPD_2 = 80\mu s$, $DPD_3 = 120\mu s$, $n = 4$, $k = 4$, $h = 1$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_b = 40\mu s$, $h = 1$, and both the control packet inter-arrival times and the burst lengths are exponentially distributed.	165
6.28	Burst loss probability of class 1 as a function of the traffic load when $DPD_0 = 0\mu s$, DPD_1 ranges from $0\mu s$ to $80\mu s$, $DPD_2 = 80\mu s$, $DPD_3 = 120\mu s$, $n = 4$, $k = 4$, $h = 1$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_b = 40\mu s$, $h = 1$, and both the control packet inter-arrival times and the burst lengths are exponentially distributed.	166
6.29	Burst loss probability of class 2 as a function of the traffic load when $DPD_0 = 0\mu s$, DPD_1 ranges from $0\mu s$ to $80\mu s$, $DPD_2 = 80\mu s$, $DPD_3 = 120\mu s$, $n = 4$, $k = 4$, $h = 1$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_b = 40\mu s$, $h = 1$, and both the control packet inter-arrival times and the burst lengths are exponentially distributed.	167

6.30	Burst loss probability of class 3 as a function of the traffic load when $DPD_0 = 0\mu s$, DPD_1 ranges from $0\mu s$ to $80\mu s$, $DPD_2 = 80\mu s$, $DPD_3 = 120\mu s$, $n = 4$, $k = 4$, $h = 1$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_b = 40\mu s$, $h = 1$, and both the control packet inter-arrival times and the burst lengths are exponentially distributed.	168
7.1	Internet 2 Abilene network topology	173
7.2	Burst loss probability as a function of the traffic load using the SBS scheme with queue policies SQ, PQ, and FQ for $n = 2$, $k = 2$, $t_b = 40\mu s$, $t_p = 4\mu$, $t_{ou} = 20\mu s$, exponentially distributed inter-arrival times, and exponentially distributed burst lengths.	177
7.3	Burst loss probability as a function of the traffic load using the SBS scheme with queueing policies ROQ, POQ, FOQ, and TOQ for $n = 2$, $k = 2$, $t_b = 40\mu s$, $t_p = 4\mu$, $t_{ou} = 20\mu s$, exponentially distributed inter-arrival times, and exponentially distributed burst lengths.	178
7.4	Burst loss probability as a function of the traffic load using the pJET scheme with queueing policies SQ, PQ, and FQ for $n = 2$, $k = 2$, $t_b = 40\mu s$, $t_p = 4\mu$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, exponentially distributed inter-arrival times, and exponentially distributed burst lengths.	179
7.5	Burst loss probability as a function of the traffic load using the pJET scheme with queueing policies ROQ, POQ, FOQ, and TOQ for $n = 2$, $k = 2$, $t_b = 40\mu s$, $t_p = 4\mu$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, exponentially distributed inter-arrival times, and exponentially distributed burst lengths.	181
7.6	Burst loss probability as a function of the traffic load using the DS scheme with the queueing policies SQ, PQ, and FQ for $n = 2$, $k = 2$, $t_b = 40\mu s$, $t_p = 4\mu$, $t_{ou} = 20\mu s$, $t_{du} = 40\mu s$, exponentially distributed inter-arrival time, and exponentially distributed burst lengths.	182
7.7	Burst loss probability as a function of the traffic load using the DS scheme with queueing policies ROQ, POQ, FOQ, and TOQ for $n = 2$, $k = 2$, $t_b = 40\mu s$, $t_p = 4\mu$, $t_{ou} = 20\mu s$, $t_{du} = 40\mu s$, exponentially distributed inter-arrival times, and exponentially distributed burst lengths.	183

7.8	Burst loss probability as a function of the traffic load using DS with various queueing policies for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 2\mu$, exponentially distributed inter-arrival time, and exponentially distributed burst lengths.	185
7.9	Burst loss probability as a function of the traffic load using PBS-SP with various queueing policies for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 2\mu$, exponentially distributed inter-arrival time, and exponentially distributed burst lengths.	186
7.10	Burst loss probability as a function of the traffic load using PJET with various queueing policies for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 2\mu$, exponentially distributed inter-arrival time, and exponentially distributed burst lengths.	187
7.11	Burst loss probability as a function of the traffic load using the schemes SBS, pJET, and DS with queueing policies SQ, PQ, and FQ for $n = 2$, $k = 2$, $t_b = 40\mu s$, $t_p = 4\mu$, exponentially distributed inter-arrival time, and exponentially distributed burst lengths.	188
7.12	Burst loss probability as a function of the traffic load using SBS-WP-ROQ, POQ, FOQ, TOQ for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 2\mu$, exponentially distributed inter-arrival time, and exponentially distributed burst lengths.	189
B.1	Simulation model for a single node	199
B.2	Simulation model for a network	200

CHAPTER 1

INTRODUCTION

1.1 Motivation

The Internet has become an important and ubiquitous commercial infrastructure. As more and more people access the Internet by means such as desktop or wireless PDA for B2B (Business to Business), B2C (Business to Consumer), B2G (Business to Government), and P2P (peer to peer) applications, more bandwidth and transport capacity are demanded [12]. How to build an Internet infrastructure that is scalable and can meet ever increasing demand and provides QoS (Quality of Service), is a very important and challenging task. Optical WDM (Wavelength Division Multiplexing) [10] has emerged as a major network transmission technology because of its ability to support a great number of high-speed channels in the range of Gbps (Giga bits per second) bandwidth channels in a single fiber. Currently, technologies make it possible to have 160 channels, each with a 20 Gbps bandwidth, in a single fiber. Researchers are continuously working hard to achieve up to 1000 channels in a fiber, each with a 40 Gbps bandwidth. However, current switching technology is electronically-based with low speed and requires O/E (optical-to-electrical) and E/O (electrical-to-optical) conventions. Typically an electronic switch can handle up to 10 Gbps data. Currently

ATM switches and IP routers can switch data using only individual wavelength because data is processed in the electronic domain. O/E and E/O conversions cause unnecessary delay. Optical switching becomes critical to the future of the Internet. Three optical switching technologies have been studied: optical circuit switching, optical burst switching and optical packet switching. Optical circuit switching in the form of wavelength routed lightpaths is currently used in WDM networks. It is effective but not bandwidth efficient unless the traffic for each lightpath connection is always large. Optical packet switching, on the other hand, is bandwidth efficient, but the technologies it requires to support the optical processing and optical RAM (random access memory) are not mature for the time being. Optical burst switching [89, 81] is most promising in the sense that it utilizes both the proved electronic control processing mechanism and the mature optical transmission technology. It electronically allocates the resources in the optical switching system ahead the optical transmission of the optical data bursts. To overcome the high discrepancy between a relatively low electronic processing speed and an extraordinarily high optical transmission rate, optical burst switching transports large bursts assembled from smaller packets such as IP packets. To further support the real-time multimedia application in the future Internet such as video on demand, telemedicine, and remote learning, optical burst switching is required to support high QoS (e.g. low delay, jitter, and loss probability).

QoS is defined as low delay, low jitter, and low loss probability. Current IP (Internet Protocol) provides only the best effort service. Two approaches have been proposed to support QoS in the future IP networks. The first approach is Integrated Services (IntServ) model. IntServ requires that per flow information be kept in each intermediate (core) node to support end-to-end QoS. For large networks, it is not

scalable to keep information for each of millions of flows. DiffServ acts on aggregated flows and per hop behavior is satisfied by each intermediate node according to code bits (priority) carried by each packet. DiffServ is thus made scalable. For high bandwidth optical WDM connections, the scalability problem of IntServ gets even worse. Relatively few wavelengths per fiber in WDM work well with the coarse granularity of DiffServ.

1.2 Related Work

1.2.1 Differentiated Optical Services Model

In this section, we describe Differentiated Optical Services (DoS) over WDM networks [44]. First we review optical DiffServ based on the ITU-T (International Telecommunication Union – Telecommunication Standardization Sector)’s G.872 reference architecture [54]. A layered architecture for OTN comprises functional capabilities provided by optical network elements for transport, multiplexing, routing, supervision, and survivability if client signals are processed predominantly in the optical domain. The optical network elements considered include optical regenerators (1R, 2R,3R), optical amplifiers (OA), optical wavelength multiplexers/demultiplexers, optical add/drop multiplexers (OADM). and optical crossconnects (OXC).

There are three independent logical transport layers in OTN:

1. The optical transmission section (OTS) — provides the functionality for transmission of optical signals on various types of optical media. Functions provided by OAs reside in this layer.
2. The optical multiplex section (OMS) — provides the transport of a multiwavelength optical signal, including the insertion of the multiplex section overhead

to ensure the integrity of the signal. It also provides multiplex section survivability. Optical network elements that belong to this layer are wavelength multiplexers and fiber crossconnects.

3. The optical channel (OCh) section - provides end-to-end networking of optical lightpaths for transparently carrying various client signals (e.g. SDH, ATM cells, and IP packets). It also prepares and inserts an overhead for the channel configuration information such as wavelength tag, port connectivity, payload label (rate, format, line code), and wavelength protection capabilities. This layer contains OXC and OADM functionality.

The Differentiated Optical Services (DoS) model is similar to the DiffServ model. This gives DoS an advantage for developing efficient support of IP differentiated services in DWDM networks. The DoS model consists of four components including an architecture model, service classes, mapping of traffic flows and service classification, signaling and optical resource allocation.

The architecture model defines the DoS domain and captures the concept of end-to-end QoS in a global network environment. The DoS domain is a set of core optical nodes such as OAs, OXCs, wavelength multiplexers, and edge nodes consisting of OADMs where electro-optical conversion and traffic grooming take place. DoS services are only defined at the edge nodes since DoS parameters are not visible in the core all-optical networks. End-to-end services are provided by concatenating multiple domains that could be engineered or administrated separately. The DoS domain consists of two major components. The first component is the interface module which implements QoS aware functions for aggregating and mapping DiffServ flows originating from the access network onto equivalent optical flows with QoS parameters

enforced in the optical domain. The performance characteristics of optical lightpaths at the OADMs are made available in this module in electrical form. Incoming DiffServ flows with similar requirements are aggregated to form a flow with a capacity equal to the standard commercial available optical capacity such as OC-12, OC-48, and OC-192. The other components are OXCs, OADMs, and OAs, in which the transmitted information along the lightpath remains entirely in the optical domain.

A DoS service is defined by a set of parameters that characterize the quality and impairments of the optical signal carried over a lightpath. The parameters are either specified in quantitative terms, such as delay, average BER (bit error rate), jitter, and bandwidth (lightpath characteristics), or based on functional capabilities such as light monitoring, lightpath protection, and lightpath security and lightpath transparency.

In the interface at the ingress point in optical networks, the incoming DiffServ flows are aggregated into fewer flows at the rate corresponding to lightpath traffic carrying capacity such as OC-48 and OC-192. The lightpaths are grouped into classes that reflect the unique qualities of optical transmission. The aggregated DiffServ flows are mapped onto lightpath classes that correspond to the QoS of the aggregated flows. An admission control and policing function is implemented for the aggregated flows so that the OTN does not accept more DiffServ flows than the available optical resources in the OTN can support.

In addition to policing and classification, reserving the optical resources is an equally important control function that is critical to making appropriate admission control decisions and to configuring the edge classifiers. A signaling protocol is required to collect state information and reserve optical resources. In-band channels or supervisory channels can be used for signaling.

1.2.2 Reservation Process Modeling and Performance Analysis

Burst Loss Probability in OBS Networks

Most OBS models have been focused on analyzing the burst loss probability in a single link because of the complexity of modeling networks. However, the link model does not consider the following effects:

- A dropped burst increases the load to the network nodes before it is discarded
- A dropped burst also reduces the load to the next node in its path

An reduced load fixed point approximation [85] can be used to investigate the affect of scheduling schemes on the burst of loss probability in OBS networks.

1.2.3 Differentiated Service Support with OBS Scheduling

Resource reservation is critical for the performance of OBS. One of the most important issues in OBS resource reservation is burst scheduling. Burst scheduling uses information contained in control packets to reserve outgoing wavelengths and switch matrix paths for the corresponding data bursts in each intermediate node. OBS burst scheduling has been studied by several researchers. Turner presented a scalable burst switch architecture with a burst scheduling scheme called Horizon [89].

The scheduler in Horizon maintains a *time horizon* for each outgoing wavelength. The *time horizon* is defined as the earliest time after which the wavelength is not reserved. The scheduler processes a control packet and assigns the corresponding data burst to the wavelength with the latest *time horizon* that is earlier than the arrival time of the data burst. Wei *et al.* [98, 99] proposed a *just-in-time* burst scheduling scheme (JIT), which also supports circuit switching. Qiao and Yoo [81] proposed and analyzed a burst scheduling scheme known as *just-enough-time* (JET). The JET uses a *delay reservation* technique to reserve a wavelength for a data burst from the data burst arrival time, not from the control packet arrival time as proposed in JIT, to the burst departure time. Callegati *et al.* [6] and Xiong *et al.* [102] designed an OBS control architecture and studied a class of burst scheduling algorithms. Verma *et al.* [90] proposed a traffic shaping scheme, which randomizes the offset time of the control packet and the data burst in order to reduce the burst loss probabilities.

Several OBS burst scheduling schemes have been further proposed to support Quality of Service (QoS) in OBS networks. Yoo *et al.* [111] described and analyzed a prioritized JET, called pJET, for multiple priority class traffic. In the pJET, a high priority burst is assigned an extra offset time, called priority offset time, than a low priority burst. A high priority burst, therefore, requests a wavelength reservation more ahead of time than a low priority burst and has a better chance to obtain a wavelength. Yang *et al.* [104] proposed a class queue based burst scheduling algorithm to support differentiated services. Chen *et al.* [11] introduced the concept of proportional QoS in OBS networks and used an intentional dropping scheme to give a controllable burst loss probability for different services classes.

Liu and Liu proposed and analyzed a priority-based burst scheduling scheme (PBS) [67]. In the PBS, high priority bursts are always scheduled before lower priority bursts no matter when they arrive. Both the PBS overcomes the synchronization problem observed in the pJET [111]. A high priority data burst, in the pJET, has a longer offset time and a longer end-to-end delay than a low priority data burst. This may impair the accuracy or performance of certain multimedia applications, which is not desirable.

An efficient, scalable and dynamic data burst scheduling scheme has to be designed to support QoS in OBS WDM networks. As part of this dissertation research, we proposed and analyzed the priority-based burst scheduling scheme (PBS) [67], the *differentiated services scheduling* (DS) [65, 64, 68, 66]. Our scheduling schemes support differentiated services without extra offset time for high priority classes and can be used together with other QoS support mechanism.

1.3 Major Contributions

The primary goal of this research is to design optical burst switching control mechanisms and resource reservation schemes to support differentiated services in OBS WDM networks. The research provides insight into OBS network architecture, and into support of differentiated services by different control and resource reservation mechanisms. The schemes proposed here are applicable to other networks with separate entities for control processing and data transmission. The major contribution can be summarized into three main parts.

First, we define Differentiated Optical Burst Services (DOBS) model for differentiated service support in OBS WDM networks. We describe DOBS framework,

DOBS architectural model, the important DOBS parameters and functional capabilities, and DOBS burst assembly and class mapping between IP DS service classes to DOBS priority classes.

Secondly, we exam optical burst switching (OBS) reservation process and discuss some important parameters and their impact on the resource reservation. A general framework for its modeling and analysis is presented. We model the OBS reservation using queueing networks. Our framework and model cover all aspects of OBS reservation process including the control packet arrival, the offset time assignment, the control packet processing, the optical switch matrix setup, and the data burst arrival and transmission. We also investigate when the conservation law about burst loss probability holds and can be used to calculate the burst loss probabilities of various priority classes. We propose how to approximate the burst loss probability when the conservation law can not be used to calculate the burst loss probability.

In third part, we first propose a priority-based burst scheduling (PBS) scheme. PBS always processes highest priority control packets in its scheduling queue first. It supports media synchronization and in-order frame delivery without require an extra offset time for each priority class. Further, we design a new data burst scheduling scheme, called *Differentiated Scheduling* (DS), which supports differentiated services in OBS. The DS schedules high priority bursts earlier than lower priority bursts only if the high priority bursts arrive within a certain period of time after the lower priority bursts. The differentiated services in terms of burst loss probability are achieved by processing the control packets of higher priority class bursts more promptly upon their arrivals than those of lower priority class bursts. Unlike the pJET, DS assigns the same priority offset time to all the bursts destined to the same edge node. With

the additional priority offset time, each intermediate node can adjust the burst loss probabilities of various priority classes by choosing its own *differentiated processing delay* value for each priority class or its own *differentiated processing delay difference* value between any pair of adjacent priority classes. According to our best knowledge, none of current QoS supporting burst scheduling schemes allows intermediate (core) nodes to dynamically adjust the burst loss probabilities of priority classes. Most performance studies of OBS burst scheduling schemes focused on a single link in a single node. However it is more important to understand how the various burst scheduling schemes perform in a network environment. In an OBS network, bursts from various flows pass through an OBS node with various offset times and priorities. In the last chapter of the third part, different queueing policies can be utilized to process control packets based on their priority classes and flow ids. The performances are evaluated in terms of burst loss probability for the various burst scheduling schemes, including the standard burst scheduling without priority (SBS), PBS-SP, PJET, and DS under various scheduling queue policies in this chapter.

1.4 Organization of the Dissertation

The rest of this dissertation is organized as follows. Chapter 2 discusses some background material necessary for understanding *differentiated services* (DiffServ), optical WDM networks, and related work in differentiated services in optical WDM networks, burst assembly and scheduling mechanisms, and burst scheduling schemes to support QoS in OBS WDM networks.

Chapter 3 describes the network architecture of optical burst switched WDM networks and proposes a *differentiated optical burst services* (DOBS) model and architecture for OBS WDM networks.

Chapter 4 exams optical burst switching reservation process and discuss some important parameters and their impact on the resource reservation. A general framework for its modeling and analysis is presented. We also investigate when the conservation law about burst loss probability holds an can be used to calculate the burst loss probabilities of various priority classes.

Chapter 5 proposes the *priority-based scheduling* (PBS) scheme and analyzes its performance compared with pJET in a single node.

Chapter 6 proposes the *differentiated scheduling* (DS) scheme to support differentiated services and evaluate and compare its performance with PBS and pJET.

Chapter 7 investigate and compare the end-to-end performances of various burst scheduling schemes with various scheduling queueing and queue ordering policies.

Finally, chapter 8 concludes the dissertation with a summary of the results. The chapter also presents future directions for research in differentiated services for optical networks.

CHAPTER 2

BACKGROUND

2.1 Introduction

In this chapter, we first describe the Differentiated Service (DiffServ) model in current IP networks. we then give the background in optical burst switching architecture, mechanism, and performance with special emphasis on QoS support.

2.2 Differentiated Services

Current IP only provides best effort service. Two approaches have been proposed to support Quality of Service in future IP networks. The first one is Integrated Services (IntServ) [5]. IntServ uses *Resource Reservation Protocol* (RSVP) to reserve resources and control admission for each receiver's request for a certain level of performance. Per-flow state information has to be kept and updated by each router/node along the way in order to fulfill the service requirement of each flow. It causes a scalability problem in wide area networks. Differentiated Service (DiffServ) [4] model is proposed to overcome the scalability problem. DiffServ does not keep per-flow information for the end-to-end per flow performance guarantees. DiffServ defines the layout of the IP TOS byte (DS field) and a base set of packet forwarding treatments

(per-hop behaviors, or PHBs). By marking the DS field of each packet differently and handling each packet based on its DS fields, several DiffServ classes can be created. Therefore, DiffServ is essentially a relative-priority scheme.

Using classification, policing, shaping, and scheduling mechanisms, many services can be provided, such as

- Premium service for applications requiring low-delay and low-jitter service
- Assured service for applications requiring better reliability than best-efforts service
- Olympic service, which provides three tiers of services: gold, silver, and bronze, with decreasing quality

DiffServ is significantly different from InServ. First, there are only a limited number of service classes indicated by the DS field. Since service is allocated in the granularity of a class, the amount of state information is proportional to the number of classes rather than the number of flows. DiffServ is therefore more scalable than IntServ. Second, sophisticated classification, marking, policing, and shaping operations are only needed at the boundary of the network. The core routers need only to have behavior aggregate (BA) classification. Therefore, it is easier to implement and deploy DiffServ. There is another reason the second feature is desirable. Core routers must forward packets very quickly, and therefore their task must be simple. Boundary routers need not forward packets very quickly because edge links are relatively slow. Two DiffServ models have been identified: Absolute Service Differentiation (ASD) and Relative Service Differentiation (RSD).

A refined RSD model, the *proportional differentiation model* [23, 24], defines the quantitative differentiation between service classes. A RSD model only guarantees that the high priority class traffic will receive no worse service when the amount of traffic in a network increases. The proportional differentiated service model quantitatively adjusts the service differentiation of a particular QoS metric to be proportional to the differentiation factors that a network service provider sets beforehand. Let q_i be the QoS metric of interest and s_i the differentiation factors for class i ($1 \leq i \leq N$). Using the proportional differentiated service model, we should have:

$$\frac{q_j}{q_i} = \frac{s_j}{s_i} \quad (i, j = 1 \cdots N)$$

for all pairs of service classes (i, j) . For example, in a packet network, assume that q_1, q_2 are the packet loss probability for class 1 and class 2 respectively. If $s_1 = 2 \times s_2$, then $q_1 = 2 \times q_2$ which means that the packet loss probability of class 2 should be half that of packet loss probability of class 1.

Further, it is desirable that the proportional differentiated service model holds not only over long time scales, but also over short time periods. The reason is that the long term average is not quite meaningful when the traffic is bursty. Then the proportional differentiated equation should hold within a short time period τ , which is called the *monitoring time-scale* in [23, 24]:

$$\frac{q_j(t, t + \tau)}{q_i(t, t + \tau)} = \frac{s_j}{s_i} \quad (i, j = 1 \cdots N)$$

where $q_i(t, t + \tau)$ is the average QoS metric in the time period τ .

In this thesis research, the service differentiation is studied only in terms of the burst loss probability. However, the new burst scheduling schemes proposed in Chapter 6 do allow the adjustment of burst loss probabilities among multiple priority burst classes.

2.3 Optical Network and WDM

The useful optical spectrum is 1540 - 1570 nanometers (nm). Wavelength Division Multiplexing (WDM) uses multiple wavelengths for transmission. One reason to use WDM instead of a faster wavelength is that currently optical devices including transmitters and receivers do not function well in bit intervals (the time to generate and detect bits one after another) less than 0.025 ns (nanoseconds) for 40 Gbps. WDM and dense WDM (DWDM) are basically the same technologies. WDM uses wavelength spacings of about 10 nm while DWDM has wavelength spacings of 1 nm or even 0.1 nm. According to [45], the current record for wavelength packing on a single fiber is 1022 channels of total throughput, only about 40 Gbps. However, since the potential serial bit transmission on fiber is 160 Gbps, DWDM systems with throughput in excess of 160 Tbps (160,000 Gbps) are possible.

The *Synchronous Optical Network* (SONET) is a set of coordinated ITU, ANSI, and Bellcore standards that define a hierarchical set of transmission rates and formats for optical fiber systems. The *Synchronous Digital Hierarchy* (SDH) is an international standard from ITU. SONET (SDH) a single-wavelength technology with one serial stream of bits. The highest speed standardized for SONET (SDH) is 10 Gbps (OC-192/STM-64). Its future possible speed is 40 Gbps (OC-768/STM-256). However the SONET (SDH) is still firmly an electrical network with optical links.

An optical networking [63, 60, 62], by definition, has network elements and components that perform at least some of the essential networking tasks at an optical level. Optical Networks consist of Optical Add/Drop Multiplexers (OADM), Optical Cross-Connects (OXC), Optical Transponders, Optical Switches, and Optical Routers.

2.4 Optical Switching

In the evolution of optical networking, the most important switching technologies [103, 101, 56, 87, 77] are wavelength routing (optical circuit switching), optical packet switching, and optical burst switching.

Wavelength routing basically follows the main concepts of traditional circuit-switched networks. A wavelength-routed network is constructed by connecting routers that provide wavelength routing mapping from $\langle \text{input port, incoming wavelength} \rangle$ to $\langle \text{output port, outgoing wavelength} \rangle$. To set up a communication channel, a path between the source and destination pair is chosen with appropriate wavelengths allocated on the links along the path. Such channels are called lightpaths. If the signaling protocol operates in a distributed mode, it is necessary to initiate a two-way reservation process for lightpath establishment. On any fiber link of the network, no wavelength sharing is allowed between two distinct lightpaths simultaneously. As a result, such coarse-grained processing makes wavelength routing suffer from low bandwidth utilization.

Optical packet switching is designed to overcome the problem of inefficient bandwidth usage of wavelength routing. An OPS processing unit is a fixed-length and unaligned packet consisting of header and payload. In this way, resources are allocated in an on-demand fashion with finer granularity and consequently bandwidth

utilization can be greatly improved. Because of the *store-and-forward* nature inherited from packet switching, packets are temporarily buffered at each intermediate node. Currently, optical buffers are implemented using fiber delay lines (FDLs). To align packets coming from various input ports, synchronization is necessary. The major problems of optical packet switching include the difficulty of realizing an optical packet synchronizer, the requirement of optical buffers, and the relatively high control overhead resulting from small payloads.

As a viable alternative to optical packet switching, optical burst switching (OBS) has been proposed [107, 106, 81, 89, 69, 57]. OBS processes control packets and reserves resources in electronic domain [74, 50] and forwarding data bursts in the optical domain. The performance of OBS has been studied in [110, 19, 116, 84, 58, 72, 22, 96, 100, 40, 71, 65, 66, 78, 114, 42].

2.5 Optical Burst Switching Mechanism

Optical Burst Switching (OBS) makes it possible to support all-optical WDM networks with current limited optical memory availability and optical processing capability. The concept of the burst switching was first proposed in the 1980s [1]. But at the time, both signaling and transmission of the burst switch were electronic-based and unnecessarily complex compared to other fast packet/cell switch technologies such as the ATM. Recently, burst switching was proposed as a new switching paradigm for optical networks, therefore, called OBS. Coupled with the mature electronic processing technology, OBS does not require any optical processing capability except optical data transmission. OBS takes advantage of both electronic control processing and optical transmission technologies. By using large bursts, OBS overcomes the high

discrepancy between a relatively low electronic processing speed and an extraordinarily high optical transmission rate. OBS sends control packets ahead of data bursts to reserve resources such as wavelengths so that the data bursts can all pass optically without opto-electronic-opto conversion or optical buffering in each intermediate (core) node. Without the bandwidth inefficiencies suffered by optical circuit switching (wavelength routing) or the optical buffering required by optical packet switching, OBS is currently the most promising optical switching technology.

In OBS WDM networks, a control packet is sent before its corresponding data burst to reserve resources such as wavelengths and optical switch matrix setups in intermediate nodes. The characteristics of OBS are listed as follows:

- Each data burst travels through an all-optical path between its source and its destination nodes.
- Neither opto-to-electronic conversion nor electronic-to-opto conversion is needed for data bursts at each intermediate node.
- A control packet is sent before its corresponding data burst to reserve resources in the switches and wavelengths along its path.
- Each control packet is processed electronically at each intermediate node to set up each optical switch/cross-connect for the corresponding data burst to pass optically.
- There is a delay, called *offset time*, between the transmission of a control packet and the transmission of its corresponding data burst.

- The offset time is the sum of the *base offset time* and the *priority offset time*.

The base offset time is used to accommodate the control processing time at each intermediate node to ensure that the control packet is always ahead of the data burst. The priority offset time is added to provide service differentiation in pJET or to allow service differentiation adjustment in DS.

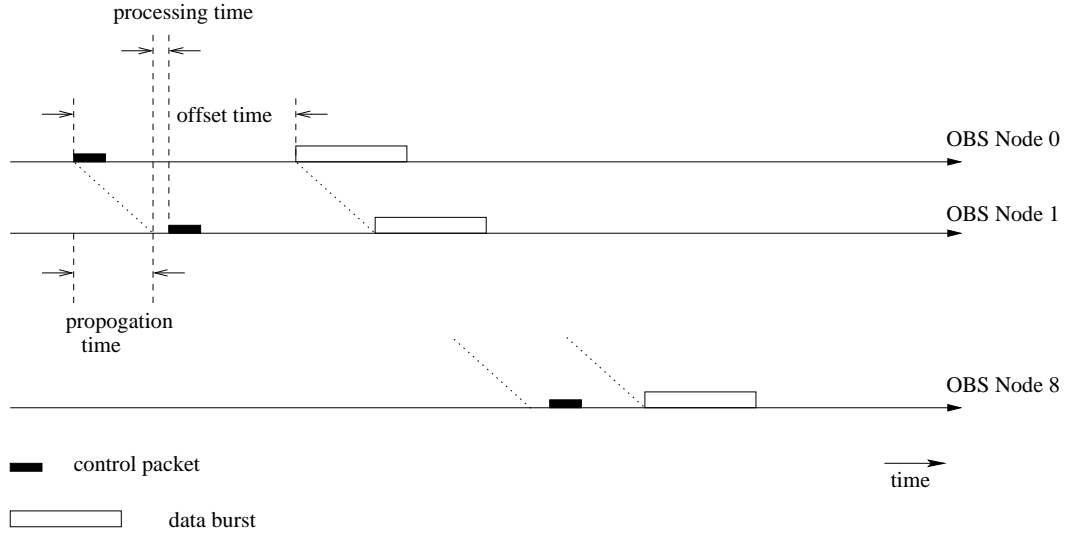


Figure 2.1: Optical Burst Switching Mechanism

The diagram in Figure 2.1 illustrates the relative positions of a control packet and its corresponding data burst along the time axis as they go through several OBS nodes. Each node takes a *processing time* to process the control packet and to set up the switch matrix. The offset time between the control packet and the data burst, therefore, decreases by a *process time* whenever they pass through a node. The initial offset time for a data burst, determined by its ingress edge node, must be long enough to ensure that the control packet is always ahead of the data burst.

In general, OBS uses one-way reservation in that bursts are transmitted without the confirmation of lightpath setups between the ingress and egress nodes. In hybrid optical switching like *wavelength-routed optical burst switching* [3, 14, 13, 26, 29, 30], lightpaths are dynamically established (two-way reservation) for the transmission of bursts to provide end-to-end delay guarantee. Performance and network design issues of *wavelength-routed optical burst switching* have been studied in [37, 28, 3, 39, 61, 35, 38].

2.6 OBS Network Architecture

OBS network architecture has been studied in [20]. In the proposed OBS WDM network architecture shown in Figure 2.2, edge nodes (routers) assemble packets into data bursts which are stored in electronic buffers and sent out after control packets. Core nodes (routers) process control packets and dynamically set up lightpaths for data bursts. By concentrating electronic buffering at the network edge, the need for optical buffering in the core nodes (routers) is eliminated. Even though optical buffering is not needed in core OBS nodes, FDL-based optical buffers [41] can still be used for better QoS support [113] and deflection routing [49].

2.7 OBS Router Architecture

In an OBS edge router [8, 9], a data burst is large, and usually consists of several or tens of average packets such as IP packets. Data bursts instead of packets are switched due to the discrepancy between low speed electronic control packet processing and high-speed optical data transmission. The packets in a data burst usually have the same destination edge router, and the same QoS requirements such as bandwidth,

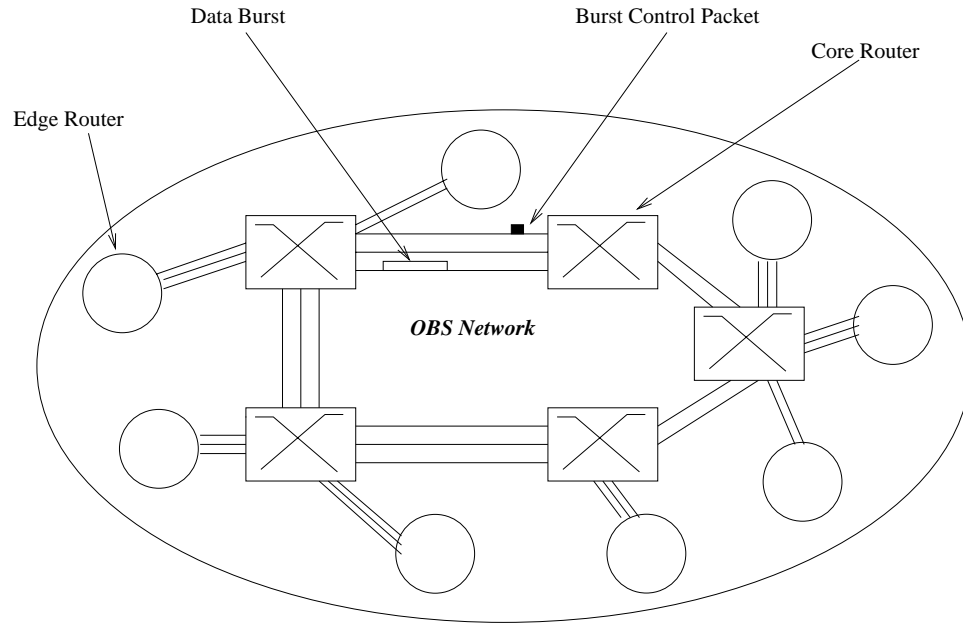


Figure 2.2: Optical Burst Switched Network Architecture

maximum delay and delay jitter. An OBS ingress router sends out a control packet for each assembled data burst and transmits the data burst after an offset time indicated by the control packet. Each core router will process the control packet electronically, select an output port and wavelength and set up its switch matrix for the data burst to go through. A typical core router is depicted in Figure 2.3 where an OBS switching router consists of input/output ports, a switch matrix, a routing unit, and a control unit. The control unit processes a control packets electronically, consults the routing unit to select an output port and wavelength for the corresponding data burst and sets up the switch matrix. No optical buffers are needed in the OBS router. If no output port or outgoing wavelength is available, a data burst will be dropped. Figure 2.4

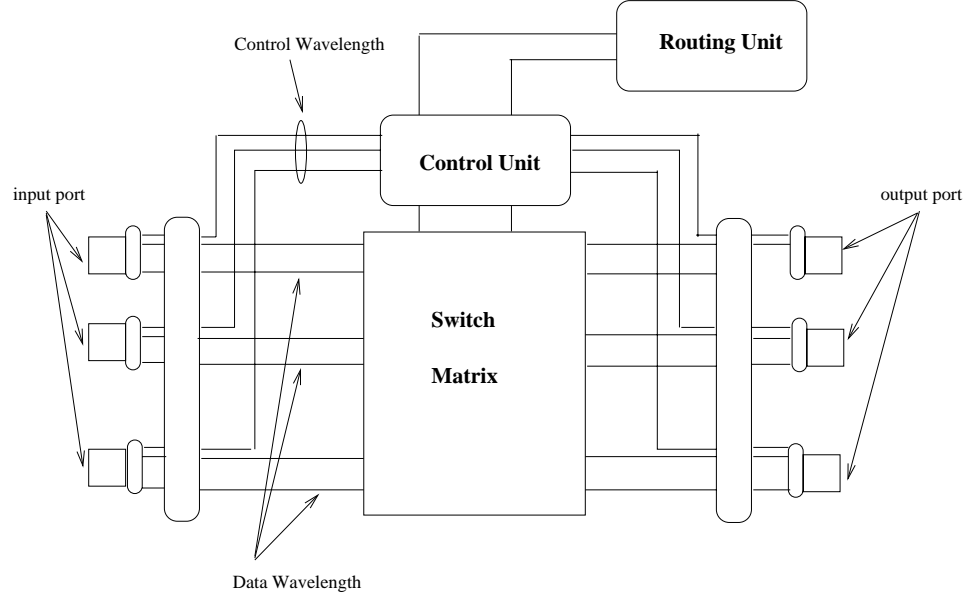


Figure 2.3: Optical Burst Switched Core Router Architecture

shows a typical edge router architecture which has burst assembler and disassembler, scheduler and electrical buffers to store assembled or incoming bursts.

2.8 Data Burst Assembly Mechanism

In OBS edge router, packets which are directed to the same destination with the same QoS requirement, or in the same FEC (flow equivalent class) defined for MPLS (Multiprotocol Label Switching), are assembled into a data burst up to a certain length in time or in bytes [7]. Current data burst arrival is modeled by exponential distribution, fractional Gaussian noise (FGN) self-similar traffic [80], ON-OFF source with different probability density functions for the ON and the OFF state [51, 52], or a heavy-tailed Pareto distribution [105, 55].

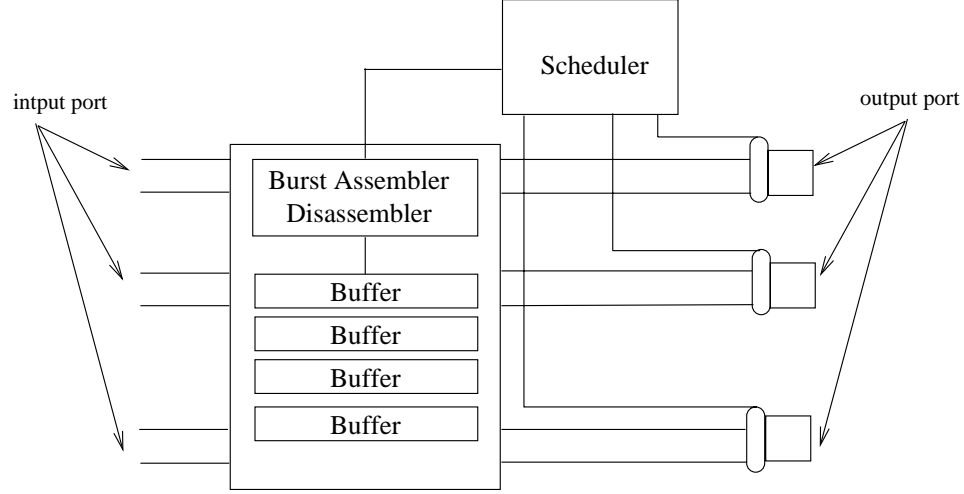


Figure 2.4: Optical Burst Switched Edge Router Architecture

An average data burst is about 15 kilobytes, containing several or few tens of IP packets. The transmission time of a data burst is about $12 \mu s$ at 10 Gbps. Assume the control packet size is 64 bytes, the CPU speed is 1 GHz, the processing time is about $5 \mu s$. The distance between Boston, MA and Seattle, WA is about 4000 m, thus the propagation time is about $20 \mu s$ due to the speed of light $2 \times 10^8 m/s$ in optical fiber. Considering that total delay allowed for multimedia application is about 350 ms, offset time less than 100 ms can be used for data bursts.

In an OBS ingress node, packets are assembled into bursts. A data burst is assembled when either an assembly time interval or a maximum data burst size is reached [102, 43, 91]. The data burst size can be either in terms of bytes [102, 43] or packet numbers [91, 93]. There will be a burst assembler for each output port. If there are E destination (egress edge router addresses) and C different QoS classes, each burst assembler needs $E \cdot C$ queues to sort arriving packets. For $1 \leq i \leq C \cdot E$,

assume the burst assembly time of queue i is $T_a(i)$ μs and the maximum size of bursts of queue i is $L_{b,max}$ (in bytes) or $L_{p,max}$ (in packets). Let $t_a(i)$ and l_b (l_p) be the assembly time past and the size of burst in bytes (packets) respectively. We have the following general burst assembly algorithm:

1) When a packet of length l arrives to queue i :

If ($l_b(i) == 0$)

$t_a(i) = 0$;

$l_b(i) = l_b + l$;

$l_p(i) = l_p + 1$;

else if ($l_b(i) + l < L_{b,max}$ (or $l_p(i) + 1 < L_{p,max}$))

generate a burst with length $l_b(i)$;

$t_a(i) = 0$;

$l_b(i) = 1$;

2) When $t_a(i) == T_a(i)$

generate a burst with length $l_b(i)$;

$l_b(i) = 0$;

The assembly time increases with the number of destinations and the number of QoS services. The increase in the burst assembly time will introduce longer packet delays in edge routers. The issue is how to choose burst assembly time in an OBS network environment.

2.9 OBS Data Burst Scheduling Schemes

Resource reservation is critical for the performance of OBS. One of the most important parts of OBS reservation is burst scheduling which uses information from control packets to reserve outgoing wavelengths for incoming data bursts. A typical control packet is composed of the following fields:

- routing information such as a label for MPLS
- data burst length in transmission time
- basic offset time to overcome the total control unit processing time (delay) of control packet
- extra (priority) offset time to isolate the high priority data bursts from lower priority data bursts
- data burst priority

OBS burst scheduling has been studied by several authors [6, 28, 53, 76, 88, 89, 90, 95, 99, 98, 102, 109, 111]. The signaling mechanism has also been studied [115, 47, 2]. Turner [89] presented a scalable burst switch architecture with a wavelength reservation scheme called Horizon. Another wavelength reservation scheme known as *just-enough-time* (JET) protocol was proposed and analyzed by Qiao and Yoo [81]. Wei *et al.* [98, 99] proposed the *just-in-time* (JIT) wavelength reservation scheme which also supports circuit switching and packet switching. The performance of OBS networks with JIT was compared with that of networks employing circuit switching or packet switching technologies. Callegati *et al.* [6] and Xiong *et al.* [102] considered OBS control architecture and studied a class of wavelength scheduling

algorithms including *latest available unused channel with void filling* (LAUC-VF). A scheduling algorithm is designed to minimize the voids generated by arriving bursts in [53]. The burst loss probabilities of JET, JIT and Horizon were compared in [22]. A traffic shaping scheme randomizing the offset to reduce the burst loss probability was proposed by Verma *et al.* [90]. A two-way reservation scheme was proposed in [25, 14, 13, 28, 34, 36, 31, 32, 33]. The design trade-offs in bandwidth utilization and wavelength re-use were described in [27]. The dynamic wavelength allocation reduces wavelength requirements and enables networks to respond to variable traffic demands. The maximum traffic load that can be supported by OBS with dynamic wavelength allocation was studied in [15]. TCP performance of OBS was also studied in [18].

2.10 QoS Support Mechanisms

QoS is supported in OBS networks through providing service differentiation [57, 70] for bursts of multiple priority classes in terms of burst or packet loss probability and delay. There are currently five categories of techniques for QoS support as follows:

- Prioritized segmentation and priority dropping [94, 92, 17, 73].
- Extra priority offset time [86].
- QoS supporting scheduling schemes [67, 64, 68, 104, 11].
- Prioritized assembly techniques [21].
- Prioritized deflection routing [92].
- QoS-oriented wavelength assignment [48, 97].

In a typical OBS network, each intermediate OBS node takes a time δ to process a control packet and set up a switch path in the node. The total processing and setup time for a data burst from the ingress node to the egress node will be $\Delta = \delta \cdot h$ where h is the number of hops between the ingress and egress nodes. A data burst is delayed for offset time T after the corresponding control packet has been sent.

In JET [81, 108], offset time T is set to be greater than Δ . A control packet carries information about offset time T and data burst length l . The switch matrix path and wavelength in the output port are reserved for a period of l from the data burst arrival. Since every intermediate node is set up before the data burst arrives, no buffer is needed for any intermediate node. The data burst is buffered in the source node for T time. An offset time based scheme called priority JET (pJET) was proposed in [111, 82, 112, 113] to support QoS. In pJET, a high priority data burst is delayed an extra offset time Θ in addition to T . The offset time carried in its control packet will be $T + \Theta$. The extra offset time allows a high priority data burst to reserve the resource earlier than the other low priority data bursts arriving in a close time period. The extra offset time is a multiple of the mean of the burst length distribution [111]. This mechanism is very similar to that of flight ticket reservations. The earlier the reservation, the better the chance of getting a ticket.

2.11 Chapter Summary

In this chapter, we presented the background of this dissertation. The current differentiated services models in the Internet were discussed. The optical network and WDM technology were presented here. Three types of optical switching mechanisms were introduced. Optical burst switching mechanism was further studied with OBS

network and router architecture, and data burst scheduling scheme. We also discussed resource reservation mechanisms, contention prevention and resolution mechanisms, and QoS support mechanisms.

CHAPTER 3

DIFFERENTIATED OPTICAL BURST SERVICES

3.1 Introduction

It is very important to define a differentiated service model in providing differentiated services support in optical WDM networks. A differentiated service model called Differentiated Optical Services (DoS) was proposed for optical circuit switching in optical WDM networks in [44]. However, there is not any differentiated service model defined for optical burst switching in optical WDM networks.

In this chapter, we propose a differentiated service model called Differentiated Optical Burst Services (DOBS) for optical burst switching WDM networks. DoS focuses on mapping DiffServ requirements to lightpath requirements, and provides differentiated service for optical networks in the lightpath level. The proposed DOBS model focuses on differentiated services support in the burst level instead. DiffServ model is packet-based and matches better with burst-based DOBS than circuit-based DOS. The DiffServ DS field maps to the DOBS priority field, which is carried in control packets. This mapping functionality is implemented in OBS ingress nodes.

3.2 DOBS Framework

We discuss a framework for providing DOBS in WDM networks. Figure 3.1 shows a layered architecture for DOBS WDM networks. Bottom two layers OTS and OMS are as defined in ITU-T Recommendation G.872. The DOBS OBS layer replaces G.872's third and top layer OCh with a OBS layer . The OCh layer of G.872 provides end-to-end optical lightpath in optical circuit switching WDM networks. The new OBS layer provides a connection-less OBS switching path. A new layer, called Differentiated Optical Burst Service layer, contains most of our DOBS model functionality and provides a mapping of IP DiffServ services onto DOBS services.

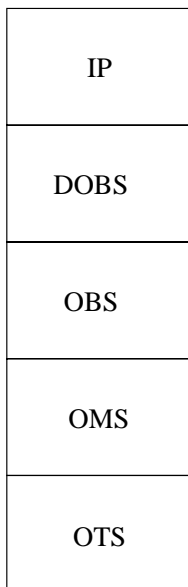


Figure 3.1: The Differentiated Optical Burst Services (DOBS)

3.3 DOBS Architectural Model

We describe an architectural model in this section. The architecture as shown in Figure 3.2 defines the DOBS domain and captures the concept of end-to-end QoS in a global network environment. Two access network, A and B, are interconnected by a backbone network. The access networks are IP networks supporting DiffServ, while the OBS WDM transit network supports DOBS. The DOBS domain consists of OBS edge nodes and OBS core nodes. End-to-end services are provided by concatenating multiple domains (or clouds) that could be engineered or administrated separately. This framework allows for flexibility in how each domain is implemented. The DOBS domain consists of the following two major components:

- The edge nodes consist of ingress edge nodes and egress edge nodes. An ingress edge node assemble and mapping DiffServ flows originating from the access network onto equivalent optical burst flows with QoS parameters enforced in the optical domain. An egress edge node disassemble optical burst flow into IP flows and forward to the IP access networks.
- The core nodes connect to each other as well as edge nodes to construct a core OBS network. The main function of a core node is to provide DOBS with QoS supporting burst scheduling and forwarding the data bursts.

The detailed description of functionalities of edge and core OBS nodes are defined in the following two sections.

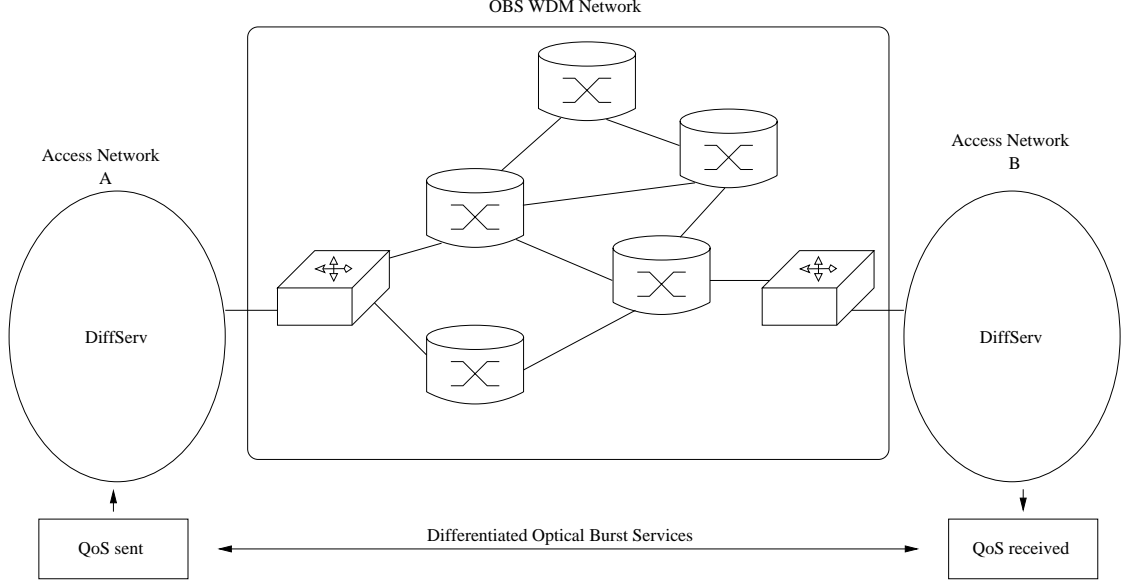


Figure 3.2: The Differentiated Optical Burst Services (DOBS) Model

3.4 DOBS Parameters and Functional Capabilities

A DOBS service is defined by a set of parameters that characterize the quality of the lightpath and a set of parameters that characterize the quality of burst flows.

Some of the relevant parameters that can be used to characterize the quality of the lightpath are the following:

- **Lightpath Characteristics** — The parameters for measuring the performance of a lightpath include bandwidth, bit error rate (BER), jitter, power, gain, and amplified spontaneous emission (ASE) level.
- **Lightpath Protection** — Lightpath protection mechanisms are needed to protect failures such as fiber cuts and wavelength failures. In a large-scale mesh optical network, traditional SONET/SDH survivability mechanisms, which offer equal

protection to all flows in the network, is not cost effective or justifiable since the need for guaranteed service availability in a DiffServ environment depends on the application. DOBS aggregates IP DiffServ flows requiring a specific degree of protection to a certain lightpath class.

- Lightpath Monitoring — The ability to monitor trails of validity, integrity, and quality should be a major part of the DOBS control and management functionality.
- Lightpath Security — There is a need to provide transport of secure applications over public transport networks and optical network in particular. Lightwave communications carrying multiple gigabits per second are vulnerable to various forms of service denials or eavesdropping attacks. The demand of secure lightpath will increase in the near future.
- Lightpath Transparency — The degree of lightpath transparency depends on the type of signal regeneration. There are three types of signal regeneration mechanisms such as 3R regeneration (regeneration, re-timing, and reshaping), 2R regeneration (regeneration and reshaping), and 1R regeneration (regeneration only).

Some parameters that characterize the burst flows are listed as follows:

- Burst flow priority class — A burst flow is assigned a priority class by its ingress node. The priority class of a burst is carried in its control packet. Both ingress and core nodes use priority class field in a control packet to process the control packet and reserve a wavelength for the transmission of the burst.

- Burst flow loss probability — The burst loss probability of a burst flow depends on its priority class and the available resources in the nodes in its path.
- Burst flow delay — The burst delay is the sum of the burst offset time, the propagation delays, and the transmission delays. The burst offset time consists of control packet process times and priority offset time or differentiated offset time for QoS.
- Burst flow jitter — The burst flow jitter is caused by the variance of the burst offset time, the propagation delays, and the transmission delays.

Figure 3.3 compare the optical transport network architectures of ITU G.872, DoS and DOBS.

3.5 DOBS Burst Assembly and Class Mapping

The main goal of DOBS is to provide a mechanism for offering various differentiated services through burst assembly, class mapping and burst scheduling. Burst scheduling is a function of OBS layer. In this section, burst assembly and class mapping functions of DOBS layer are defined, as shown in Figure 3.4. The DOBS layer of an ingress node assembles IP packets of various DiffServ classes into bursts of various classes based on the their DiffServ classes, source and destination addresses, and flow ids. The corresponding control packets are created accordingly and forwarded to various scheduling queues based on the burst scheduling scheme and the scheduling queueing policy of the ingress node.

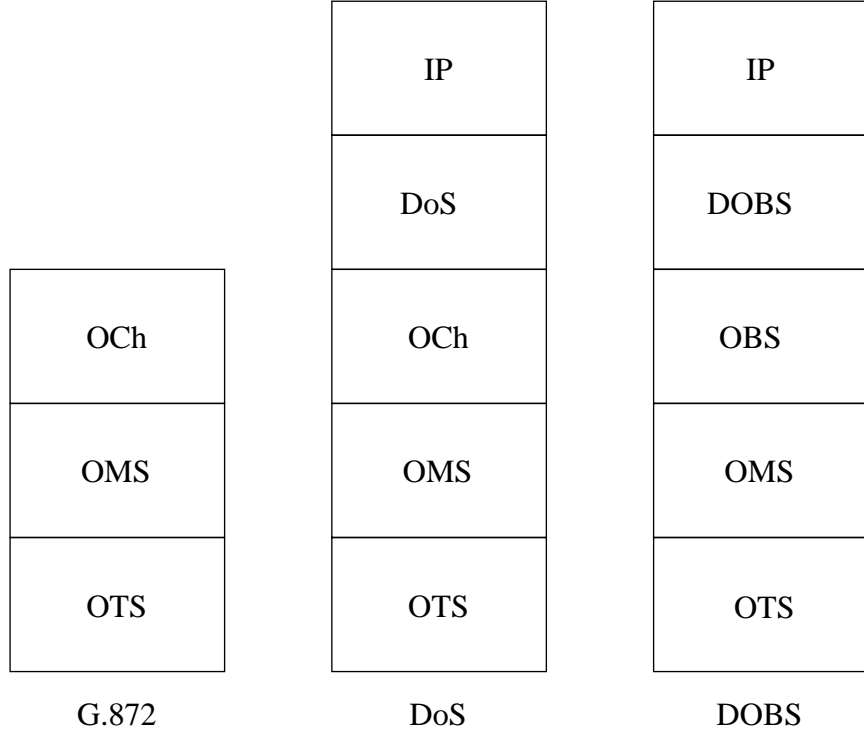


Figure 3.3: The Optical Transport Network Architectures of G.872, DoS, and DOBS

3.6 Chapter Summary

In this chapter, the Differentiated Optical Burst Services (DOBS) model and its architecture are proposed for OBS WDM networks. DOBS parameters and functional capabilities are defined and studied. General DOBS burst assembly and class mapping are proposed for DOBS model. In the next chapter, reservation modeling and performance analysis will be discussed.

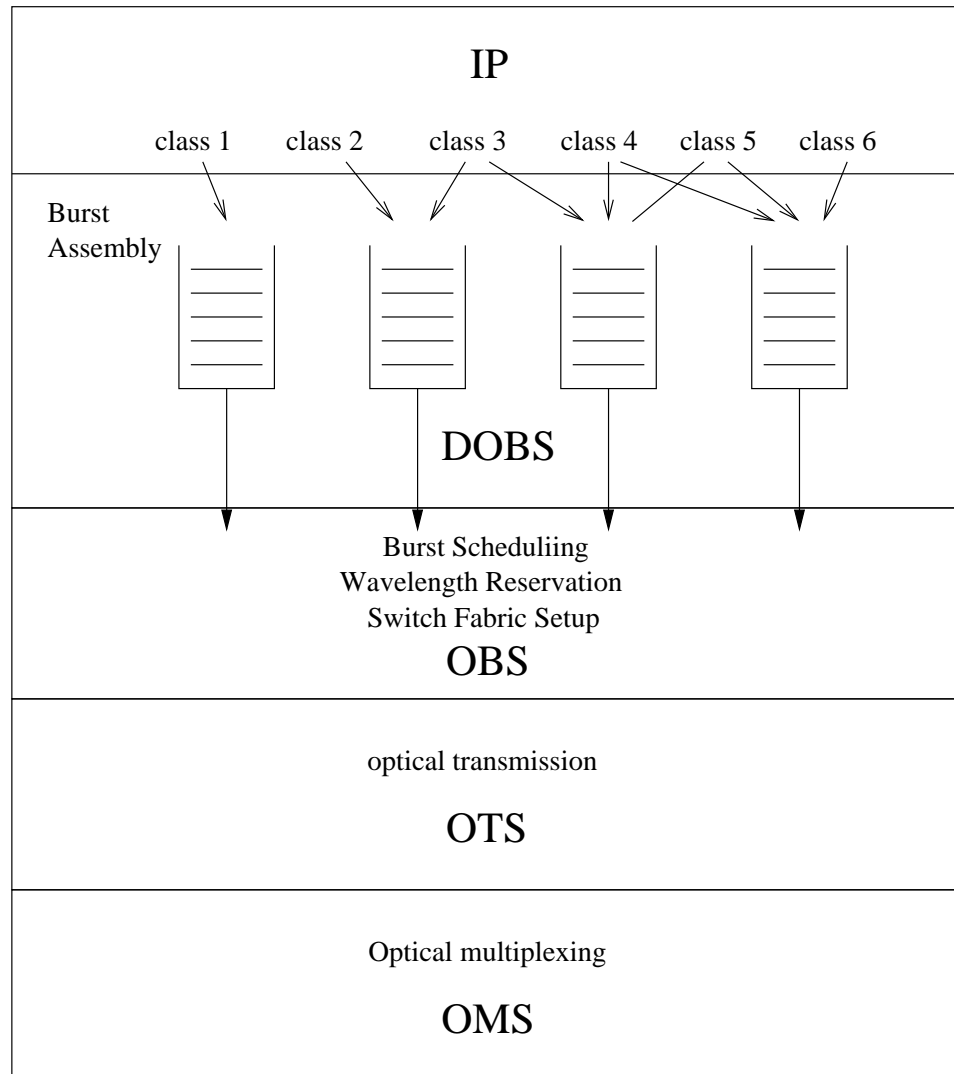


Figure 3.4: DOBS functionalities

CHAPTER 4

RESERVATION PROCESS MODELING AND PERFORMANCE ANALYSIS

4.1 Introduction

The resource reservation is critical for the performance of the OBS. It is very important to analyze and model the reservation process in order to evaluate its performances. Most of the reservation process modeling and analysis focus only on offset time assignment, burst arrival process and wavelength reservation. The conservation law about burst loss probability is widely used to compute the burst loss probabilities for various priority classes.

In this chapter, we exam optical burst switching (OBS) reservation process and discuss some important parameters and their impact on the resource reservation. A general framework for its modeling and analysis is presented. We model the OBS reservation using queueing networks. Our framework and model cover all aspects of OBS reservation process including the control packet arrival, the offset time assignment, the control packet processing, the optical switch matrix setup, and the data burst arrival and transmission. We also investigate when the conservation law about burst loss probability holds and can be used to calculate the burst loss probabilities

of various priority classes. We also show that the burst loss probabilities of various priority classes can be approximated even when the conservation law can not be used to calculate the burst loss probability.

The rest of the chapter is organized as follows. In Section 4.2 we examine the optical burst switching reservation process. We also study all its important parameters and their impact on the performance of OBS. OBS reservation processing is modeled as queueing networks consisting of a scheduling waiting process, a control packet process, a burst offset process, a switch setup process, and the burst transmission process in Section 4.3. In Section 4.5, we analyze achievable burst loss probabilities for priority classes of bursts. We also use a simple example to invalidate the general assumption of conservation law for the average burst loss probability of prioritized burst reservations used by many researchers. Finally, we present some concluding remarks in Section 4.7.

4.2 OBS Reservation Process and Parameters

4.2.1 Reservation Process

In this thesis, the RFD (reserve-a-fixed-duration) approach is used in the OBS reservation process. In this approach, a control packet contains both the arrival time and the transmission time of its data burst. When a control packet arrives at an OBS node, the node's control packet processing unit (CPPU) will assign a *control packet waiting time* (CPWT) based on the control packet's priority class and the node's capacity. The control packet has to wait before it is processed at *control packet processing starting time* (CPPST), which is equal to the *control packet arrival time* (CPAT) + CPWT. In other word, the control packet will be processed in the order

of its CPPST. The scheduler processes the control packet and try to reserve a wavelength for a duration appropriate for its data burst transmission. If no wavelength is available for the duration, the data burst will be dropped upon its arrival. If the reservation succeeds, the CPPU will send a request for a switch matrix path setup for the data burst. During the time the switch matrix is reconfigured, the wavelength is unavailable for the transmissions of other data bursts even though the wavelength is reserved only for the duration of the data burst transmission. This is the overhead caused by the switch matrix path setup.

The Figure 4.1 illustrates the OBS reservation process with some of the time parameters, where W is the control packet waiting time; D is the constant control packet processing time; R is the remaining offset time, the time between the end of control packet processing and the beginning of the switch reconfiguration; S is the optical matrix path setup time or switch matrix reconfiguration time; T_b is the burst transmission time. The offset time, which is a field in the control packet, therefore equals to $W + D + R + S$. Some other important related parameters, not shown in Figure 4.1, include control packet inter-arrival time and burst inter-arrival time.

4.2.2 Reservation Process Parameters

The various important parameters for the OBS reservation process are described in detail as follows

- *control packet and burst inter-arrival times* The control packet inter-arrival time is assumed to be exponentially distributed in most of OBS reservation process models. Pareto distribution is also considered for self-similar traffic [28]. The burst inter-arrival time is related to the control packet inter-arrival time If the

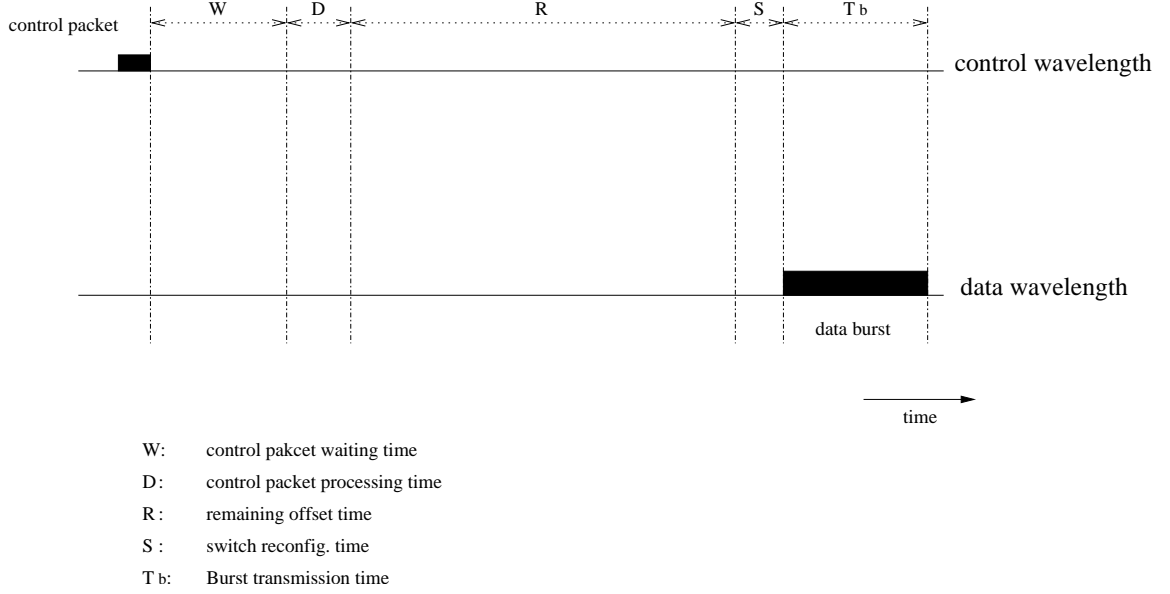


Figure 4.1: OBS reservation process and its time parameters

offset time is the same for all the bursts, the burst inter-arrival time will have the same distribution as the control inter-arrival time if the offset time is the same for all the bursts. When different offset times are assigned to different bursts according to their destination and priority class, the inter-arrival time distribution for the bursts of the same priority class and the same destination will still be the same as the control packet inter-arrival time distribution. The overall burst inter-arrival time distribution however will be different. With different offset times, the overall burst inter-arrival time will be exponentially distributed if the control packet inter-arrival time is exponentially distributed due to the property of the exponential distribution. The burst inter-arrival time can also be shaped to be exponentially distributed as in [90].

- *control packet waiting time* In most of OBS resource reservation schemes, a control packet is processed in the order of their arrivals or just a short time before its burst arrival. We first proposed to assign different control packet waiting times according to the priority classes of burst to reorder the control packets and therefore to provide differentiated services in OBS networks in [64]
- *control packet processing time* In general, it takes a constant time to process a control packet. Since not all ready control packet can be processed immediately, a control packet has to wait in queue for an extra time, which will be discussed further later in this chapter.
- *remaining offset time* This is the the time between the end of control packet processing and the beginning of the switch reconfiguration. The longer a remaining offset time, the relatively earlier a reservation is made, therefore, the better the chance that a burst will be scheduled. [111].
- *optical switch matrix reconfiguration time* Currently it takes 7 - 10 milliseconds (ms) to reconfigure an optical switch matrix. This makes the optical burst switch feasible. The optical packet switching will require the reconfigure time to be about 1 nanoseconds (ns).
- *burst transmission time* The burst transmission time is determined by the burst length in bytes and the bandwidth of each wavelength. It takes less than 1 μs to transmit a 10 kilobytes burst in a 10 Gbps wavelength. The burst transmission time is assumed to be exponentially distributed in most of OBS reservation process models. Pareto distribution is considered for self-similar traffic [28].

- *offset time* The offset time for a burst must be greater than the sum of the control packet process times and the optical switch reconfiguration times along the burst's path to ensure that the corresponding control packet is always ahead of the burst.

4.3 OBS Reservation Process Modeling

The queueing network of the OBS reservation process is shown in Figure 4.2. Each process will be fully discussed in the following sections.

4.3.1 Scheduling Wait Process

The *scheduling wait process* (SWP) can be described as $M/G_{sw}/S/C$ which is a queueing process with exponential inter-arrival times, general service times, C servers, and the maximum number of customers S allowed in the system, and first-come, first-serve queue discipline. The service time t_{sw} is a discrete random variable with

$$t_{sw}(cp) = V_i \text{ if priority of cp is } i, 1 \leq i \leq N$$

where cp represents a control packet and N is the number of priority classes.

4.3.2 Control Packet Process

In the *control packet process* (CPP), the control packets are processed after they have been ordered by SWP. CPP is a queueing process of G/D/1. Here we assume that there will be one control processor which finds out which wavelength is available out of the total K wavelengths.

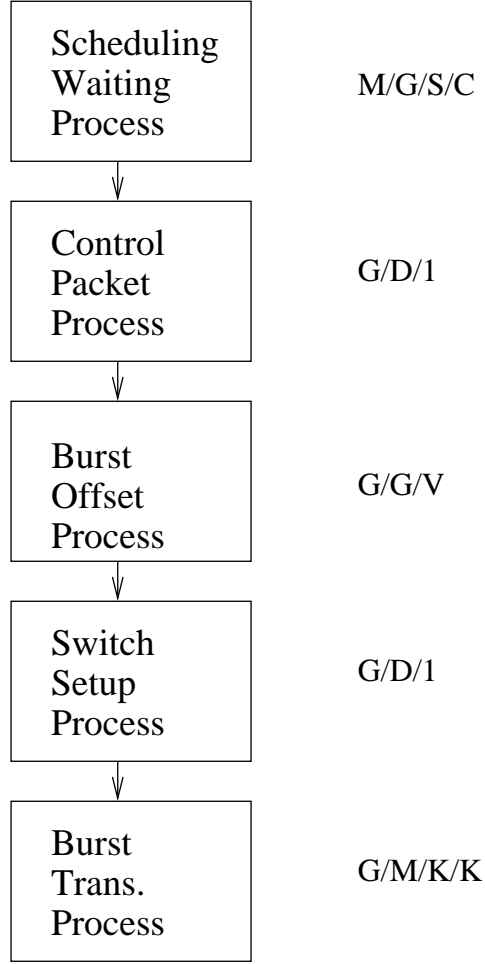


Figure 4.2: Queueing network model of OBS reservation process

4.3.3 Burst Offset Process

The burst offset here indicates the time difference between the control packet processing time and the burst arrival time. Usually the higher the priority, the longer the burst offset as in [111]. the *burst offset process* (BOP) can be represented as a queueing process $G/G_{bo}/V$, similar to the SWP described above.

4.3.4 Switch Setup Process

Two possible designs of the optical switch are the optical crossbar for strict non-blocking or the Wavelength Grating Router (WGR) of low cost but potential blocking [83]. The optical switch may involve wavelength conversion. The *switch setup process* (SSP) depends on the optical switch design. For simplicity, we assume that the switch matrix setup time is a constant. Therefore a queueing process G/D/1 can be used to describe SSP.

4.3.5 Burst Transmission Process

The *burst transmission process* (BTP) has been considered in studies such as [111]. Even though the bursts arrive exponentially to the optical burst switch node, the scheduled bursts for transmission are not exponentially distributed due to the preferential treatment of high priority bursts by the reservation process. In general, the BTP can be represented by the queueing process $G/M/K/K$ where K is the number of wavelengths.

In summary, all five processes can be modeled as different types of queues. The SWP makes it possible to support differentiated services. The CPP is the possible bottleneck since each CPP takes care of multiple wavelengths. How to distribute the functions of the CPP is worthy of study. Some of the processes may be pipelined. For example, the BOP and the SSP can overlap for different bursts.

4.4 Burst Loss Probability Conservation

The general idea of conservation in queue theory is that the expected change of a state function is zero over any finite (include infinitesimal) span of time picked

at random in the steady state as in [46]. A *conservation law* regarding the burst loss probability of OBS was first mentioned by Yoo and Qiao in [109]. It states that the burst loss probability averaged over all classes of a network stays the same regardless of the number of classes and the degree of isolation. The isolation in OBS describe a condition that a reservations for a priority class burst is not affected by the reservation for a low priority class burst. Although this so called *conservation law* has been widely applied in computing burst loss probabilities of various classes in many OBS performance models, it has not be proved, but only be verified in case of high intensity (≥ 0.8) traffic in [111]. A brief proof will be given next, followed by an M/M/1 priority preemption example.

4.4.1 Loss Probability Conservation

Theorem 4.1 (Loss Conservation) Consider the M/M/c/c loss system with priority where the customers from each priority class i arrive in a Poisson steam at the same rate λ_i with the same service rate μ . If a customer with a higher priority is allowed to preempt a customer with a lower priority from service when the system is busy, and the preempted customer will be dropped from the system, the over all burst loss probability is the same as that of M/G/c/c loss system without priority. The over all loss probability is

$$P_{loss}(c, \rho) = \frac{\rho^c / c!}{\sum_{j=0}^K \rho^j / j!},$$

where $\rho = (\sum_{i=1}^n \lambda_i) / \mu$, and n is the number of priorities.

Proof: We only need to show that the unfinished work $U(t)$ does not change after a high priority customer H replace a lower priority customer L . Let the unfinished

work be $W(t)$. Then

$$W(t) = U(t) - \langle \text{H's remaining service time} \rangle + \langle \text{L's service time} \rangle$$

Since the services times of H and L follow the same exponential distribution, the $\langle \text{H's remaining service time} \rangle$ is equal to $\langle \text{L's service time} \rangle$ on a steady state, thanks to the memoryless property of the exponential distribution. Therefore $W(t)$ equals $U(t)$. The unfinished work of the system does not change after the preemption.

The loss probability is derived from the Erlang's B loss formula. ■

4.4.2 M/M/1 Two Priority Preemption

We use a simple example to illustrate that conservation law does hold for the average burst loss probability of a priority loss system. A M/M/1 with two priority class system is considered here. For simplicity, we assume class 1 is of higher priority than class 2, and that they have the mean arrival rate λ_1 and λ_2 respectively, and the same mean service rate μ . Let $p_{mnr} \equiv \Pr\{\text{in steady state, m units of priority 1 and n units of priority 2 are in the system, and a unit of priority } r = 1 \text{ or } 2 \text{ is in service or no unit is in service with } r = 0\}$. For our system, only p_{000} , p_{101} and p_{012} are not zero. The loss probability for priority 1 is

$$p_{loss,pri,1} = \frac{\lambda_1 \cdot p_{101}}{\lambda_1 + \lambda_2}.$$

The loss probability for priority 2 is

$$p_{loss,pri,2} = \frac{\lambda_1 \cdot p_{101} + (\lambda_1 + \lambda_2) \cdot p_{012}}{\lambda_1 + \lambda_2}.$$

The average loss probability is

$$p_{loss,pri} = p_{loss,pri,1} + p_{loss,pri,2} = p_{101} + p_{012}.$$

The state transition diagram is shown in Figure 4.3 where a 3-tuple notation (m,n,r) represents a state in which m units of priority 1 and n units of priority 2 are in the system, and a unit of priority $r = 1$ or 2 is in service. The notation $(0,0,0)$ indicates an empty system. The system of difference equations may be derived using the global-balance equations [59] as follows:

$$(\lambda_1 + \lambda_2)p_{000} = \mu_1 p_{101} + \mu_2 p_{012} \quad (4.1)$$

$$\lambda_1 p_{000} + \lambda_1 p_{012} = \mu_1 p_{101} \quad (4.2)$$

$$(\lambda_1 + \mu_2)p_{012} = \lambda_2 p_{000} \quad (4.3)$$

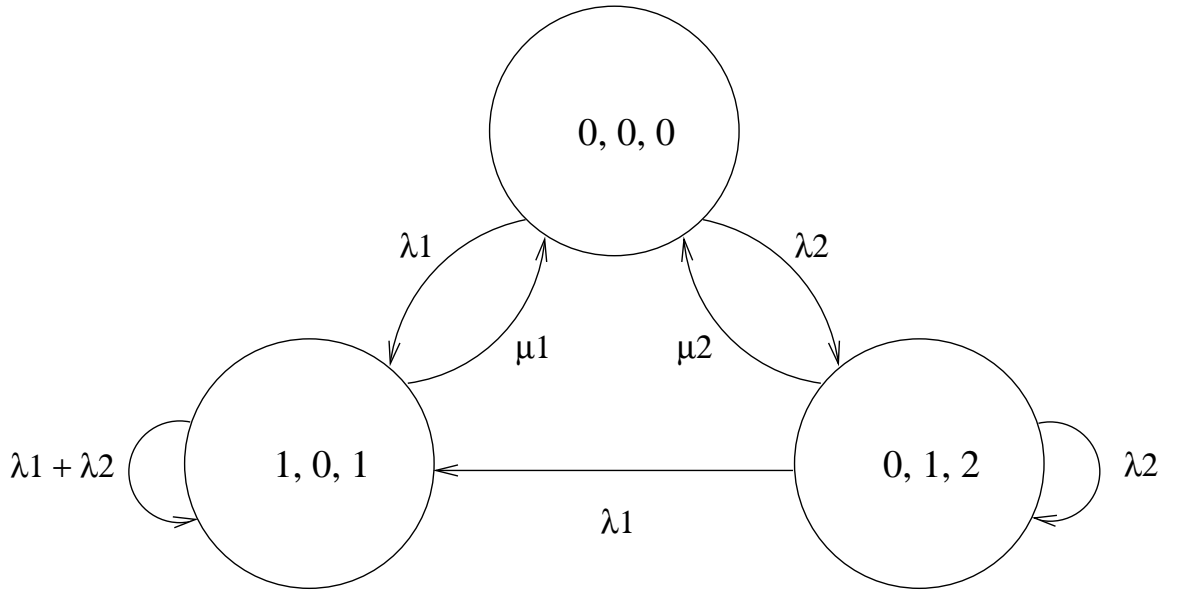


Figure 4.3: State transition diagram of M/M/1/ with priority

Only two of three equations (4.1), (4.2) and (4.3) are independent. Combining with the following equation 4.4:

$$p_{000} + p_{101} + p_{012} = 1 \quad (4.4)$$

We obtain

$$p_{000} = \frac{\mu_1(\lambda_1 + \mu_2)}{(\lambda_1 + \mu_1)(\lambda_1 + \lambda_2 + \mu_2)} \quad (4.5)$$

$$p_{101} = \frac{\lambda_1}{\lambda_1 + \mu_1} \quad (4.6)$$

$$p_{012} = \frac{\lambda_2\mu_1}{(\lambda_1 + \mu_1)(\lambda_1 + \lambda_2 + \mu_2)} \quad (4.7)$$

Therefor the average loss probability according to formula 4.4.2 is

$$p_{loss,pri} = p_{101} + p_{012} \quad (4.8)$$

$$= \frac{\lambda_1(\lambda_1 + \mu_2) + \lambda_2(\lambda_1 + \mu_1)}{(\lambda_1 + \mu_1)(\lambda_1 + \lambda_2 + \mu_2)} \quad (4.9)$$

and

$$p_{loss,pri} = \frac{\lambda_1 + \lambda_2}{\lambda_1 + \lambda_2 + \mu},$$

when $\mu_1 = \mu_2 = \mu$.

The Erlang loss formula for the system M/M/1/1 with an average rate $\lambda_1 + \lambda_2$ and a service rate μ is

$$B(1, \frac{\lambda_1 + \lambda_2}{\mu}) = \frac{\lambda_1 + \lambda_2}{\lambda_1 + \lambda_2 + \mu}. \quad (4.10)$$

Therefore,

$$B(1, \frac{\lambda_1 + \lambda_2}{\mu}) = p_{loss,pri}, \quad (4.11)$$

when $\mu_1 = \mu_2 = \mu$. Our example illustrates that the conservation law does hold for the average burst loss probability of a 2-priority loss system. It remains to be seen how the conservation law holds for general priority loss systems.

4.5 OBS Reservation Performance Analysis

4.5.1 Achievable Burst Loss Probability

It is important to know the best (lowest) loss probability each burst class can achieve. We assume that there are N priority classes of bursts. Class 1 is the highest

priority and class N is the lowest priority. Each class i ($1 \leq i \leq N$) arrives independently with an exponential distribution of rate λ_i and the average transmission time l_i . Thus the class i traffic intensity is $\rho_i = \lambda_i \cdot l_i / K = r_i / K$ where $r_i = \lambda_i \cdot l_i$. There are K wavelengths for burst transmission. To obtain the lowest (best) burst loss probability, we can simply use the $M/G/K/K$ queue model. The lowest burst loss probability for class 1 is achieved when the class 1 burst is only blocked by other class 1 bursts, but not bursts from other lower priority class bursts. Therefore the lowest burst loss probability of class 1 is

$$p_1 \geq B(K, \rho_1) = \frac{\rho_1^K / K!}{\sum_{k=0}^K \rho_1^k / k!}$$

Similarly for any class i , its burst loss probability is lowest when the class i bursts can only be blocked by any higher priority class j ($1 \leq j < i$) bursts but not lower priority class bursts. The lowest burst loss probability of class i is

$$p_i \geq B(K, \rho_{1,i}) = \frac{\rho_{1,i}^K / K!}{\sum_{k=0}^K \rho_{1,i}^k / k!}$$

where $\rho_{1,i} = \sum_{j=1}^i \rho_j$.

We obtained the achievable burst loss probabilities for multiple priority classes. In some cases, it is a goal to achieve the best burst loss probability for each class. In other cases, we may want to achieve proportional and relative burst loss probabilities among priority classes.

4.6 Burst Loss Probability Analysis

In this section, the burst loss probability of each priority class is given an analytic formula when both the burst loss conservation law and total priority class isolation property hold.

We assume that n priority classes will be supported, and there is K wavelengths in the link. Class i ($1 \leq i \leq n$) bursts have a mean arrival rate of λ_i and a mean serve rate of μ_i . The traffic load or density of class i , denoted as ρ_i , is equal to λ_i/μ_i . We model the burst scheduling process in a link as an $M/M/K/K$ [59] queue. Since class 1 is not blocked by any other lower priority classes, the burst loss probability of class 1 can be calculated using the Erlang's B loss formula as

$$P_{loss,1} = \frac{\rho_1^K / K!}{\sum_{j=0}^K \rho_1^j / j!} \quad (4.12)$$

Since the data bursts from high priority classes are not blocked by any data bursts from lower priority classes, the data bursts from class 1 to class i for $1 \leq i < n$ are isolated from the data bursts from any lower priority class j for $i < j \leq n$, and Erlang's B loss formula can be used for the data bursts from class 1 to class i . The total traffic load for classes from 1 to i is $\rho_{1,i} = \sum_{j=1}^i \rho_j$. Then the burst loss probability formula for the data bursts of classes from 1 to i is:

$$B_{loss,i} = \frac{\rho_{1,i}^K / K!}{\sum_{j=0}^K \rho_{1,i}^j / j!} \quad (4.13)$$

According to the conservation law in [111], we have

$$B_{loss,i} = \frac{\lambda_i}{\sum_{j=1}^i \lambda_j} P_{loss,i} + \frac{\sum_{j=1}^{i-1} \lambda_j}{\sum_{j=1}^i \lambda_j} B_{loss,i-1}$$

Therefore, the burst loss probability of class i bursts

$$P_{loss,i} = \frac{(\sum_{j=1}^i \lambda_j)}{\lambda_i} (B_{loss,i} - \frac{\sum_{j=1}^{i-1} \lambda_j}{\sum_{j=1}^i \lambda_j} B_{loss,i-1}) \quad (4.14)$$

4.7 Chapter Summary

We have studied the OBS reservation process and investigated the important parameters which affect the OBS performance in this chapter. The OBS reservation

process framework and queue network model presented here will permit us to further understand and study OBS and its performance. We also show that the conservation law does hold for the average burst loss probability of a 2-priority loss system. In the following several chapters, we will use this framework and model to study the performance of a single OBS node as well as OBS performance network-wide using different resource reservation protocols through analysis and simulation.

CHAPTER 5

PRIORITY-BASED SCHEDULING

5.1 Introduction

The offset time based pJET burst scheduling scheme [111, 82, 112, 113] is well-known and supports QoS in OBS networks. However, the pJET does not meet some multimedia requirements such as media synchronization and in-order frame delivery. Multimedia applications require synchronizations between text, voice and video streams. Data packets and bursts for voice should have a higher priority than those for video because data packet or burst loss is less tolerable for voice than for video. The pJET assigns longer offset times to data bursts for voice than to data bursts for video, and as a results, voice lags behind video in multimedia applications. When this happens, a speaker appears to speak after his/hers mouth movement. Some multimedia applications also require in-order delivery. In MPEG video, high priority I frames must arrive before the corresponding P and B frames. The pJET also has a *path length priority effect* problem that a burst with more remaining hops to its destination has a longer offset time than a burst with fewer hops, and seems to have a higher priority as defined in the pJET. A high priority data burst with a short path may have the same offset time as a low priority data burst with a long path.

The pJET will not be able to distinguish them, but schedule them in the same way. In a WAN environment, a burst's basic offset time may be longer than its priority offset time, and the pJET will not be effective. For example, an OBS WAN support 4 priority classes. Let us assume that the control packet processing time is $10 \mu s$, and the average burst length is $10 \mu s$. A typical priority offset time assigned by the pJET is $(4 - 1) \cdot 3 \cdot 10 = 90 \mu s$. A burst with 12 remaining hops has a base offset time equal to $12 * 10 = 120 \mu s$, which is larger than its priority offset time.

In this chapter, a new burst scheduling scheme, called *priority-based scheme* (PBS), is designed to support differentiated services without the problem mentioned above. PBS does not assign an extra priority time to a high priority class, but uses a priority queuing technique to schedule a high priority data burst earlier than a lower priority data burst.

5.2 Burst Scheduling Framework

A framework for burst scheduling is formulated here before a *priority-based scheme* (PBS) is defined in the follow section. This burst scheduling framework will be used in the remaining chapters. It is assumed that the traffic is even distributed to all output links/ports. It is therefore sufficient to investigate only one output link. The following assumptions are made for the burst scheduling in an output link of a core OBS node.

- A link has k data channels (wavelengths): Wl_1, Wl_2, \dots, Wl_k , and a control channel.
- Each output link is associated with a scheduler that is in charge of scheduling the data bursts sent to that link.

- The control packets for the data bursts to be transmitted on an output link are processed in the order they are received at the scheduler for that link.
- A control packet has an offset time field t_o that is the time interval between the control packet arrival time and the data burst arrival time.
- A control packet has a length field t_b that specifies the length of its data burst measured in time.
- A control packet has a priority field p that specifies the priority class of its data burst, ranging from 1 (the highest) to n (the lowest).
- A control packet can be described as $CP(t_c, t_o, t_b, p)$, where t_c is the control packet arrival time, t_o the offset time field, t_b the data burst size measured in time, and i the priority class.
- A wavelength reservation is defined as $WR(w, t_{ws}, t_{wd})$, where w is the wavelength reserved, t_{ws} is the wavelength reservation starting time, t_{wd} is the wavelength reservation duration.
- A control packet $CP(t_c, t_o, t_b, i)$ is processed by the scheduler to reserve a wavelength w and an optical switch path from $t_c + t_o$ to $t_c + t_o + t_b$.

5.3 Priority-based Scheme

PBS processes a control packet as follows:

- A control packet waits in a priority scheduling queue.
- A scheduler processed the control packet with the highest priority from the queue.

- For a control packet $CP(t_c, t_o, t_b, p)$, the scheduler searches from wavelength 1 to wavelength k until one wavelength is found available between t_a and $t_a + t_b$, where t_a is the burst arrival time and equals $t_c + t_o$.
- If none of the wavelengths is available for the data burst, the scheduler reserve a wavelength for the data burst if one or more existing reservations for lower priority bursts can be dropped and the new reservation will not conflicts with other reservations.
- Three policies are defined with regard to whether one or more reservation are dropped and which wavelength will be reserved if more than one wavelength satisfies the condition as follows:
 1. Preempt one reservation and choose the wavelength whose dropped reservation has the lowest priority. A reservation $WR(w, t_{ws}, t_{wd}, p_{wr})$ can be dropped if $p < p_{wr}$. PBS with this preemption policy is called *PBS-Strong One Preemption* (PBS-SP).
 2. Preempt one reservation and choose the wavelength whose dropped reservation has the lowest priority. A reservation $WR(w, t_{ws}, t_{wd}, p_{wr})$ can be dropped if $p < p_{wr}$ and $t_a < t_{ws}$. We define PBS with the preemption policy as *PBS-Weak One Preemption* (PBS-WP).
 3. Preempt one or more lower priority reservations and choose the wavelength whose number of the dropped reservations is minimum. PBS with this preemption policy is denoted as *PBS-Minimum Preemption* (PBS-MP).

Here we show how the different schemes schedule two consecutive data bursts of different priorities in Figure 5.1. PBS-SP can preempt the low priority data burst

if another higher priority data burst arrives before the low priority data burst is switched out through an output port. In the case of PBS-WP, high priority data bursts can only preempt the low priority data bursts if their data bursts arrive earlier than the low priority data burst. For PBS, data bursts are not scheduled in the order of control packet arrival time, in contrast to JET and pJET as we can see in Figure 5.2.

5.4 Simulation Results and Discussion

5.4.1 Simulation Model and Parameters

Simulation results are presented in this section. We consider two traffic models, Poisson and self-similar traffic. In Poisson traffic model, both the burst inter-arrival time and the burst length are generated using exponential distribution. To simulate self-similar traffic, a Pareto distribution [79] and a exponential distribution are used to generate the burst inter-arrival time and the burst length respectively. The Pareto distribution has the a cumulative distribution of the form $F(x) = 1 - (A/x)^\alpha$ for $x \geq A$, where α is a parameter that decides the heaviness of the distribution tail and $1 < \alpha < 2$.

The simulation results are obtained for a single OBS core node with an outgoing link having k wavelengths. In this simulation, we assume that all priority classes generate an equal amount of traffic with the same control packet inter-arrival distribution of the average inter-arrival time l_{iar} , and the same burst length distribution of the average service time l_{srv} . Therefore, all priority classes have the same traffic load $\frac{l_{srv}}{l_{iar}}$. The total traffic load per wavelength ρ equals $\frac{nl_{iar}}{kl_{srv}}$. The burst loss probability is evaluated as a function of traffic intensity (load) ρ with a fixed average burst size t_b ,

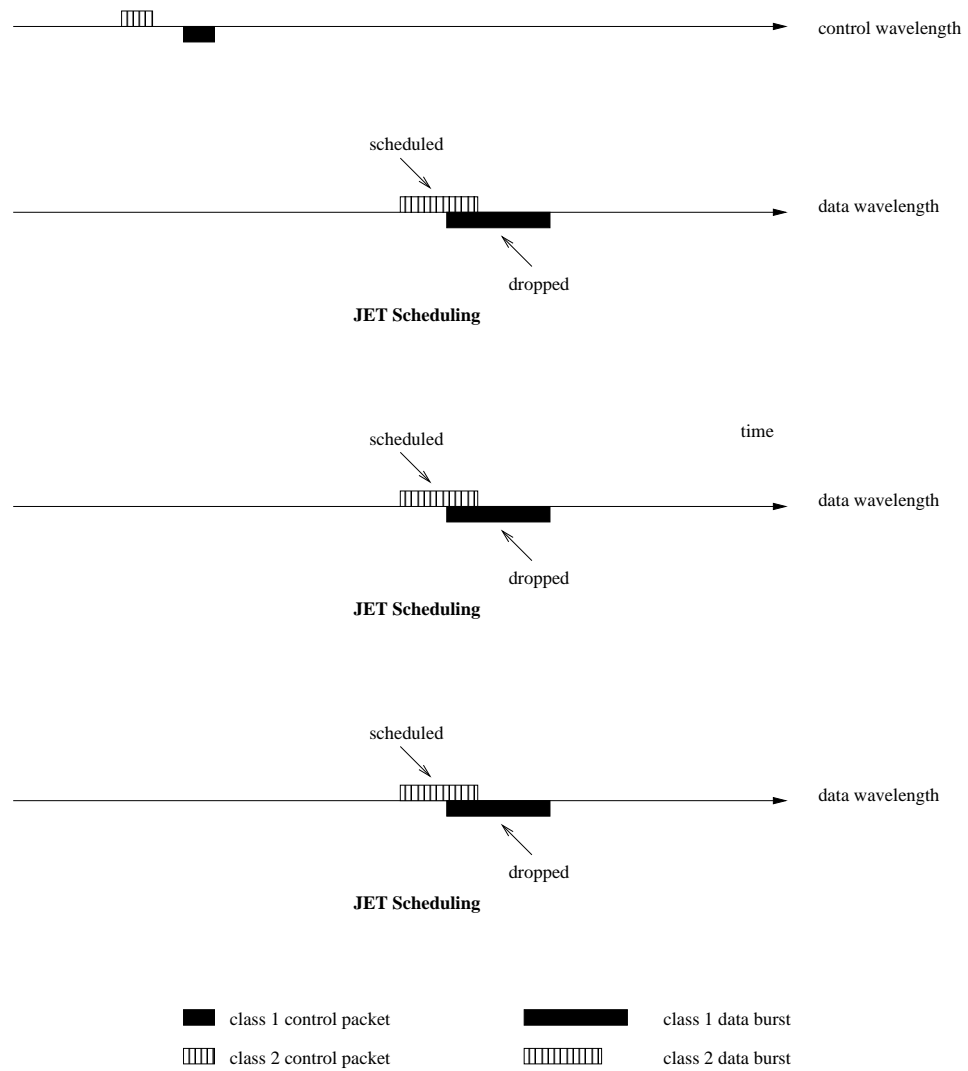


Figure 5.1: Scheduling Qos Data Bursts

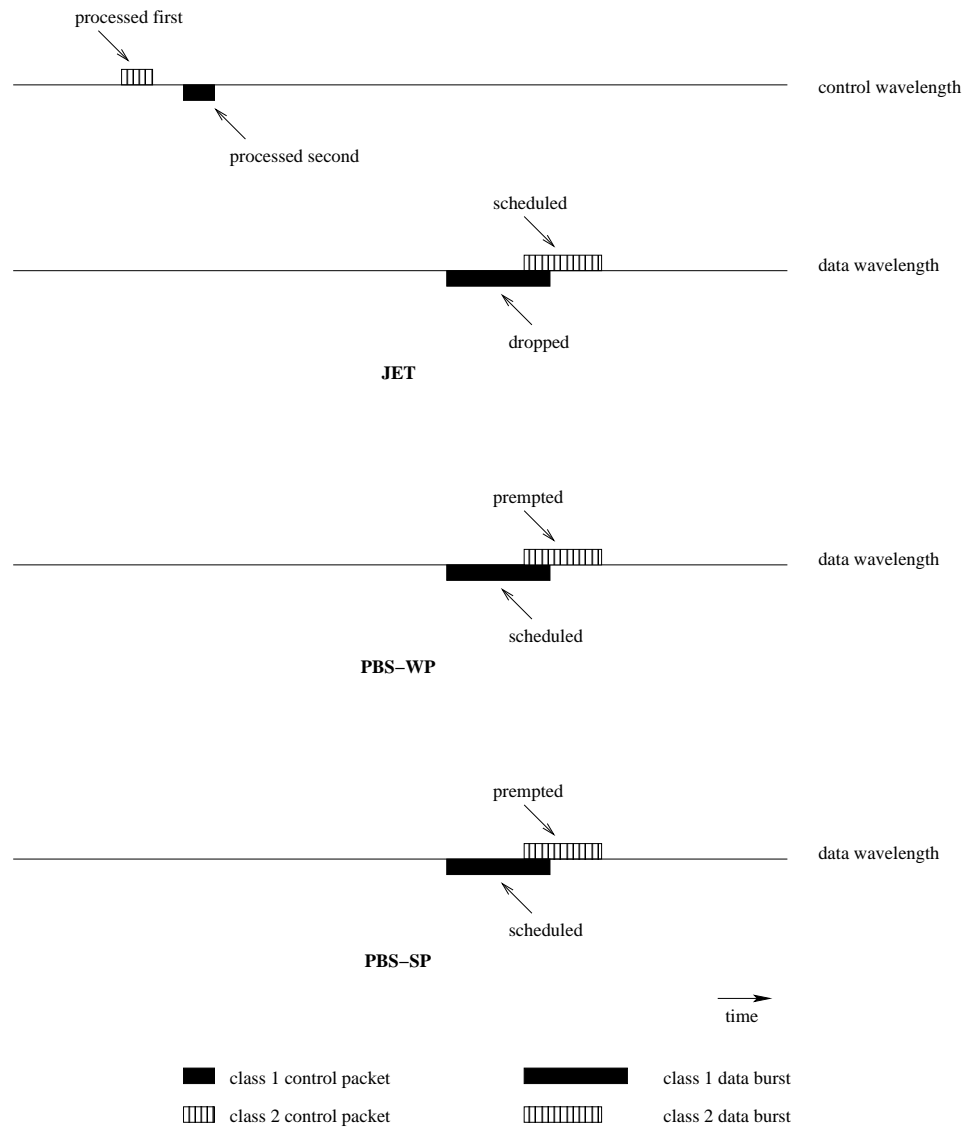


Figure 5.2: Scheduling Qos Data Bursts

Variable	Description
k	the number of wavelengths on the link
t_p	the control packet service time by a scheduler
t_{ou}	the offset time needed per hop
t_{pu}	the extra offset time needed per priority
h	maximum number of the remaining hops of flows
ρ	traffic load per wavelength
n	the number of priority classes
$iar_ \alpha$	the α value of the Pareto distribution of the control packet inter arrival times
$srv_ \alpha$	the α value of the Pareto distribution of the burst service times

Table 5.1: SBS, PBS, and pJET system and flow variables

the control packet processing time t_p , the number of priority classes n , the number of wavelengths k , the offset time t_o , and the maximum number of flow hops h in case of multiple flows per class, and the parameter α if the control packet inter-arrival time has a Pareto distribution. The average control packet inter-arrival time, thus the average burst inter-arrival time, is defined as $t_b/(n \cdot \rho)$. If the control packet inter-arrival time has a Pareto distribution, the parameter A of the Pareto distribution is $A = ((\alpha - 1) \cdot t_b)/(\alpha \cdot n \cdot \rho)$. In multiple flow case, there are h flows and i th flow has i remaining hops for $1 \leq i \leq h$. In multiple flow case, there are h flows and i th flow has i remaining hops for $1 \leq i \leq h$. The schemes considered include the standard burst scheduling (SBS), PBS, pJET. In SBS, a control packet is processed first-come-first-serve and the offset time of a burst is determined only by its remaining hop to its destination and control packet processing time at each node. These parameters are described in Table 5.1.

5.4.2 Single Traffic Flow

A traffic flow is defined as all the burst from a source edge node to a destination edge node. Let's assume that all the bursts in a flow have the same offset time. A traffic flow may consists of bursts of various priorities. We investigate how the burst loss probabilities of various priority classes are affected by the traffic load, the number of wavelengths, and the number of classes in a single flow with various burst scheduling schemes.

SBS Service Differentiation

With SBS, the burst loss probability is the same for all the priority classes. as shown in Figures 5.3, 5.4, 5.4, and 5.6.

Figure 5.3 plots the burst loss probability as a function of the traffic load for 4 priority classes using the SBS scheme when the burst traffic has the exponentially distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, and $n = 4$.

Figure 5.4 plots the burst loss probability as a function of the traffic load for 4 priority classes using the SBS scheme when the burst traffic has the Pareto distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, and $n = 4$.

Figure 5.5 plots the burst loss probability as a function of the traffic load for 4 priority classes using the SBS scheme when the burst traffic has the Pareto distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, and $n = 4$.

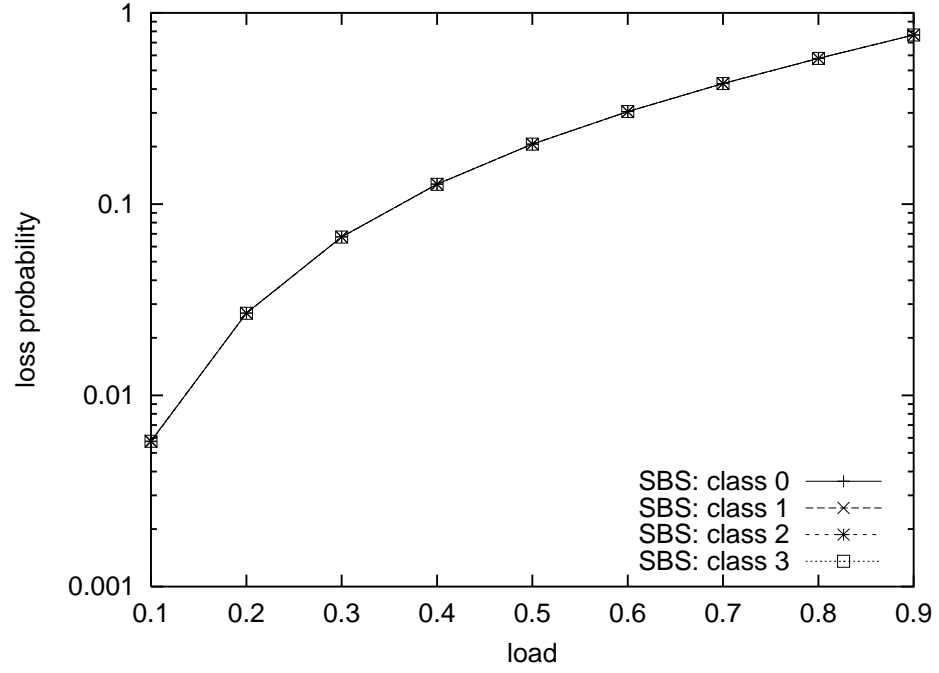


Figure 5.3: Burst loss probability as a function of the traffic load for 4 priority classes using SBS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.

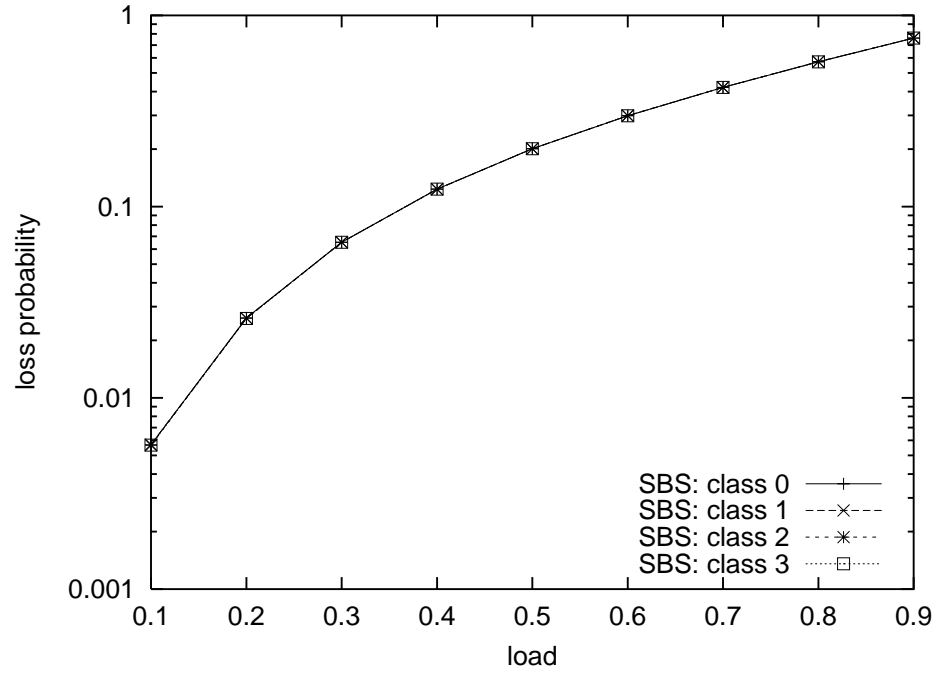


Figure 5.4: Burst loss probability as a function of the traffic load for 4 priority classes using the SBS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths

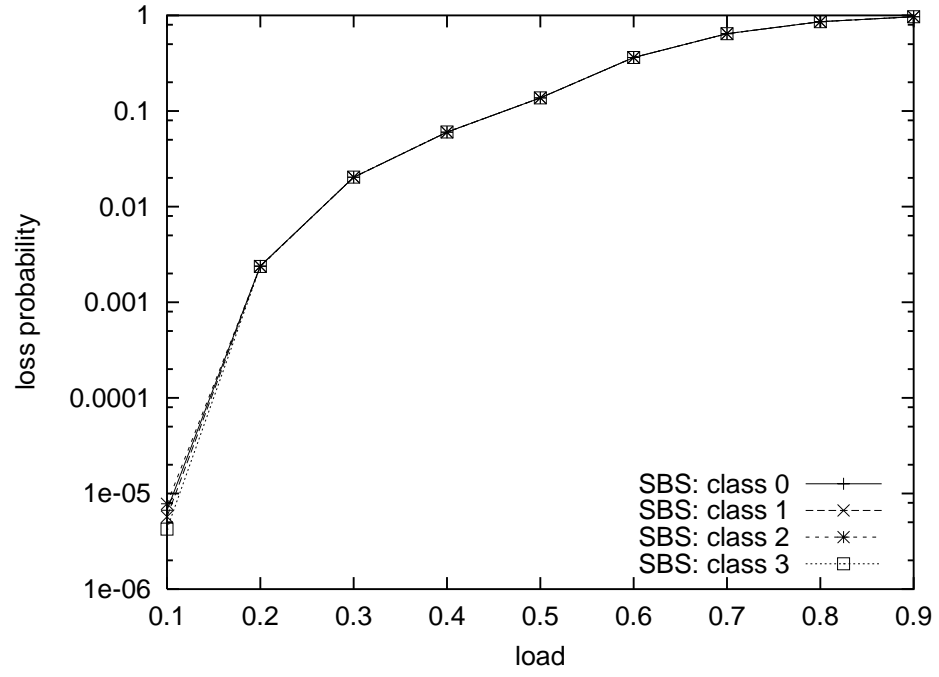


Figure 5.5: Burst loss probability as a function of the traffic load for 4 priority classes using the SBS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, Pareto distributed inter-arrival time, and exponentially distributed burst lengths

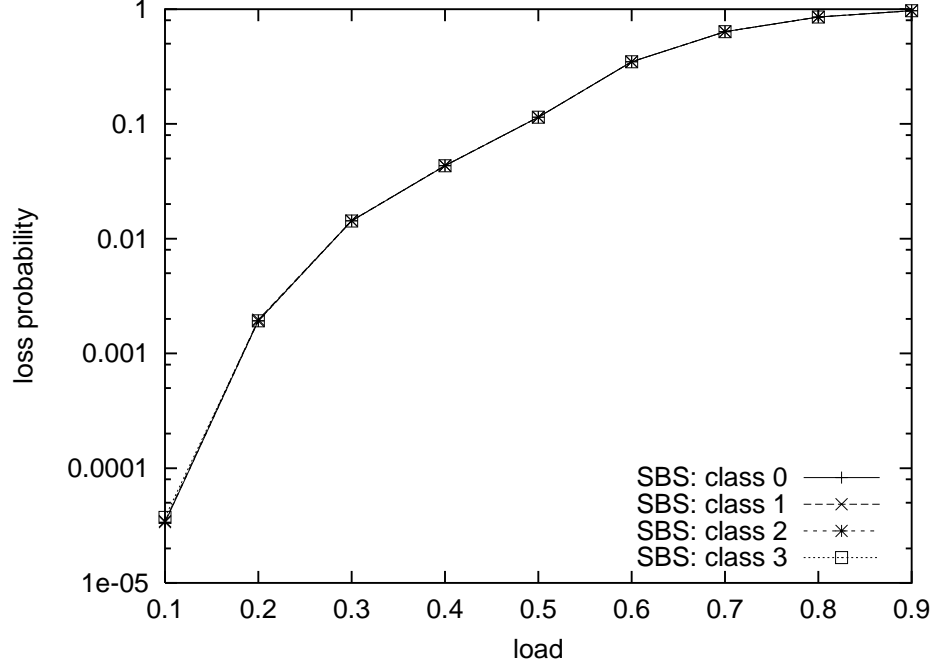


Figure 5.6: Burst loss probability as a function of the traffic load for 4 priority classes using the SBS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, Pareto distributed inter-arrival time, and Pareto distributed burst lengths

Figure 5.6 plots the burst loss probability as a function of the traffic load for 4 priority classes using the SBS scheme when the burst traffic has the Pareto distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, and $n = 4$.

PBS-SP Service Differentiation

Figures 5.7, 5.8, 5.9, and 5.10 show that PBS-SP supports service differentiations with exponentially or Pareto distributed inter-arrival times, and exponentially or Pareto distributed burst lengths.

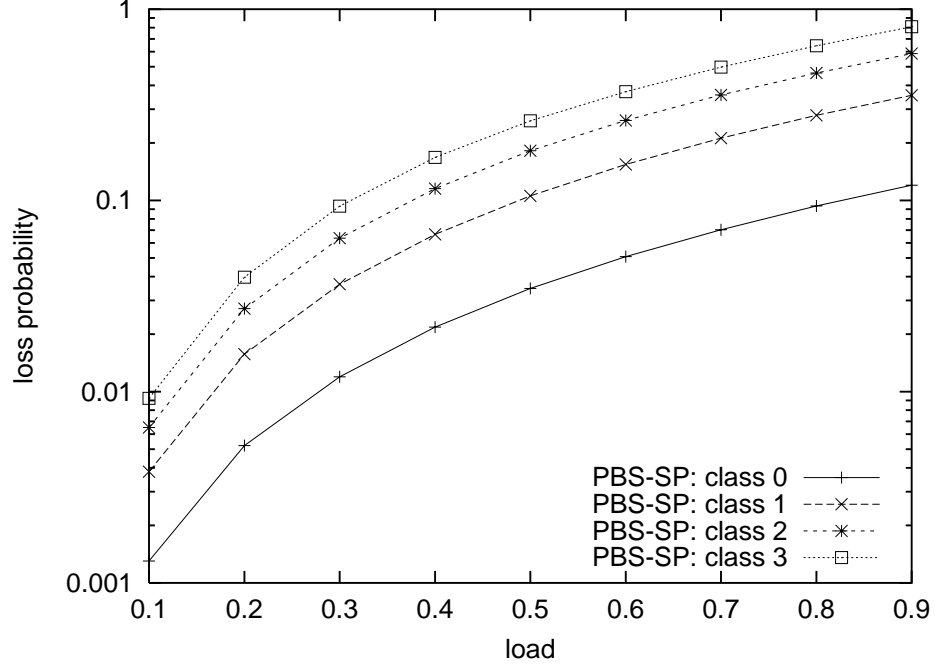


Figure 5.7: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.

Figure 5.7 plots the burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme when the burst traffic has the exponentially distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, and $n = 4$.

Figure 5.8 plots the burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme when the burst traffic has the exponentially distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, and $n = 4$.

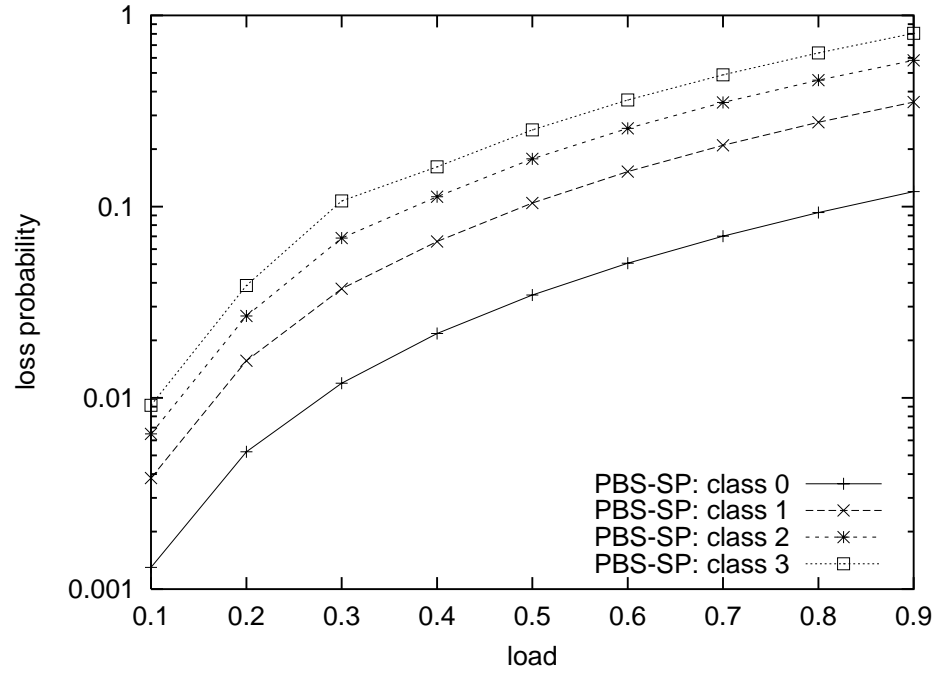


Figure 5.8: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths

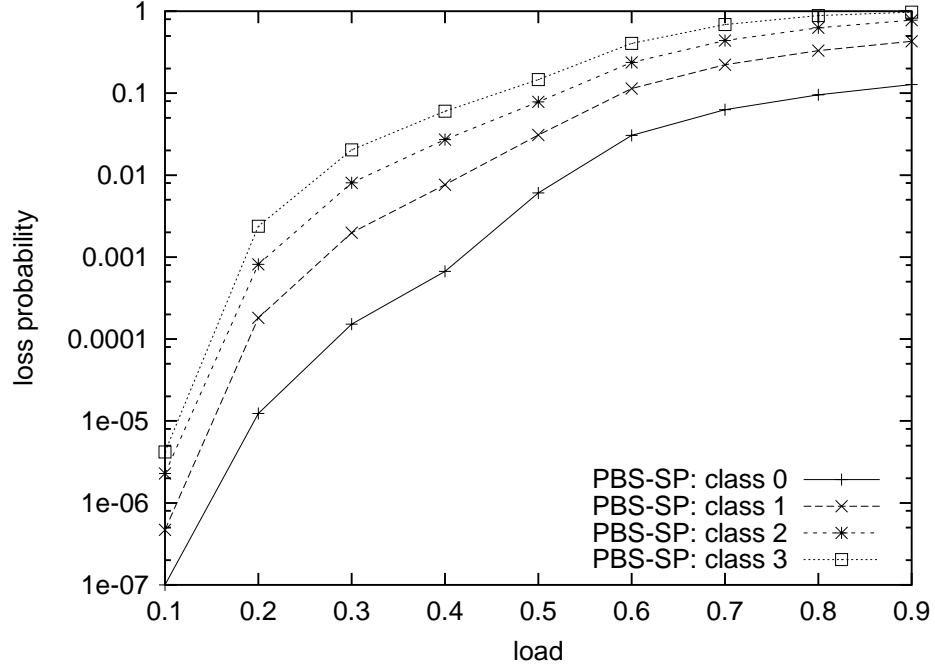


Figure 5.9: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths

Figure 5.9 plots the burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme when the burst traffic has the Pareto distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, and $n = 4$.

Figure 5.10 plots the burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme when the burst traffic has the Pareto distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, and $n = 4$.

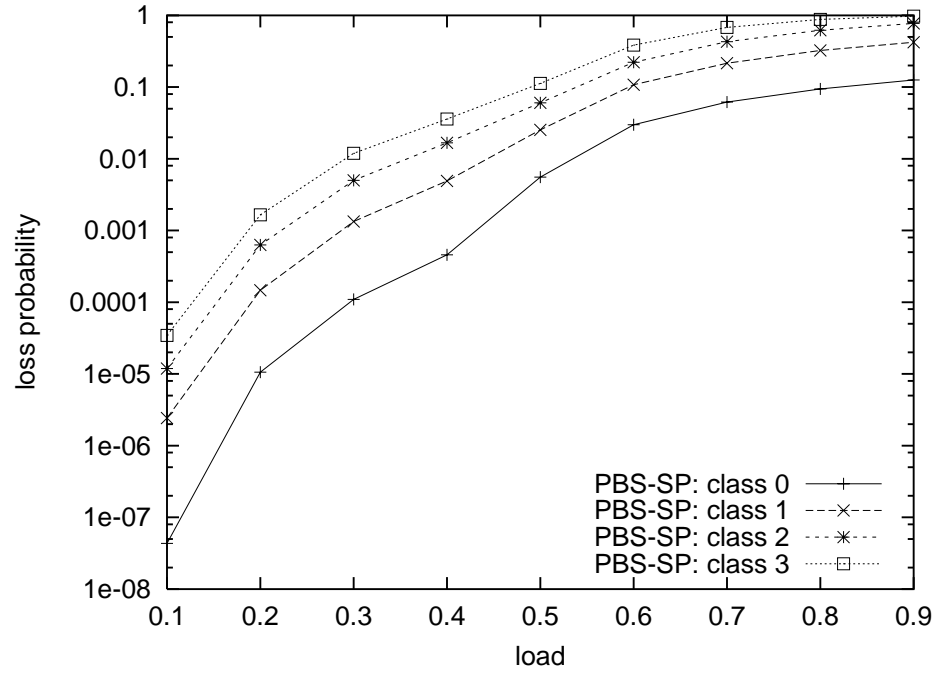


Figure 5.10: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, Pareto distributed inter-arrival time, and Pareto distributed burst lengths

PBS-WP Service Differentiation

Figures 5.11, 5.12, 5.9, and 5.10 show that PBS-WP supports service differentiations when the inter-arrival times are exponentially times, but not when the inter-arrival times are Pareto distributed.

Figure 5.11 plots the burst loss probability as a function of the traffic load for 4 priority classes using the PBS-WP scheme when the burst traffic has the exponentially distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, and $n = 4$.

Figure 5.12 plots the burst loss probability as a function of the traffic load for 4 priority classes using the PBS-WP scheme when the burst traffic has the exponentially distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, and $n = 4$.

Figure 5.13 plots the burst loss probability as a function of the traffic load for 4 priority classes using PBS-WP scheme when the burst traffic has the Pareto distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, and $n = 4$.

Figure 5.14 plots the burst loss probability as a function of the traffic load for 4 priority classes using the PBS-WP scheme when the burst traffic has the Pareto distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, and $n = 4$.

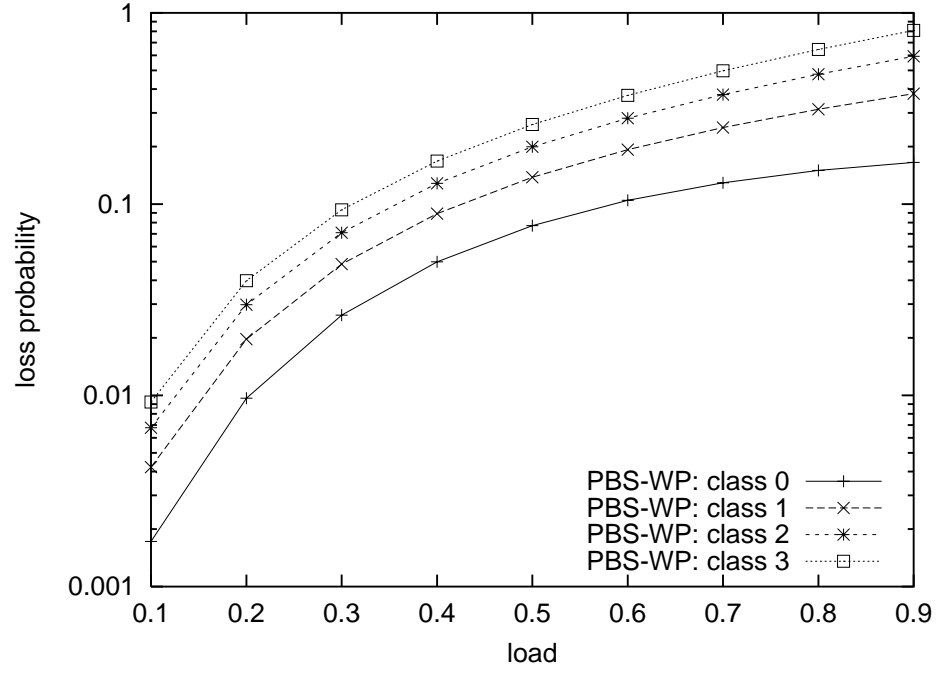


Figure 5.11: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-WP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.

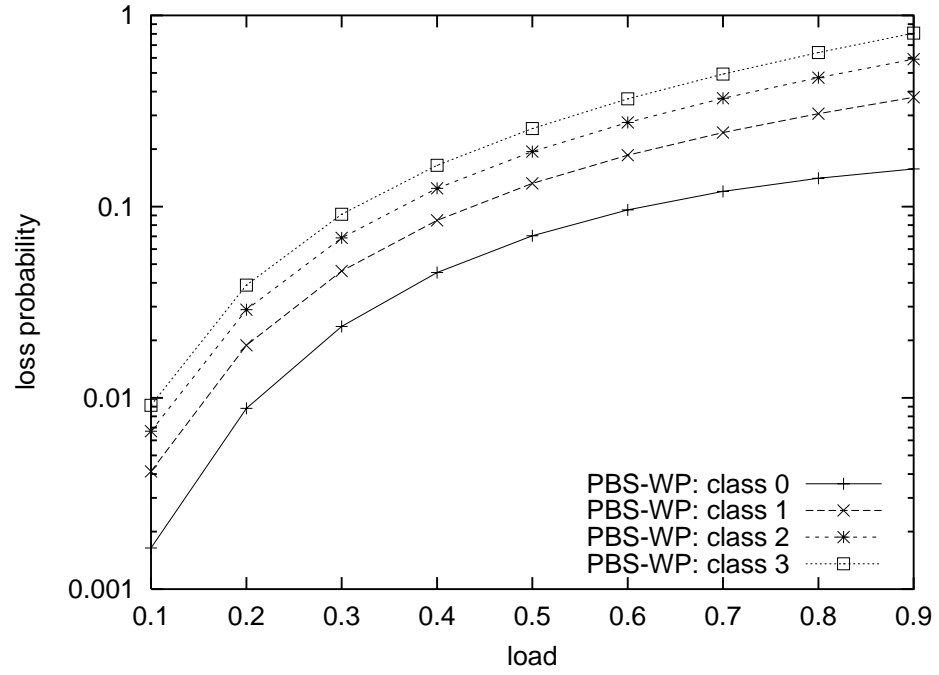


Figure 5.12: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-WP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths

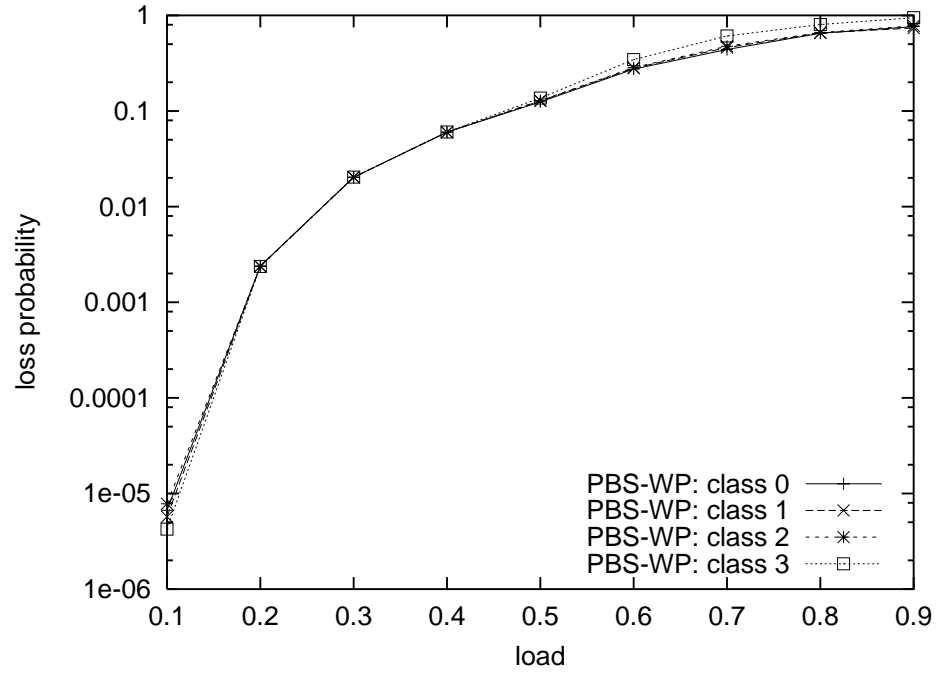


Figure 5.13: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-WP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths

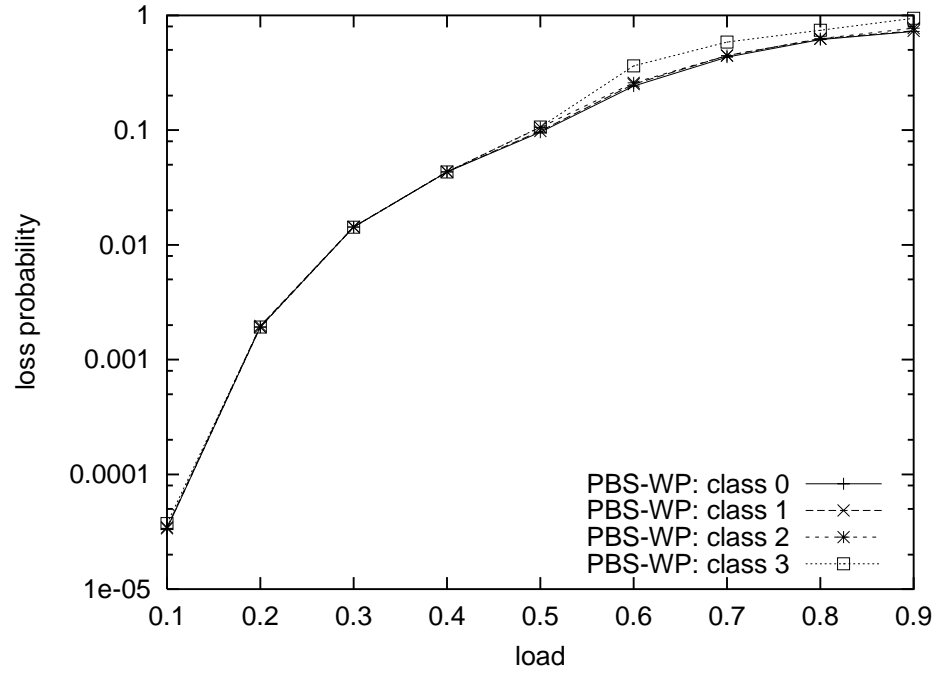


Figure 5.14: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-WP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, Pareto distributed inter-arrival time, and Pareto distributed burst lengths

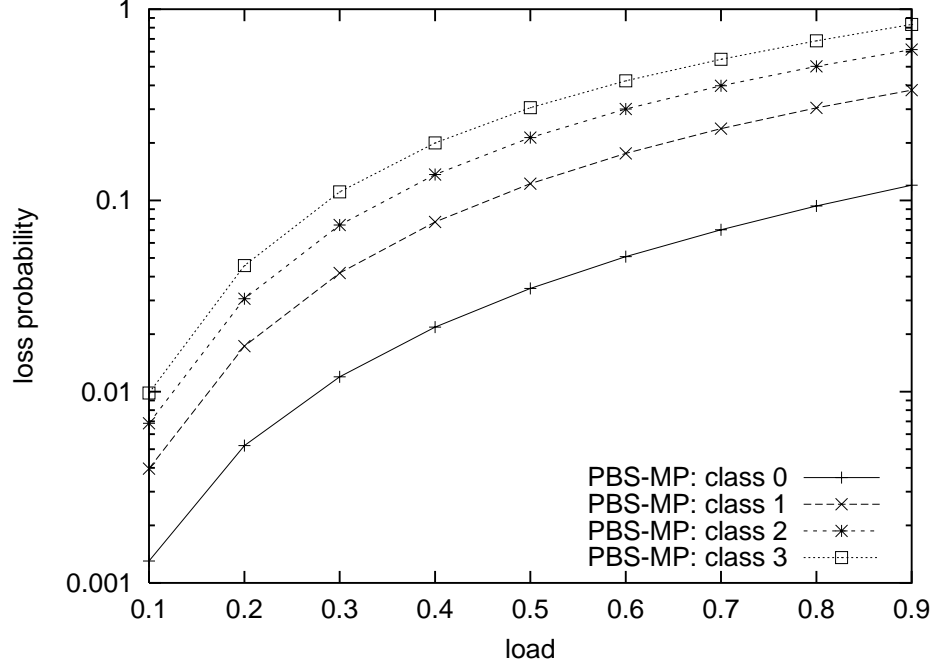


Figure 5.15: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.

PBS-MP Service Differentiation

As shown in Figures 5.15, 5.16, 5.17, and 5.18, PBS-MP supports service differentiation as expected.

Figure 5.15 plots the burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme when the burst traffic has the exponentially distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, and $n = 4$.

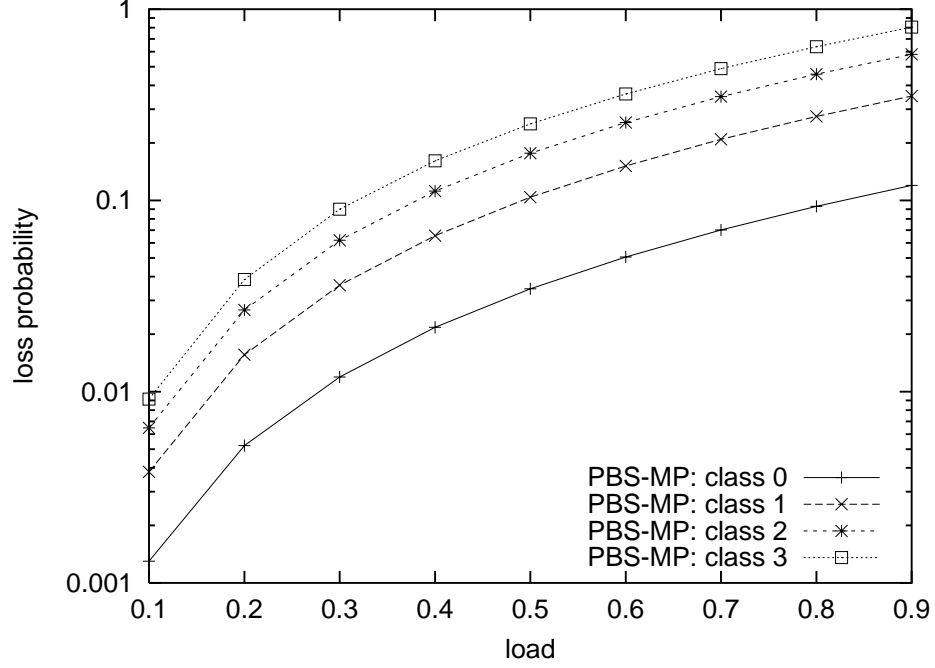


Figure 5.16: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths

Figure 5.16 plots the burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme when the burst traffic has the exponentially distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, and $n = 4$.

Figure 5.17 plots the burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme when the burst traffic has the Pareto distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, and $n = 4$.

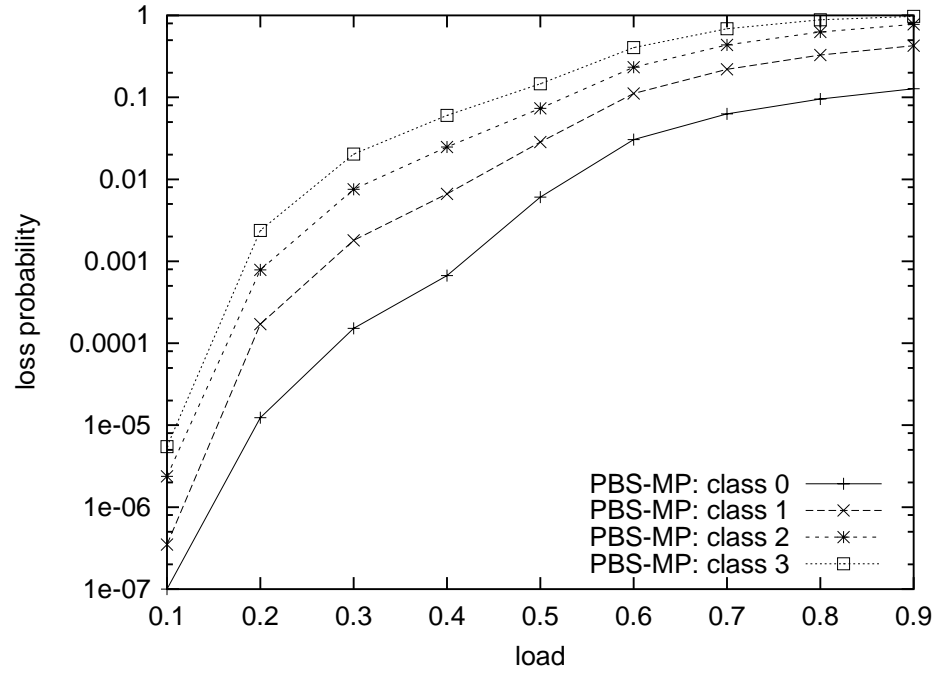


Figure 5.17: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths

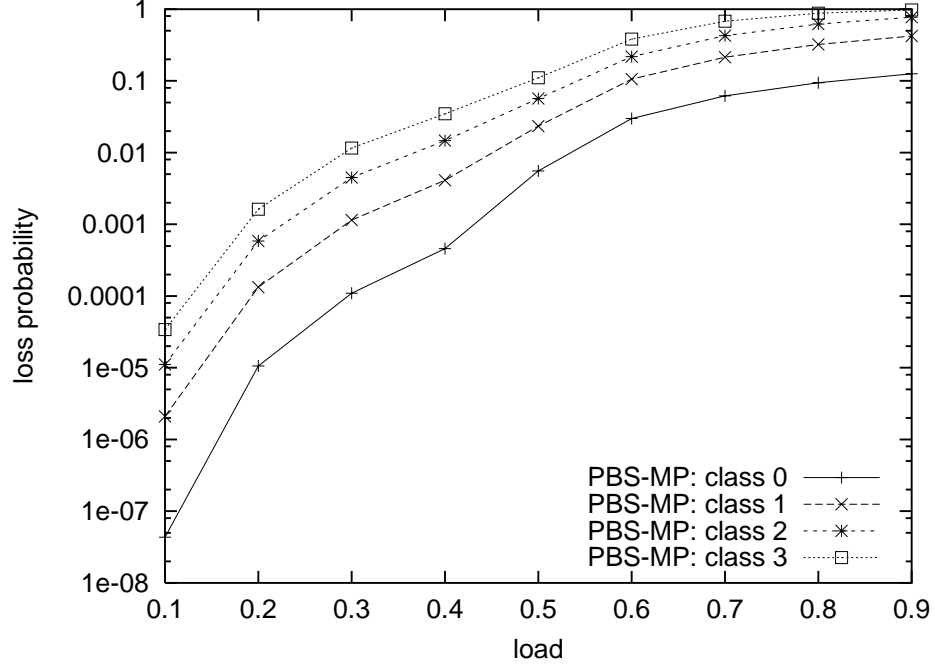


Figure 5.18: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, $n = 4$, Pareto distributed inter-arrival time, and Pareto distributed burst lengths

Figure 5.18 plots the burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme when the burst traffic has the Pareto distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 1$, and $n = 4$.

The Comparison of Scheduling Schemes

The performances of SBS, PBS-SP, PBS-WP, PBS-MP and pJET are compared in terms of burst loss probabilities for both priority 0 and priority 3 bursts in this section. When both the inter-arrival times and burst lengths are exponentially distributed, Figure 5.19 shows that, for priority class 0 with various loads, pJET provides lowest

burst loss probability, PBS-SP and PBS-MP have the similar burst loss probabilities and are better than PBS-WP and SBS, and PBS-WP provides better burst loss probability than SBS. Figure 5.20 shows that, for priority class 3 with various loads, SBS provides lowest burst loss probability, PBS-SP, PBS-WP, PBS-MP, and pJET have the similar burst loss probabilities.

Figure 5.19 plots the burst loss probability of priority class 0 as a function of the traffic load for burst schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET when the burst traffic has the exponentially distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, and $n = 4$.

Figure 5.20 plots the burst loss probability of priority class 3 as a function of the traffic load for burst schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET when the burst traffic has the exponentially distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, and $n = 4$.

When both the inter-arrival times are exponentially distributed and the burst lengths are Pareto distributed, Figure 5.21 shows that, for priority class 0 with various loads, pJET provides lowest burst loss probability, PBS-SP and PBS-MP have the similar burst loss probabilities and are better than PBS-WP and SBS, and PBS-WP provides better burst loss probability than SBS. Figure 5.22 shows that, for priority class 3 with various loads, SBS provides lowest burst loss probability, PBS-SP, PBS-WP, PBS-MP, and pJET have the similar burst loss probabilities.

Figure 5.21 plots the burst loss probability of priority class 0 as a function of the traffic load for burst schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET when the

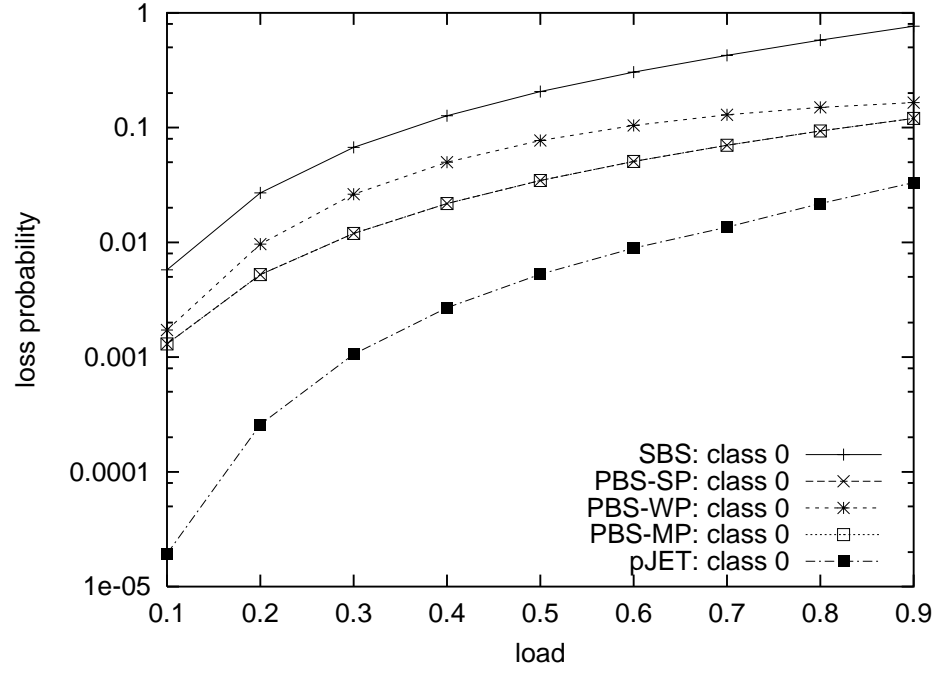


Figure 5.19: Burst loss probability as a function of the traffic load for priority class 0 for schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.

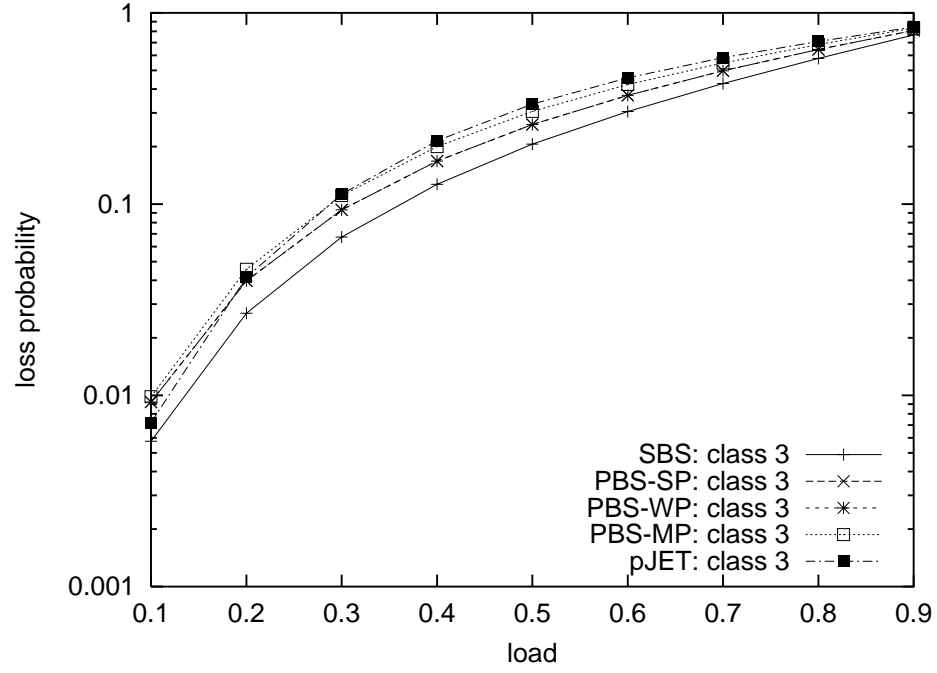


Figure 5.20: Burst loss probability as a function of the traffic load for priority class 3 for schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.

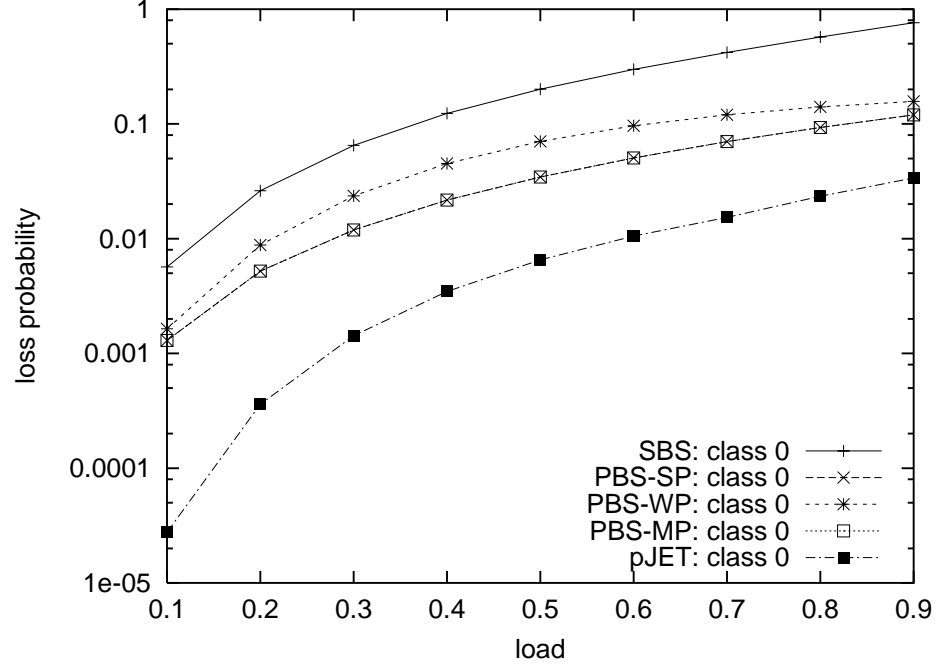


Figure 5.21: Burst loss probability as a function of the traffic load for priority class 0 for schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, $n = 4$, exponentially distributed control packet inter-arrival times, and Pareto distributed burst lengths.

burst traffic has the exponentially distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, and $n = 4$.

Figure 5.22 plots the burst loss probability of priority class 3 as a function of the traffic load for burst schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET when the burst traffic has the exponentially distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, and $n = 4$.

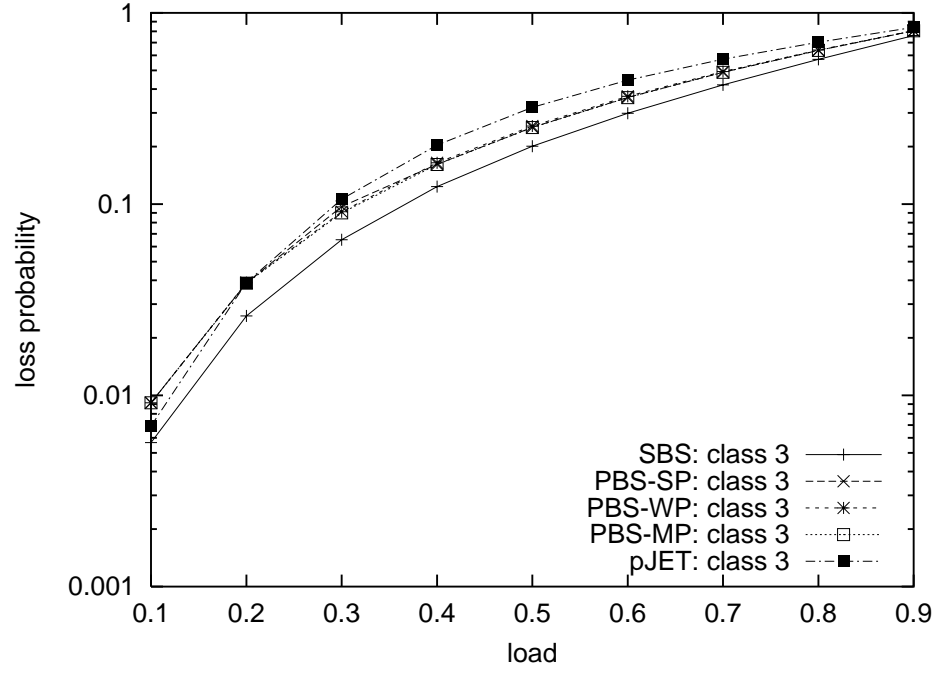


Figure 5.22: Burst loss probability as a function of the traffic load for priority class 3 for schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, $n = 4$, exponentially distributed control packet inter-arrival times, and Pareto distributed burst lengths.

When both the inter-arrival times are Pareto distributed, and burst lengths are exponentially distributed, Figure 5.23 shows that, for priority class 0 with various loads, PBS-SP and PBS-MP perform as well as pJET in terms of burst loss probability. Figure 5.24 shows that, for priority class 3 with various loads, pJET gives highest burst loss probability, SBS, PBS-SP, PBS-WP, and PBS-MP have the similar burst loss probabilities.

Figure 5.23 plots the burst loss probability of priority class 0 as a function of the traffic load for burst schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET when the burst traffic has the Pareto distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, and $n = 4$.

Figure 5.24 plots the burst loss probability of priority class 3 as a function of the traffic load for burst schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET when the burst traffic has the Pareto distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, and $n = 4$.

When both the inter-arrival times and burst lengths are Pareto distributed, Figure 5.25 shows that, for priority class 0 with various loads, pJET provides lowest burst loss probability, PBS-SP and PBS-MP have the similar burst loss probabilities and are better than PBS-WP and SBS, and PBS-WP provides better burst loss probability than SBS. Figure 5.26 shows that, for priority class 3 with various loads, SBS provides lowest burst loss probability, PBS-SP, PBS-WP, PBS-MP, and pJET have the similar burst loss probabilities.

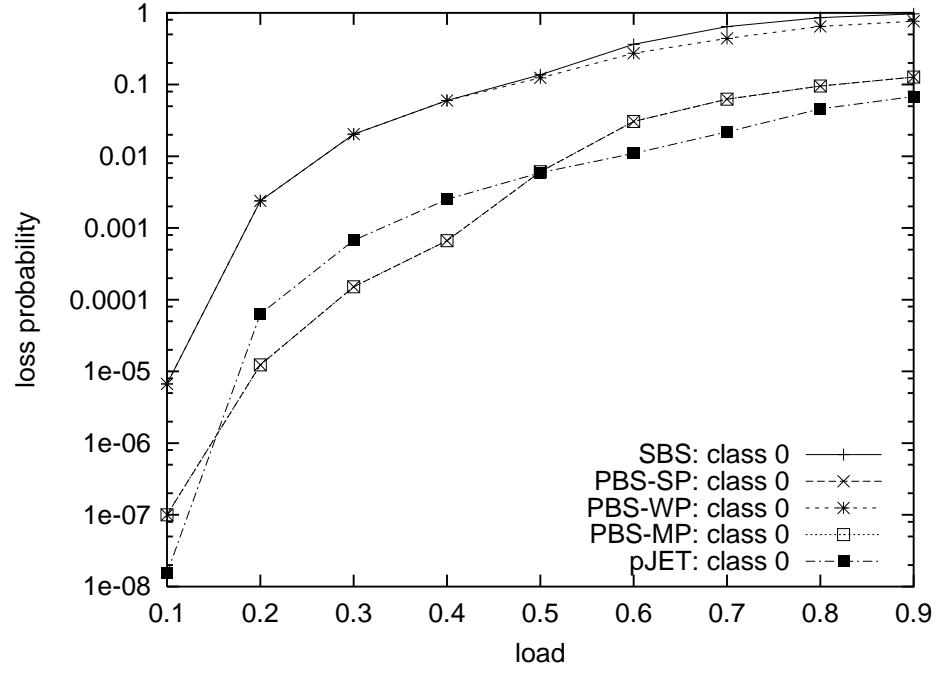


Figure 5.23: Burst loss probability as a function of the traffic load for priority class 0 for schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, $n = 4$, Pareto distributed control packet inter-arrival times, and exponentially distributed burst lengths.

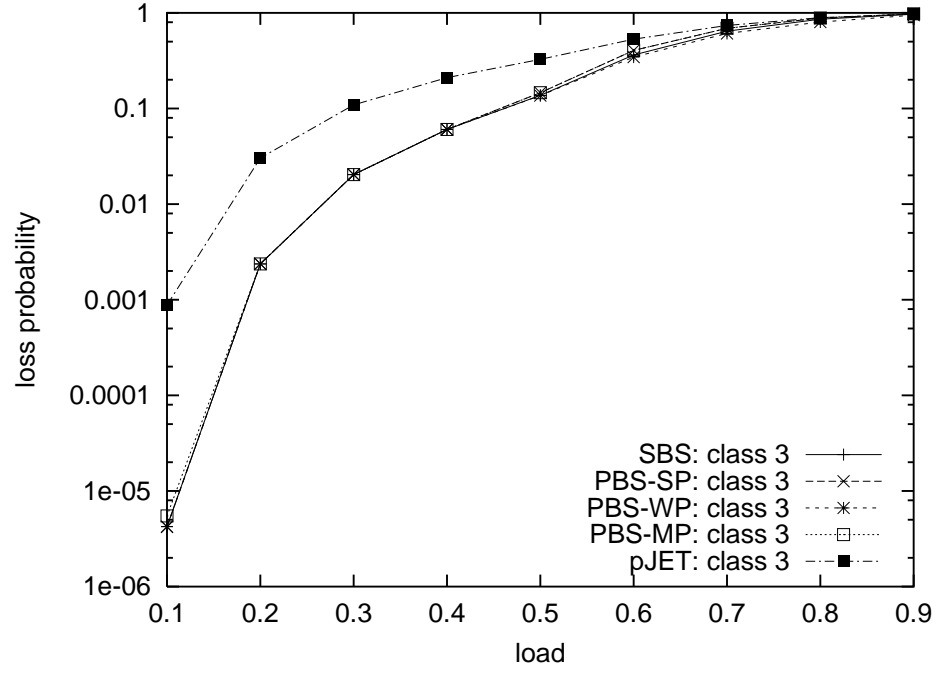


Figure 5.24: Burst loss probability as a function of the traffic load for priority class 3 for schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, $n = 4$, Pareto distributed control packet inter-arrival times, and exponentially distributed burst lengths.

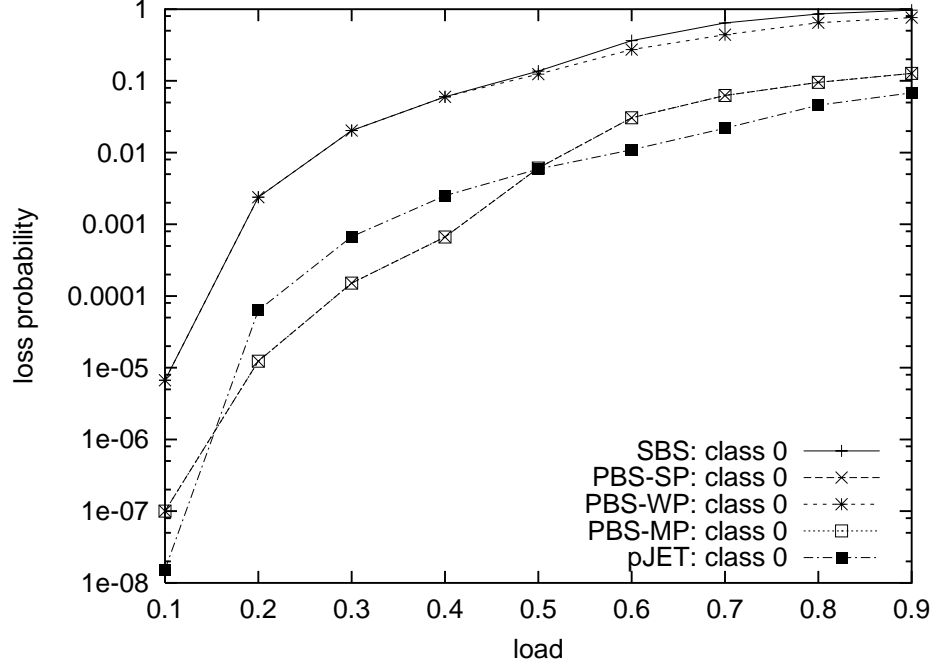


Figure 5.25: Burst loss probability as a function of the traffic load for priority class 0 for schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, $n = 4$, Pareto distributed control packet inter-arrival times, and Pareto distributed burst lengths.

Figure 5.25 plots the burst loss probability of priority class 0 as a function of the traffic load for burst schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET when the burst traffic has the Pareto distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, and $n = 4$.

Figure 5.26 plots the burst loss probability of priority class 3 as a function of the traffic load for burst schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET when the burst traffic has the Pareto distributed control packet inter-arrival times and

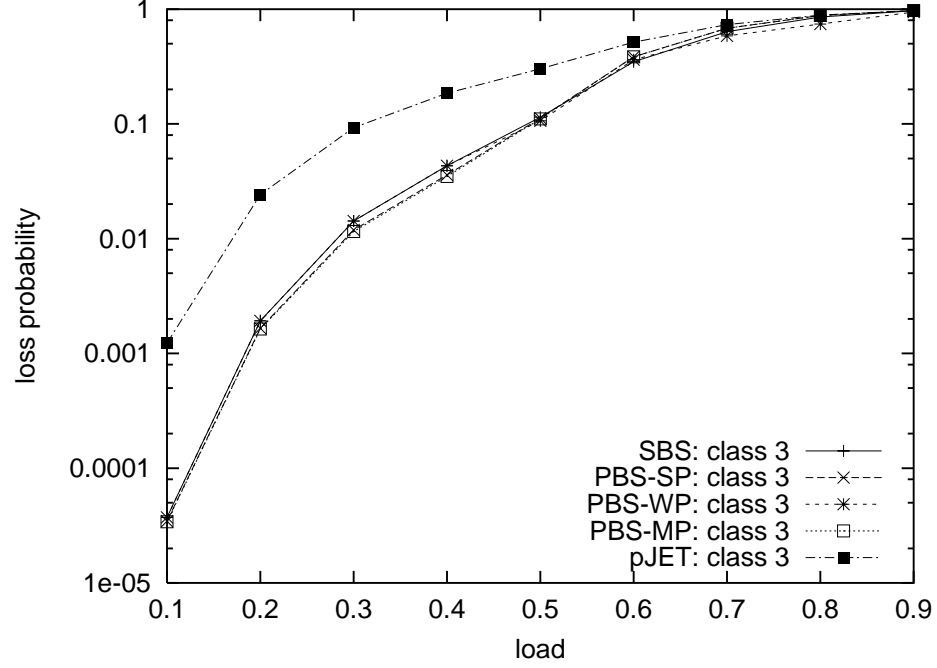


Figure 5.26: Burst loss probability as a function of the traffic load for priority class 3 for schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, $n = 4$, Pareto distributed control packet inter-arrival times, and Pareto distributed burst lengths.

the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 1$, and $n = 4$.

The Role of the Traffic Type

Figures 5.27 and 5.28 show that the burst loss probabilities of both class 0 and class3 are higher when the burst inter-arrival times are exponentially distributed than when the burst inter-arrival times are Pareto distributed. In both cases, the burst length distribution does not affect the burst loss probabilities significantly.

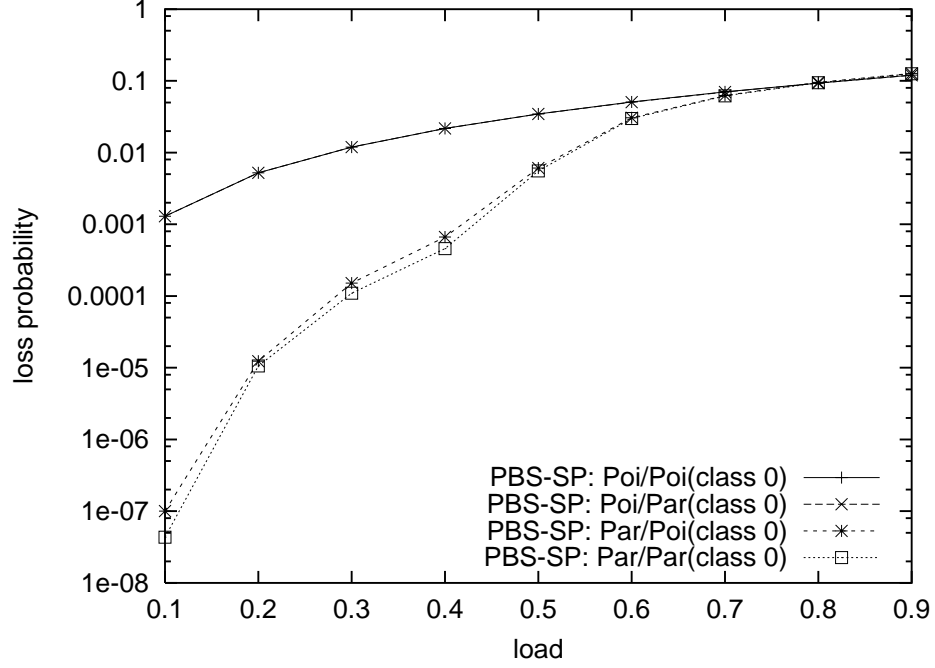


Figure 5.27: Burst loss probability of class 0 as a function of the traffic load using burst scheduling scheme PRI for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, $t_{ou} = 20\mu$, $t_{du} = 40\mu$, the burst traffic has an Pareto inter-arrival time distribution and an exponential burst length distribution.

Figure 5.27 plots the burst loss probability of class 0 as a function of the traffic load using the PBS-SP scheme when burst traffic inter-arrival time and burst length distributions varying from exponential distribution (Poi) to Pareto distribution (Par), $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, and $t_{ou} = 20\mu$, $t_{du} = 40\mu s$.

Figure 5.28 plots the simulated burst loss probability of class 3 as a function of the traffic load using PBS-SP scheme when burst traffic inter-arrival time and burst length distributions varying from exponential distribution (Poi) to Pareto distribution (Par), $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, and $t_{ou} = 20\mu$, $t_{du} = 40\mu s$.

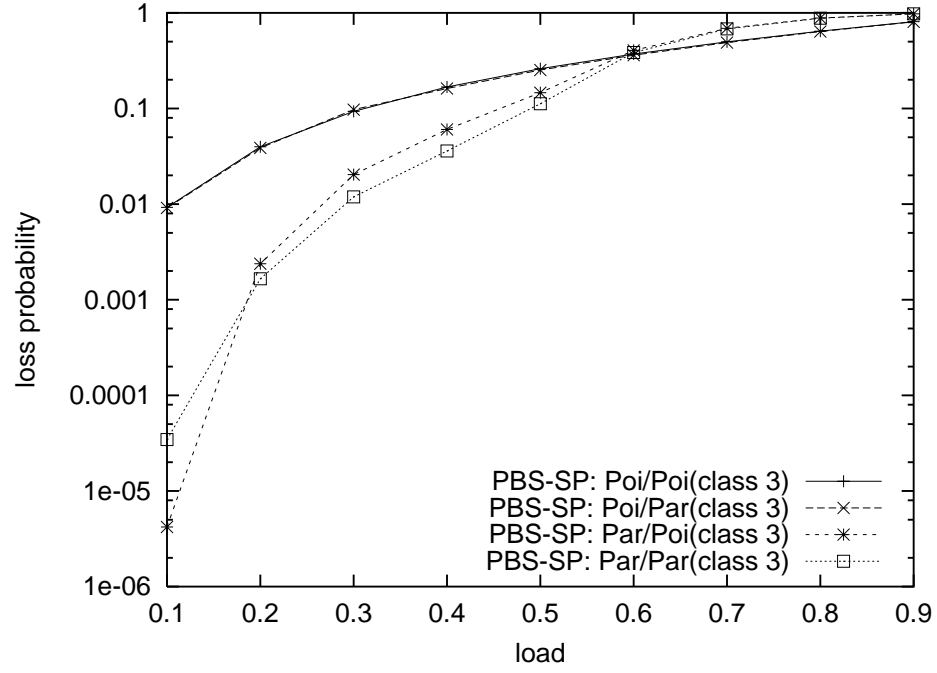


Figure 5.28: Burst loss probability of class 3 as a function of the traffic load using burst scheduling scheme PRI for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, $t_{ou} = 20\mu$, $t_{du} = 40\mu$, the burst traffic has an Pareto inter-arrival time distribution and an exponential burst length distribution.

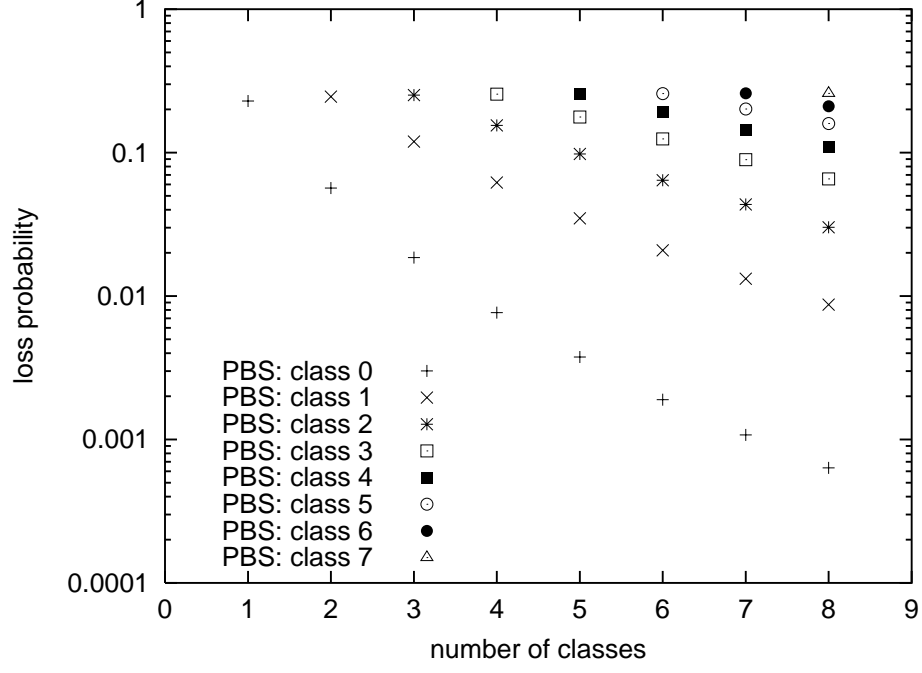


Figure 5.29: Burst loss probability as a function of the maximum number of the number of priority classes for $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 40\mu s$, and $\rho = 0.8$.

The Role of the Number of Classes

Figure 5.29 shows the burst loss probability as function of the number of priority classes using the PBS-SP scheme for $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 40\mu s$, and $\rho = 0.8$ where the total load is even distributed among the priority classes, and the percentage share of each priority class is lower as the number of classes increases. It indicates that the burst loss probability of the highest priority class 0 gets lower as more priority classes are supported.

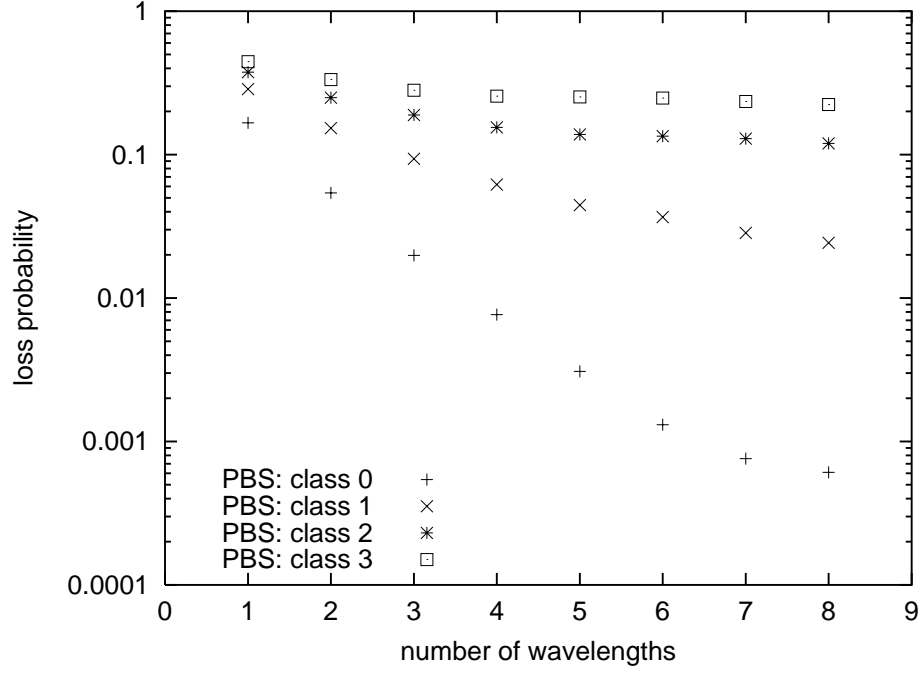


Figure 5.30: Burst loss probability as a function of the maximum number of the number of wavelengths for $n = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 40\mu s$, and $\rho = 0.8$.

The Role of the Number of Wavelengths

Figure 5.30 displays the burst loss probability as function of the number of wavelengths t_{ou} for $n = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 40\mu s$, and $\rho = 0.8$. It shows that the burst loss probabilities of all priority classes become lower as more wavelengths are used, and the higher the priority, the quicker the burst loss probability decreases.

The Role of the Offset-Time Unit

The pretransmission delay of a burst is proportional to the hop offset time unit. It is important to see the effect of the offset time unit on burst loss probability as well. Figure 5.31 shows the burst loss probability as function of the offset time unit

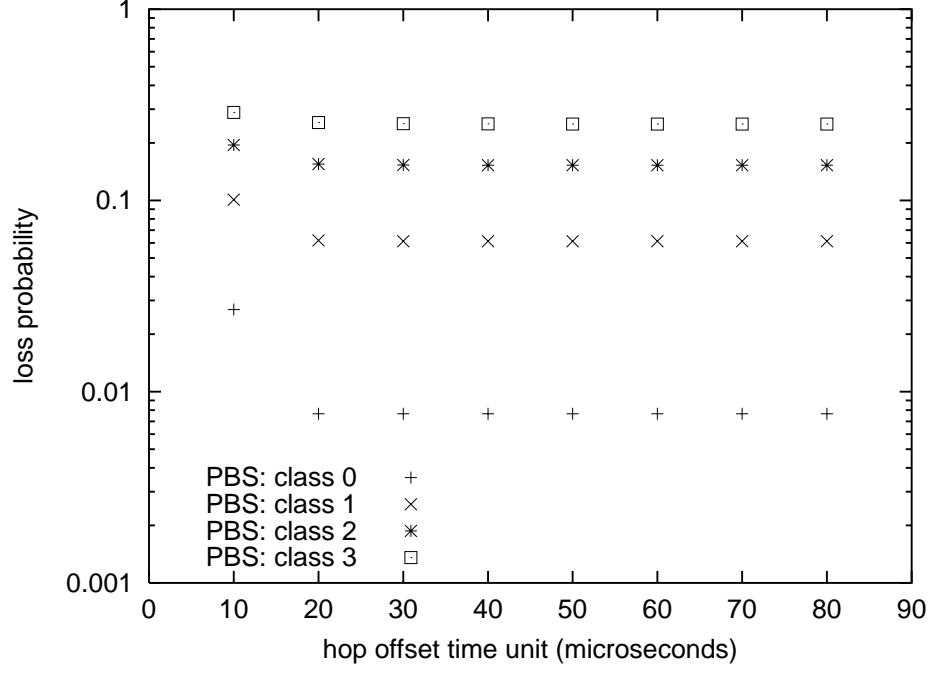


Figure 5.31: Burst loss probability as a function of the offset time unit for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, and $\rho = 0.8$.

for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, and $\rho = 0.8$. It shows that the burst loss probabilities decrease as the hop offset time unit increases from $10\mu s$ to $30\mu s$, and flats out afterwards. The reason is that a large hop offset time unit will increase the priority class isolation and thus the burst loss probability of each priority class to some extent.

5.4.3 Multiple Traffic Flows

In this section, we consider PBS's performance when bursts arrive at a core node with different destinations. The control packets for these bursts thus have different

offset time values. We define the maximum remaining hop number as h and assume that the bursts have evenly distributed hop numbers between 1 and h .

SBS Service Differentiation

With multiple traffic flows with evenly distributed destinations, Figures 5.32, 5.33, 5.34, and 5.35 shows that the same burst loss probability for each priority class with various inter-arrival time distribution and various burst length distribution.

Figure 5.32 plots the burst loss probability as a function of the traffic load for 4 priority classes using the SBS scheme when the burst traffic has the exponentially distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, and $n = 4$.

Figure 5.33 plots the burst loss probability as a function of the traffic load for 4 priority classes using the SBS scheme when the burst traffic has the exponentially distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, and $srv_{\alpha} = 1.5$.

Figure 5.34 plots the burst loss probability as a function of the traffic load for 4 priority classes using the SBS scheme when the burst traffic has the Pareto distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, and $n = 4$.

Figure 5.35 plots the burst loss probability as a function of the traffic load for 4 priority classes using the SBS scheme when the burst traffic has the Pareto distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system

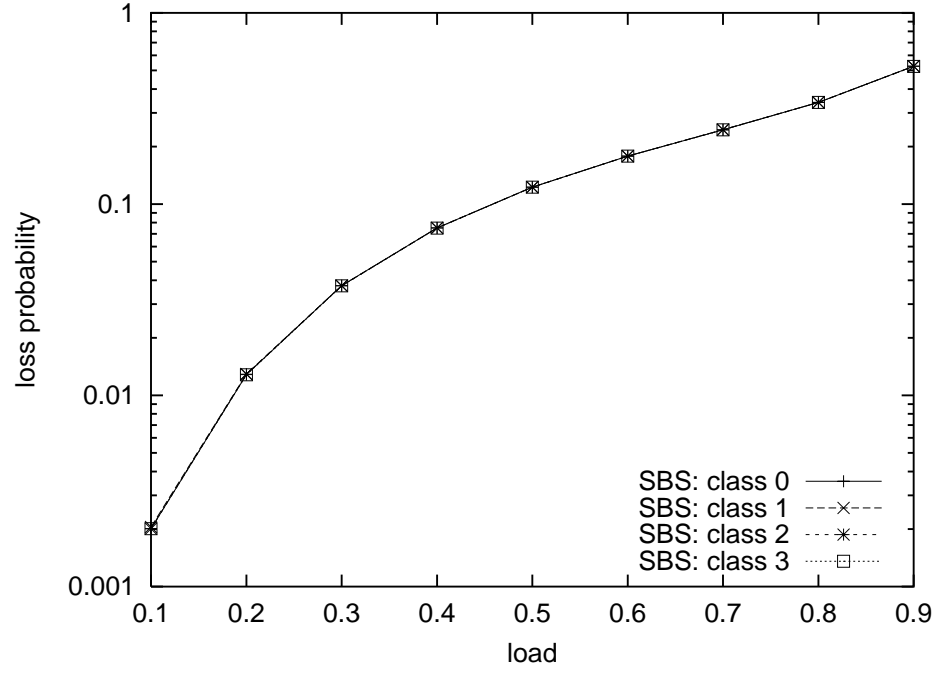


Figure 5.32: Burst loss probability as a function of the traffic load for 4 priority classes using the SBS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.

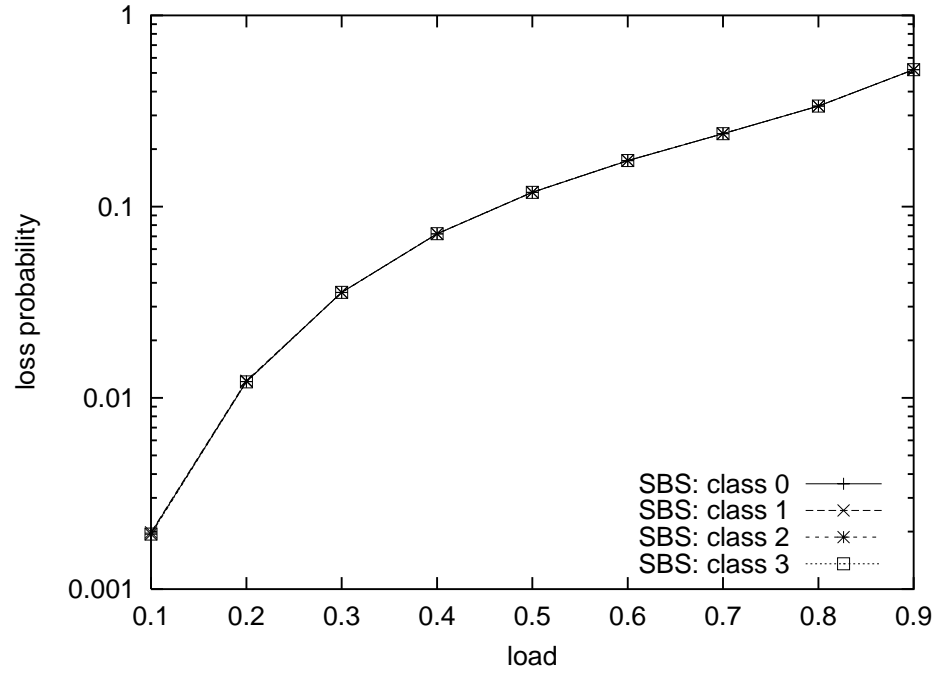


Figure 5.33: Burst loss probability as a function of the traffic load for 4 priority classes using the SBS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $srv_{\alpha} = 1.5$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths

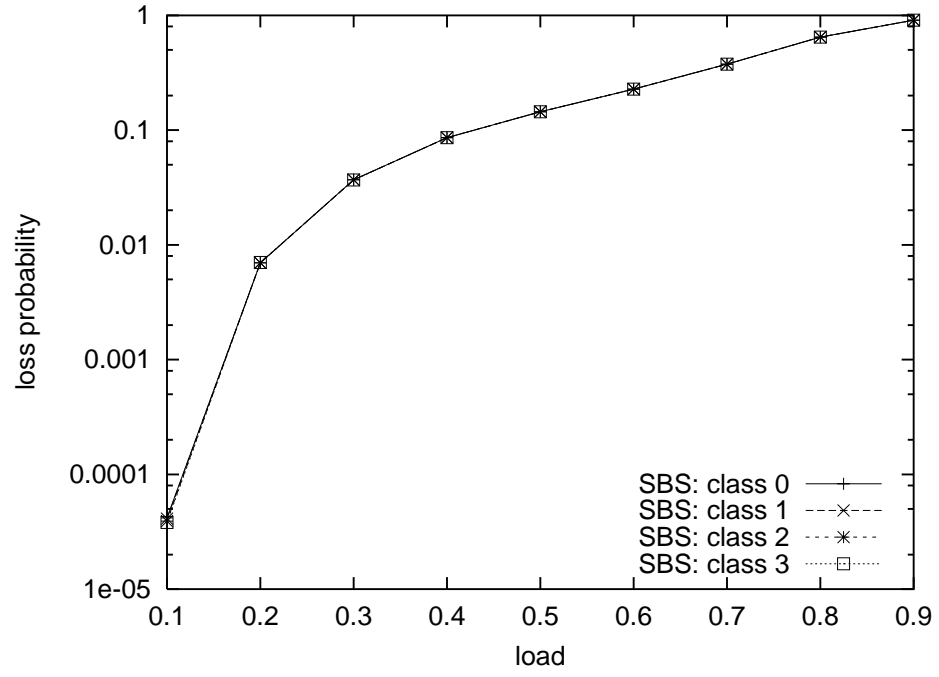


Figure 5.34: Burst loss probability as a function of the traffic load for 4 priority classes using the SBS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $iar_{\alpha} = 1.5$, Pareto distributed inter-arrival time, and exponentially distributed burst lengths

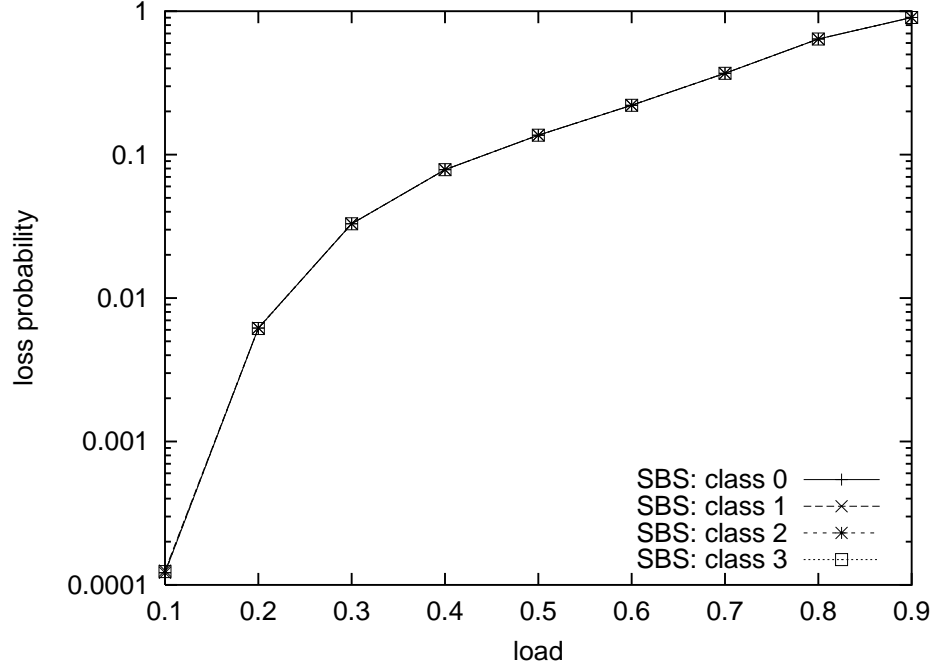


Figure 5.35: Burst loss probability as a function of the traffic load for 4 priority classes using the SBS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $iar_{\alpha} = 1.5$, $srv_{\alpha} = 1.5$, Pareto distributed inter-arrival time, and Pareto distributed burst lengths

and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $iar_{\alpha} = 1.5$, and $srv_{\alpha} = 1.5$.

PBS-SP Service Differentiation

In multiple traffic flow cases, PBS-SP still support service differentiations as shown in Figures 5.36, 5.37, 5.38, and 5.39.

Figure 5.36 plots the burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme when the burst traffic has the exponentially distributed control packet inter-arrival times and the exponentially distributed burst

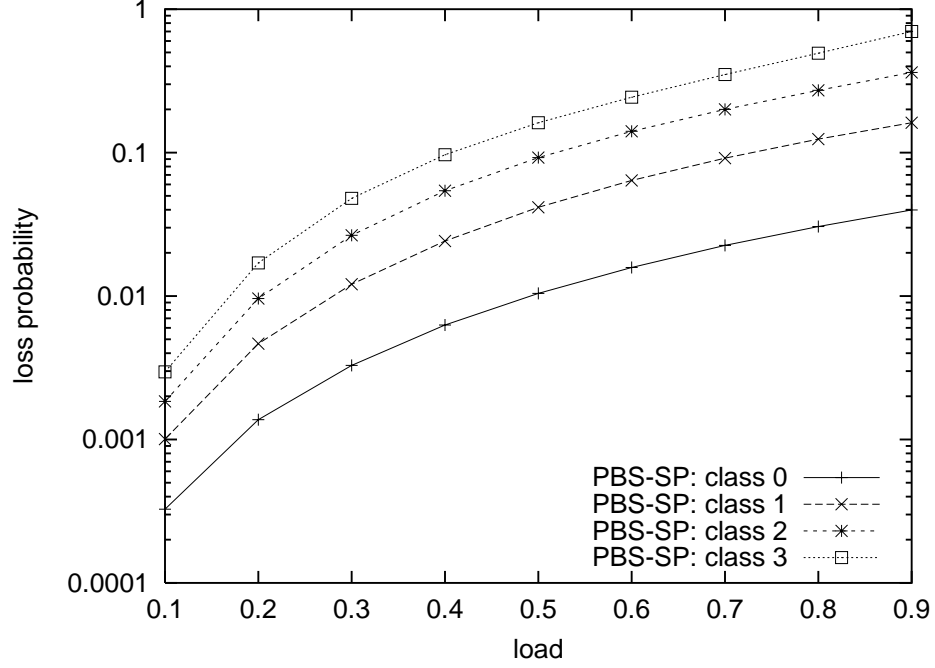


Figure 5.36: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.

lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, and $n = 4$.

Figure 5.37 plots the burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme when the burst traffic has the exponentially distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, and $srv_a = 1.5$.

Figure 5.38 plots the burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme when the burst traffic has the Pareto

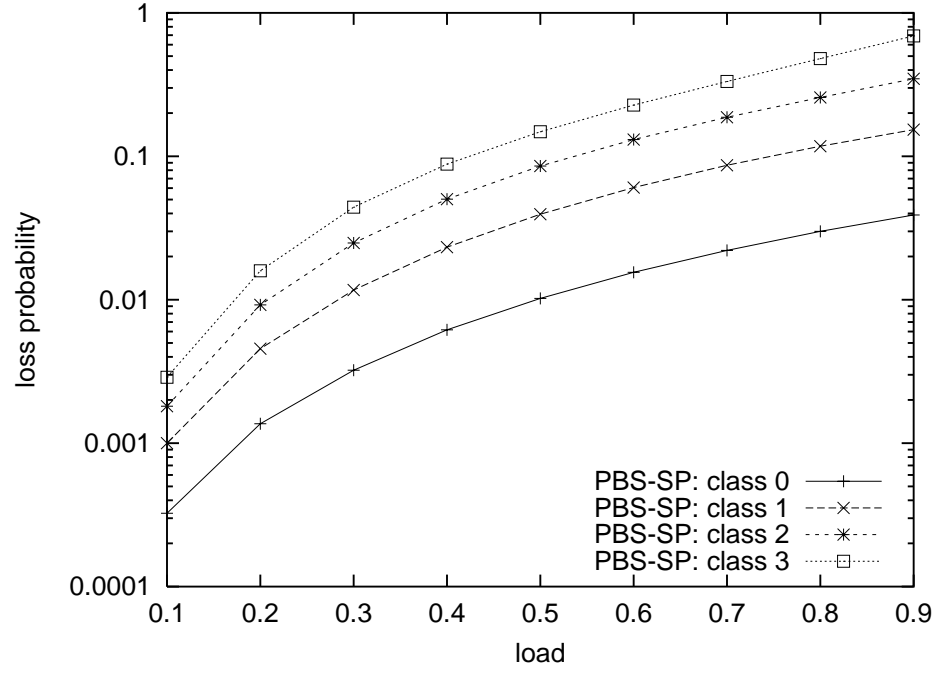


Figure 5.37: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $srv_a = 1.5$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths

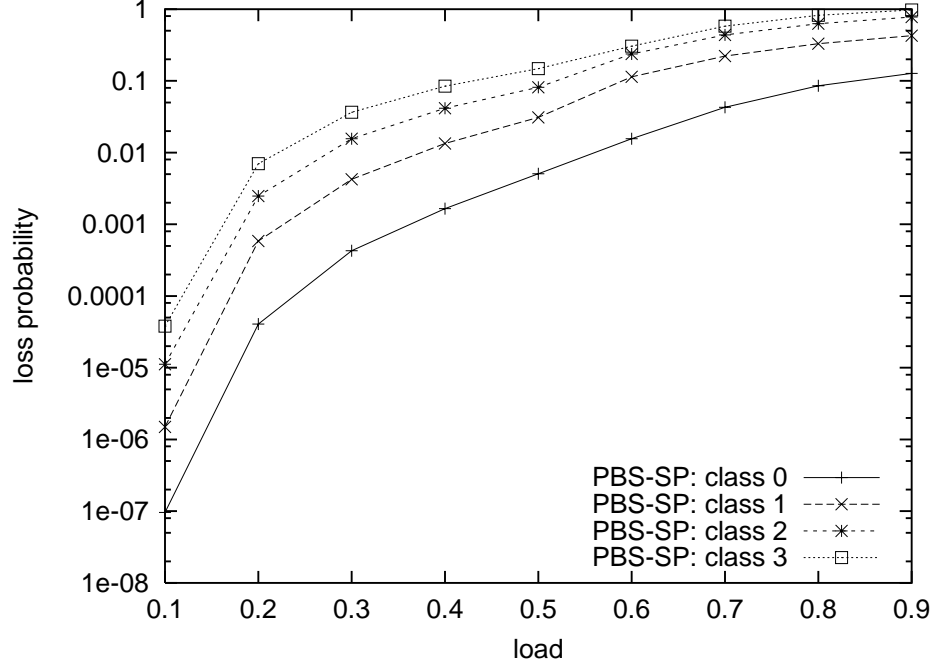


Figure 5.38: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $iar_a = 1.5$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths

distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $iar_a = 1.5$.

Figure 5.39 plots the burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme when the burst traffic has the Pareto distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $iar_a = 1.5$, and $srv_a = 1.5$.

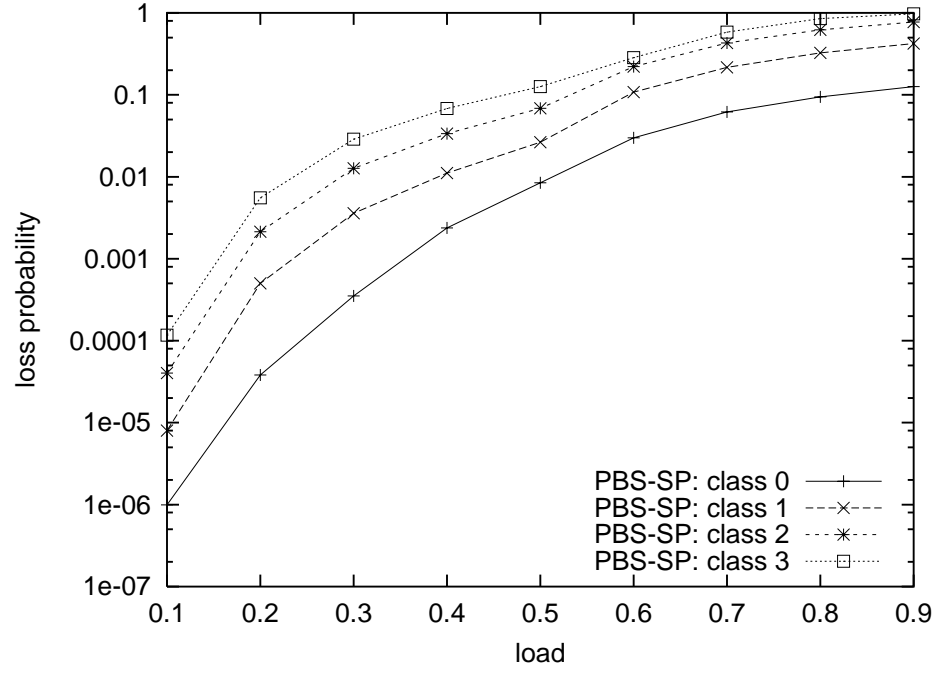


Figure 5.39: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-SP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $iar_ \alpha = 1.5$, and $srv_ \alpha = 1.5$, Pareto distributed inter-arrival time, and Pareto distributed burst lengths

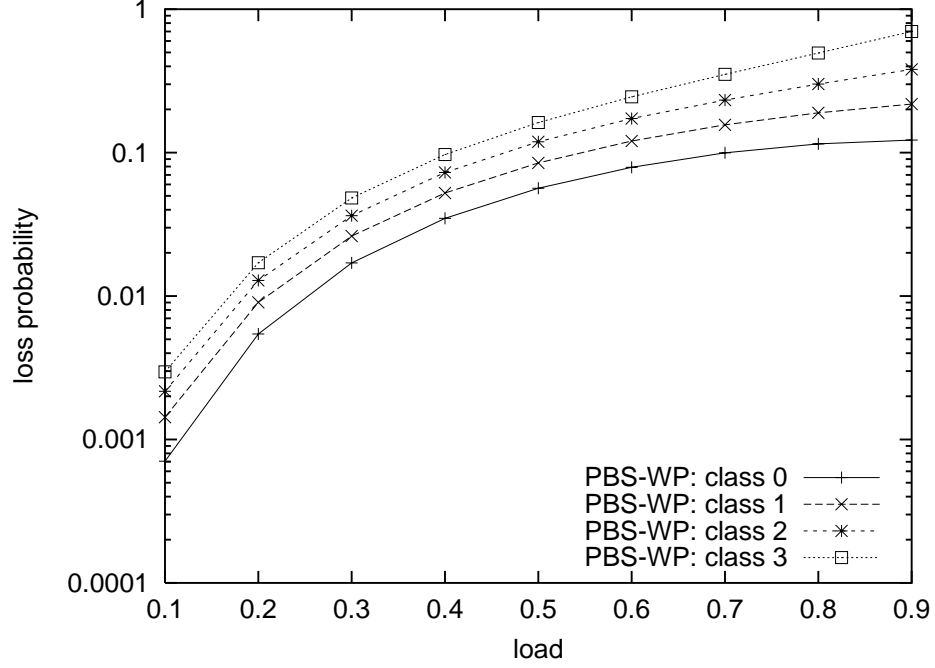


Figure 5.40: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-WP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.

PBS-WP Service Differentiation

With multiple traffic flows with evenly distributed destinations, PBS-WP still support service differentiations as shown in Figures 5.40, 5.41, 5.42, and 5.43.

Figure 5.40 plots the burst loss probability as a function of the traffic load for 4 priority classes using the PBS-WP scheme when the burst traffic has the exponentially distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, and $n = 4$.

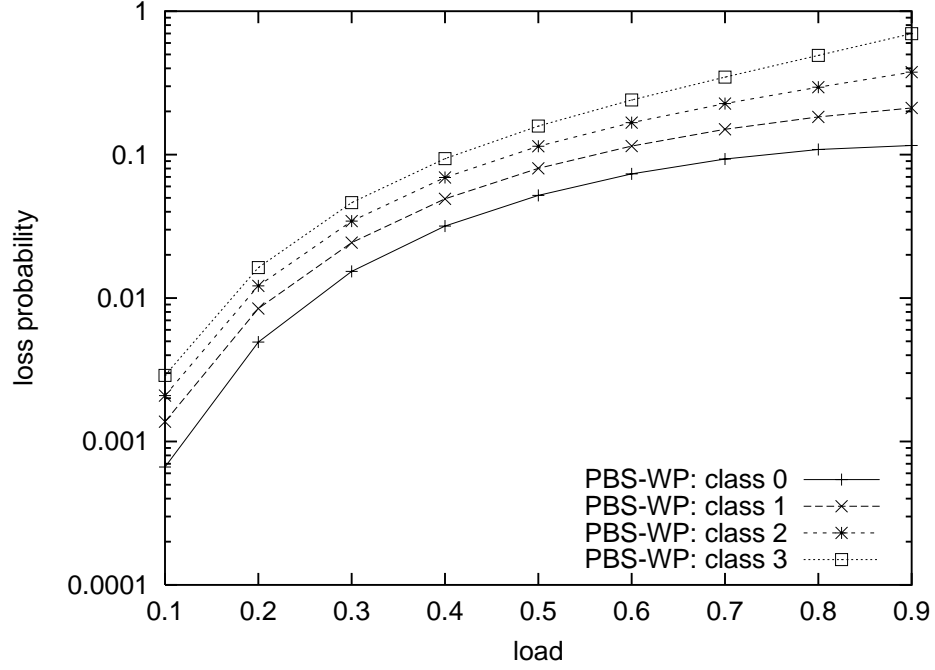


Figure 5.41: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-WP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $srv_a = 1.5$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths

Figure 5.41 plots the burst loss probability as a function of the traffic load for 4 priority classes using the PBS-WP scheme when the burst traffic has the exponentially distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, and $srv_a = 1.5$.

Figure 5.42 plots the burst loss probability as a function of the traffic load for 4 priority classes using the PBS-WP scheme when the burst traffic has the Pareto distributed control packet inter-arrival times and the exponentially distributed burst

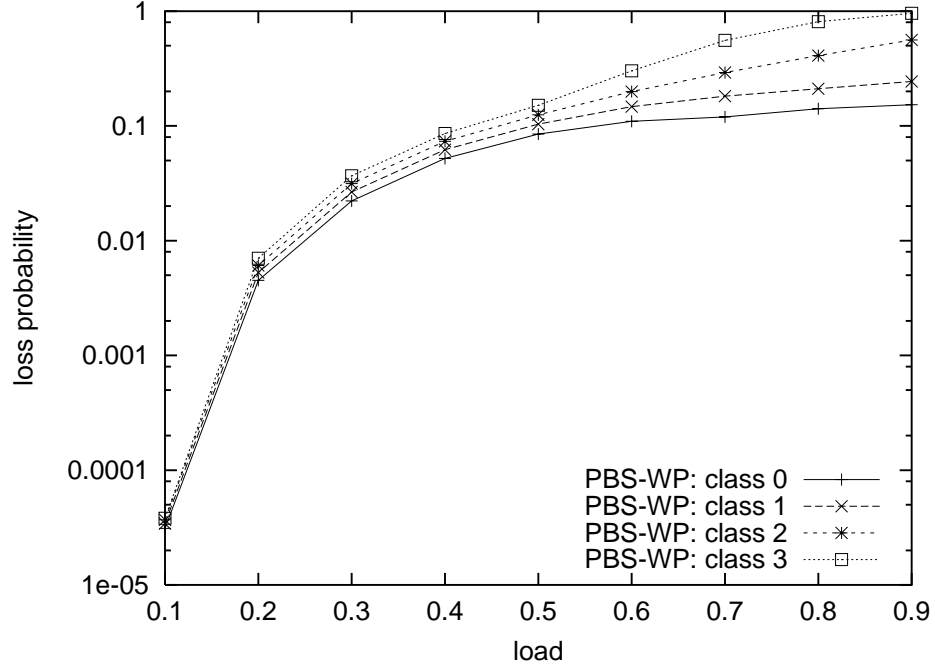


Figure 5.42: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-WP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $iar_{\alpha} = 1.5$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths

lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, and $iar_{\alpha} = 1.5$.

Figure 5.43 plots the burst loss probability as a function of the traffic load for 4 priority classes using the PBS-WP scheme when the burst traffic has the Pareto distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $iar_{\alpha} = 1.5$, and $srv_{\alpha} = 1.5$.

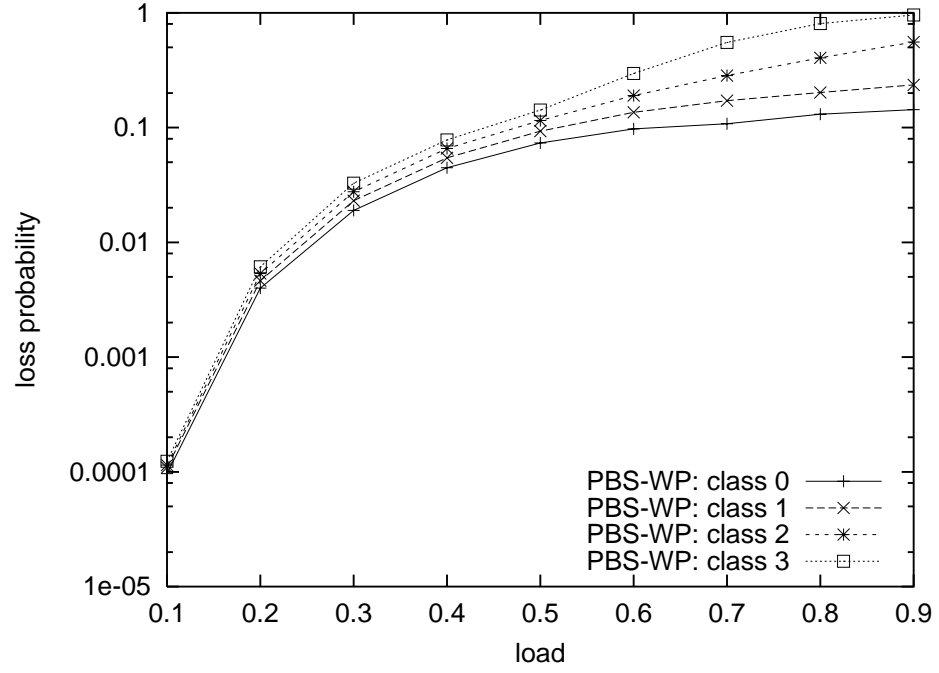


Figure 5.43: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-WP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $iar_a = 1.5$, $srv_a = 1.5$, Pareto distributed inter-arrival time, and Pareto distributed burst lengths

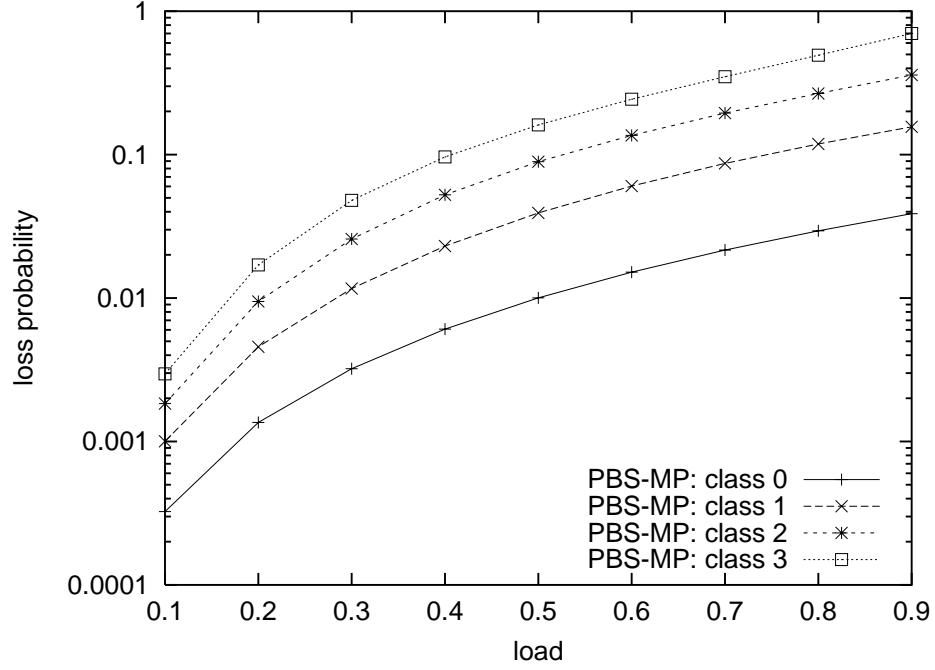


Figure 5.44: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.

PBS-MP Service Differentiation

Figure 5.44 plots the burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme when the burst traffic has the exponentially distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, and $n = 4$.

Figure 5.45 plots the burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme when the burst traffic has the exponentially

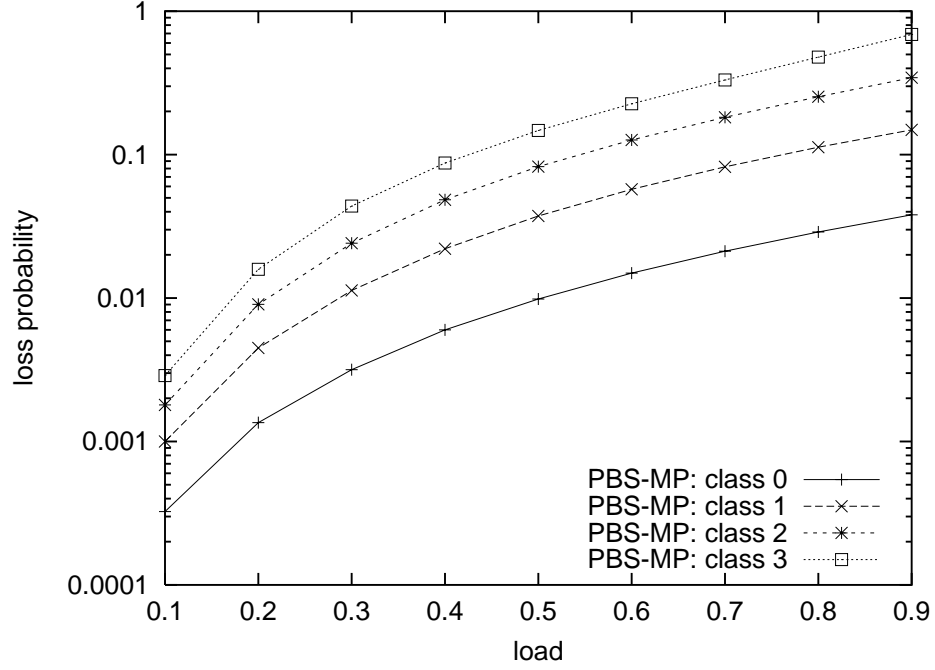


Figure 5.45: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $srv_a = 1.5$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths

distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, and $srv_a = 1.5$.

Figure 5.46 plots the burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme when the burst traffic has the Pareto distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, and $iar_a = 1.5$.

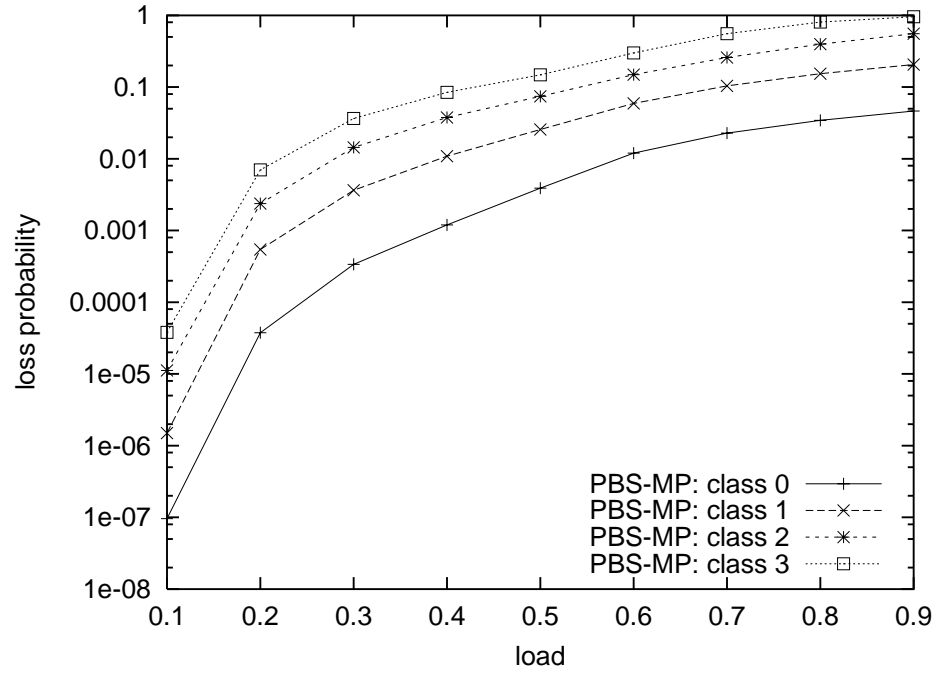


Figure 5.46: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $iar_a = 1.5$, Pareto distributed inter-arrival time, and Pareto distributed burst lengths

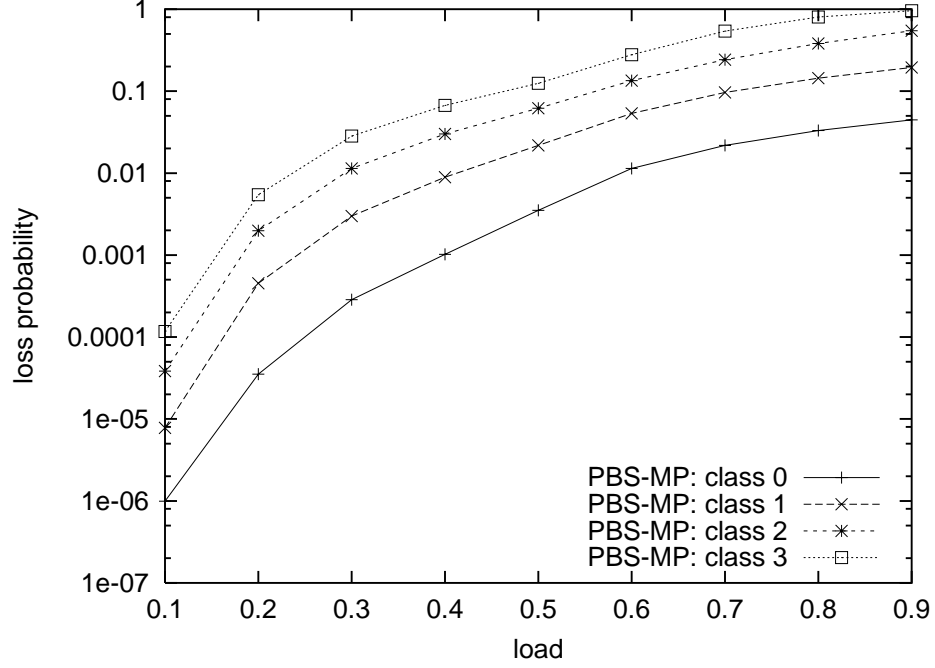


Figure 5.47: Burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $iar_{\alpha} = 1.5$, $srv_{\alpha} = 1.5$, Pareto distributed inter-arrival time, and Pareto distributed burst lengths

Figure 5.47 plots the burst loss probability as a function of the traffic load for 4 priority classes using the PBS-MP scheme when the burst traffic has the Pareto distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $h = 4$, $n = 4$, $iar_{\alpha} = 1.5$, and $srv_{\alpha} = 1.5$.

The Comparison of Scheduling Schemes

The performances of SBS, PBS-SP, PBS-WP, PBS-MP and PJET are compared in terms of burst loss probabilities for both priority 0 and priority 3 bursts. When

the burst inter-arrival times are exponentially distributed, Figure 5.48 shows that the PBS-SP and PBS-MP perform as good as the pJET with multiple traffic flow case, compared with the single traffic flow case in Figure 5.19 where pJET performs better than PBS-SP and PBS-MP. When the burst inter-arrival times are Pareto distributed, PBS-SP and PBS-MP seem to perform better in terms of burst loss probability of the priority class 0 than pJET as shown in Figures 5.52 and 5.54.

Figure 5.48 plots the burst loss probability of priority class 0 as a function of the traffic load using the burst schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET, respectively, when the burst traffic has the exponentially distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, and $n = 4$.

Figure 5.49 plots the burst loss probability of priority class 3 as a function of the traffic load for the burst schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET, respectively, when the burst traffic has the exponentially distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, and $n = 4$.

Figure 5.50 plots the burst loss probability of priority class 0 as a function of the traffic load for the burst schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET, respectively, when the burst traffic has the exponentially distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, $n = 4$, and $srv_a = 1.5$.

Figure 5.51 plots the burst loss probability of priority class 3 as a function of the traffic load for the burst schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET,

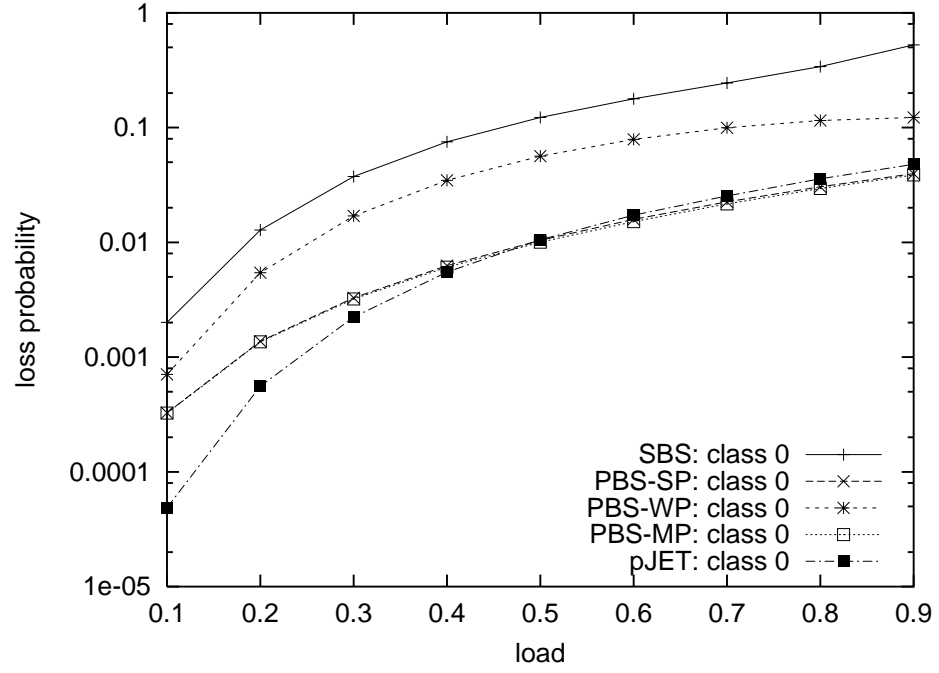


Figure 5.48: Burst loss probability as a function of the traffic load for priority class 0 for the schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.

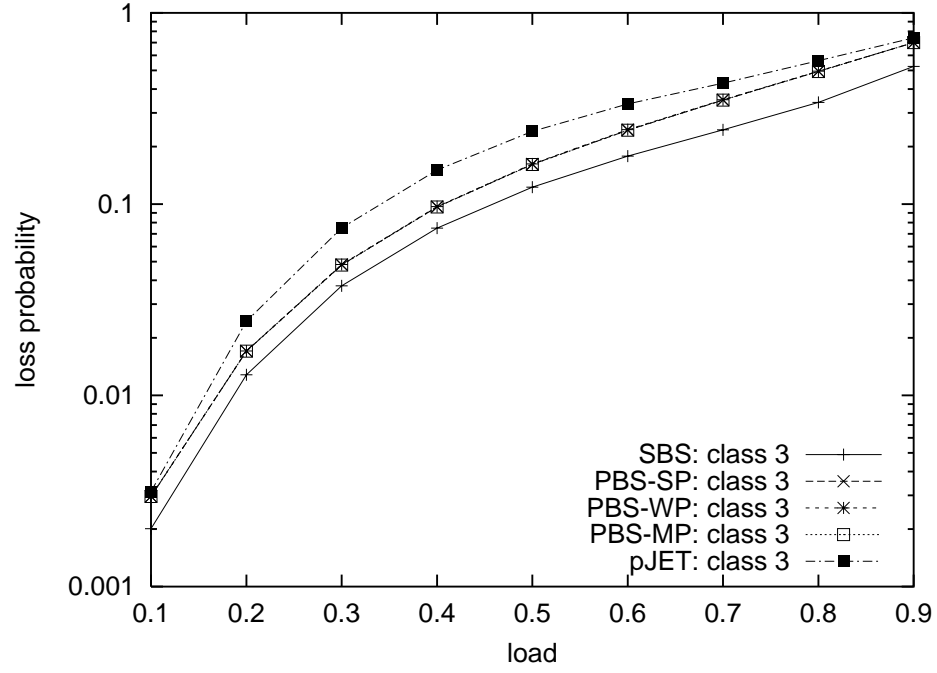


Figure 5.49: Burst loss probability as a function of the traffic load for priority class 3 for the schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.

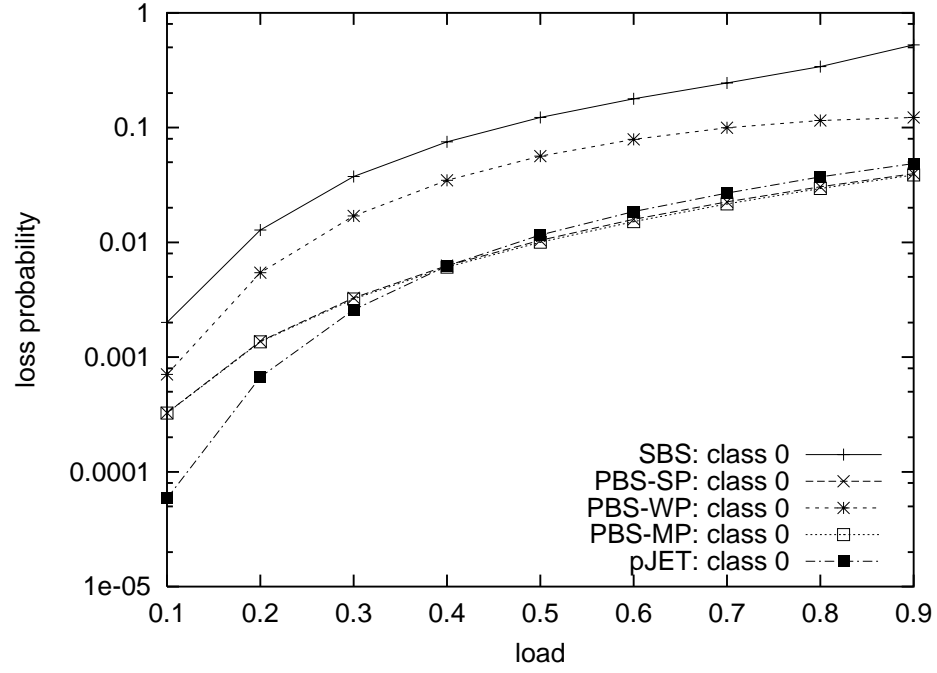


Figure 5.50: Burst loss probability as a function of the traffic load for priority class 0 for the schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, $n = 4$, $srv_a = 1.5$, exponentially distributed control packet inter-arrival times, and Pareto distributed burst lengths.

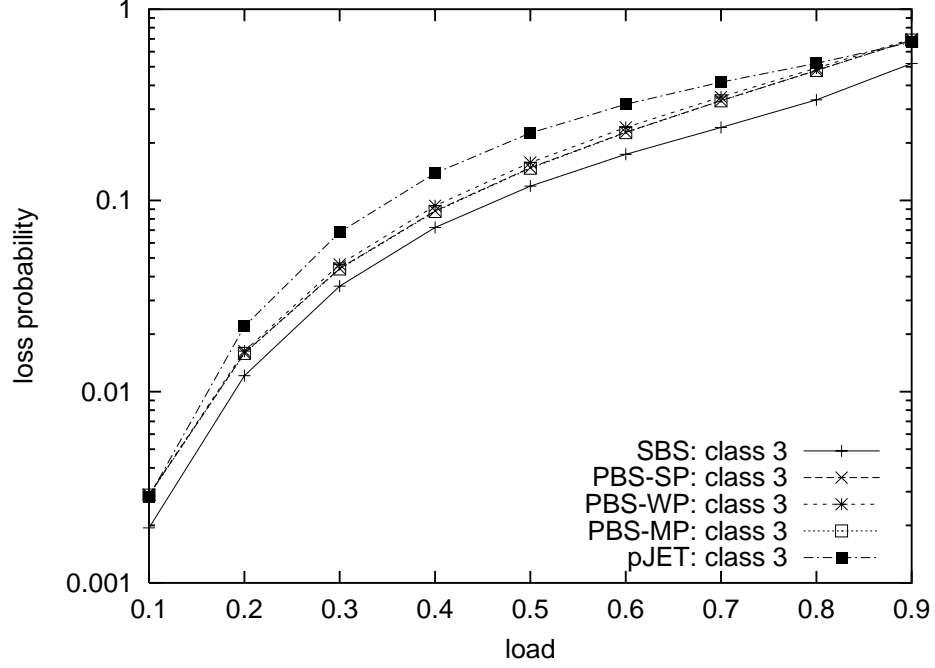


Figure 5.51: Burst loss probability as a function of the traffic load for priority class 3 for the schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, $n = 4$, $srv_a = 1.5$, exponentially distributed control packet inter-arrival times, and Pareto distributed burst lengths.

respectively, when the burst traffic has the exponentially distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, $n = 4$, and $srv_a = 1.5$.

Figure 5.52 plots the burst loss probability of priority class 0 as a function of the traffic load for the burst schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET, respectively, when the burst traffic has the Pareto distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, and $n = 4$.

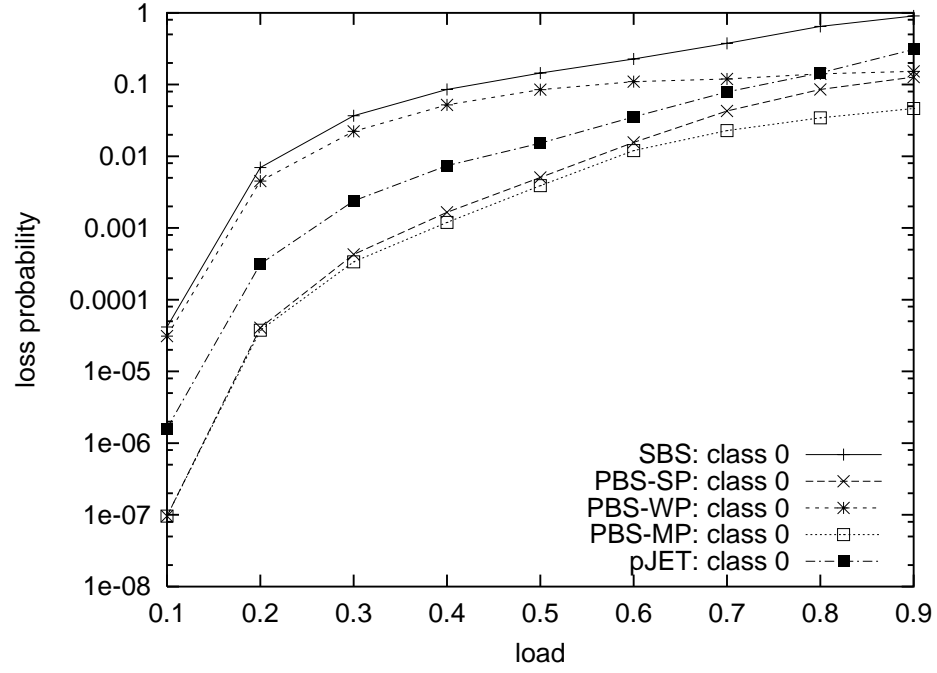


Figure 5.52: Burst loss probability as a function of the traffic load for priority class 0 for schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, $n = 4$, Pareto distributed control packet inter-arrival times, and exponentially distributed burst lengths.

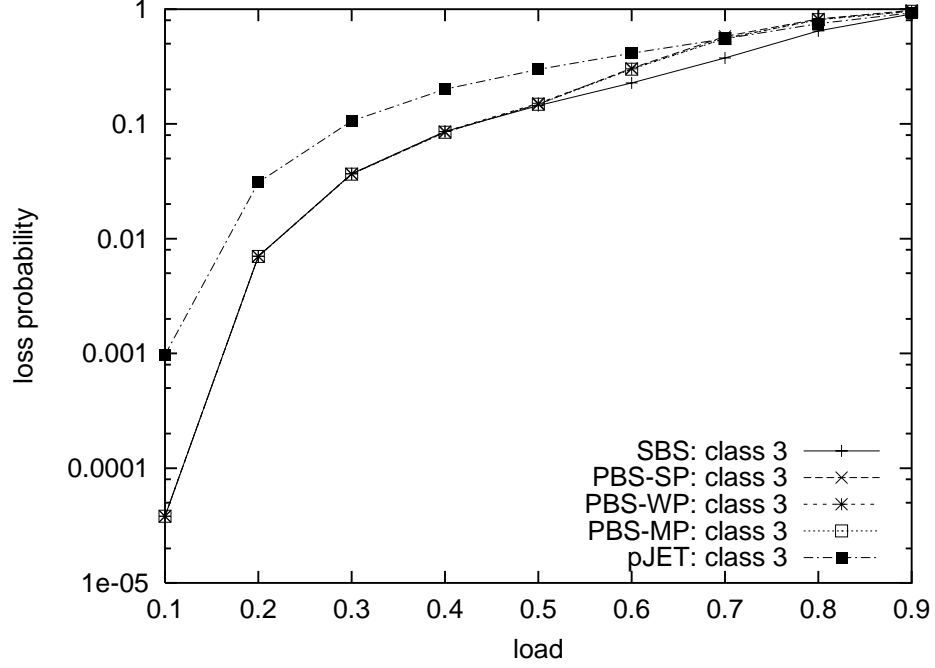


Figure 5.53: Burst loss probability as a function of the traffic load for priority class 3 for the schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, $n = 4$, $iar_alpha = 1.5$, Pareto distributed control packet inter-arrival times, and Pareto distributed burst lengths.

Figure 5.53 plots the burst loss probability of priority class 3 as a function of the traffic load for burst schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET when the burst traffic has the Pareto distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, $n = 4$, and $iar_alpha = 1.5$.

Figure 5.54 plots the burst loss probability of priority class 0 as a function of the traffic load for burst schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET when the burst traffic has the Pareto distributed control packet inter-arrival times and

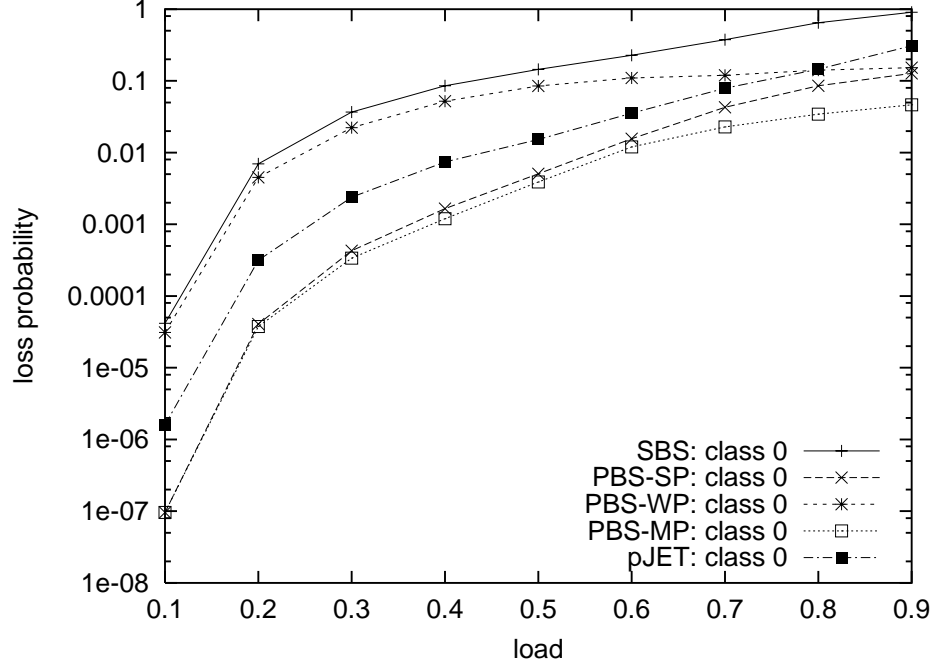


Figure 5.54: Burst loss probability as a function of the traffic load for priority class 0 for the schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, $n = 4$, $iar_a = 1.5$, $srv_a = 1.5$, Pareto distributed control packet inter-arrival times, and Pareto distributed burst lengths.

the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, $n = 4$, $iar_a = 1.5$, and $srv_a = 1.5$.

Figure 5.55 plots the burst loss probability of priority class 3 as a function of the traffic load for burst schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET when the burst traffic has the Pareto distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, $n = 4$, $iar_a = 1.5$, and $srv_a = 1.5$.

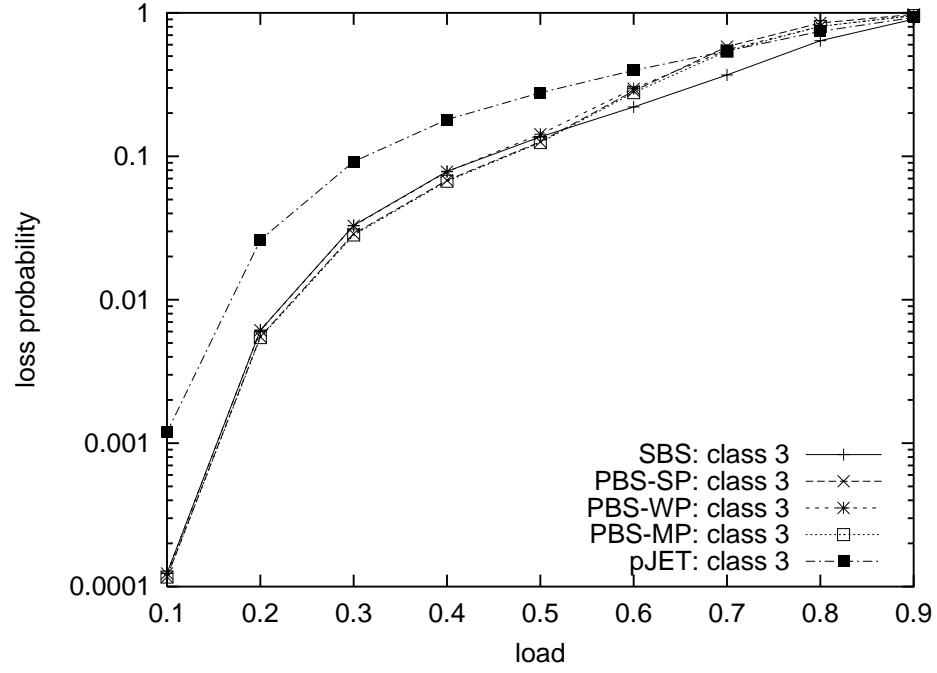


Figure 5.55: Burst loss probability as a function of the traffic load for priority class 3 for the schemes SBS, PBS-SP, PBS-WP, PBS-MP, and pJET for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, $h = 4$, $n = 4$, $iar_alpha = 1.5$, and $srv_alpha = 1.5$, Pareto distributed control packet inter-arrival times, and Pareto distributed burst lengths.

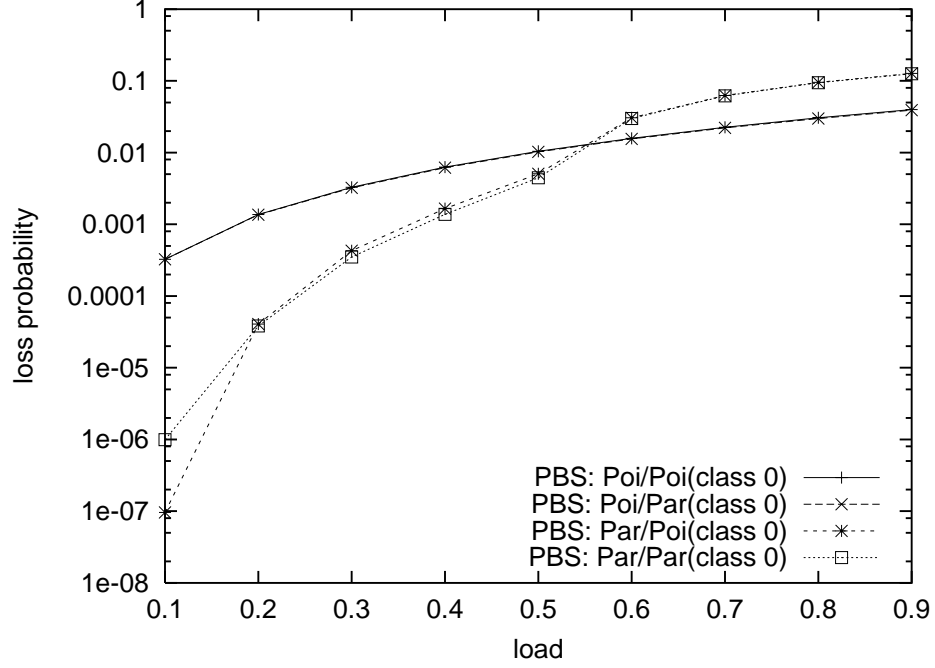


Figure 5.56: Burst loss probability of class 0 as a function of the traffic load using the burst scheduling scheme PBS-SP for $n = 4$, $k = 4$, $h = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, $t_{ou} = 20\mu$, $t_{du} = 40\mu$, $iar_a = 1.5$, and $srv_a = 1.5$.

The Role of the Traffic Type

Figure 5.56 shows the similar results as in single traffic flow case in Figure 5.27. Figure 5.56 plots the burst loss probability of class 0 as a function of the traffic load using the PBS-SP scheme when both burst traffic inter-arrival time and burst length distributions varying from an exponential distribution (Poi) to an Pareto distribution (Par), $n = 4$, $k = 4$, $h = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, and $t_{ou} = 20\mu s$, $t_{du} = 40\mu s$, $iar_a = 1.5$, and $srv_a = 1.5$.

Figure 5.57 plots the simulated burst loss probability of class 3 as a function of the traffic load using PBS-SP scheme when burst traffic inter-arrival time and burst length

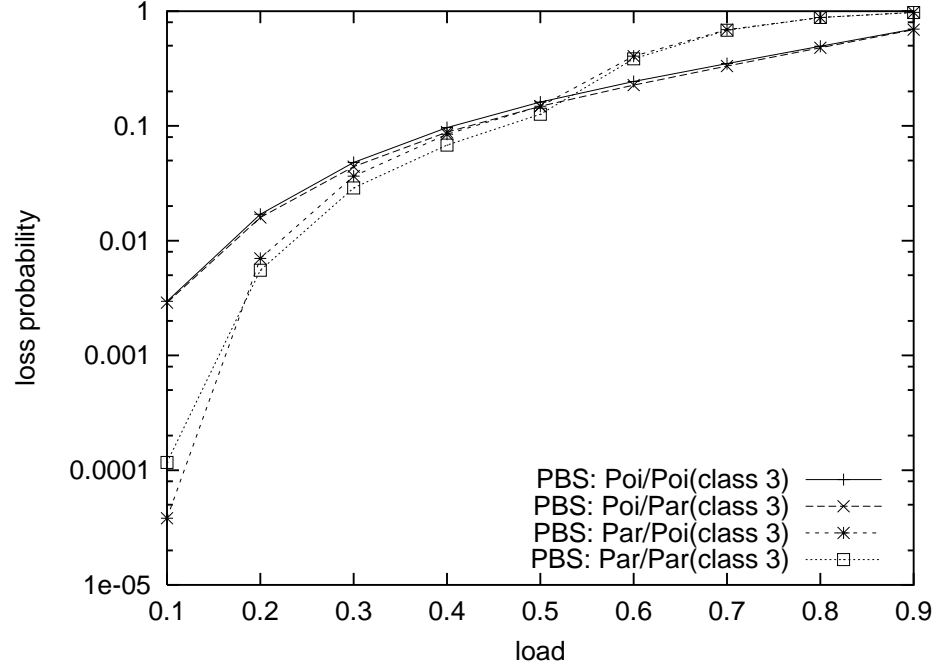


Figure 5.57: Burst loss probability of class 3 as a function of the traffic load using the burst scheduling scheme PBS-SP for $n = 4$, $k = 4$, $h = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, $t_{ou} = 20\mu$, $t_{du} = 40\mu$, $iar_a = 1.5$, and $srv_a = 1.5$.

distributions varying from an exponential distribution (Poi) to an Pareto distribution (Par), $n = 4$, $k = 4$, $h = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, and $t_{ou} = 20\mu s$, $t_{du} = 40\mu s$, $iar_a = 1.5$, and $srv_a = 1.5$.

The Role of the Number of Classes

Figure 5.58 shows the similar results as in single traffic flow case in Figure 5.29. Figure 5.58 shows the burst loss probability as function of the number of priority classes for $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$.

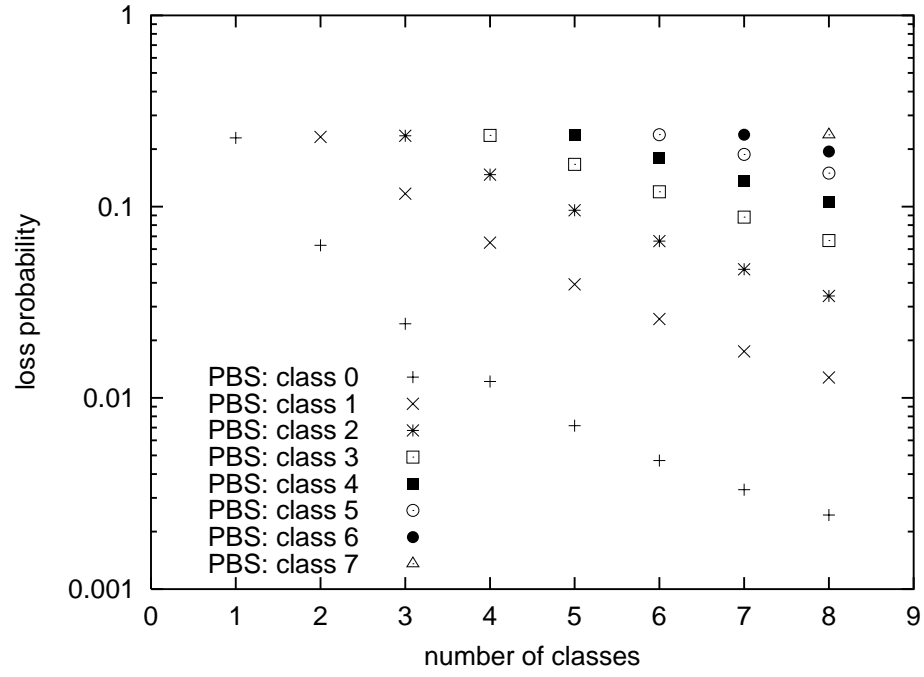


Figure 5.58: Burst loss probability as a function of the maximum number of the number of priority classes for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_p = 10\mu s$ and $t_{ou} = 20\mu s$

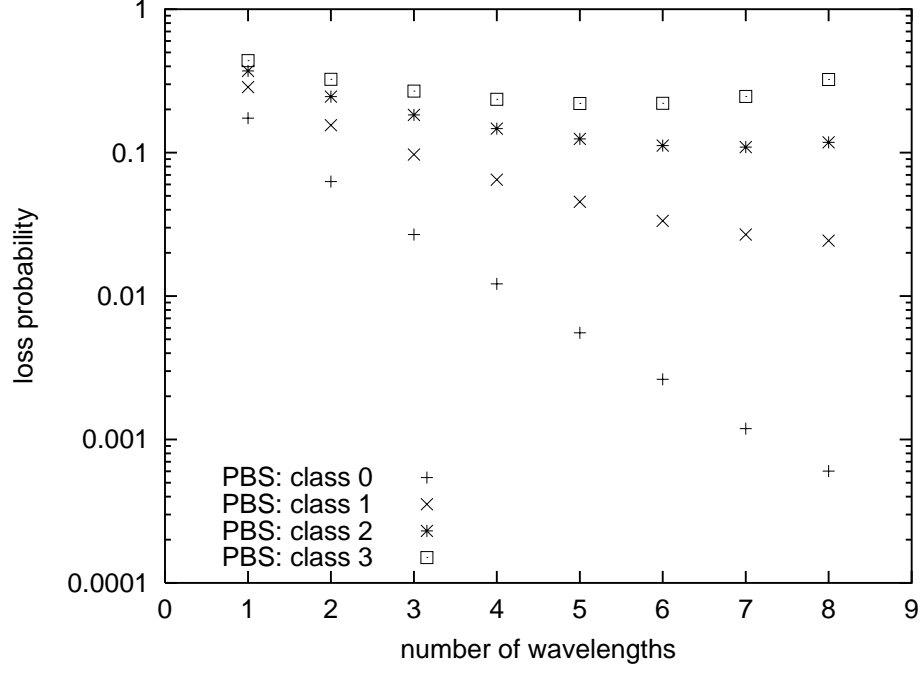


Figure 5.59: Burst loss probability as a function of the maximum number of the number of wavelengths per link for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$

The Role of the Number of Wavelengths

Figure 5.59 shows the similar results as in single traffic flow case in Figure 5.30. Figure 5.59 shows the burst loss probability as function of the number of wavelengths per link for $n = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$.

The Role of the Offset-Time Unit

Figure 5.60 shows the similar results as in single traffic flow case in Figure 5.31. Figure 5.60 shows the burst loss probability as function of the remaining hops t_{ou} for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, and $\rho = 0.8$.

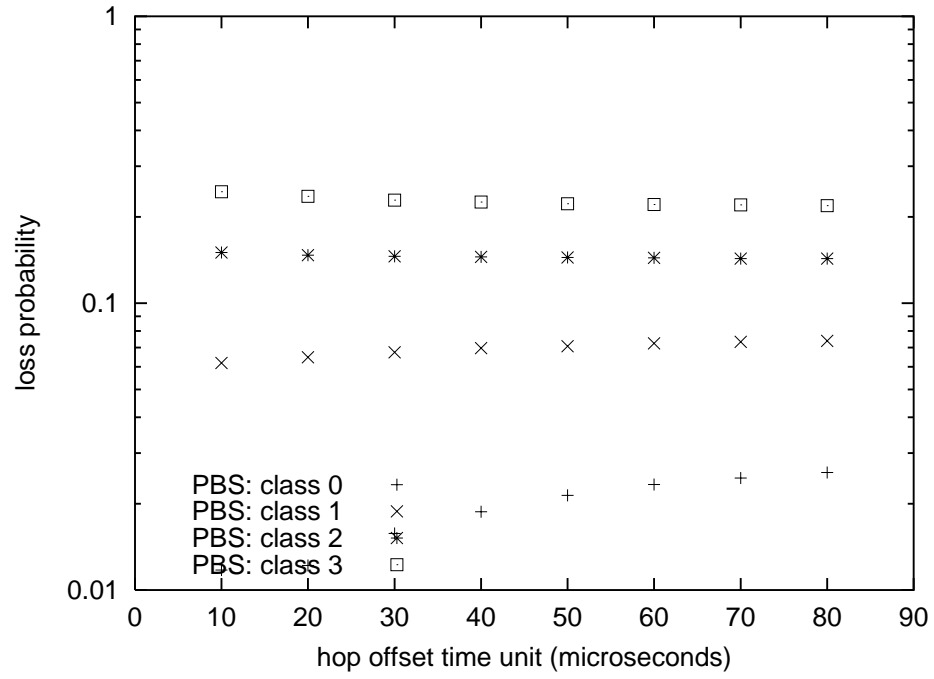


Figure 5.60: Burst loss probability as a function of the maximum number of the remaining hops for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, and $\rho = 0.8$.

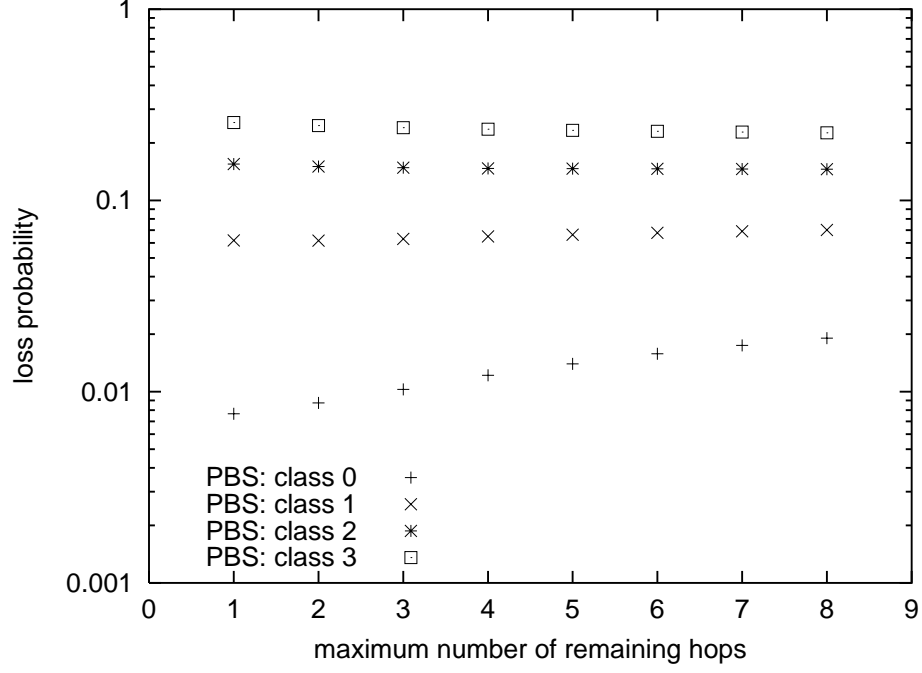


Figure 5.61: Burst loss probability as a function of the maximum number of the remaining hops for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, and $\rho = 0.8$.

The Role of the Maximum Number of Remaining Hops

Figure 5.61 shows as the maximum number of even distributed hops increases, the burst loss probability of a high priority class increases and the burst loss probability of a low priority class decrease, but the service differentiation is still supported.

Figure 5.61 shows the burst loss probability as function of the remaining hops h for $n = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, and $\rho = 0.8$.

5.5 Chapter Summary

In this chapter, a new burst scheduling scheme is proposed to support QoS in optical burst-switched WDM networks. Our scheme provides data bursts with different

priorities without undesirable extra delays for high priority class data bursts. Our burst scheduling algorithm is scalable and performs better in data burst loss probability than JET in supporting QoS in optical burst switched WDM WAN. In terms of scheduling flexibility, PBS supports PBS-SP, PBS-WP, and PBS-MP to adjust the relative burst loss probabilities between two adjacent priority classes. In the following chapter, a new burst scheduling scheme will be developed with much flexibility to differentiate burst loss probability between different priority classes.

CHAPTER 6

DIFFERENTIATED SCHEDULING

6.1 Introduction

In this chapter, a new data burst scheduling scheme, called *Differentiated Scheduling* (DS), is designed to support differentiated services in OBS. The DS schedules high priority bursts earlier than lower priority bursts only if the high priority bursts arrive within a certain period of time after the lower priority bursts. The differentiated services in terms of burst loss probability are achieved by processing the control packets of higher priority class bursts more promptly upon their arrivals than those of lower priority class bursts. Unlike the pJET, DS assigns the same priority offset time to all the bursts destined to the same edge node. With the additional priority offset time, each intermediate node can adjust the burst loss probabilities of various priority classes by choosing its own *differentiated processing delay* value for each priority class or its own *differentiated processing delay difference* value between any pair of adjacent priority classes. According to our best knowledge, none of current QoS supporting burst scheduling schemes allows intermediate (core) nodes to dynamically adjust the burst loss probabilities of priority classes.

The rest of the chapter is organized as follows. A new burst scheduling scheme DS is proposed and investigated in Section 6.2. The performance of DS is evaluated in Section 6.3. Finally, concluding remarks and future research work are presented in Section 6.4.

6.2 Differentiated Service Scheduling

In this section, *Differentiated Scheduling* (DS) is described. Various parameters associated with DS are also investigated.

6.2.1 Scheduling Scheme

In this simulation, the following assumptions are made for the burst scheduling in a core OBS node:

- A link has k data channels (wavelengths): Wl_1, Wl_2, \dots, Wl_k , and a control channel.
- Each output link is associated with a scheduler that is in charge of scheduling the data bursts sent to that link.
- The control packets for the data bursts to be transmitted on an output link are processed in the order they are received at the scheduler for that link.
- A control packet has an offset time field t_o that is the time interval between the control packet arrival time and the data burst arrival time.
- A control packet has a length field t_b that specifies the length of its data burst measured in time.

- A control packet has a priority field i that specifies the priority class of its data burst, ranging from 1 (the highest) to n (the lowest).
- A control packet can be described as $CP(t_c, t_o, t_b, i)$, where t_c is the control packet arrival time, t_o the offset time field, t_b the data burst size measured in time, and i the priority class.

We assume that an intermediate (core) node using DS has a separate queue for the control packets destined to each destination edge node. The control packets in a queue, therefore, have the same base offset time. The control packets in each queue are processed in the FIFO order. The scheduler uses the round-robin rule to process the control packets in different queues. In this chapter, we only focus on how the scheduler processes the control packets in one queue.

In DS, a control packet is not sent to the scheduler immediately upon its arrival, but is delayed for a period of time, called the *differentiated processing delay* (DPD), according to its priority class. An edge OBS node EN determines the number of priority classes n and their DPDs ($DPD_1^0 < DPD_2^0 < \dots < DPD_n^0$). For a path of h hops, each intermediate OBS node IN_s ($s = 1, 2, \dots, h - 1$) in turn chooses its own number of priority classes n_s it can support and its own set of DPDs ($DPD_1^s < DPD_2^s < \dots < DPD_{n_s}^s$). The DPD difference between a pair of adjacent priority classes is called the *differentiated processing delay difference* (DPDD). An intermediate (core) OBS node can adjust its DPDs by modifying its DPDDs. Since a control packet of a high priority class i has a shorter DPD than a control packet of a low priority class j for ($j > i$), the control packet of the priority class i will be processed by the scheduler earlier than the control packet of the priority class j .

if they arrive at the node within the time period of $DPD_j - DPD_i$. By modifying its DPDs or DPDDs, an intermediate node can adjust the burst loss probabilities of priority classes. DS is, therefore, dynamic and flexible. In DS, a control packet is processed as follows:

1. Each scheduler obtains the DPDs from the node's resource manager.
2. Each scheduler processes the control packets in its queue in the FIFO order.
3. A control packet CP (t_c, t_o, t_b, i) is delayed for a DPD_i time before being sent to the scheduling queue.
4. For a control packet CP (t_c, t_o, t_b, i) , the scheduler searches from wavelength 1 to wavelength k until one wavelength is found available between t_a and $t_a + t_b$, where t_a is the burst arrival time and equals $t_c + t_o$.
5. If none of the wavelengths is available for the data burst, the data burst will not be scheduled but will be dropped.

Figure 6.1 demonstrates an example how a high priority data burst is scheduled and a low priority data burst is dropped when they contend for a wavelength, even when the high priority data burst arrives later than the low priority data burst. In this example, a class 1 control packet arrives later than a class 2 control packet in the control wavelength. The corresponding class 1 data burst will arrive later than the corresponding class 2 data burst in the data wavelength since they have the same offset time in DS. Let us assume that the transmission of the class 1 data burst overlaps with the transmission of the class 2 data burst. Other burst scheduling schemes such as the JET [81] will schedule the class 2 data burst and drop the class

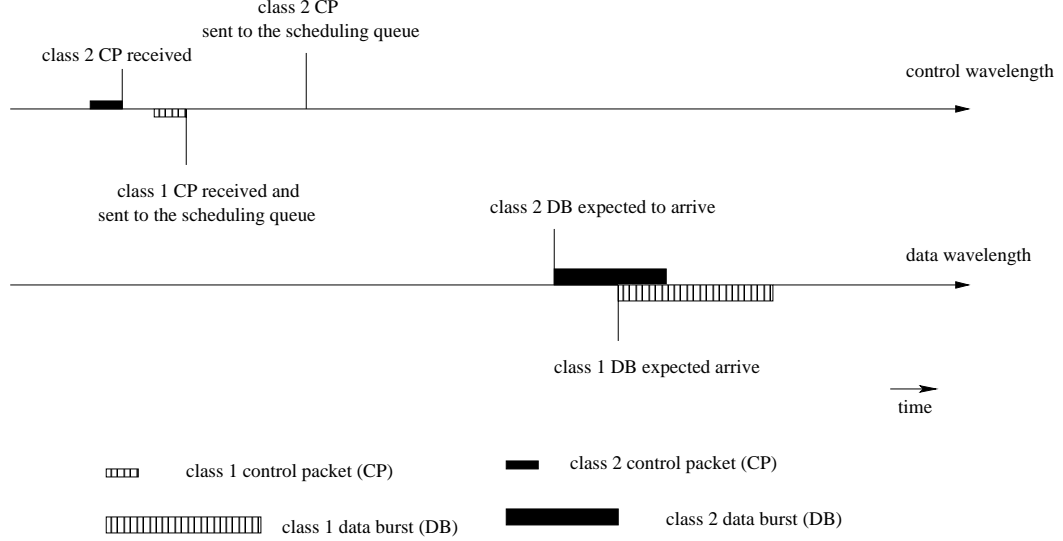


Figure 6.1: Differentiated Scheduling

1 data burst because the class 2 control packet arrives earlier than the class 1 control packet. In DS, however, the class 1 data burst will be scheduled because its shorter DPD compensates the arrival time difference between the class 1 data burst and the class 2 data burst. In fact, the class 1 control packet is processed by the scheduler earlier than the class 2 control packet.

A control packet contains information about its corresponding data burst such as the burst priority (i), the offset time(t_o), and the burst size (t_b) as discussed above. In the rest of this section, theses parameters and their relations will be discussed.

6.2.2 Base Offset Time

The base offset time for a burst is equal to the sum of the control packet processing times and the optical switch matrix setup times along the path from its source edge node to its destination edge node. At each core OBS node except the last one, the

transmission of a control packet to the next OBS node can be overlapped with the optical switch matrix setup for the control packet's data burst. There is no need for resource reservation at the egress OBS node. If we assume that at each node, the control packet processing time is t_p and the optical matrix setup time is t_s , then for a path of h hops, the base offset time t_{bo} equals $(h - 1) \cdot t_p + t_s$.

6.2.3 Differentiated Processing Delay

In DS, a class 1 control packet is processed immediately. A control packet from other classes will be delayed before being processed. The lower the priority class, the longer the control packet will be delayed. If the DPDD between any two adjacent priority classes is the same, then this DPDD value is called *differentiated processing delay unit* (DPDU) value and the scheduling scheme *Uniform Differentiated Scheduling* (DS-U). Otherwise, the scheme is called *Nonuniform Differentiated Scheduling* (DS-N). For DS-U, a priority class i control packet will be processed DPD_i after its arrival, where $DPD_i = (i - 1) \cdot DPDU$ for $1 \leq i \leq n$. DS-N only requires $DPD_o < DPD_1 \cdots < DPD_n$, for n priority classes.

6.2.4 Priority Offset Time

The priority offset time for a data burst is the sum of all the DPDDs. In DS-U with n priority classes, the priority offset time is

$$t_{po} = (n - 1) \cdot t_d$$

where t_d is the DPDU.

For DS-N, the priority offset time is

$$t_{po} = \sum_{i=1}^{n-1} t_{d,i}$$

where $t_{d,i}$ is the DPDD between class i and class $i + 1$.

6.2.5 Burst Offset Time

The burst offset time for a data burst is the sum of the base offset time and the priority offset time. For all the bursts from n priority classes with the same path of h hops, we obtain the burst offset time

$$t_o = (h - 1) \cdot t_p + t_s + (n - 1) \cdot t_d, \quad \text{for DS-U}$$

or

$$t_o = (h - 1) \cdot t_p + t_s + \sum_{i=1}^{n-1} t_{d,i}, \quad \text{for DS-N}$$

6.2.6 Support of Different Number of Priority Classes

A core node may not be able to support as many number of priority classes as the ingress edge node due to its resource constraints or QoS capacity. DS allows each core node to choose its own number of priority classes. The core node will then adjust its DPDs or DPDDs accordingly to meet the condition that its total DPDD value equals that of the ingress edge node.

For example, DS-U can be applied to an ingress edge node to support n priority classes with a DPDU of t_d . If n is an odd number, then DS-U can be used by a core node to support $(n + 1)/2$ priority with a DPDU of $2 * t_d$. If n is an even number, a core node can use DS-N to support $n/2 + 1$ priority classes with $n/2 - 1$ DPDDs of $2 * t_d$ and one DPDD of t_d . A core node can certainly support any number of priority

classes, up to the number of priority classes supported by the ingress edge node, as long as its total DPDD value equals the total DPDD value of the ingress edge node.

6.2.7 Priority Class Isolation

Priority class isolation describes a condition that bursts from a high priority class can not be blocked by bursts from a low priority class. In an OBS network, data bursts are assembled from IP packets with an assembly time intervals and/or a maximum data burst assembly size [102]. When all the data bursts have a maximum data burst size, DS-U guarantees total priority class isolation if the DPDU equals the maximum burst size. A proof is given as follows.

We assume that the class i bursts have a maximum burst size of $T_{b,i}$, for $1 \leq i \leq n$, where n is the number of priority classes. Let $T_b = \max_{1 \leq i \leq n} T_{b,i}$. The DPDU, denoted as t_d , is set to T_b as stated. Two data bursts B_i and B_j from any two burst priority classes i and j ($i < j$) are considered. The control packet arrival times of B_i and B_j are denoted as $t_{c,i}$ and $t_{c,j}$, respectively. The arrival time can therefore be defined as $t_{a,i} = t_{c,i} + t_o$ for B_i and $t_{a,j} = t_{c,j} + t_o$ for B_j , where t_o is the same offset time for all the priority classes in DS. The control packet of B_i will be processed at $t_{s,i} = t_{c,i} + (i - 1) \cdot t_d$. Similarly, the control packet of B_j will be processed at $t_{s,j} = t_{c,j} + (j - 1) \cdot t_d$. If the transmission of B_i overlaps with the transmission of B_j , then we have either $t_{a,i} \leq t_{a,j} < t_{a,i} + t_{b,i}$ (case 1) or $t_{a,j} \leq t_{a,i} < t_{a,j} + t_{b,j}$ (case 2), where $t_{b,i}$ and $t_{b,j}$ are the burst size of B_i and B_j , respectively.

In case 1, the control packet of B_i is processed earlier than the control packet of burst B_j because

$$t_{s,i} - t_{s,j} = (t_{c,i} + (i - 1) \cdot t_d) - (t_{c,j} + (j - 1) \cdot t_d)$$

$$\begin{aligned}
&= (t_{c,i} - t_{c,j}) - (j - i) \cdot t_d \\
&< t_{c,i} - t_{c,j} \\
&= (t_{a,i} - t_o) - (t_{a,j} - t_o) \\
&= t_{a,i} - t_{a,j} \\
&\leq 0
\end{aligned}$$

In case 2, we have $t_{a,j} \leq t_{a,i} < t_{a,j} + t_{b,j}$. Since $t_d = T_b \geq T_{b,j} \geq t_{b,j}$, we have

$$\begin{aligned}
t_{s,i} - t_{s,j} &= (t_{c,i} + (i - 1) \cdot t_d) - (t_{c,j} + (j - 1) \cdot t_d) \\
&= t_{c,i} - t_{c,j} - (j - i) \cdot t_d \\
&= (t_{a,i} - t_o) - (t_{a,j} - t_o) - (j - i) \cdot t_d \\
&= (t_{a,i} - t_{a,j}) - (j - i) \cdot t_d \\
&< t_{b,j} - (j - i) \cdot t_d \\
&\leq t_{b,j} - t_d \\
&\leq 0
\end{aligned}$$

Since $t_{s,i} \leq t_{s,j}$, the control packet of B_i is processed earlier than the control packet of B_j in case 2.

In both cases, the control packet of B_i is processed earlier than the control packet of B_j . B_i will not be blocked by B_j . The higher priority bursts, therefore, are not blocked by lower priority bursts.

Without the assumption of the maximum burst size, DISPO will not guarantee the total priority class isolation. The blocking probability of a high priority class

by any lower priority class, however, will be very small if the DPDU or the DPDDs are set appropriately. Let us assume that the burst size is exponentially distributed with the mean burst size of $T_{mb,i}$ for class i ($1 \leq i \leq n$). If we choose the DPDU $t_d = 5 \cdot \max_{1 \leq i \leq n} T_{mb,i}$, then the probability that a class i burst is blocked by any lower priority class j ($i < j$) burst is less than $1 - e^{-5}$ (about 0.0068). If the DPDU t_d is equal to $3 \cdot \max_{1 \leq i \leq n} T_{bm,i}$, then the probability that a class i burst is blocked by any lower priority class j ($i < j$) burst is less than $1 - e^{-3}$ (about 0.049). A high priority class, therefore, is less likely blocked and has a lower burst loss probability than a low priority class.

6.3 Performance Evaluation

The performance of DS is evaluated through simulation in this section. We consider two traffic models, Poisson and self-similar traffic. In Poisson traffic model, both the burst inter-arrival time and the burst length are generated using exponential distribution. To simulate self-similar traffic, a Pareto distribution [79] and a exponential distribution are used to generate the burst inter-arrival time and the burst length respectively. The Pareto distribution has the a cumulative distribution of the form $F(x) = 1 - (A/x)^\alpha$ for $x \geq A$, where α is a parameter that decides the heaviness of the distribution tail and $1 < \alpha < 2$.

The simulation results are obtained for a single OBS core node with an outgoing link having k wavelengths. We assume that all priority classes generate an equal amount of traffic with the same control packet inter-arrival distribution of the average inter-arrival time l_{iar} , and the same burst length distribution of the average service time l_{srv} . Therefore, all priority classes have the same traffic load $\frac{l_{srv}}{l_{iar}}$. The total

Variable	Description
k	the number of wavelengths on each link
t_p	the control packet service time by a scheduler
t_{ou}	the offset time needed per hop
t_{du}	the differentiated processing delay unit
h	maximum number of the remaining hops of flows
ρ	traffic load per wavelength
n	the number of priority classes
$iar_ \alpha$	the α value of the Pareto distribution of the control packet inter arrival times
$srv_ \alpha$	the α value of the Pareto distribution of the burst service times

Table 6.1: SBS, PBS, pJET, and DS system and flow variables

traffic load per wavelength ρ equals $\frac{nl_{iar}}{kl_{srv}}$. The burst loss probability is evaluated as a function of traffic intensity (load) ρ with a fixed average burst size t_b , the control packet processing time t_p , the number of priority classes n , the number of wavelengths k , the offset time t_o , and the maximum number of flow hops h in case of multiple flows per class, and the parameter α if the control packet inter-arrival time has a Pareto distribution. The average control packet inter-arrival time, thus the average burst inter-arrival time, is defined as $t_b/(n \cdot \rho)$. If the control packet inter-arrival time has a Pareto distribution, the parameter A of the Pareto distribution is $A = ((\alpha - 1) \cdot t_b)/(\alpha \cdot n \cdot \rho)$.

These parameters are described in Table 6.1.

6.3.1 Single Traffic Flow

A traffic flow is defined as all the burst from a source edge node to a destination edge node. Let's assume that all the bursts in a flow have the same offset time. A traffic flow may consists of bursts of various priorities. We investigate how the

burst loss probabilities of various priority classes are affected by the traffic load, the number of wavelengths, and the number of classes in a single flow with various burst scheduling schemes.

Service Differentiation

Figures 6.2, 6.3, 6.4, and 6.5 show that DS supports service differentiation for both the exponentially or Pareto distributed burst inter-arrival times and the exponentially or Pareto distributed burst lengths.

Figure 6.2 plots the burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme when the burst traffic has the exponentially distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_b = 40\mu s$, $t_{du} = 40\mu s$, $h = 1$, and $n = 4$.

Figure 6.3 plots the burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme when the burst traffic has the exponentially distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_b = 40\mu s$, $t_{du} = 40\mu s$, $h = 1$, $n = 4$, and $srv_{\alpha} = 1.5$.

Figure 6.4 plots the burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme when the burst traffic has the Pareto distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_b = 40\mu s$, $t_{du} = 40\mu s$, $h = 1$, and $n = 4$.

Figure 6.5 plots the burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme when the burst traffic has the Pareto distributed

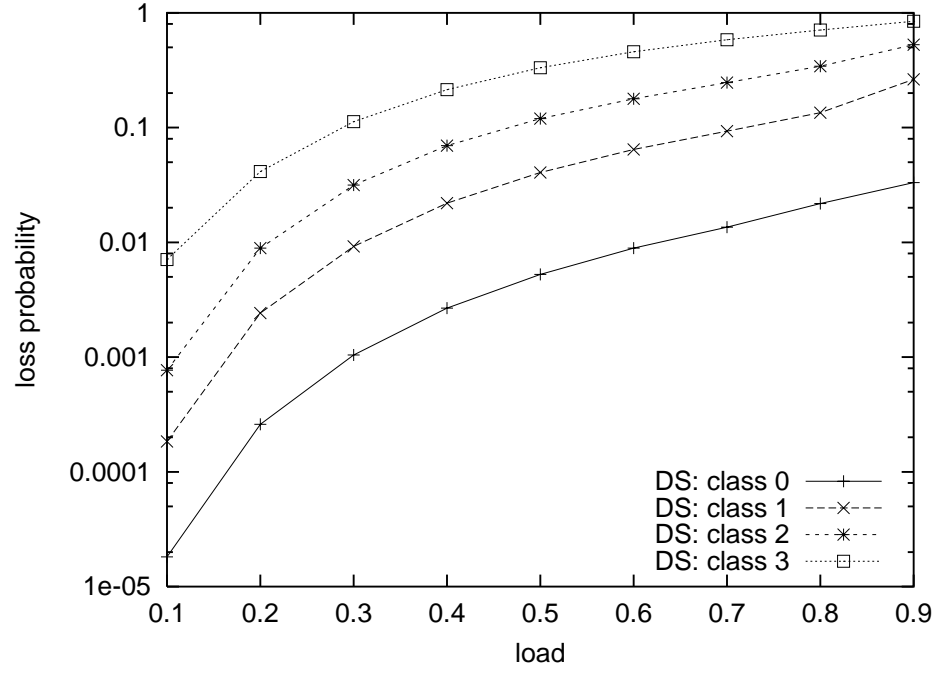


Figure 6.2: Burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_b = 40\mu s$, $t_{du} = 40\mu s$, $h = 1$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.

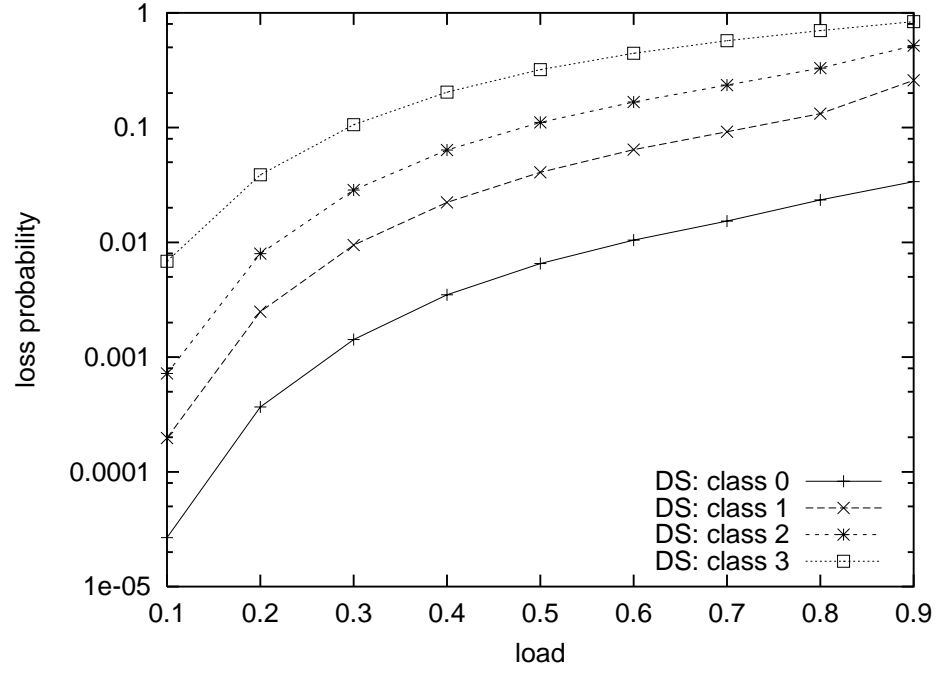


Figure 6.3: Burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_b = 40\mu s$, $t_b = 40\mu s$, $t_{du} = 40\mu s$, $h = 1$, $n = 4$, $srv_a = 1.5$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths

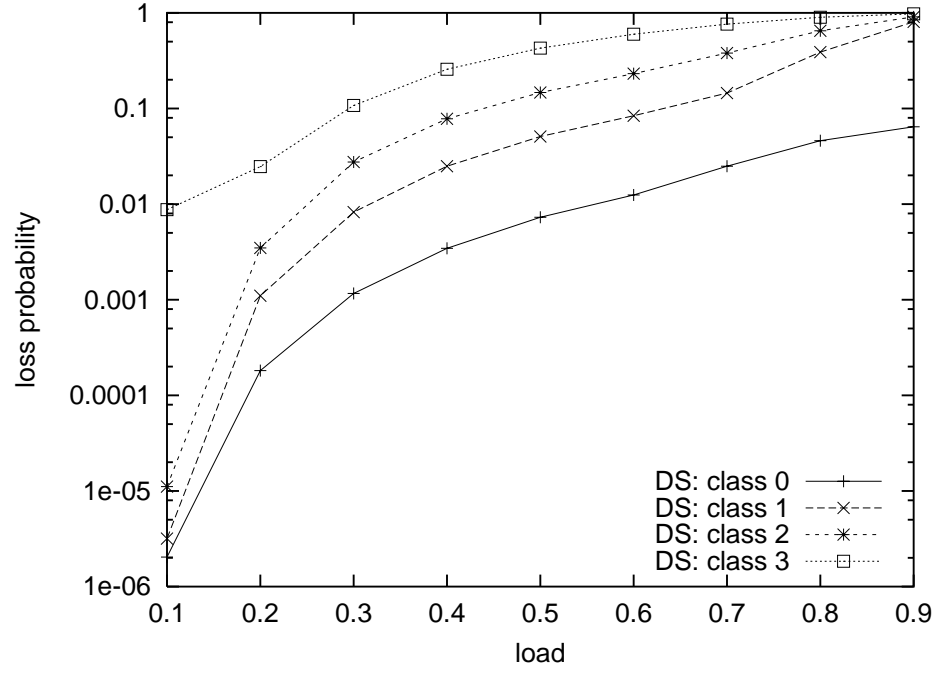


Figure 6.4: Burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_b = 40\mu s$, $t_{du} = 40\mu s$, $h = 1$, $n = 4$, and $iar_a = 1.5$, Pareto distributed inter-arrival time, and exponentially distributed burst lengths

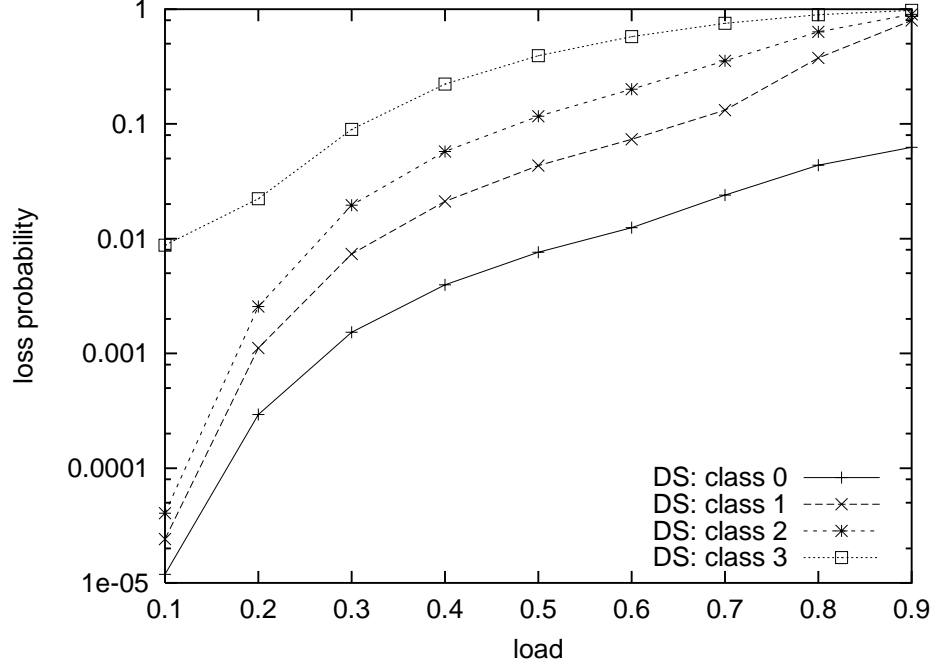


Figure 6.5: Burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_b = 40\mu s$, $t_{du} = 40\mu s$, $h = 1$, $n = 4$, $iar_{\alpha} = 1.5$, $srv_{\alpha} = 1.6$, Pareto distributed inter-arrival time, and Pareto distributed burst lengths.

control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_b = 40\mu s$, $t_{du} = 40\mu s$, $h = 1$, $n = 4$, $iar_{\alpha} = 1.5$, and $srv_{\alpha} = 1.5$.

The Comparison of Scheduling Schemes

The performances of SBS, PBS-SP, PBS-WP, PBS-MP, PJET, DS are compared in terms of burst loss probabilities for priority 0 and priority 3 bursts. Figures 6.6 and 6.7 show that DS performs as well as pJET in terms of burst loss probability.

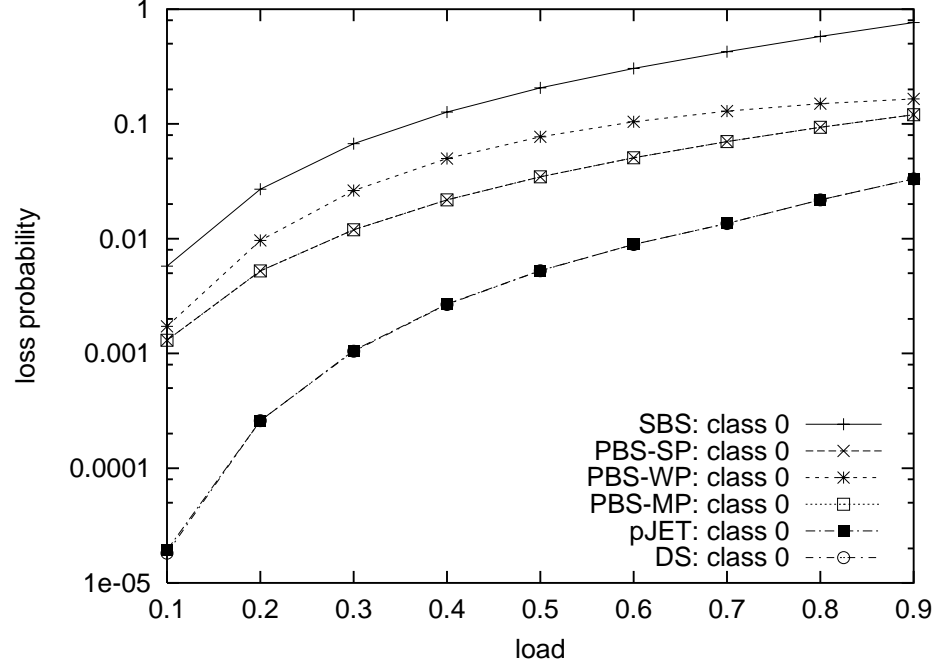


Figure 6.6: Burst loss probability of class 0 as a function of the traffic load varying burst scheduling schemes for SBS, PBS-SP, PBS-WP, PBS-MP, PJET, and DS for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, exponentially distributed inter-arrival time, and exponentially distributed burst lengths, and PJET uses priority offset unit $40\mu s$

Figure 6.6 plots the simulated burst loss probabilities as a function of the traffic load using PBS-SP scheme when the burst traffic has an Pareto inter-arrival time distribution and an exponential burst length distribution, $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, and $t_o = 40\mu s$. Figure 6.7 plots the simulated burst loss probabilities as a function of the traffic load using PBS-SP scheme when the burst traffic has an Pareto inter-arrival time distribution and an exponential burst length distribution, $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, and $t_o = 40\mu s$.

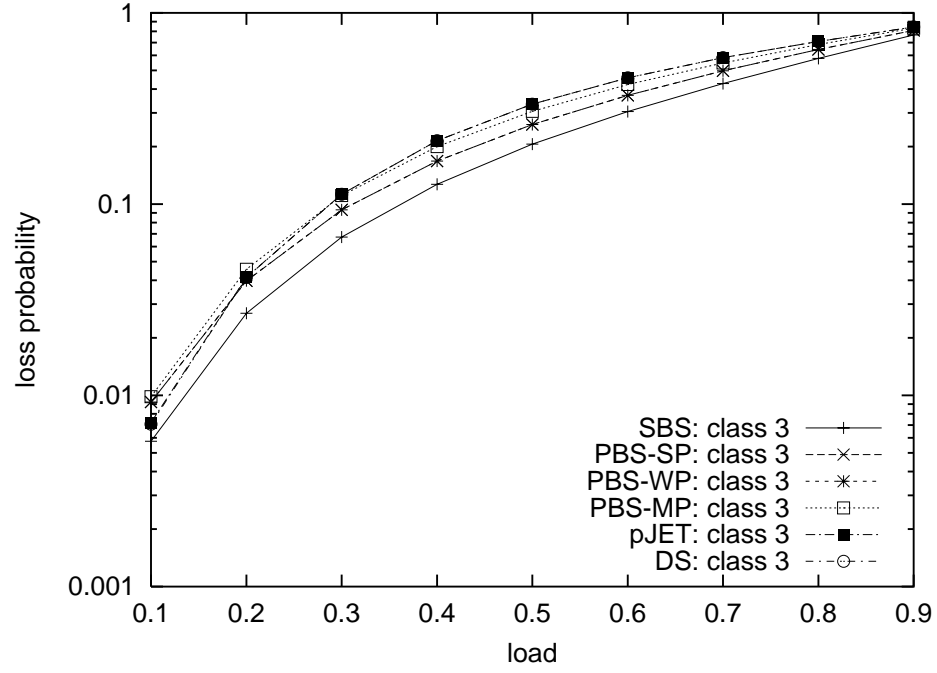


Figure 6.7: Burst loss probability of class 0 as a function of the traffic load varying burst scheduling schemes for SBS, PBS-SP, PBS-WP, PBS-MP, PJET, and DS for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, exponentially distributed inter-arrival times, and exponentially distributed burst lengths, and PJET uses priority offset unit $40\mu s$

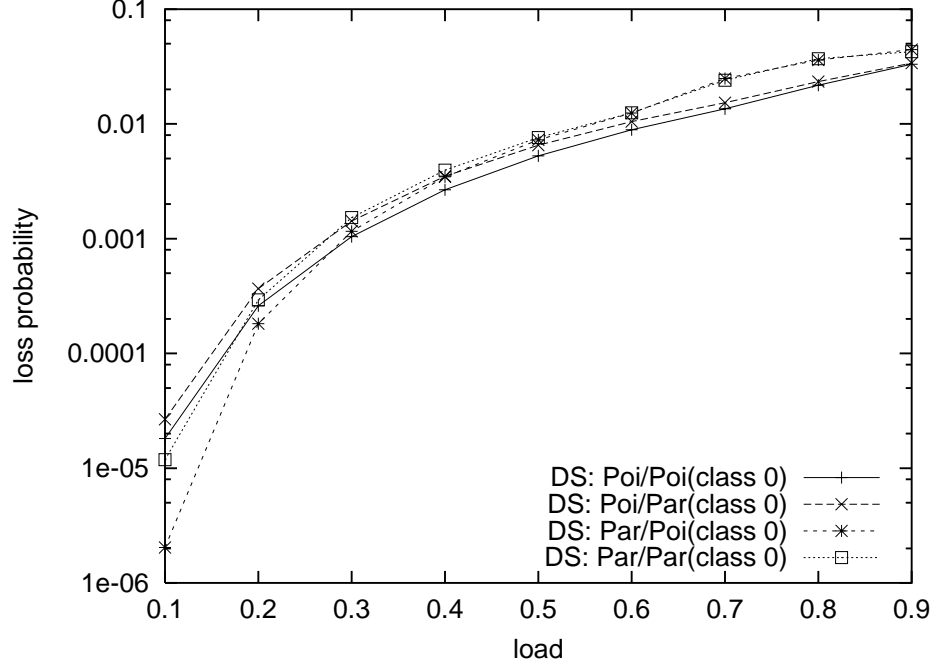


Figure 6.8: Burst loss probability of class 0 as a function of the traffic load using burst scheduling scheme DS for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, $t_{ou} = 20\mu$, $t_{du} = 40\mu$, the burst traffic has an exponentially or Pareto distributed inter-arrival times and burst lengths.

The Role of the Traffic Type

It shows that the traffic type does not affect the performance of DS in terms of burst loss probability in Figures 6.8 and 6.9. Figure 6.8 plots the simulated burst loss probability of class 0 as a function of the traffic load using the DS scheme when burst traffic inter-arrival time and burst length distributions varying from exponential distributions (Poi) to Pareto distributions (Par), $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, and $t_{ou} = 20\mu$, $t_{du} = 40\mu s$, $iarr_{\alpha} = 1.5$, and, $serv_{\alpha} = 1.5$.

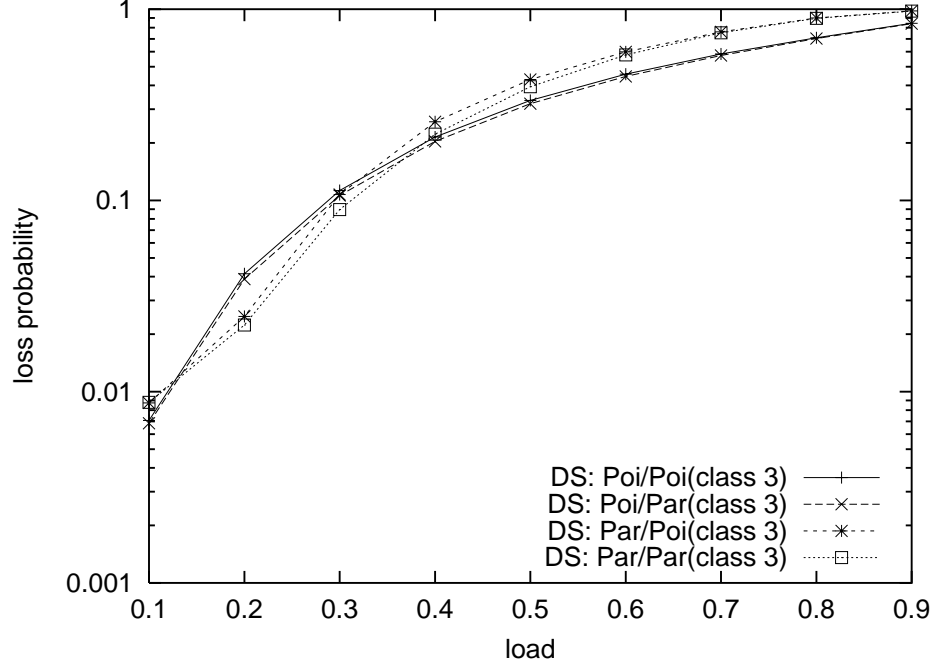


Figure 6.9: Burst loss probability of class 3 as a function of the traffic load using burst scheduling scheme DS for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, $t_{ou} = 20\mu$, $t_{du} = 40\mu$, the burst traffic has an exponentially or Pareto distributed inter-arrival times and burst lengths.

Figure 6.9 plots the simulated burst loss probability of class 3 as a function of the traffic load using PBS-SP scheme when burst traffic inter-arrival time and burst length distributions varying from exponential distributions (Poi) to Pareto distributions (Par), $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, and $t_{ou} = 20\mu$, $t_{du} = 40\mu s$, $iar_a = 1.5$, and, $srv_a = 1.5$.

The Role of the Number of Classes

It is important to see the effect of the number of priority classes on burst loss probability as well. Figure 6.10 shows that as more priority classes are supported,

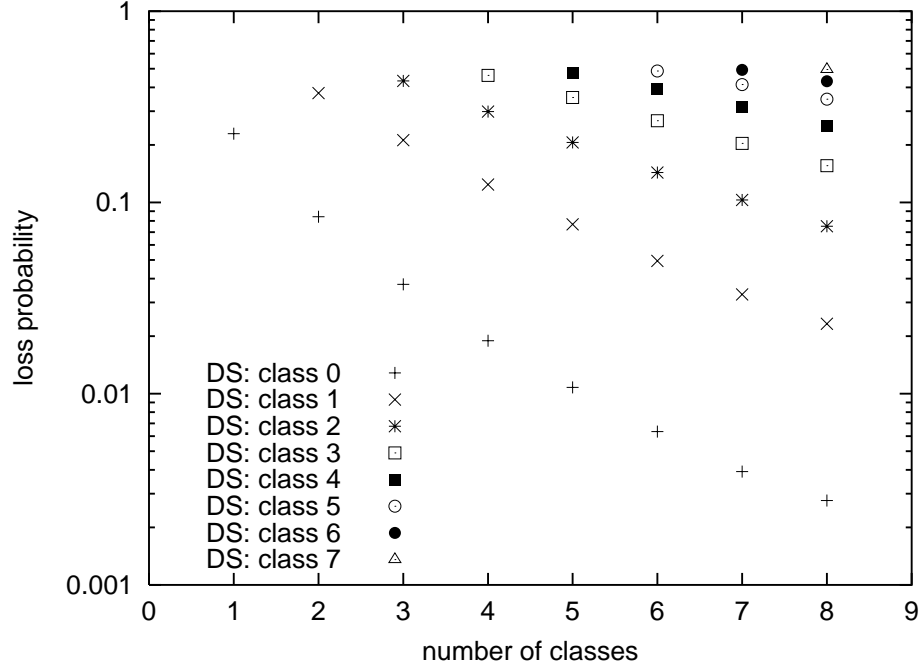


Figure 6.10: Burst loss probability as a function of the maximum number of the remaining hops for $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{du} = 40\mu s$, $\rho = 0.8$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths

a high priority class still commands better burst loss probability than a low priority class. Figure 6.10 shows the burst loss probability as function of the number of priority classes for $k = 4$, $t_{ou} = 20\mu s$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{du} = 40\mu s$, $\rho = 0.8$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.

The Role of the Number of Wavelengths

With more wavelengths used, DS decreases the burst probability of a high priority class more than that of a low priority class as shown in Figure 6.11. Figure 6.11

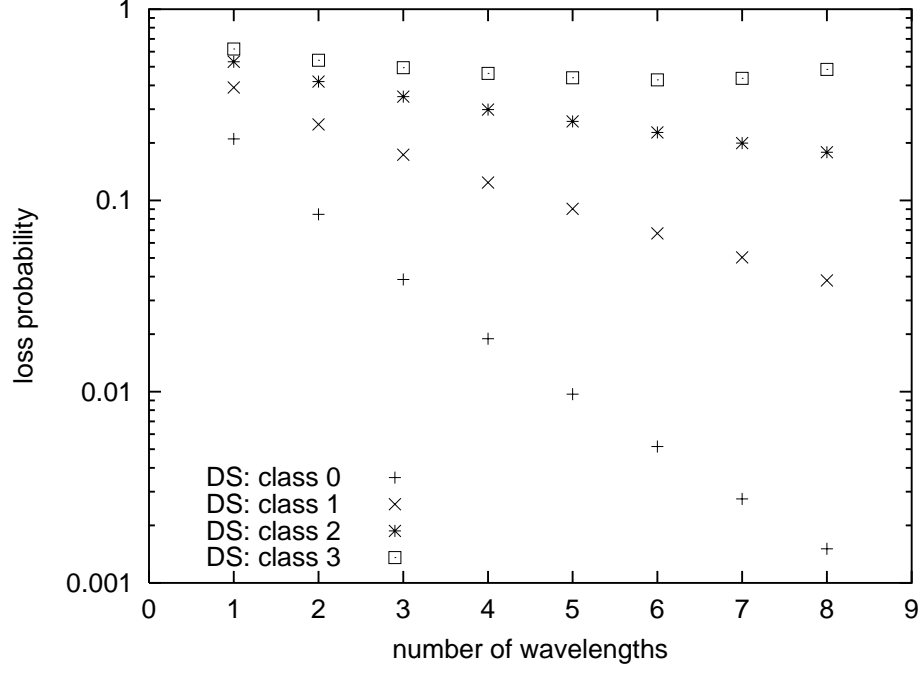


Figure 6.11: Burst loss probability as a function of the maximum number of the number of wavelengths for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{du} = 40\mu s$, $\rho = 0.8$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.

displays the burst loss probability as function of the number of wavelengths for $n = 4$, $t_{ou} = 20\mu s$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{du} = 40\mu s$, $\rho = 0.8$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.

The Role of the Offset-Time Unit

As shown in Figure 6.12, the performance of DS is not affected by the hop offset-time unit, which is better than PBS.

Figure 6.12 shows the burst loss probability as function of the offset time unit for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{du} = 40\mu s$, and $\rho = 0.8$.

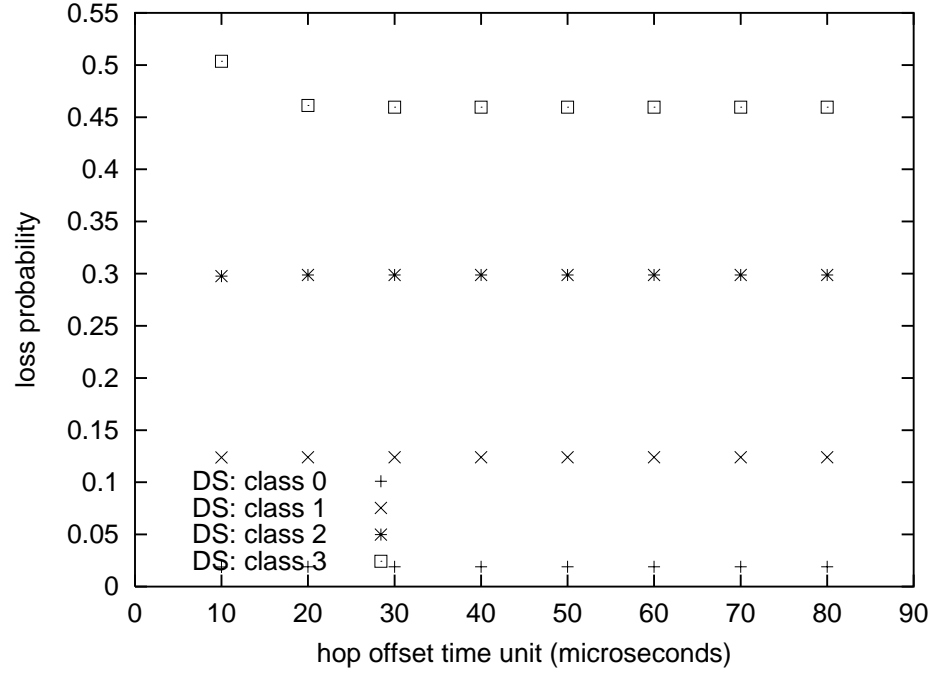


Figure 6.12: Burst loss probability as a function of the maximum number of the offset time unit for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{du} = 40\mu s$, $\rho = 0.8$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.

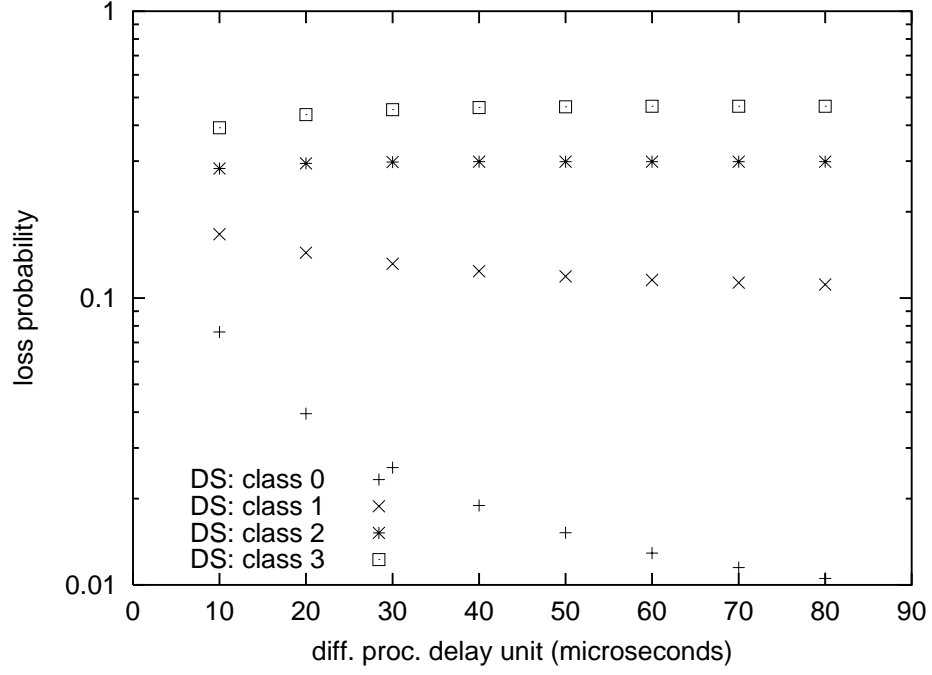


Figure 6.13: Burst loss probability as a function of the differentiated processing delay unit for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, and $\rho = 0.8$. exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths

The Role of the Differentiated Processing Delay Unit

As the differentiated processing delay unit increases, a high priority class gets better treatment than a low priority class.

Figure 6.13 shows the burst loss probability as function of the differentiated processing delay unit for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, and $\rho = 0.8$.

6.3.2 Multiple Traffic Flows

In this section, we consider the performance of DS when bursts arrive at a core node with different destinations. The control packets for these bursts thus have

different offset time values. We define the maximum remaining hop number as h and assume that the bursts have evenly distributed hop numbers between 1 and h .

Service Differentiation

As in the single traffic flow case, DS supports service differentiation in the multiple traffic flow case. Figure 6.14 plots the burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme when the burst traffic has the exponentially distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_b = 40\mu s$, $t_{ou} = 20\mu s$, $t_{du} = 40\mu s$, $h = 4$, and $n = 4$.

Figure 6.15 plots the burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme when the burst traffic has the exponentially distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_b = 40\mu s$, $t_{ou} = 20\mu s$, $t_{du} = 40\mu s$, $h = 4$, and $n = 4$.

Figure 6.16 plots the burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme when the burst traffic has the Pareto distributed control packet inter-arrival times and the exponentially distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{du} = 40\mu s$, $h = 4$, and $n = 4$.

Figure 6.17 plots the burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme when the burst traffic has the Pareto distributed control packet inter-arrival times and the Pareto distributed burst lengths, and system and flow parameters are $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{du} = 40\mu s$, $h = 4$, and $n = 4$.

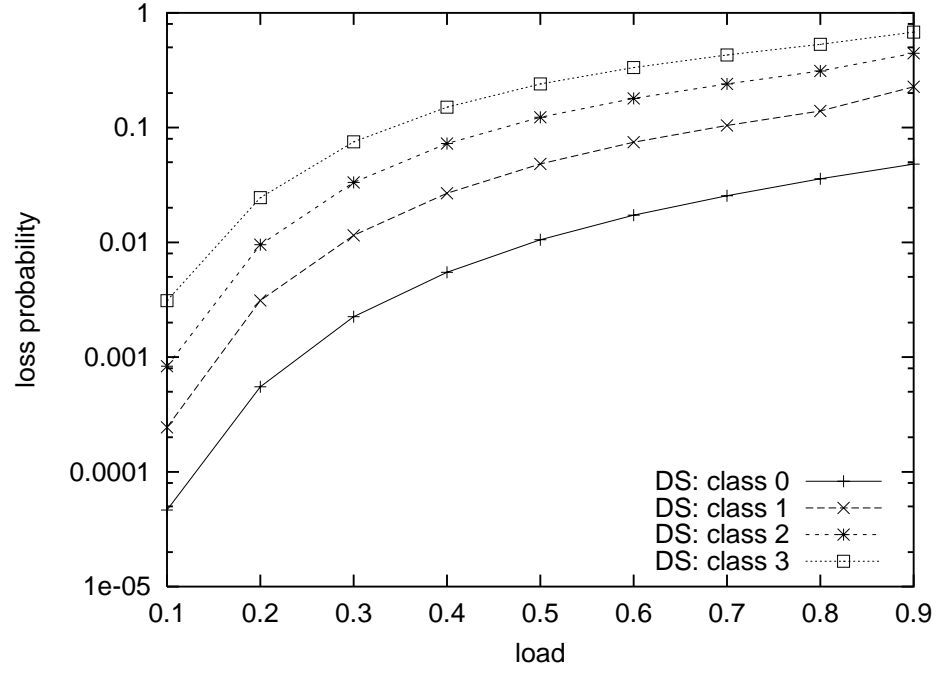


Figure 6.14: Burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme for $k = 4$, $t_p = 10\mu s$, $t_b = 40\mu s$, $t_{ou} = 20\mu s$, $t_{du} = 40\mu s$, $h = 4$, $n = 4$, exponentially distributed control packet inter-arrival times, and exponentially distributed burst lengths.

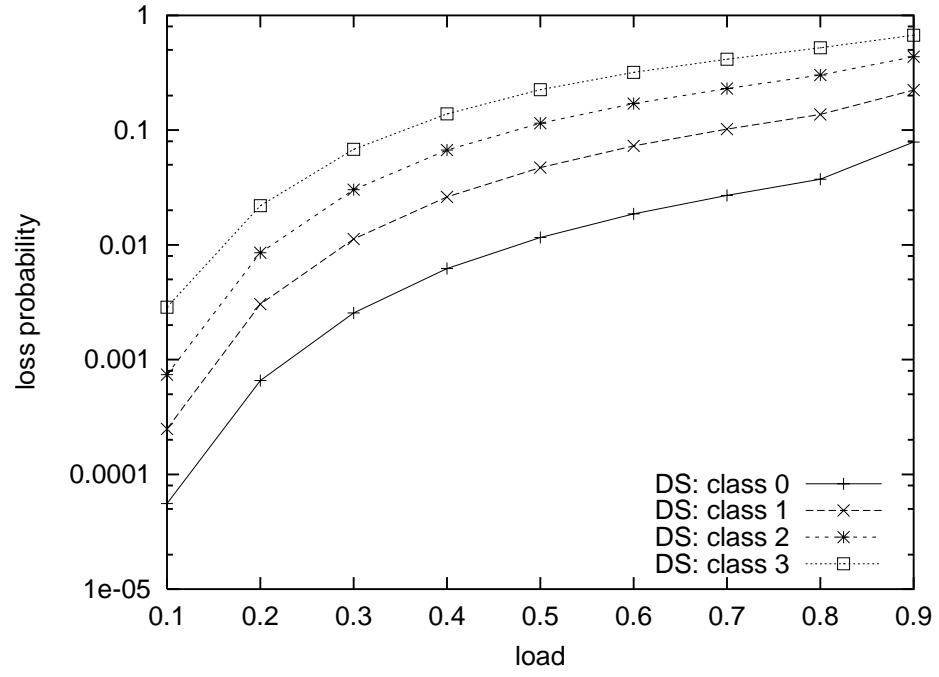


Figure 6.15: Burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{du} = 40\mu s$, $h = 4$, $n = 4$, exponentially distributed inter-arrival time, and Pareto distributed burst lengths

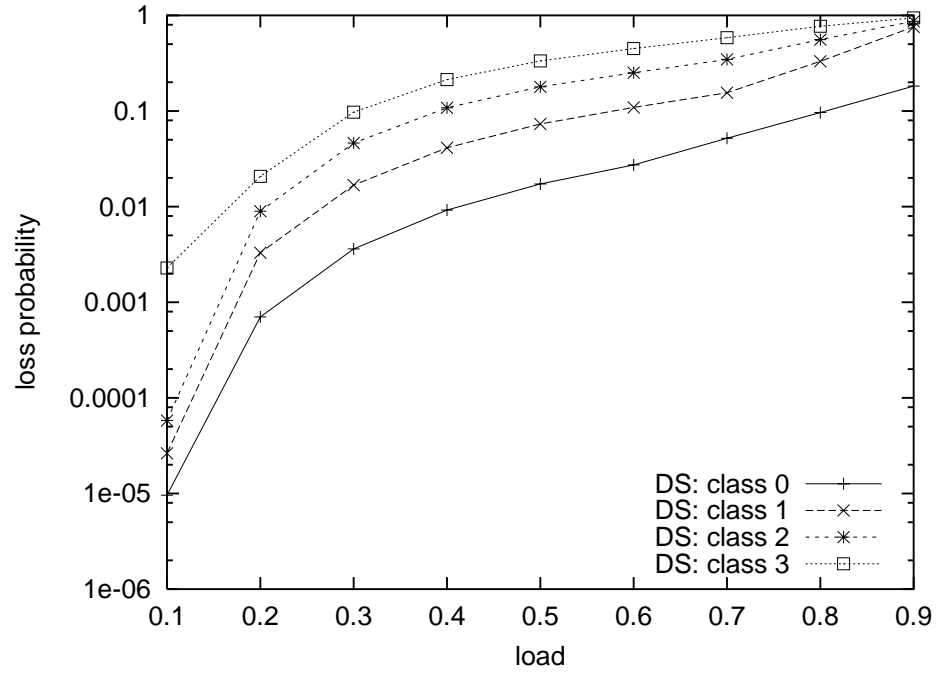


Figure 6.16: Burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{du} = 40\mu s$, $h = 4$, $n = 4$, Pareto distributed inter-arrival time, and exponentially distributed burst lengths

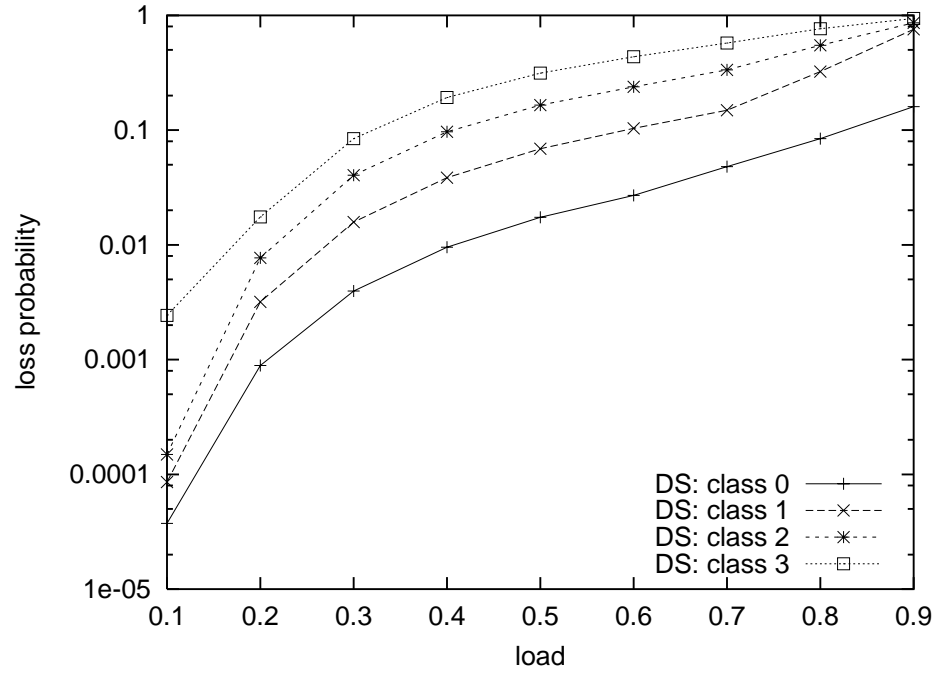


Figure 6.17: Burst loss probability as a function of the traffic load for 4 priority classes using the DS scheme for $k = 4$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{du} = 40\mu s$, $h = 4$, $n = 4$, Pareto distributed inter-arrival time, and Pareto distributed burst lengths

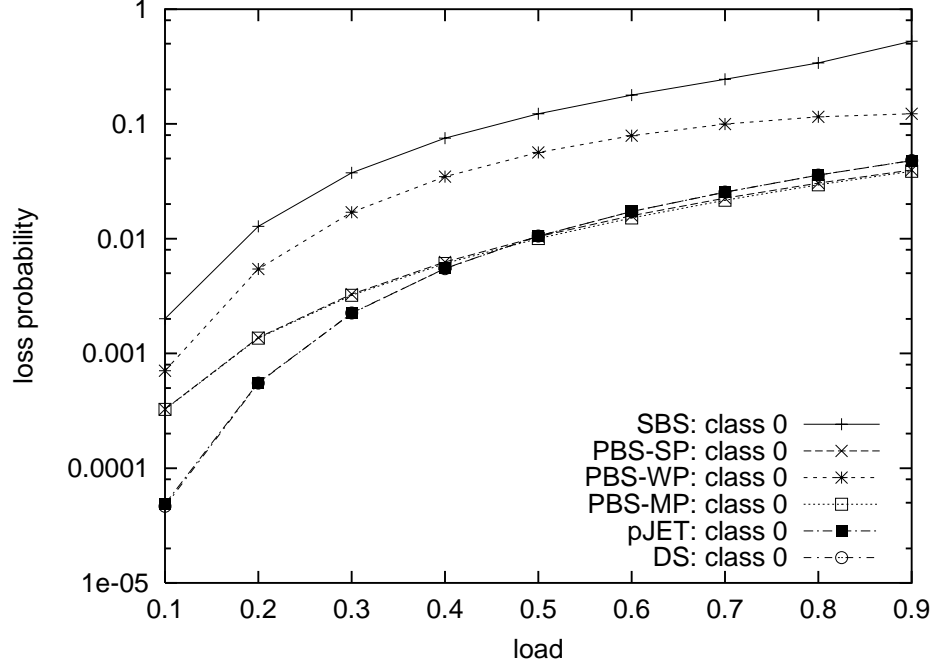


Figure 6.18: Burst loss probability of class 0 as a function of the traffic load varying burst scheduling schemes for SBS, PBS-SP, PBS-WP, PBS-MP, PJET, and DS for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, exponentially distributed inter-arrival time, and exponentially distributed burst lengths, and PJET uses priority offset unit $40\mu s$

The Comparison of Scheduling Schemes

The performances of SBS, PBS-SP, PBS-WP, PBS-MP, PJET, and DS are compared in terms of burst loss probabilities for priority 0 and priority 1 bursts. Figure 6.18 plots the burst loss probability of class 0 as a function of the traffic load using the SBS, PBS-SP, PBS-WP, PBS-MP, PJET, and DS schemes when the burst traffic has an exponentially inter-arrival time distribution and an exponential burst length distribution, $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, and $t_{du} = 40ms$. Figure 6.19 plots the simulated burst loss probabilities as a function of

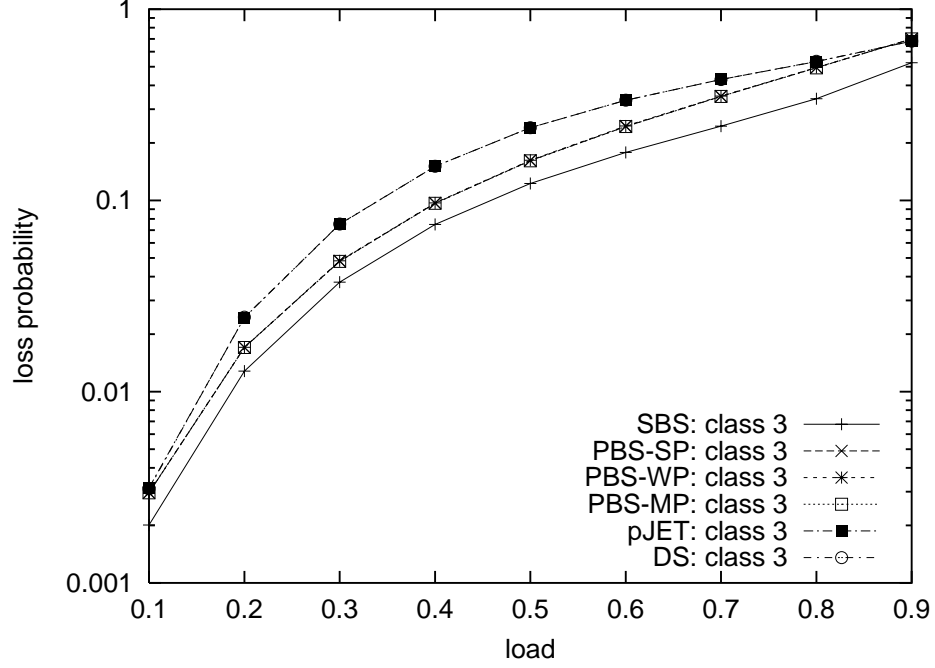


Figure 6.19: Burst loss probability of class 0 as a function of the traffic load varying burst scheduling schemes for SBS, PBS-SP, PBS-WP, PBS-MP, PJET, and DS for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, exponentially distributed inter-arrival time, and exponentially distributed burst lengths, and PJET uses priority offset unit $40\mu s$

the traffic load using the SBS, PBS-SP, PBS-WP, PBS-MP, PJET, and DS schemes when the burst traffic has an Pareto inter-arrival time distribution and an exponential burst length distribution, $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, and $t_o = 40\mu s$.

Figures 6.18 and 6.19 show that DS performs as well as pJET, PBS-SP and PBS-MP in the multiple traffic flow case.

The Role of the Traffic Type

Both Figures 6.20 and 6.21 show that the performance of DS is not affected much by the traffic type.

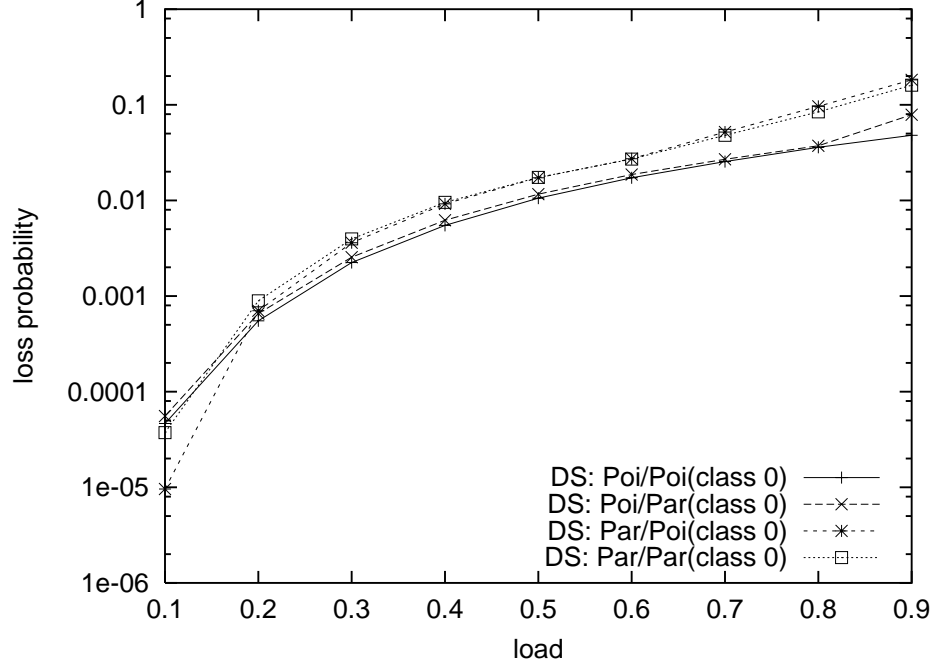


Figure 6.20: Burst loss probability of class 0 as a function of the traffic load using burst scheduling scheme DS for $n = 4$, $k = 4$, $h = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, $t_{ou} = 20\mu$, $t_{du} = 40\mu$, the burst traffic has an Pareto inter-arrival time distribution and an exponential burst length distribution.

Figure 6.20 plots the simulated burst loss probability of class 0 as a function of the traffic load using PBS-SP scheme when burst traffic inter-arrival time and burst length distributions varying from exponential distributions (Poi) to Pareto distributions (Par), $n = 4$, $k = 4$, $h = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, and $t_{ou} = 20\mu s$, $t_{du} = 40\mu s$.

Figure 6.21 plots the burst loss probability of class 3 as a function of the traffic load using PBS-SP scheme when burst traffic inter-arrival time and burst length distributions varying from exponential distribution (Poi) to Pareto distribution (Par), $n = 4$, $k = 4$, $h = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, and $t_{ou} = 20\mu s$, $t_{du} = 40\mu s$.

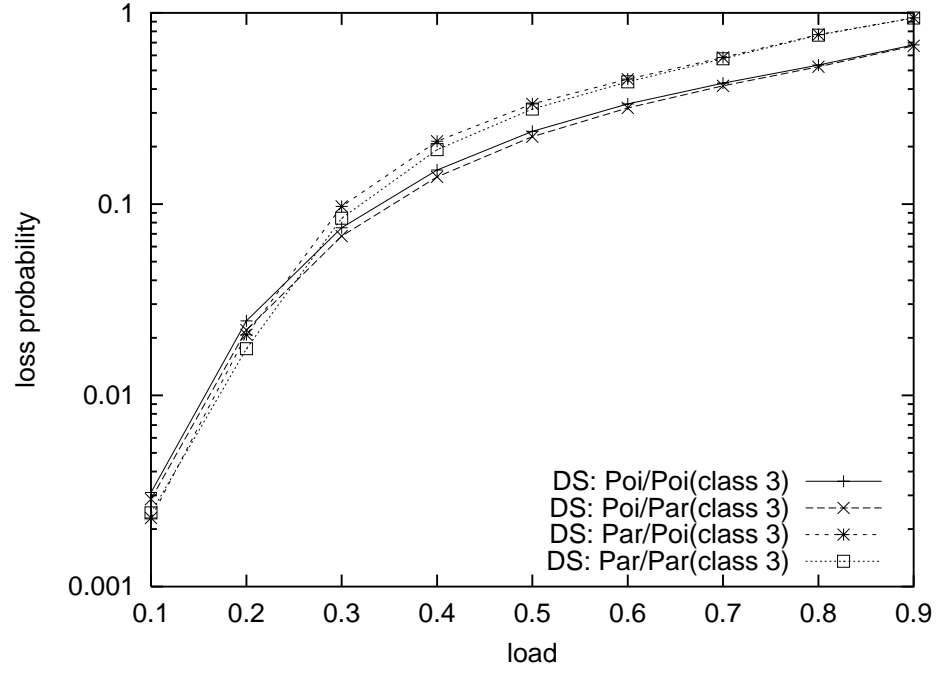


Figure 6.21: Burst loss probability of class 3 as a function of the traffic load using burst scheduling scheme DS for $n = 4$, $k = 4$, $h = 4$, $t_b = 40\mu s$, $t_p = 10\mu$, $t_{ou} = 20\mu$, $t_{du} = 40\mu$, the burst traffic has an Pareto inter-arrival time distribution and an exponential burst length distribution.

The rest of this section shows that the number of classes, the number of wavelengths, the offset time unit, and the differentiated processing unit play similar roles in the multiple traffic flow case as in the single traffic flow case with regard to the burst loss probabilities of various priority classes when DS is used. As the maximum number of remaining hops increases, the burst loss probability of a high priority class such as class 0 and class 1 increases while the burst loss probability of a low priority class such as class 2 and class 3 decreases.

The Role of the Number of Classes

The pretransmission delay of a burst is proportional to the offset time unit. It is important to see the effect of the offset time unit on burst loss probability as well. Figure 6.22 shows the burst loss probability as function of the number of priority classes for $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{du} = 40ms$, $\rho = 0.8$, exponentially distributed control inter-arrival times, and exponentially distributed burst lengths.

The Role of the Number of Wavelengths

The pretransmission delay of a burst is proportional to the offset time unit. Figure 6.23 shows the burst loss probability as function of the number of wavelengths for $n = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_{du} = 40ms$, $\rho = 0.8$, exponentially distributed control inter-arrival times, and exponentially distributed burst lengths.

The Role of the Offset-Time Unit

The pretransmission delay of a burst is proportional to the offset time unit. Figure 6.24 shows the burst loss probability as function of the remaining hops t_{ou} for $n = 4$,

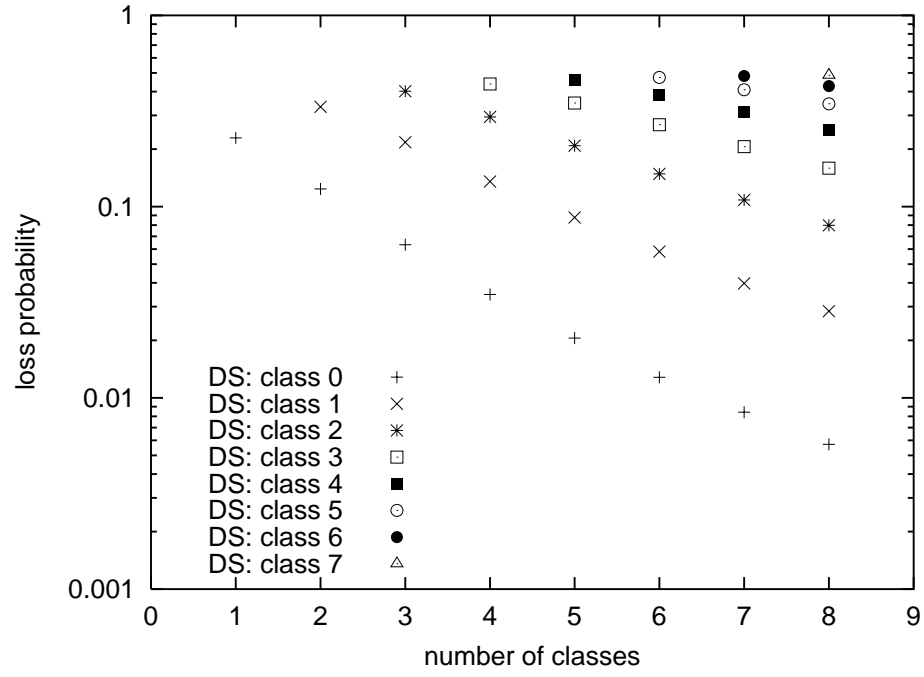


Figure 6.22: Burst loss probability as a function of the maximum number of the remaining hops for $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{du} = 40ms$, $\rho = 0.8$, exponentially distributed control inter-arrival times, and exponentially distributed burst lengths.

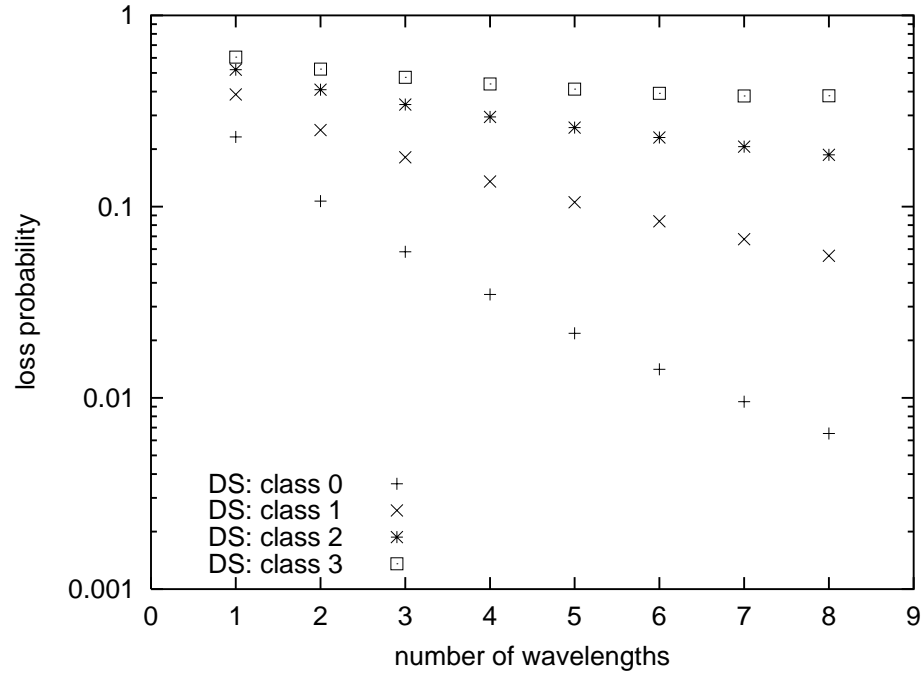


Figure 6.23: Burst loss probability as a function of the maximum number of the remaining hops for $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{du} = 40ms$, $\rho = 0.8$, exponentially distributed control inter-arrival times, and exponentially distributed burst lengths.

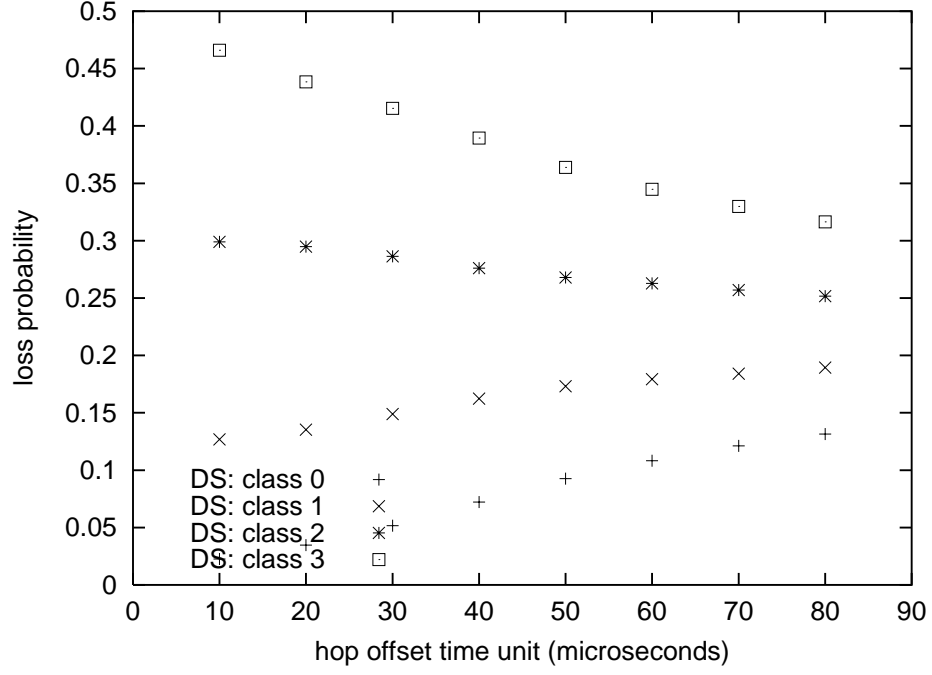


Figure 6.24: Burst loss probability as a function of the maximum number of the remaining hops for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{du} = 40ms$, $\rho = 0.8$, exponentially distributed control inter-arrival times, and exponentially distributed burst lengths.

$k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{du} = 40ms$, $\rho = 0.8$, exponentially distributed control inter-arrival times, and exponentially distributed burst lengths.

The Role of the Differentiated Process Delay Unit

The pretransmission delay of a burst is proportional to the offset time unit. Figure 6.25 shows the burst loss probability as function of the remaining hops t_{ou} for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $\rho = 0.8$, exponentially distributed control inter-arrival times, and exponentially distributed burst lengths.

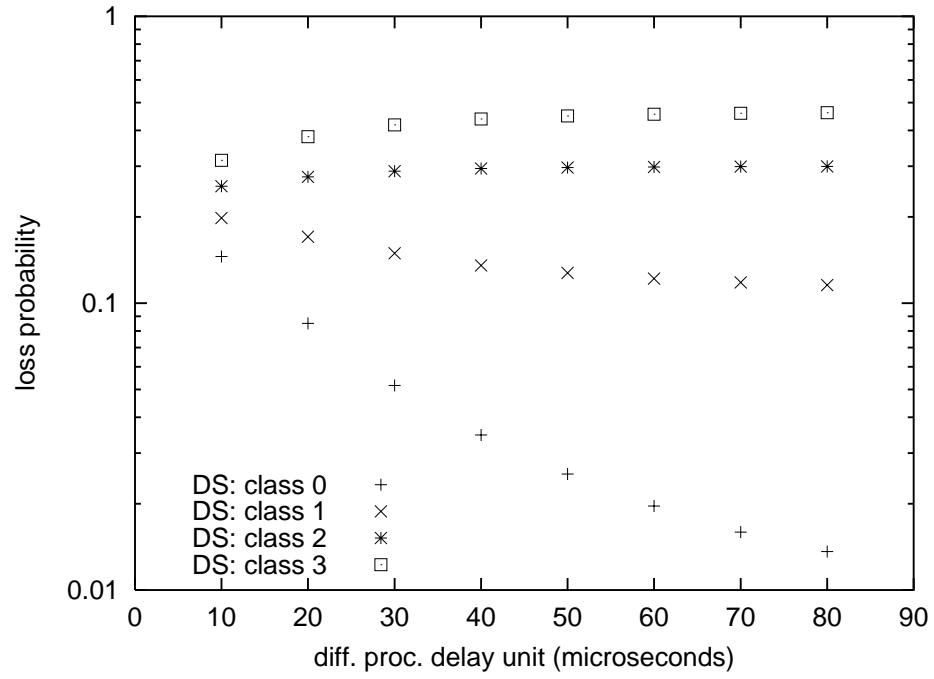


Figure 6.25: Burst loss probability as a function of the maximum number of the remaining hops for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$

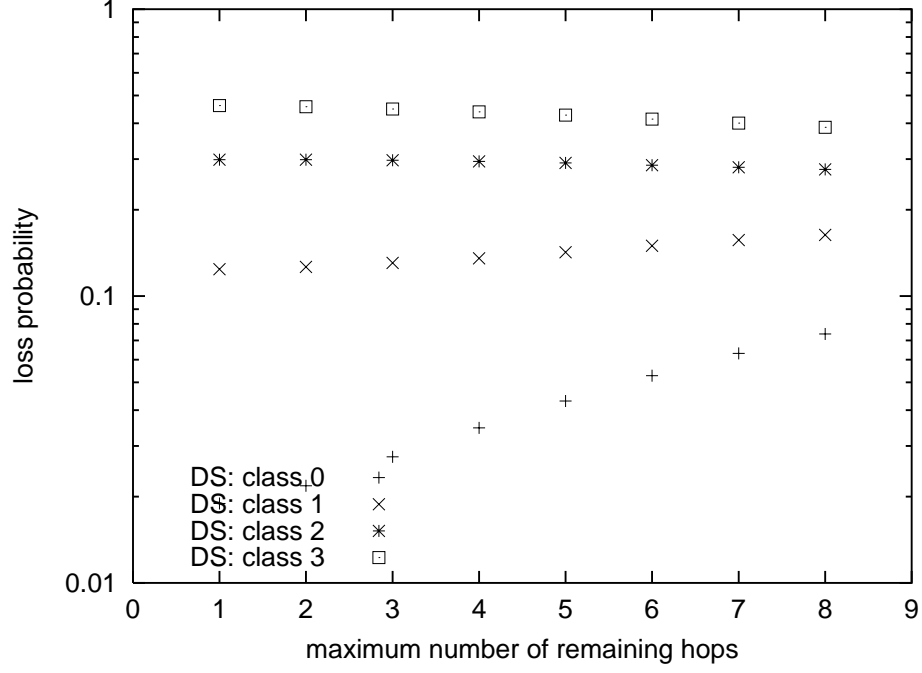


Figure 6.26: Burst loss probability as a function of the maximum number of the remaining hops for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $\rho = 0.8$, exponentially distributed control inter-arrival times, and exponentially distributed burst lengths

The Role of the Maximum Number of Remaining Hops

Figure 6.26 shows the burst loss probability as function of the remaining hops h for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $\rho = 0.8$, exponentially distributed control inter-arrival times, and exponentially distributed burst lengths

6.3.3 Control of Service Differentiation

We investigate how DS-N supports various service differentiations in this section. By modifying its DPDDs, an OBS node can obtain various service differentiations between priority classes. Figure 6.27 shows the burst loss probability of class 0 decreases

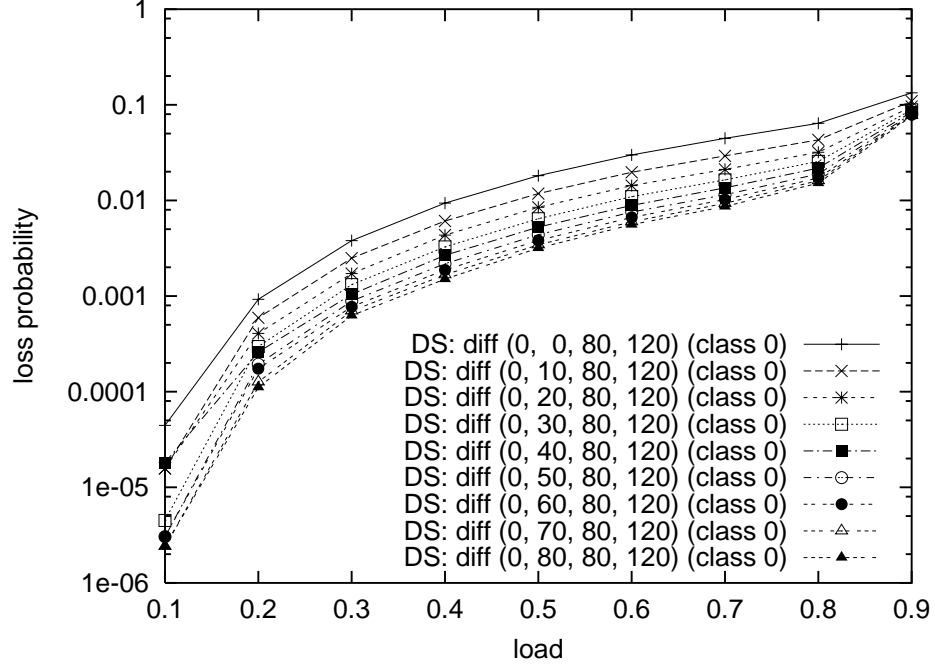


Figure 6.27: Burst loss probability of class 0 as a function of the traffic load when $DPD_0 = 0\mu s$, DPD_1 ranges from $0\mu s$ to $80\mu s$, $DPD_2 = 80\mu s$, $DPD_3 = 120\mu s$, $n = 4$, $k = 4$, $h = 1$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_b = 40\mu s$, $h = 1$, and both the control packet inter-arrival times and the burst lengths are exponentially distributed.

as $DPD_0 = 0\mu s$, DPD_1 increase from $0\mu s$ to $80\mu s$, $DPD_2 = 80\mu s$, $DPD_3 = 120\mu s$, $n = 4$, $k = 4$, $h = 1$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_b = 40\mu s$, $h = 1$, and both the control packet inter-arrival times and the burst lengths are exponentially distributed.

Figure 6.28 show how the burst loss probability of class 1 increases as $DPD_0 = 0\mu s$, DPD_1 increases from $0\mu s$ to $80\mu s$, $DPD_2 = 80\mu s$, $DPD_3 = 120\mu s$, $n = 4$, $k = 4$, $h = 1$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_b = 40\mu s$, $h = 1$, and both the control packet inter-arrival times and the burst lengths are exponentially distributed. Figure 6.29 show how the burst loss probability of class 2 decrease as $DPD_0 = 0\mu s$, DPD_1 decreases from $0\mu s$ to $80\mu s$, $DPD_2 = 80\mu s$, $DPD_3 = 120\mu s$, $n = 4$, $k = 4$, $h = 1$,

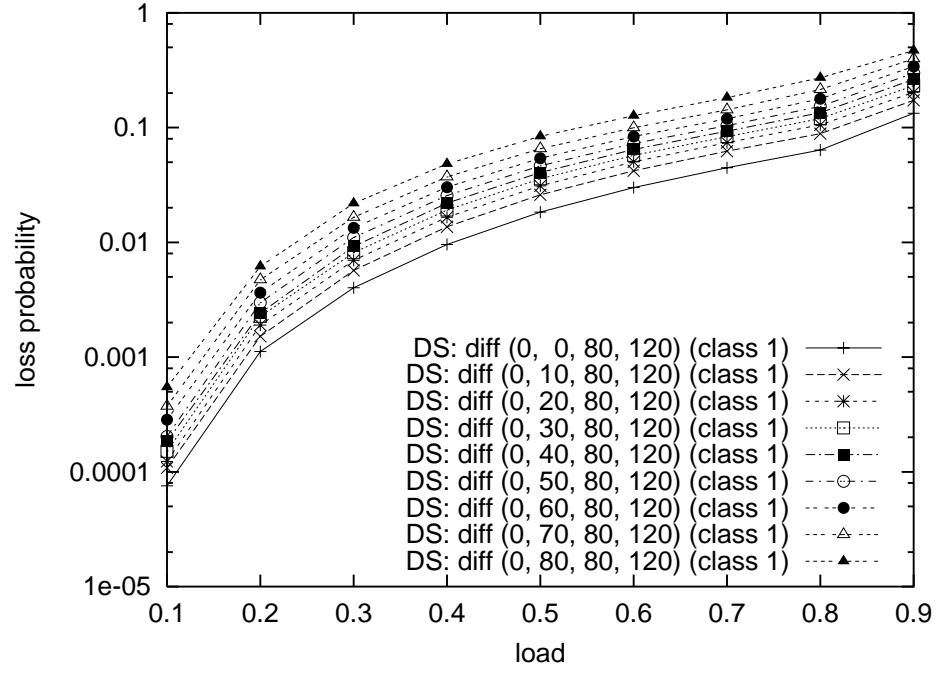


Figure 6.28: Burst loss probability of class 1 as a function of the traffic load when $DPD_0 = 0\mu s$, DPD_1 ranges from $0\mu s$ to $80\mu s$, $DPD_2 = 80\mu s$, $DPD_3 = 120\mu s$, $n = 4$, $k = 4$, $h = 1$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_b = 40\mu s$, $h = 1$, and both the control packet inter-arrival times and the burst lengths are exponentially distributed.

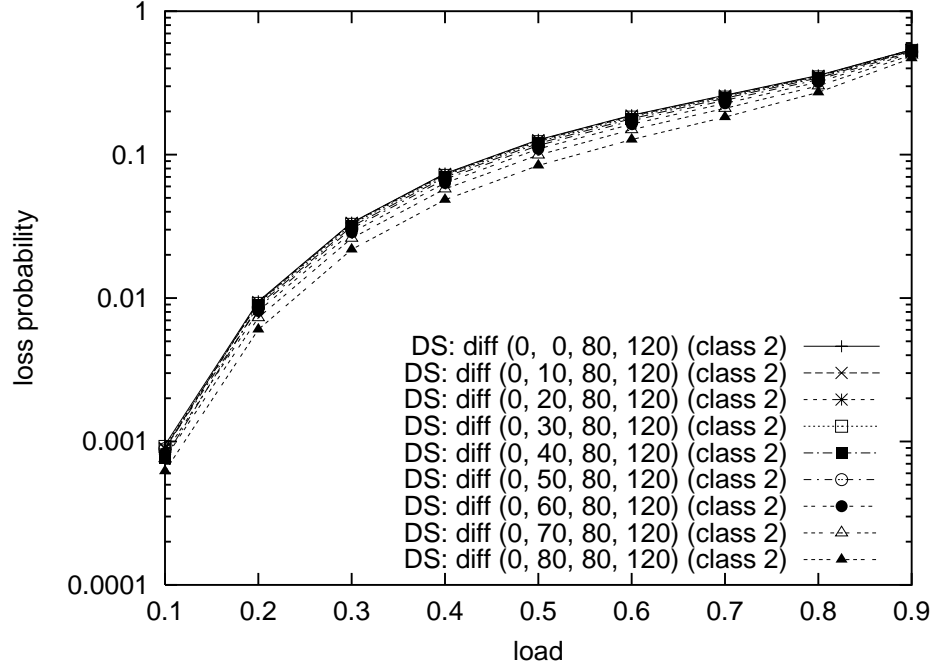


Figure 6.29: Burst loss probability of class 2 as a function of the traffic load when $DPD_0 = 0 \mu s$, DPD_1 ranges from $0 \mu s$ to $80 \mu s$, $DPD_2 = 80 \mu s$, $DPD_3 = 120 \mu s$, $n = 4$, $k = 4$, $h = 1$, $t_p = 10 \mu s$, $t_{ou} = 20 \mu s$, $t_b = 40 \mu s$, $h = 1$, and both the control packet inter-arrival times and the burst lengths are exponentially distributed.

$t_p = 10 \mu s$, $t_{ou} = 20 \mu s$, $t_b = 40 \mu s$, $h = 1$, and both the control packet inter-arrival times and the burst lengths are exponentially distributed.

Figure 6.30 show how the burst loss probability of class 3 stays pretty much the same as function of the load when $DPD_0 = 0 \mu s$, DPD_1 increases from $0 \mu s$ to $80 \mu s$, $DPD_2 = 80 \mu s$, $DPD_3 = 120 \mu s$, $n = 4$, $k = 4$, $h = 1$, $t_p = 10 \mu s$, $t_{ou} = 20 \mu s$, $t_b = 40 \mu s$, $h = 1$, and both the control packet inter-arrival times and the burst lengths are exponentially distributed.

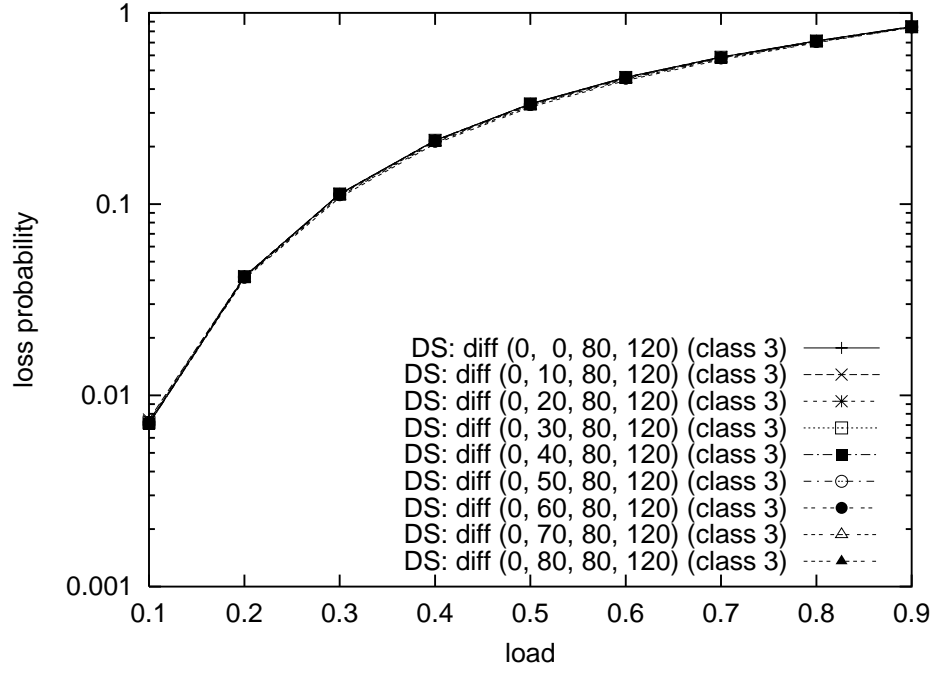


Figure 6.30: Burst loss probability of class 3 as a function of the traffic load when $DPD_0 = 0\mu s$, DPD_1 ranges from $0\mu s$ to $80\mu s$, $DPD_2 = 80\mu s$, $DPD_3 = 120\mu s$, $n = 4$, $k = 4$, $h = 1$, $t_p = 10\mu s$, $t_{ou} = 20\mu s$, $t_b = 40\mu s$, $h = 1$, and both the control packet inter-arrival times and the burst lengths are exponentially distributed.

6.4 Conclusion

In this chapter, we proposed a burst scheduling scheme *Differentiated Scheduling* (DS) to support differentiated services in OBS networks. DS has two modes: *uniform or non-uniform differentiated processing delay difference*. Based on its resources and QoS requirements, an intermediate (core) OBS node can support a different number of priority classes from the ingress node. We model and analyze DS in terms of burst loss probability. The performance of DS is further evaluated by simulation. In current DS, the *differentiated processing delay* (DPD) is a function of priority class, and does not depend on the total traffic load. When the total traffic load is low in an OBS network, the average burst loss probability provided by the network is sufficient for high priority classes, and no service differentiation is necessary. We can therefore define DPD as a function of both priority class and traffic load, which approaches a constant as the total traffic load approaches zero to ensure that a low priority class has a low burst loss probability just as a high priority class when the total traffic load is low in an OBS network. Our future work will focus on the differentiated service support with different mix of high and low priority traffic loads and analyze the end-to-end performance of DS in OBS networks.

CHAPTER 7

END-TO-END DIFFERENTIATED SERVICES

7.1 Introduction

Most performance studies of OBS burst scheduling schemes focused on a single link in a single node. It also is important to understand how the various burst scheduling schemes perform in a network environment. In an OBS network, bursts from various flows pass through an OBS node with various offset times and priorities.

In this chapter, we use simulation to study the performance of SBS, pJET, and DS in a network environment, and apply different queueing policies for control packets based on their priority classes and flow ids. The performances are evaluated in terms of burst loss probabilities of various priority classes and burst traffic flows. The simulation results shown that DS performs better than pJET in a WAN environment.

This chapter is organized as follows. Section 7.2 describes how a burst scheduler uses various queues and queueing policies to process the control packets from various traffic flows with various priorities. Section 7.3 lays out the simulation model and parameters. The simulation results are discussed in Section 7.4. The chapter is concluded in Section 7.5.

7.2 Scheduling Queue Policies

We assume that there is a burst scheduler for each link at each node. A control packet in a network is defined as $CP(s, d, f, p, t_a, t_o, t_b)$, where s is the control packet's source edge node address, d is the control packet's destination edge node address, f is the burst's flow id, p is the burst's priority, t_a is the control packet arrival time, t_o is the burst's offset time, and t_b is the burst length. In this chapter, we assign a flow id to all the control packets and data bursts from a source edge node address to a destination edge node address and assume there is only one traffic flow between a pair of source and destination edge nodes. Shortest path routing algorithm is used to find the path between a pair of source and destination edge nodes. The control packets in a link is stored by a scheduler in one or more queues as follows:

- SQ: a single queue for all control packet in the link.
- PQ: a queue for each priority class.
- FQ: a queue for each flow.
- TQ: a queue for each pair of priority and flow (source-destination pair).

A scheduler processes the control packets from various queues in a order. With a single queue, control packets are processed in the FCFS order. A scheduler processes the control packets from the queue with the highest priority first with a queue for each priority class. When there is a queue for each flow, a scheduler processes from the lowest flow id to the highest flow id. With a queue for each pair of priority and flow, various processing orders are considered as follows:

- both priority and flow are chosen evenly among all pairs of priority and flow values. This is defined as random ordering (RO).
- highest priority and lowest flow id in the same priority. This ordering policy is defined as priority ordering (PO).
- lowest flow id and highest priority in the same flow id. This ordering policy is defined as flow ordering (FO).
- the next available control packet when the queues are ordered from the highest priority to lowest priority and from the smallest flow id to the largest flow id in the same priority. This is defined as total ordering (TO).

The end-to-end performance of SBS, PJET, and DS will be evaluated under the following combinations:

- scheduling with a single queue: SBS-SQ, PJET-SQ, and DS-SQ.
- scheduling with a queue per priority: SBS-PQ, PJET-PQ, and DS-PQ.
- scheduling with a queue per flow: SBS-Q, PJET-FQ, and DS-FQ.
- scheduling with a queue per pair of priority and flow, and random ordering scheduling: SBS-ROQ, PJET-ROQ, and DS-(DS-ROQ)
- scheduling with a queue per pair of priority and flow, and priority ordering: SBS-POQ, PJET-POQ, and DS-POQ.
- scheduling with a queue per pair of priority and flow, and flow ordering: SBS-FOQ, PJET-FOQ, and DS-FOQ.

- scheduling with a queue per pair of priority and flow, and total ordering: SBS-TOQ, PJET-TOQ, and DS-TOQ.

7.3 Simulation Model

In order to evaluate the end-to-end performance of DS, a simulation model was developed and performed on the 11-node Internet 2 Abilene network shown in Figure 7.1.

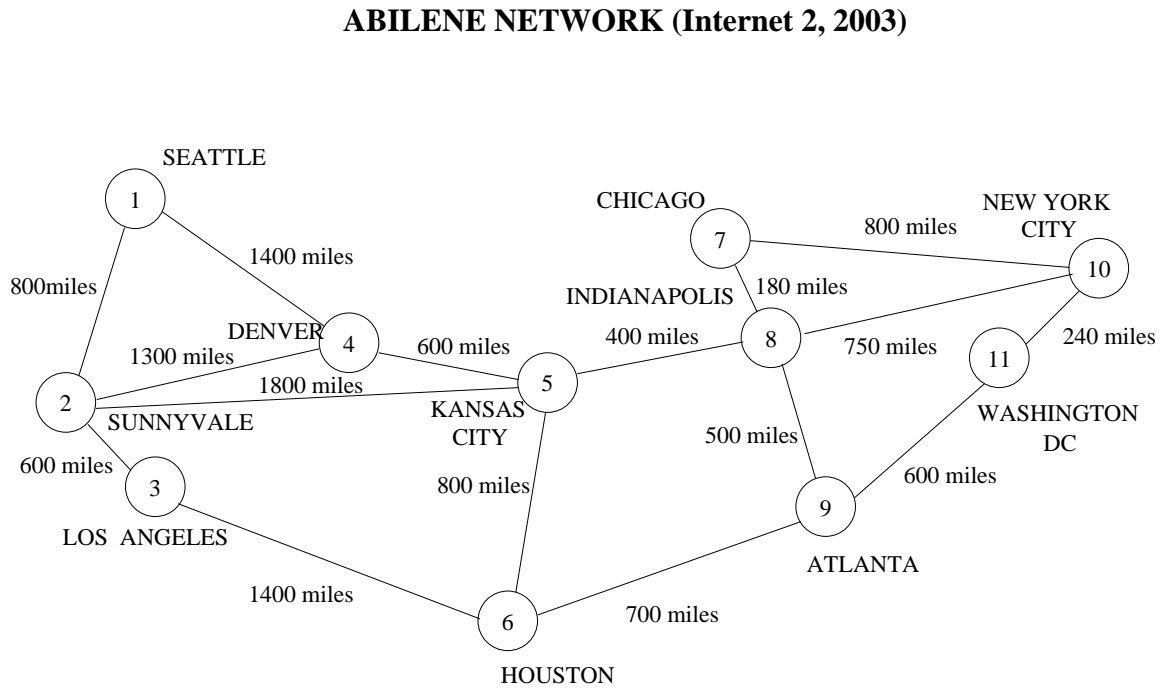


Figure 7.1: Internet 2 Abilene network topology

In our simulation, the following assumptions are made:

- there are two wavelengths per link.
- Two priority classes are considered.

Flow	Source	Dest	Routing Path
0	1	10	1-4-5-8-10
1	2	11	2-5-8-10-11
2	3	7	3-6-9-8-7

Table 7.1: Traffic Route Description

- the control packet inter-arrival times are exponential distributed with mean value of
- the control packet service time is $2\mu s$ at each node. The total control packet processing time (include service time and waiting time) is $4\mu s$.
- Burst length (in time) is exponentially distributed with mean value $40 \mu s$
- differentiated processing delay time is $40\mu s$.
- there are three flows: a flow from node 1 to node 10, a flow from node 2 to node 11, and a flow from node 3 to node 7.
- All three traffic flows have the same the traffic load per wavelength ρ at their ingress nodes 1, 2, and 3.
- The shortest paths are used between ingress nodes and egress nodes as shown in Table 7.1.

We compared four different scheduling queueing policies for handling multiple priority classes and multiple source-destination pairs as follows: These parameters are described in Table 7.2.

Variable	Description
k	the number of wavelengths on each link
t_p	the control packet service time by a scheduler
t_{ou}	the offset time needed per hop
t_{pu}	the extra offset time needed per priority
t_{du}	the differentiated processing delay unit
ρ	traffic load per wavelength (the same at ingress nodes 1,2, and 3)
n	the number of priority classes

Table 7.2: System and flow variables

7.4 Simulation Results and Performance Analysis

The performances of SBS, pJET, and DS are evaluated in terms of burst loss probabilities of the high priority classes of various flows for queueing policy in the first part of this section. In the second subsection, the burst loss probabilities are considered with various queueing policies for each traffic flow. In the last part of this section, we compare the performances of SBS, pJET, and DS for each queueing policy.

7.4.1 Burst Loss Probability of High Priority Class

We investigate how SBS, pJET, and DS support service differentiations with different queueing policies.

Standard Burst Scheduling Scheme

With each queueing policy, SBS provides the lowest burst loss probability to flow 2, the second lowest burst loss probability to flow 1 in Figures 7.2 and 7.3. This is

because flow 2 has the least traveled route path $3 - 6 - 9 - 8 - 7$, and flow 1 passes through the contending route path $5 - 8$ earlier than flow 0.

Figure 7.2 plots the burst loss probability of class 0 as a function of the traffic load using the SBS scheme with queueing policies SQ, PQ and FQ when each burst traffic flow has an identical exponential inter-arrival time distribution and an identical exponential burst length distribution, $n = 2$, $k = 2$, $t_p = 4\mu s$, $t_b = 40\mu s$, and $t_{ou} = 20\mu s$.

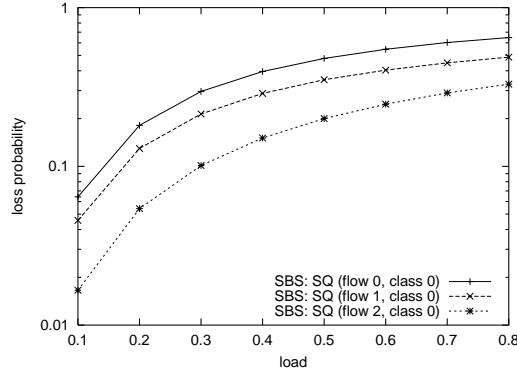
Figure 7.3 plots the burst loss probability of class 0 as a function of the traffic load using SBS scheme with queueing policies ROQ, POQ, FOQ, and TOQ when each burst traffic flow has an identical exponential inter-arrival time distribution and an identical exponentially burst length distribution, $n = 2$, $k = 2$, $t_p = 4\mu s$, $t_b = 40\mu s$, and $t_{ou} = 20\mu s$.

PJET Scheduling

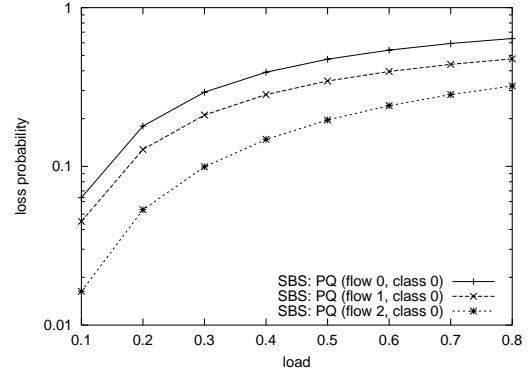
With each queueing policy, like SBS, pJET also provides the lowest burst loss probability to flow 2, the second lowest burst loss probability to flow 1 in Figures 7.4 and 7.5.

Figure 7.4 plots the burst loss probability of class 0 as a function of the traffic load using pJET with queueing policies SQ, PQ, and FQ when each burst traffic flow has an identical exponential inter-arrival time distribution and an identical exponential burst length distribution, $n = 2$, $k = 2$, $t_p = 4\mu s$, $t_b = 40\mu s$, $t_{ou} = 20\mu s$, and $t_{pu} = 40\mu s$.

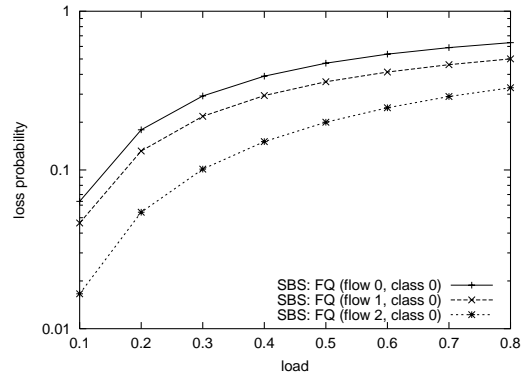
Figure 7.5 plots the burst loss probability of class 0 as a function of the traffic load using the pJET scheme with queueing policies ROQ, POQ, FOQ, and TOQ when each burst traffic flow has an identical exponential inter-arrival time distribution and an



(a) SBS-SQ

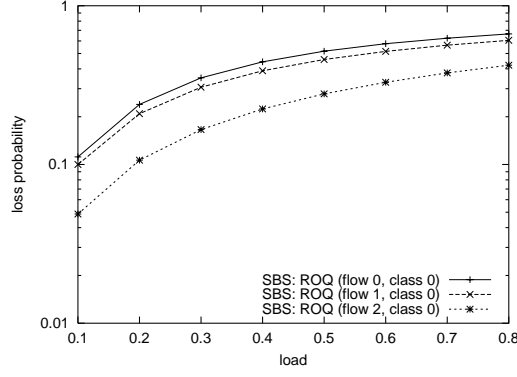


(b) SBS-PQ

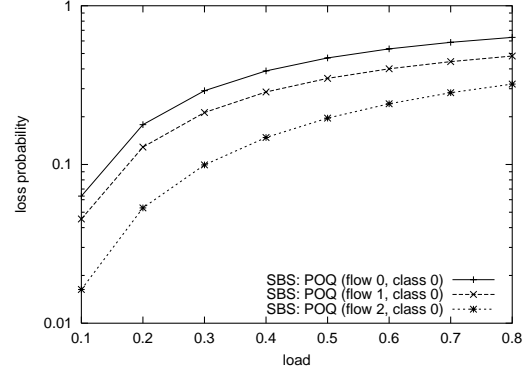


(c) SBS-FQ

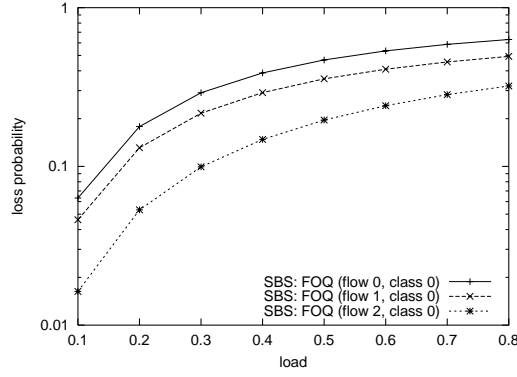
Figure 7.2: Burst loss probability as a function of the traffic load using the SBS scheme with queue policies SQ, PQ, and FQ for $n = 2$, $k = 2$, $t_b = 40\mu s$, $t_p = 4\mu$, $t_{ou} = 20\mu s$, exponentially distributed inter-arrival times, and exponentially distributed burst lengths.



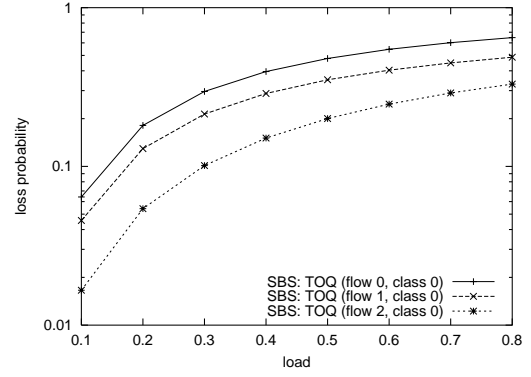
(a) SBS-ROQ



(b) SBS-POQ

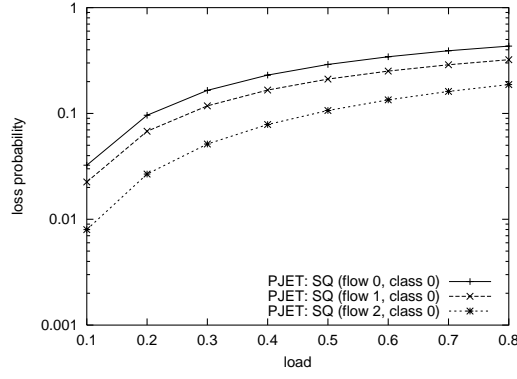


(c) SBS-FOQ

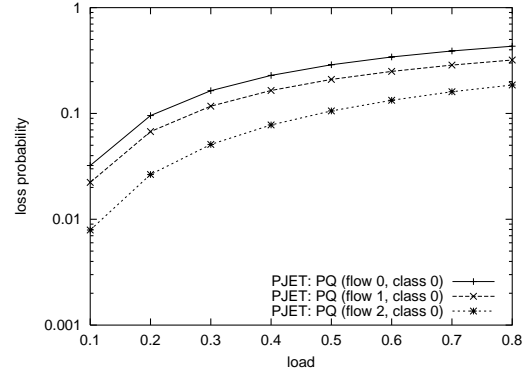


(d) SBS-TOQ

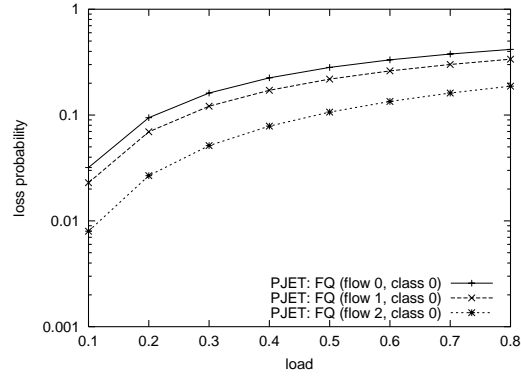
Figure 7.3: Burst loss probability as a function of the traffic load using the SBS scheme with queueing policies ROQ, POQ, FOQ, and TOQ for $n = 2$, $k = 2$, $t_b = 40\mu s$, $t_p = 4\mu$, $t_{ou} = 20\mu s$, exponentially distributed inter-arrival times, and exponentially distributed burst lengths.



(a) pJET-SQ



(b) pJET-PQ



(c) pJET-FQ

Figure 7.4: Burst loss probability as a function of the traffic load using the pJET scheme with queueing policies SQ, PQ, and FQ for $n = 2$, $k = 2$, $t_b = 40\mu s$, $t_p = 4\mu$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, exponentially distributed inter-arrival times, and exponentially distributed burst lengths.

identical exponentially burst length distribution, $n = 2$, $k = 2$, $t_p = 4\mu s$, $t_b = 40\mu s$, and $t_{ou} = 20\mu s$, and $t_{pu} = 40\mu s$.

Differentiated Scheduling

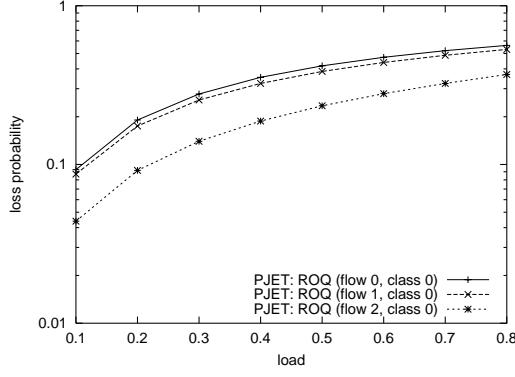
With each queueing policy, like SBS and pJET, DS provides the lowest burst loss probability to flow 2, the second lowest burst loss probability to flow 1 in Figures 7.6 and 7.7.

Figure 7.6 plots the burst loss probability of class 0 as a function of the traffic load using DS with queueing policies SQ, PQ, and FQ when each burst traffic has an identical exponential inter-arrival time distribution and an identical exponentially burst length distribution, $n = 2$, $k = 2$, $t_p = 4\mu s$, $t_b = 40\mu s$, and $t_{ou} = 20\mu s$, and $t_{du} = 40\mu s$.

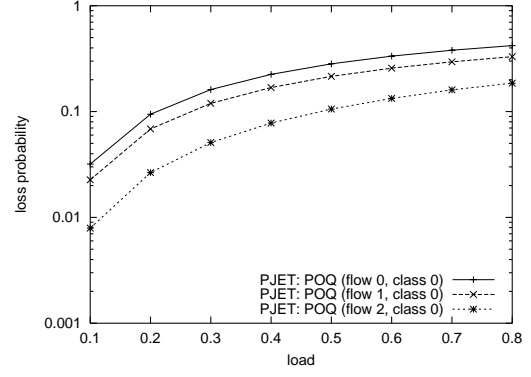
Figure 7.7 plots the burst loss probability of class 0 as a function of the traffic load using the DS scheme with queueing policies ROQ, POQ, FOQ, and TOQ when each burst traffic flow has an identical exponential inter-arrival time distribution and an identical exponentially burst length distribution, $n = 2$, $k = 2$, $t_p = 4\mu s$, $t_b = 40\mu s$, $t_{ou} = 20\mu s$, and $t_{du} = 40\mu s$.

7.4.2 Burst Loss Probability over Flow

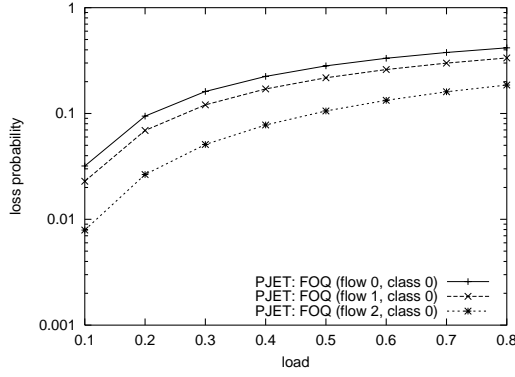
We investigate the over all burst loss probability per flow with DS, PBS-SP, and pJET. The queueing policy ROQ has higher burst loss probabilities for all three flows than other queueing policies. The queueing policies SQ, PQ, FQ, POQ, FOQ, and TOQ have the almost the same burst loss probabilities for all three flows as shown in Figures 7.8, 7.9, and 7.10



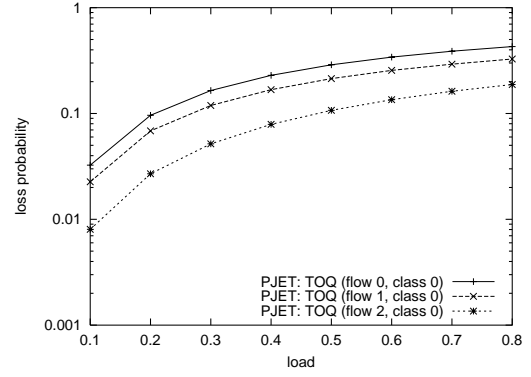
(a) pJET-ROQ



(b) pJET-POQ

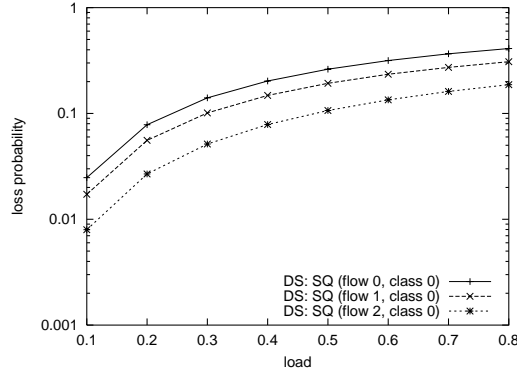


(c) pJET-FOQ

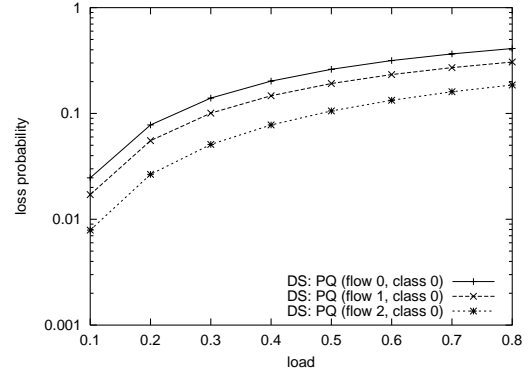


(d) pJET-TOQ

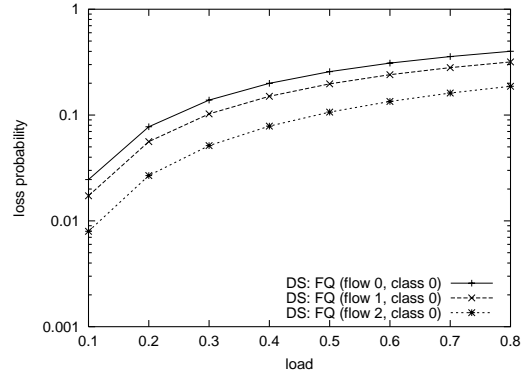
Figure 7.5: Burst loss probability as a function of the traffic load using the pJET scheme with queueing policies ROQ, POQ, FOQ, and TOQ for $n = 2$, $k = 2$, $t_b = 40\mu s$, $t_p = 4\mu$, $t_{ou} = 20\mu s$, $t_{pu} = 40\mu s$, exponentially distributed inter-arrival times, and exponentially distributed burst lengths.



(a) DS-SQ

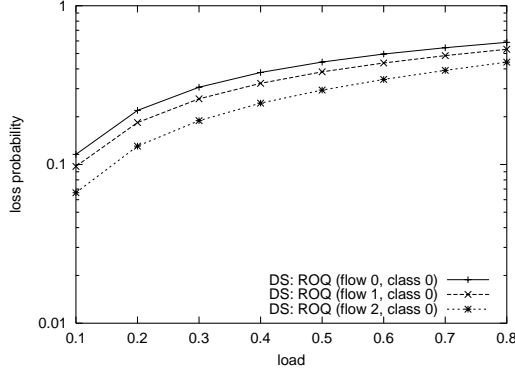


(b) DS-PQ

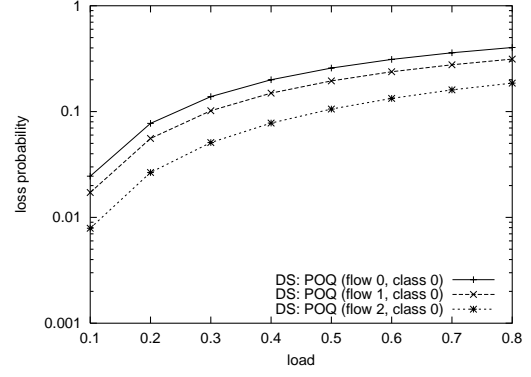


(c) DS-FQ

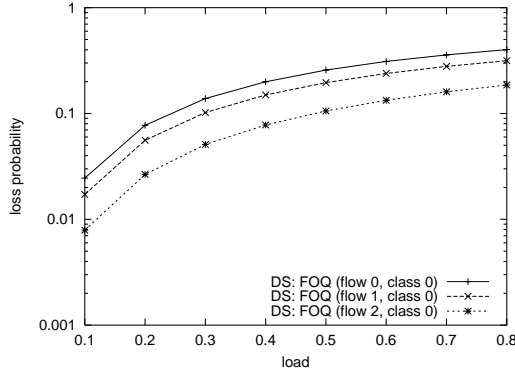
Figure 7.6: Burst loss probability as a function of the traffic load using the DS scheme with the queueing policies SQ, PQ, and FQ for $n = 2$, $k = 2$, $t_b = 40\mu s$, $t_p = 4\mu$, $t_{ou} = 20\mu s$, $t_{du} = 40\mu s$, exponentially distributed inter-arrival time, and exponentially distributed burst lengths.



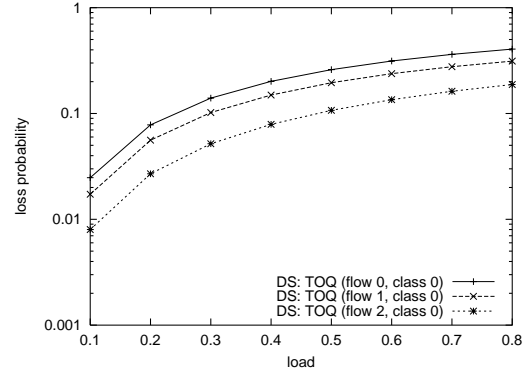
(a) DS-ROQ



(b) DS-POQ



(c) DS-FOQ



(d) DS-TOQ

Figure 7.7: Burst loss probability as a function of the traffic load using the DS scheme with queueing policies ROQ, POQ, FOQ, and TOQ for $n = 2$, $k = 2$, $t_b = 40\mu s$, $t_p = 4\mu$, $t_{ou} = 20\mu s$, $t_{du} = 40\mu s$, exponentially distributed inter-arrival times, and exponentially distributed burst lengths.

Figure 7.8 plots the simulated burst loss probabilities as a function of the traffic load using DS with queueing policies SQ, PQ, FQ, ROQ when the burst traffic has an exponential inter-arrival time distribution and an exponentially burst length distribution, $n = 2$, $k = 2$, $t_b = 40\mu s$, $t_p = 2\mu s$, and $t_{ou} = 10\mu s$.

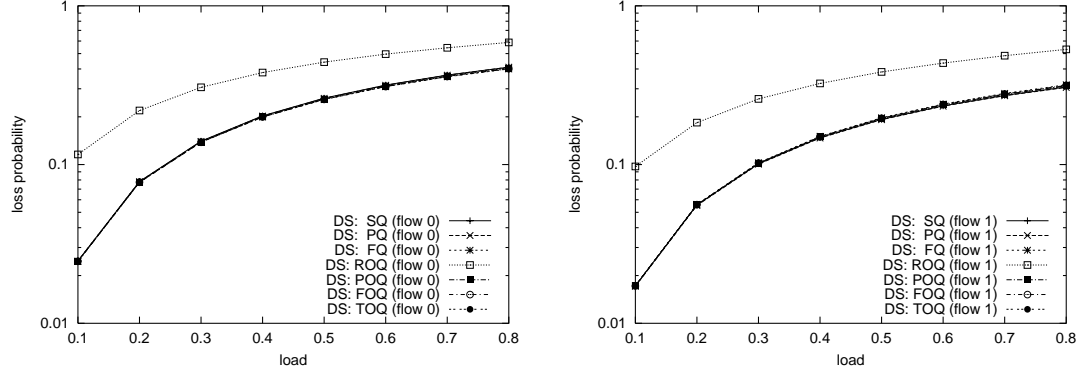
Figure 7.9 plots the simulated burst loss probabilities as a function of the traffic load using PBS-SP with queueing policies SQ, PQ, FQ, ROQ when the burst traffic has an exponential inter-arrival time distribution and an exponentially burst length distribution, $n = 2$, $k = 2$, $t_b = 40\mu s$, $t_p = 2\mu s$, and $t_{ou} = 10\mu s$. Figure 7.10 plots the simulated burst loss probabilities as a function of the traffic load using PJET with queueing policies SQ, PQ, FQ, ROQ when the burst traffic has an exponential inter-arrival time distribution and an exponentially burst length distribution, $n = 2$, $k = 2$, $t_b = 40\mu s$, $t_p = 2\mu s$, and $t_{ou} = 10\mu s$.

7.4.3 Performance Comparison of Burst Scheduling Schemes

With each queueing policy, DS performs better than both pJET and SBS in terms of burst loss probability. The pJET is better than SBS in terms of burst loss probability.

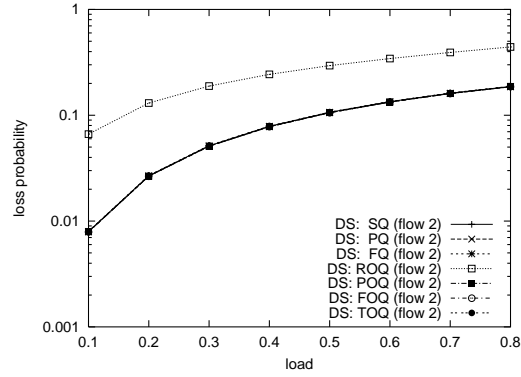
Figure 7.11 plots the simulated burst loss probabilities as a function of the traffic load using SBS with queueing policies SQ, PQ, FQ, ROQ when the burst traffic has an exponential inter-arrival time distribution and an exponentially burst length distribution, $n = 2$, $k = 2$, $t_b = 40\mu s$, $t_p = 2\mu s$, and $t_{ou} = 10\mu s$.

Figure 7.12 plots the simulated burst loss probabilities as a function of the traffic load using SBS scheme with ROQ, POQ, FOQ, and TOQ queueing policies when the



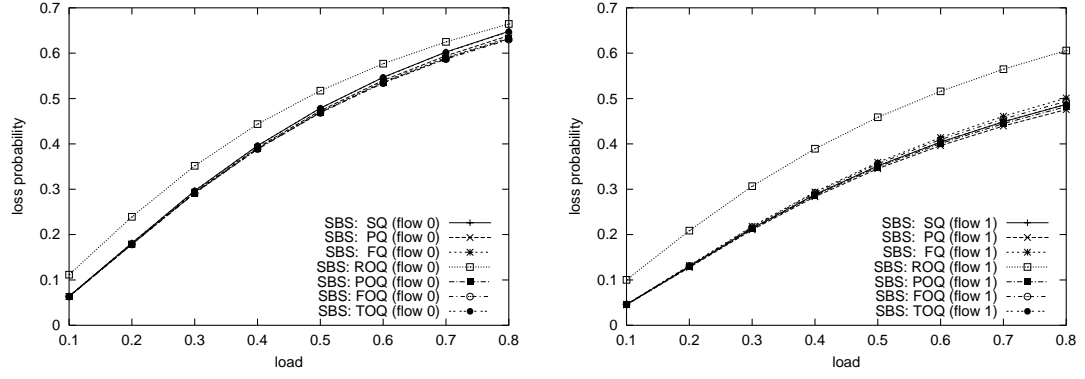
(a) Flow 0

(b) Flow 1



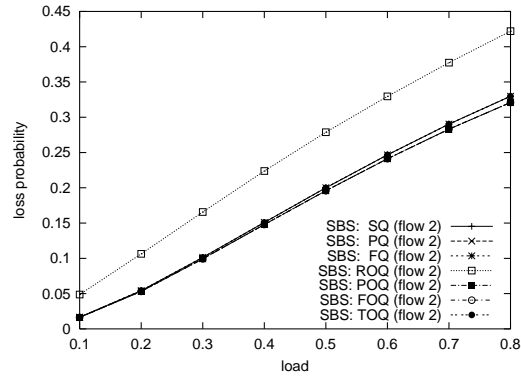
(c) Flow 2

Figure 7.8: Burst loss probability as a function of the traffic load using DS with various queueing policies for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 2\mu$, exponentially distributed inter-arrival time, and exponentially distributed burst lengths.



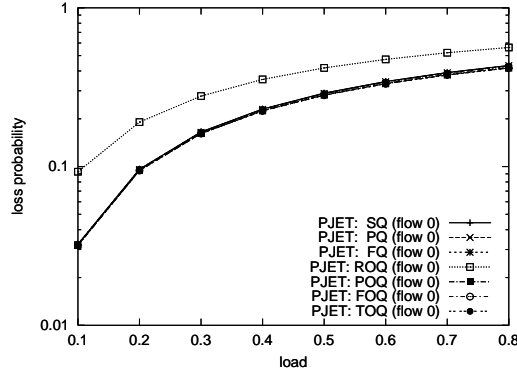
(a) Flow 0

(b) Flow 1

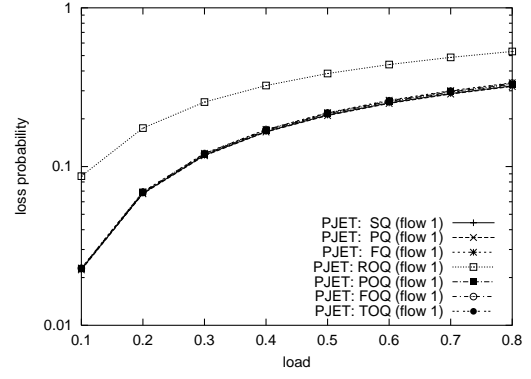


(c) Flow 2

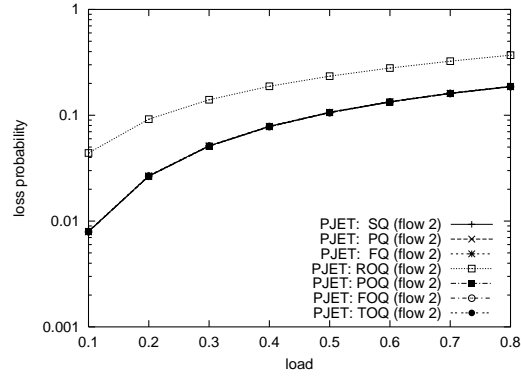
Figure 7.9: Burst loss probability as a function of the traffic load using PBS-SP with various queueing policies for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 2\mu$, exponentially distributed inter-arrival time, and exponentially distributed burst lengths.



(a) Flow 0

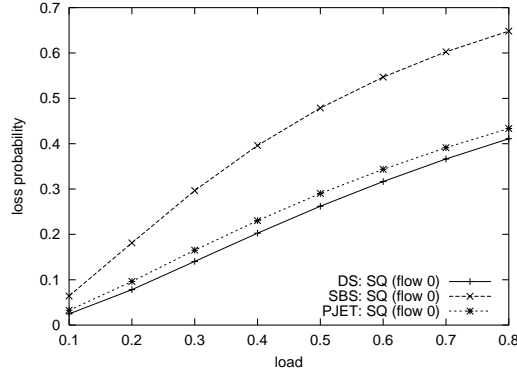


(b) Flow 1

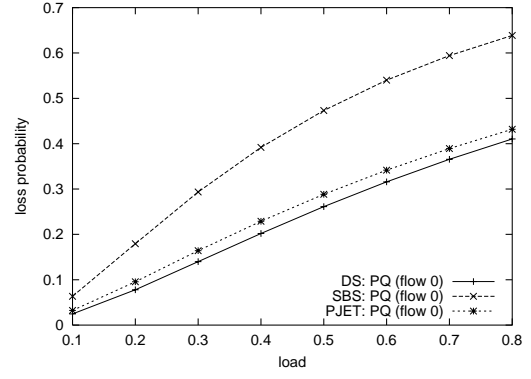


(c) Flow 2

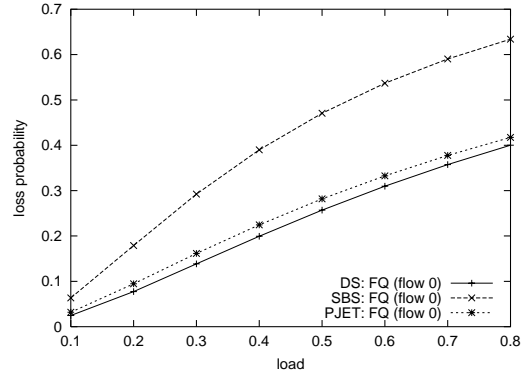
Figure 7.10: Burst loss probability as a function of the traffic load using PJET with various queueing policies for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 2\mu$, exponentially distributed inter-arrival time, and exponentially distributed burst lengths.



(a) SQ



(b) PQ



(c) FQ

Figure 7.11: Burst loss probability as a function of the traffic load using the schemes SBS, pJET, and DS with queueing policies SQ, PQ, and FQ for $n = 2$, $k = 2$, $t_b = 40\mu s$, $t_p = 4\mu$, exponentially distributed inter-arrival time, and exponentially distributed burst lengths.

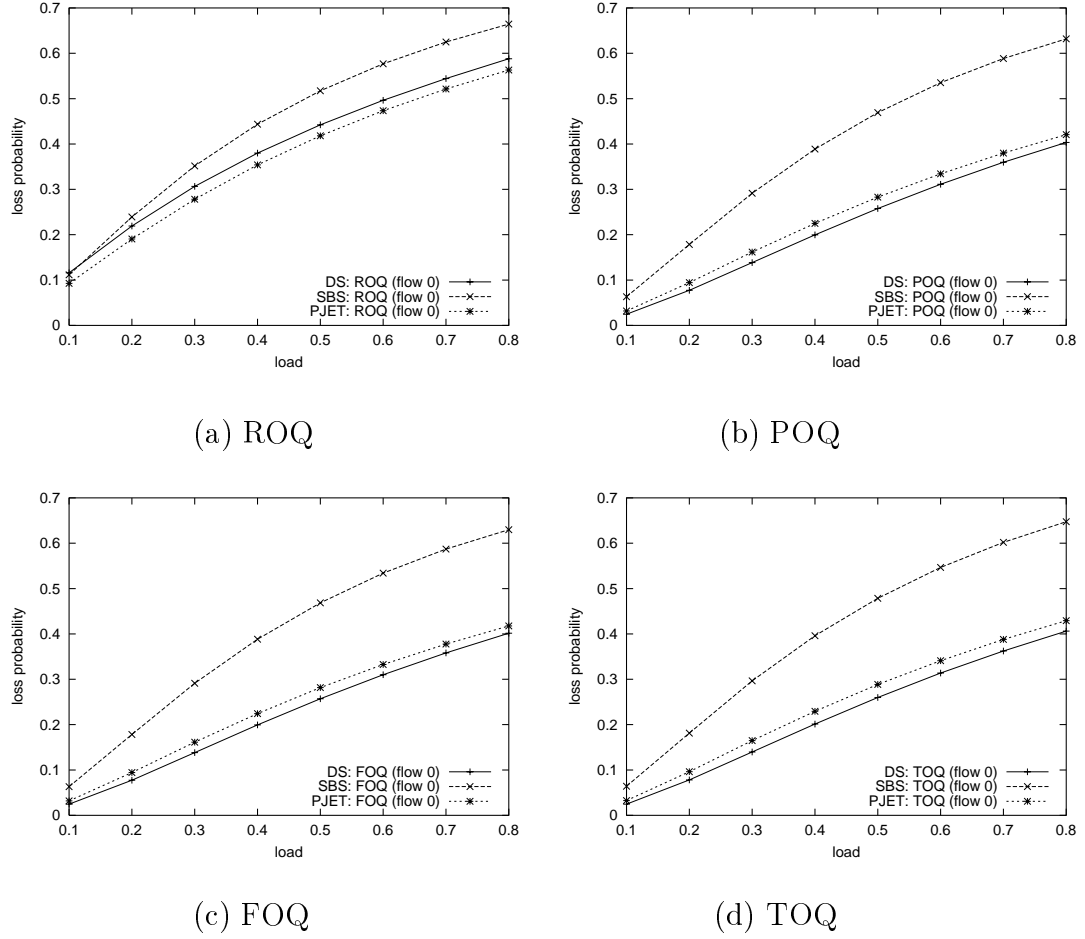


Figure 7.12: Burst loss probability as a function of the traffic load using SBS-WP-ROQ, POQ, FOQ, TOQ for $n = 4$, $k = 4$, $t_b = 40\mu s$, $t_p = 2\mu$, exponentially distributed inter-arrival time, and exponentially distributed burst lengths.

burst traffic has an exponential inter-arrival time distribution and an exponentially burst length distribution, $n = 2$, $k = 2$, $t_b = 40\mu s$, $t_p = 2\mu s$, and $t_{ou} = 10\mu s$.

7.5 Chapter Summary

The end-to-end performance of various burst scheduling schemes, include standard burst scheduling scheme, PBS scheme with strong, weak or minimum preemption,

PJET scheme, and DS scheme, is investigated in this chapter. Different control packet queueing and queue ordering policies, such as priority-based queueing, flow-based queueing, and priority/flow based queueing with random queue ordering, priority-based queue ordering, flow-based queueing ordering, and priority and flow based ordering, are proposed and applied to these burst scheduling schemes. Performance is evaluated in terms of burst loss probability per priority, per flow or per node by simulation. The simulations show that DS performs better than SBS and pJET in an WAN environment.

CHAPTER 8

CONTRIBUTIONS AND FUTURE WORK

The future optical Internet will require differentiated services support over WDM networks. Optical Burst Switching takes advantages of efficient electronic control and resource reservation, and ultra-fast optical transmission.

This dissertation presented a study of supporting differentiated services for optical burst switching WDM networks. This chapter summarizes our results and presents some direction for future work.

8.1 Key Results

In this dissertation, we first proposed Differentiated Optical Burst Service (DOBS) model and its network architecture to support DiffServ in OBS WDM networks. Secondly, we exam optical burst switching (OBS) reservation process and discuss some important parameters and their impact on the resource reservation. A general framework for its modeling and analysis is presented. We model the OBS reservation using queueing networks. Our framework and model cover many aspects of OBS reservation process including the control packet arrival, the offset time assignment, the control packet processing, the optical switch matrix setup, and the data burst arrival and transmission. The burst loss probability conservation law is proved for

the M/M/K/K priority loss system when all bursts of various priority classes have the same service rate. When the conservation law about burst loss probability and priority class isolation hold, analytical formulas are derived the burst loss probabilities of various priority classes.

In third part, we first propose a priority-based burst scheduling (PBS) scheme. processes control packets based on their priority classes and preempts one or more lower priority bursts if necessary. It supports media synchronization and in-order frame delivery without require an extra offset time for each priority class. Further, we design a second data burst scheduling scheme, called *Differentiated Scheduling* (DS), which supports differentiated services in OBS. The DS schedules high priority bursts earlier than lower priority bursts only if the high priority bursts arrive within a certain period of time after the lower priority bursts. The differentiated services in terms of burst loss probability are achieved by processing the control packets of higher priority class bursts more promptly upon their arrivals than those of lower priority class bursts. Unlike the pJET, DS assigns the same priority offset time to all the bursts destined to the same edge node. With the additional priority offset time, each intermediate node can adjust the burst loss probabilities of various priority classes by choosing its own *differentiated processing delay* value for each priority class or its own *differentiated processing delay difference* value between any pair of adjacent priority classes. According to our best knowledge, none of current QoS supporting burst scheduling schemes allows intermediate (core) nodes to dynamically adjust the burst loss probabilities of priority classes. Most performance studies of OBS burst scheduling schemes focused on a single link in a single node. However it is more important to understand how the various burst scheduling schemes perform in a

network environment. In an OBS network, bursts from various flows pass through an OBS node with various offset times and priorities. In the last chapter of the third part, different queueing policies can be utilized to process control packets based on their priority classes and flow ids. The performances of SBS, PBS-SP, pJET, and DS are evaluated in terms of burst loss probability under various scheduling queue policies in the ABILENE network with two wavelengths per link and two priority classes.

8.2 Future Work

This dissertation has mainly focused on differentiated services support with the integration of burst assembly and scheduling, and different scheduling schemes on OBS WDM network. This work is a very important first step toward making OBS WDM network a reality. We would like to point out some issues for further research.

One important issue is the design and performance evaluation of differentiated services support scheduling schemes in an OBS network environment. In a network, different bursts flow from different sources to different destinations will aggregate into a core OBS node. How to schedule them accordingly and maintain fairness among different burst flows is a very challenging task.

Another issue is burst contention resolution. Several approaches have been proposed. One approach uses burst segmentation [16, 94]. Deflection routing [49] is another approach. It remains to be seen whether there is a better way to resolve the burst contentions, and to integrate it with appropriate scheduling schemes to satisfy possible different differentiated services over OBS WDM networks.

To support a OBS network, further work needs to be done in the areas of routing protocol for OBS networks, software and hardware designs of OBS edge and core nodes, and network management system of OBS networks.

APPENDIX A

ABBREVIATION AND ACRONYMS

AON	all optical network
DS	differentiated scheduling
DWDM	dense wavelength division multiplexing
FO	flow-based ordering (in scheduling queue)
OBS	optical burst switching
OCS	optical circuit switching
O/E/O	opto-electro-optic
OPS	optical packet switching
PBS	priority-based scheduling
PBS-SP	priority-based scheduling with strong one preemption policy
PBS-WP	priority-based scheduling with weak one preemption policy
PBS-MP	priority-based scheduling with the minimum preemption policy
PO	priority ordering (in scheduling queue)
pJET	prioritized JET

QoS	quality of services
RO	random ordering (in scheduling queue)
TO	total ordering (in scheduling queue)
WDM	wavelength division multiplexing

APPENDIX B

SIMULATION MODELS

In this appendix, first we give a brief introduction to the CSIM package, which is used in our simulation for all the burst scheduling schemes we proposed in this dissertation. Then we describe the simulation models we use for Chapter 5, 6, and 7. Specifically we will describe in detail the simulation model for the Differentiated Scheduling scheme (Chapter 6).

B.1 CSIM Simulation Package

CSIM is a process-oriented discrete-event simulation package for use in C or C++ programs [75]. It provides a library of classes and procedures which can be used to create simulation programs. A CSIM program models a system as a collection of CSIM processes which interact with each other by using the data structures defined in the program. The model maintains timing of the system comprised of all the objects and thus can yield insight into the dynamic characteristics of the modeled system.

The primary unit of a CSIM program is a *process*. A process is initiated by another process except `main()` program which is the first process. All concurrently active processes execute in a quasi-parallel fashion. Once a process is initiated, it can either wait for a simulated time period to pass using *hold* statement; or wait for an

event to occur by executing a *wait* or *queue* statement; or cause an event to occur using a *it set* statement; or eventually terminate; or proceed other operations.

For example, *event* utility of CSIM can be used to synchronize the operations of different processes. In CSIM, an event consists of a state variable and two queues for processes waiting for the event to “happen”. One queue is for processes which have executed a *wait* statement and another is for processes which have executed a *queue* statement. When the event “happens”, all of the “waiting” processes and one of the “queued” processes are allowed to proceed. Statement *set(ev)* can be used to set event *ev* to the *occurred* state which means event *ev* has “happened”; when *ev* is set, all waiting processes will be returned to the *active* state, which means they are activated again.

CSIM automatically collects and produces some statistics on the usage of simulated resources. For example, CSIM used *table* to contain the statistical summary of the values which have been recorded (in the table). CSIM can process the records and get the information such as the mean, the minimum and the maximum values, the sum, and the variance for the values recorded in the table.

In this dissertation, in order to simulate an OBS WDM network, we represent a control packet as a CSIM process. The nodes, links or wavelengths are modeled as special types of CSIM data structures. The wavelength reservations for control packets in each node is programmed as accessing to these data structures.

B.2 General Simulation Run Times and Data Variances

In all the simulations, a single *long* run is done for each set of system and input parameters. Each run takes about 3000 minutes of simulation time in a single node

case, 6000 minutes of simulation time in the network environment. CSIM provides 90%, 95%, and 98% confidence intervals for the burst loss probabilities and other output parameters.

B.3 Basic Process and Data Structures for Simulation

The CSIM program can be viewed as a black box in which all control packets. A single node is simulated as in Figure B.1. Figure B.2 depicts how an OBS network is modeled

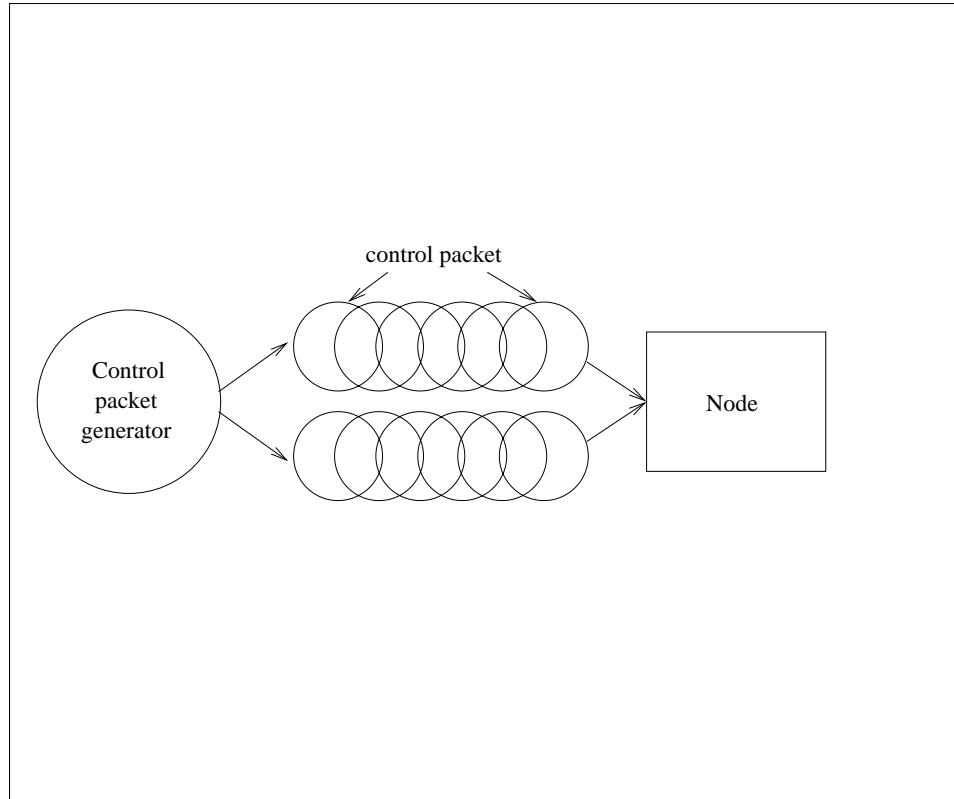


Figure B.1: Simulation model for a single node

in simulation. The input is the traffic demands and the system parameters. The traffic

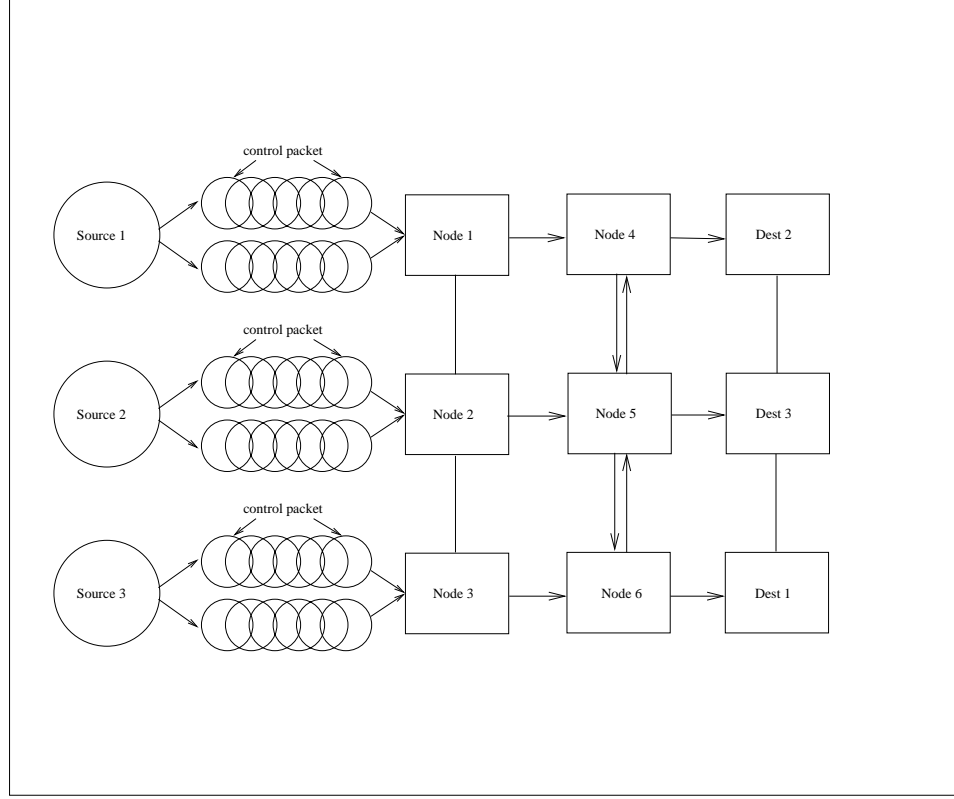


Figure B.2: Simulation model for a network

demands include parameters such as control packet inter-arrival time distribution and mean inter-arrival time, burst service (length) distribution and mean service time. The system parameters include parameters such as the control packet service time, priority offset time unit or differentiated offset time unit. The input of the simulation will be discussed in Section B.3.1. The output is the performance measures of the system simulated by the CSIM program, which include burst loss probabilities for various priority classes or for various traffic flows at each node or in a network. They will be discussed in Section B.3.5.

B.3.1 Input of the simulation Program

Input parameters include the OBS system parameters, the design parameters of burst scheduling schemes, and the traffic parameters.

The input parameters for PBS scheme are as follows (Chapter 4):

- OBS system parameters
 - Simulation time: how long the simulation will run (minutes)
 - rsv_type: reservation type such as SBS, PBS-SP, PBS-WP, PBS-MP
- Design parameters of the PBS scheme
- Traffic demand descriptors
 - flow_nm: the number of traffic flows, where flow i ($0 \leq i \leq flow_nm$) has $i + 1$ remaining hops to go
 - trf_type: traffic type: exponentially or Pareto inter-arrival time
 - srv_type: burst service type: exponentially or Pareto service time
 - bst_load: burst load per wavelength
 - bst_size: burst service time (μ seconds)
 - base_off: base offset time (not used in simulation, offset_unit is used for the same purpose)
 - off_unit: offset time (μ seconds) per remaining hop
 - class: the number of priority classes
 - trf_alpha: α values of Pareto distribution for traffic inter-arrival time

- `srv_alpha`: α values of Pareto distribution for burst service time
- The run command for PBS is


```
>pbs loss_scale simtime flow_nm trf_type srv_type cpkt_proc bst_load bst_size
base_off off_unit wave class rsv_type trf_alpha srv_alpha
```

The SBS is just PBS with `rsv_type` equal to 0.

The input parameters for pJET scheme are as follows (Chapter 5):

- OBS system parameters
 - Simulation time: how long the simulation will run (minutes)
 - `rsv_type`: reservation type such as SBS, PBS-SP, PBS-WP, PBS-MP
- Design parameters of the pJET scheme
- Traffic demand descriptors
 - `flow_nm`: the number of traffic flows, where flow i ($0 \leq i \leq flow_nm$) has $i + 1$ remaining hops to go
 - `trf_type`: traffic type: exponentially or Pareto inter-arrival time
 - `srv_type`: burst service type: exponentially or Pareto service time
 - `bst_load`: burst load per wavelength
 - `bst_size`: burst service time (μ seconds)
 - `base_off`: base offset time (not used in simulation, `offset_unit` is used for the same purpose)
 - `off_unit`: offset time per remaining hop (μ seconds)

- class: the number of priority classes
- trf_alpha: α values of Pareto distribution for traffic inter-arrival time
- srv_alpha: α values of Pareto distribution for burst service time
- The run command for pJET is


```
>pjet loss_scale simtime flow_nm trf_type srv_type cpkt_proc bst_load bst_size
base_off off_unit pri_unit wave class rsv_type trf_alpha srv_alpha
```

The input parameters for DS scheme are as follows (Chapter 6):

- OBS system parameters
 - Simulation time: how long the simulation will run (minutes)
 - rsv_type: reservation type such as SBS, PBS-SP, PBS-WP, PBS-MP
- Design parameters of the DS scheme
- Traffic demand descriptors
 - flow_nm: the number of traffic flows, where flow $i(0 \leq i \leq flow_nm)$ has $i + 1$ remaining hops to go
 - trf_type: traffic type: exponentially or Pareto inter-arrival time
 - srv_type: burst service type: exponentially or Pareto service time
 - bst_load: burst load per wavelength
 - bst_size: burst service time (μ seconds)
 - base_off: base offset time (not used in simulation, offset_unit is used for the same purpose)

- off_unit: offset time per remaining hop (μ seconds)
 - class: the number of priority classes
 - trf_alpha: α values of Pareto distribution for traffic inter-arrival time
 - srv_alpha: α values of Pareto distribution for burst service time
- The run command for DS is


```
>ds loss_scale simtime flow_nm trf_type srv_type cpkt_proc bst_load bst_size
base_off off_unit diff_unit wave class rsv_type trf_alpha srv_alpha
```

The input parameters for NPBSQ, NPJETQ, NDSQ schemes (Chapter 7) include the input parameters of PBS, PJET, and DS, respectively, and additional network parameters as follows:

- nodes: the number of nodes in the network
- q_type: the scheduling queue type such as random, priority-based, flow-based, or priority and flow based
- q_order: the processing orders of scheduling queues

The run commands are as follows:

- For NPBSQ is


```
>npbsq loss_scale simtime nodes flow trf_type srv_type cpkt_proc bst_load bst_size
base_off off_unit wave class rsv_type trf_alpha srv_alpha q_type q_order
```
- For NPJETQ is


```
>npjetq loss_scale simtime nodes flow trf_type srv_type cpkt_proc bst_load bst_size
base_off off_unit pri_unit wave class rsv_type trf_alpha srv_alpha q_type q_order
```


- For NDSQ is

```
>ndsq loss_scale simtime nodes flow trf_type srv_type cpkt_proc bst_load bst_size
base_off off_unit diff_unit wave class rsv_type trf_alpha srv_alpha q_type q_order
```

B.3.2 Time Control of the Simulation

One of the core tasks of the simulation program is to simulate the operations of control packets. In order to do this, the time control is very important. Here two aspects need to be taken into account for the time control: the representation of time, and the synchronization of events.

The base simulation time unit is a μ second. In the simulations, most parameters are a few or tens of μ seconds. Most of simulations run about 3000 seconds. We use *hold()* statement in CSIM to simulate a time period. For example, *hold(cpkt_proc_m)* will let the control packet to stay for a time period of control packet service time. In Figure, if the *scheduler[nid][nextnid]* is busy, a control packet is going to wait in an event queue *qeve[nid][fid][pid]* until the event is set for it.

B.3.3 Simulation of Basic Processes

Simulation of the Control Packet Generation

The control packet generation process is an infinite loop. Each loop represents the generation of one control packet. Its operation are described as follows:

1. generates a random value for the priority class
2. generates a random value for the control packet interarrival time
3. wait for the time of the control packet interarrival time generated in Step 2.
4. call the control packet process creation function

5. goto Step 1.

Simulation of the Control Packet Process

1. creates the control packet process
2. records the simulation time as control packet arrival time
3. records the burst arrival time and the end of the burst transmission time
4. records the control packet scheduling time
5. if the scheduler is busy, wait in one scheduling queue as specified by the queueing policy;
6. reserve the scheduler as a facility
6. reserve the wavelength according to the scheduling scheme;
7. records the reservation results for data collection;
8. holds for the control packet service time;
9. release the scheduler as a facility;
10. set one of scheduling queue according to the scheduling queueing policy;
11. if the current node is the destination node, terminates the control packet process
12. update the next node id, the burst arrival time, the end of the burst transmission time, the control packet arrival time, and the control packet scheduling time at the next node
13. go to Step 5.

B.3.4 Data Structures

A control packet is represented by a structure in C++ language as follows:

```
typedef struct bco_msg {  
    double bcp_sch_t;    /* control packet processing time */  
    double bcp_start_t; /* burst arrival time */  
    double bcp_end_t;    /* the end time of the burst transmission */  
    double bcp_cpk_t;    /* control packet arrival time */  
    int bcp_src;          /* burst source node id */  
    int bcp_dest;         /* burst destination node id */  
    int bcp_flow;         /* burst flow id */  
    int bcp_pri;          /* burst priority class */  
} bcp_msg;
```

A node consists of the following data:

```
-- node id  
-- a link object for each link  
    class link{  
        int wv_num;  
        wv **wvlist;  
        char link_name[20];  
        int snid;  
        int enid;  
        .....  
    }
```

Each link object consists of a list of wavelength object

Each wavelength object has a list to link the control packet data for the scheduler for the link

-- counters for the number of the control packets processed, and the number of the control packets lost per node, per pair of node and flow, per pair of node and priority class, per triplet of node, flow, and priority class, implemented as meter object in CSIM

-- a scheduler implemented as a facility for each scheduler per link

-- a event for each triplet of node, flow id, and priority class to be wait on if the scheduler facility is busy.

B.3.5 Data Collection and Processing of the Simulation Program

As introduced in Section, the CSIM package provides various kind of structures which can be used to gather statistical data for simulation model. We use *tables* to record the burst loss rates and use the CSIM table functions to process them. The results are listed as follows for DS scheme in a network environment.

- total burst loss rate at a node
- the burst loss rate per flow at a node
- the burst loss rate per class at a node
- the burst loss rate per flow for each class at a node

- the burst loss rate per class for each flow at a node
- the overall burst loss rate per flow for each class in the network
- the overall burst loss rate per class for each flow in the network

B.3.6 Simulation Results: An Example

The simulations were performed on the research SUN workstation running SunOS 5.8 at the Department of Computer and Information Science of the Ohio State University. An example of running simulation for DS scheme with a single node is shown as follows. The simulation is run using command

```
ds 6    3000  1  1  1  10 0.1 40  0 20 40 4 4 0 0 0
```

The output is as follows with explanations after —

Parameters

```
1 1 4      --- # of nodes = 1; # of flows = 1; # of classes = 4
```

Loss rates at node

```
0 0.002011207748 --- node number = 0; # the overall burst loss rate
per flow
```

```
0.002011207748 --- burst loss rate
```

```
per class  -- the collumns for classes 0 --> 3
```

```
0.000018129507 0.000183928177 0.000769964049 0.007077224209
```

```
per flow, per class  -- the collumns for classes 0 --> 3
```

```
0.000018129507 0.000183928177 0.000769964049 0.007077224209
```

per class, per flow -- one line per class, the columns for flows

0.000018129507

0.000183928177

0.000769964049

0.007077224209

overall:

per flow per class -- one line per flow, columns for classes 0 --> 3,

-- and the average

0.000018129507 0.000183928177 0.000769964049 0.007077224209 0.002011207748

per class per flow -- one line per class, the last column is

-- the average over flows

0.000018129507 0.000018129507

0.000183928177 0.000183928177

0.000769964049 0.000769964049

0.007077224209 0.007077224209

C++/CSIM Simulation Report (Version 18.1 for SPARC Solaris)

ds

Mon Jun 30 18:46:53 2003

Ending simulation time: 3000.000
Elapsed simulation time: 3000.000
CPU time used (seconds): 3196.970

output file = output/DSs6t3000h1tt1st1p10r0.1bs40bo0ou20du40w4c4st0tta0sra0.out

loss scale = 1000000.000

sim time = 3000.000 seconds

flow number = 1

load type = Poisson

srv type = Poisson

control packet interarrival time mean = 0.000100 seconds

burst load = 0.100000

control packet processsing time = 0.000010 seconds

burst length = 0.000040

base offset = 0.000000

offset_unit = 0.000020

diff_unit = 0.000040

wavelength number = 4

class number = 4

rsv_type = 0

Path from node 0 to node 1: 1

TABLE 144: bbr node 0 --- burst loss rate at this node

minimum	0.000000	mean	2011.207748
maximum	2383.372472	variance	991.065994
range	2383.372472	standard deviation	31.481201
observations	2998437	coefficient of var	0.015653

confidence intervals for the mean after 2995200 observations

level	confidence interval	rel. error
90 %	2011.200877 +/- 1.635531 = [2009.565346, 2012.836407]	0.000814
95 %	2011.200877 +/- 1.950049 = [2009.250828, 2013.150925]	0.000971
98 %	2011.200877 +/- 2.316458 = [2008.884418, 2013.517335]	0.001153

TABLE 1: bbr node 0 flow 0 --- burst loss rate of flow 0 at node 0

minimum	0.000000	mean	2011.207748
maximum	2383.372472	variance	991.065994
range	2383.372472	standard deviation	31.481201
observations	2998437	coefficient of var	0.015653

confidence intervals for the mean after 2995200 observations

level	confidence interval		rel. error
90 %	2011.200877 +/- 1.635531 = [2009.565346, 2012.836407]		0.000814
95 %	2011.200877 +/- 1.950049 = [2009.250828, 2013.150925]		0.000971
98 %	2011.200877 +/- 2.316458 = [2008.884418, 2013.517335]		0.001153

TABLE 100: bbr node 0 pri 0 --- burst loss rate of priority 0 at node 0

minimum	0.000000	mean	18.129507
maximum	28.047119	variance	11.895175
range	28.047119	standard deviation	3.448938
observations	749608	coefficient of var	0.190239

confidence intervals for the mean after 749600 observations

level	confidence interval		rel. error
90 %	18.129508 +/- 0.065538 = [18.063970, 18.195046]		0.003628
95 %	18.129508 +/- 0.078097 = [18.051411, 18.207605]		0.004326
98 %	18.129508 +/- 0.092698 = [18.036810, 18.222206]		0.005139

TABLE 101: bbr node 0 pri 1 --- burst loss rate of priority 1 at node 0

minimum	0.000000	mean	183.928177
---------	----------	------	------------

maximum	502.512563	variance	41.609395
range	502.512563	standard deviation	6.450534
observations	750106	coefficient of var	0.035071

confidence intervals for the mean after 750000 observations

level	confidence interval	rel. error
90 %	183.927076 +/- 0.166207 = [183.760869, 184.093283]	0.000904
95 %	183.927076 +/- 0.198063 = [183.729013, 184.125139]	0.001078
98 %	183.927076 +/- 0.235105 = [183.691971, 184.162182]	0.001280

TABLE 102: bbr node 0 pri 2 --- burst loss rate of priority 2 at node 0

minimum	0.000000	mean	769.964049
maximum	1006.261181	variance	924.171926
range	1006.261181	standard deviation	30.400196
observations	749314	coefficient of var	0.039483

confidence intervals for the mean after 742400 observations

level	confidence interval	rel. error
90 %	769.964049 +/- 0.566207 = [769.397842, 770.530256]	0.000736

95 %	769.964049 +/- 1.980544 = [767.983505, 771.944593]	0.002578
98 %	769.964049 +/- 2.352086 = [767.611963, 772.316135]	0.003064

TABLE 103: bbr node 0 pri 3 --- burst loss rate of priority 3 at node 0

minimum	0.000000	mean	7077.224209
maximum	8423.153693	variance	11546.855562
range	8423.153693	standard deviation	107.456296
observations	749409	coefficient of var	0.015183

confidence intervals for the mean after 748800 observations

level	confidence interval	rel. error
90 %	7077.217168 +/- 5.642812 = [7071.574356, 7082.859980]	0.000798
95 %	7077.217168 +/- 6.727944 = [7070.489224, 7083.945112]	0.000952
98 %	7077.217168 +/- 7.992108 = [7069.225060, 7085.209276]	0.001131

TABLE 159: bbr node 0 flow 0 pri 0 --- blr of pri 0 and flow 0 at node 0

minimum	0.000000	mean	18.129507
maximum	28.047119	variance	11.895175
range	28.047119	standard deviation	3.448938
observations	749608	coefficient of var	0.190239

confidence intervals for the mean after 749600 observations

level	confidence interval	rel. error
90 %	18.129508 +/- 0.065538 = [18.063970, 18.195046]	0.003628
95 %	18.129508 +/- 0.078097 = [18.051411, 18.207605]	0.004326
98 %	18.129508 +/- 0.092698 = [18.036810, 18.222206]	0.005139

TABLE 161: bbr node 0 flow 0 pri 1 --- blr of pri 1 and flow 0 at node 0

minimum	0.000000	mean	183.928177
maximum	502.512563	variance	41.609395
range	502.512563	standard deviation	6.450534
observations	750106	coefficient of var	0.035071

confidence intervals for the mean after 750000 observations

level	confidence interval	rel. error
90 %	183.927076 +/- 0.166207 = [183.760869, 184.093283]	0.000904
95 %	183.927076 +/- 0.198063 = [183.729013, 184.125139]	0.001078
98 %	183.927076 +/- 0.235105 = [183.691971, 184.162182]	0.001280

TABLE 163: bbr node 0 flow 0 pri 2 --- blr of pri 2 and flow 0 at node 0

minimum	0.000000	mean	769.964049
maximum	1006.261181	variance	924.171926
range	1006.261181	standard deviation	30.400196
observations	749314	coefficient of var	0.039483

confidence intervals for the mean after 742400 observations

level	confidence interval	rel. error
90 %	769.964049 +/- 0.566207 = [769.397842, 770.530256]	0.000736
95 %	769.964049 +/- 1.980544 = [767.983505, 771.944593]	0.002578
98 %	769.964049 +/- 2.352086 = [767.611963, 772.316135]	0.003064

TABLE 165: bbr node 0 flow 0 pri 3 --- blr of pri 3 and flow 0 at node 0

minimum	0.000000	mean	7077.224209
maximum	8423.153693	variance	11546.855562
range	8423.153693	standard deviation	107.456296
observations	749409	coefficient of var	0.015183

confidence intervals for the mean after 748800 observations

level	confidence interval	rel. error
90 %	7077.217168 +/- 5.642812 = [7071.574356, 7082.859980]	0.000798
95 %	7077.217168 +/- 6.727944 = [7070.489224, 7083.945112]	0.000952
98 %	7077.217168 +/- 7.992108 = [7069.225060, 7085.209276]	0.001131

B.4 Summary

In this appendix, we gave a brief look at the simulation model we use in the performance evaluation for the schemes proposed in this dissertation.

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