

Simon S. Lam, *Packet Switching in a Multi-Access Broadcast Channel with Application to Satellite Communication in a Computer Network*, Ph.D. Dissertation, Computer Science Department, University of California at Los Angeles, March 1974; published as Technical Report UCLA-ENG-7429 (ARPA), School of Engineering and Applied Science, UCLA, April 1974, 306 pages.

Available in eleven .pdf files:

- TRcovers.pdf
- Abstract+ToC.pdf
- Chapter1.pdf
- Chapter2.pdf
- Chapter3.pdf
- Chapter4.pdf
- Chapter5.pdf
- Chapter6.pdf
- Chapters7-8.pdf
- Bibliography.pdf
- Appendices.pdf

UNIVERSITY OF CALIFORNIA

Los Angeles

Packet Switching in a Multi-Access Broadcast Channel  
with Application to  
Satellite Communication in a Computer Network

A dissertation submitted in partial satisfaction of the  
requirements for the degree Doctor of Philosophy  
in Engineering

by

Simon Sin-Sing Lam

1974

© Copyright by

Simon Sin-Sing Lam

1974

The dissertation of Simon Sin-Sing Lam is approved, and  
it is acceptable in quality for publication on microfilm.

*Wesley W. Chu*

Wesley W. Chu

*James R. Jackson*

James R. Jackson

*Stephen E. Jacobsen*

Stephen E. Jacobsen

*Steven A. Lippman*

Steven A. Lippman

*Leonard Kleinrock*

Leonard Kleinrock, Committee Chairman

University of California, Los Angeles

1974

To my mother, brother and sisters  
and to my wife Amy

## CONTENTS

	<u>Page</u>
LIST OF FIGURES . . . . .	viii
LIST OF TABLES . . . . .	xi
ACKNOWLEDGMENTS . . . . .	xii
VITA AND PUBLICATIONS . . . . .	xiii
ABSTRACT . . . . .	xiv
CHAPTER 1      INTRODUCTION . . . . .	1
1.1      Present Computer-Communication Schemes . . . . .	2
1.2      Satellite and Radio Communications in Large Networks . . . . .	4
1.3      Packet Switching Techniques . . . . .	9
1.4      Summary of Results . . . . .	13
CHAPTER 2      THE CHANNEL MODEL . . . . .	20
2.1      Advantages of Satellite and Radio Packet Communications . . . . .	20
2.2      Satellite Channel Characteristics and Cost Trends . . . . .	23
2.3      An Abstract Model . . . . .	28
2.3.1      The Channel . . . . .	28
2.3.2      Channel Users . . . . .	33
CHAPTER 3      THROUGHPUT-DELAY PERFORMANCE . . . . .	37
3.1      Introduction . . . . .	37
3.2      The Infinite Population Model . . . . .	38
3.2.1      Assumptions . . . . .	38
3.2.2      The Analysis . . . . .	39
3.2.3      Throughput-Delay Results . . . . .	47
3.3      The Large User Model . . . . .	57
3.3.1      The Large User Effect . . . . .	57

## CONTENTS (continued)

		<u>Page</u>
	3.3.2 Throughput-Delay Results . . . . .	58
3.4	The Finite Population Model . . . . .	68
	3.4.1 Channel Capacity . . . . .	68
	3.4.2 Simulation Results . . . . .	71
CHAPTER 4	CHANNEL DYNAMICS . . . . .	75
4.1	An Exact Analysis . . . . .	76
4.2	An Approximate Solution . . . . .	80
4.3	Some Fluid Approximation Results . . . . .	83
CHAPTER 5	CHANNEL STABILITY . . . . .	92
5.1	The Model . . . . .	93
	5.1.1 The Mathematical Model . . . . .	94
	5.1.2 Practical Considerations . . . . .	95
	5.1.3 Channel Throughput . . . . .	101
	5.1.4 Equilibrium Contours . . . . .	102
5.2	Stability Considerations . . . . .	107
	5.2.1 Stable and Unstable Channels . . . . .	107
	5.2.2 A Stability Measure . . . . .	117
5.3	Numerical Results . . . . .	120
	5.3.1 An Efficient Computational Algorithm. . . . .	121
	5.3.2 Average First Exit Times (FET) . . . . .	123
	5.3.3 The Stability-Throughput-Delay Tradeoff . . . . .	127
CHAPTER 6	DYNAMIC CHANNEL CONTROL . . . . .	131
6.1	Introduction . . . . .	131
6.2	Some Results from Markov Decision Theory . . . . .	133
	6.2.1 Markov Processes with Costs . . . . .	133
	6.2.2 Markov Decision Processes . . . . .	136
	6.2.3 The Policy-Iteration Method . . . . .	138
6.3	The Controlled Random Access Channel Model . . . . .	141
	6.3.1 The Markov Process . . . . .	142

CONTENTS (continued)

		<u>Page</u>
	6.3.2 Channel Control Procedures . . . . .	145
	6.3.3 The Input Control Procedure (ICP) . . .	148
	6.3.4 The Retransmission Control Procedure (RCP) . . . . .	155
	6.3.5 The Input-Retransmission Control Procedure (IRCP) . . . . .	158
6.4	A Theorem on the Equivalence of the Performance Measures . . . . .	163
6.5	An Efficient Computational Algorithm (POLITE). .	170
6.6	Evaluation of Control Procedures by POLITE . . .	175
	6.6.1 Computational Costs and Convergence . .	175
	6.6.2 "Optimality" of the Control Limit Policy . . . . .	177
	6.6.3 Channel Performance . . . . .	184
6.7	Practical Control Schemes . . . . .	201
	6.7.1 Channel Control-Estimation Algorithms (CONTEST) . . . . .	202
	6.7.2 Another Retransmission Control Procedure . . . . .	209
	6.7.3 Simulation Results . . . . .	212
	6.7.4 Other Proposed Schemes . . . . .	218
	6.7.5 Channel Design Considerations . . . . .	222
CHAPTER 7	MULTI-PACKET MESSAGE DELAY AND SATELLITE RESERVATION SCHEMES . . . . .	226
	7.1 Multi-Packet Message Delay . . . . .	227
	7.2 A Reservation System for Multi-Packet Messages . . . . .	232
	7.3 Reservation-ALOHA Schemes . . . . .	234
CHAPTER 8	CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH . . . . .	237
BIBLIOGRAPHY	. . . . .	243
APPENDIX A	Simulation Results for the Poisson Assumption. .	250
APPENDIX B	Analysis for the Large User Model . . . . .	256

CONTENTS (continued)

	<u>Page</u>	
APPENDIX C	Derivation of Eqs. (4.3) and (4.4), Theorem 4.1 and Its Proof . . . . .	265
APPENDIX D	Algorithm 5.1, Its Derivation and Some Monotone Properties . . . . .	270
APPENDIX E	Algorithm 6.5, Its Derivation and Some Monotone Properties . . . . .	276
APPENDIX F	A General Dynamic Channel Control Procedure . .	286

LIST OF FIGURES

		<u>Page</u>
1-1	An Abstract Model for a Computer-Communication Network . . . . .	1
1-2	Packet Switch in the Sky . . . . .	6
1-3	Slotted ALOHA Random Access . . . . .	11
1-4	Summary of Results in this Dissertation . . . . .	17
2-1	Probability Density Function for a Retransmission Delay (RD) . . . . .	31
2-2	Delay Incurred by a Small User Packet . . . . .	32
2-3	Delay Incurred by a Large User Packet . . . . .	36
3-1	Channel Traffic into a Time Slot . . . . .	42
3-2	Probability of Success as a Function of K . . . . .	48
3-3	S Versus G . . . . .	50
3-4	Throughput-Delay Tradeoff . . . . .	51
3-5	Average Packet Delay Versus K . . . . .	52
3-6	$K_{opt}$ Versus S . . . . .	53
3-7	Simulation Run with a Short Duration of Channel Equilibrium . . . . .	56
3-8	The Large User Model . . . . .	58
3-9	Throughput Surface . . . . .	63
3-10	Allowable Throughput Rates for the Large User Model . . . . .	63
3-11	Throughput-Delay Tradeoff at $S_1 = 0.1$ . . . . .	65
3-12	Optimum Throughput-Delay Tradeoffs . . . . .	67
3-13	Allowable Throughput Rates for the Finite Population Model . . . . .	72
3-14	Throughput-Delay Tradeoffs for the Finite Population Model . . . . .	73
4-1	Channel Response to an Input Pulse ( $R=12, K=20$ ) . . . . .	84
4-2	Channel Saturation ( $R=12, K=20$ ) . . . . .	85
4-3	Simulations Corresponding to Figure 4-1 . . . . .	86
4-4	Simulations Corresponding to Figure 4-2 . . . . .	87
4-5	Channel Response to a Ramp Pulse ( $R=12, K=6$ ) . . . . .	89
4-6	Channel Recovery Time Versus Channel Backlog Size ( $R=12, K=6$ ) . . . . .	91
5-1	Comparison of Four RD Probability Distributions . . . . .	100
5-2	Channel Throughput Surface on the (n, S) Plane . . . . .	102
5-3	Equilibrium Contours on the (n, S) Plane . . . . .	103
5-4	M(t) . . . . .	106
5-5	Fluid Approximation Trajectories . . . . .	106
5-6	Stable and Unstable Channels . . . . .	108

LIST OF FIGURES (Continued)

		<u>Page</u>
5-7	Channel Performance Versus M at $K = 10$ and $S_o = 0.36$ . . . . .	112
5-8	Channel Performance Versus M at $K = 60$ and $S_o = 0.346$ . . . . .	113
5-9	$M_{max}$ Versus K . . . . .	114
5-10	Channel Performance Versus K at $M = 250$ and $1/\sigma = 675$ . . . . .	116
5-11	FET Values for the Infinite Population Model . . . . .	124
5-12	FET Versus M . . . . .	125
5-13	FET Values for a Finite User Population ( $M=150$ ) . . . . .	126
5-14	Stability-Throughput-Delay Tradeoff . . . . .	128
6-1	The Policy-Iteration Cycle . . . . .	140
6-2	An ICP Control Limit Policy Example . . . . .	149
6-3	An RCP Control Limit Policy Example . . . . .	149
6-4	An Interpretation of the Rejection Cost . . . . .	151
6-5	Average Number of Packets in the System Under ICP . . . . .	154
6-6	Optimum Performance of a Channel Control Procedure . . . . .	169
6-7	POLITE Iterations for ICP with Delay Costs--Control Limits . . . . .	179
6-8	POLITE Iterations for ICP with Delay Costs-- $v_i$ . . . . .	180
6-9	POLITE Iterations for RCP with Throughput Costs--Control Limits . . . . .	182
6-10	POLITE Iterations for RCP with Throughput Costs-- $v_i$ . . . . .	183
6-11	RCP Channel Performance Versus $K_c$ . . . . .	186
6-12	Channel Performance Versus ICP Control Limit for $M = 200$ . . . . .	188
6-13	Channel Performance Versus RCP Control Limit for $M = 200$ . . . . .	189
6-14	Channel Performance Versus ICP Control Limit for $M = 400$ . . . . .	190
6-15	Channel Performance Versus RCP Control Limit for $M = 400$ . . . . .	191
6-16	ICP and RCP Channel Performance Versus M . . . . .	193
6-17	ICP Optimum Throughput-Delay Tradeoffs at Fixed M . . . . .	196
6-18	RCP Optimum Throughput-Delay Tradeoffs at Fixed M . . . . .	197
6-19	ICP Optimum Throughput-Delay Tradeoffs at Fixed $\sigma$ . . . . .	198
6-20	RCP Optimum Throughput-Delay Tradeoffs at Fixed $\sigma$ . . . . .	199
6-21	The Channel History Window at Time t . . . . .	204
6-22	Determination of $\bar{F}^t$ . . . . .	209
6-23	Simulation Run for IRCP-CONTEST Subject to a Channel Input Pulse . . . . .	219

LIST OF FIGURES (Continued)

	<u>Page</u>
6-24 Simulation Run for Heuristic RCP Subject to a Channel Input Pulse . . . . .	220
7-1 Multi-Packet Message Delay Versus Throughput . . . . .	230
7-2 Throughput-Delay Tradeoff for Single-Packet and Eight- Packet Messages . . . . .	231
8-1 A Typical Throughput-Load Curve for a Contention System. . . .	241

## LIST OF TABLES

	<u>Page</u>
6.1 Points on the K=10 Contour . . . . .	185
6.2 Comparison of ICP, RCP and IRCP. . . . .	201
6.3 Throughput-delay results of a controlled channel (M=200, $S_o=0.32$ ) . . . . .	214
6.4 Throughput-delay results of a controlled channel (M=400, $S_o=0.32$ ) . . . . .	215
6.5 Throughput-delay results of a controlled channel (M=200, $S_o=0.36$ ) . . . . .	216
6.6 Throughput-delay results of a controlled channel (M=400, $S_o=0.36$ ) . . . . .	217
A.1 Channel traffic probability distribution (infinite population model). . . . .	252
A.2 Channel traffic probability distribution (M=200) . . . . .	254
A.3 Channel traffic probability distribution (controlled channels). . . . .	255

## ACKNOWLEDGMENTS

I wish to express my appreciation to my doctoral committee members, Professors Wesley Chu, James Jackson, Stephen Jacobsen, Leonard Kleinrock (chairman) and Steven Lippman. I am especially grateful to my advisor, Professor Leonard Kleinrock, for his encouragement and guidance throughout the course of this research.

Thanks are in order to my friends and colleagues in the Computer Science Department at UCLA, among them Dr. Holger Opderbeck for his useful suggestions, William Naylor and Lou Nelson for their help in facilitating my use of the XDS Sigma-7 computer and the IBM 360 Model 91. Thanks also go to Jon Spencer and Evelyn Walton who coded the simulation programs in this research. I am also indebted to Carol Mason and Diana Skocypec for their patient assistance in the typing and preparation of this dissertation.

Finally I must thank my wife Amy. Without her encouragement and support, none of this would have been possible.

This research was supported in part by the Advanced Research Projects Agency of the Department of Defense under Contract Number DAHC-15-73-C-0368 and by a UCLA Chancellor's Dissertation Fellowship.

## VITA

July 31, 1947--Born, Macao

1969--B.S.E.E., Washington State University

1969-1970--Phi Kappa Phi Sparks Memorial Fellow

1969-1973--UCLA Chancellor's Fellow

1970--M.S., University of California, Los Angeles

1970-1972--Teaching Associate, System Science Department  
University of California, Los Angeles

1971-1974--Postgraduate Research Engineer, Computer Science Department  
University of California, Los Angeles

## PUBLICATIONS

Kleinrock, Leonard and Simon S. Lam. "Packet-Switching in a Slotted Satellite Channel," National Computer Conference, New York, June 4-8, 1973, AFIPS Conference Proceedings, 1973, Vol. 42, pp. 703-710.

Kleinrock, Leonard and Simon S. Lam. "On Stability of Packet Switching in a Random Multi-Access Broadcast Channel," Seventh Hawaii International Conference on System Sciences, University of Hawaii, Honolulu, January 8-10, 1974, Proceedings of the Special Subconference on Computer Nets, 1974.

ABSTRACT OF THE DISSERTATION

Packet Switching in a Multi-Access Broadcast Channel  
with Application to  
Satellite Communication in a Computer Network

by

Simon Sin-Sing Lam

Doctor of Philosophy in Engineering

University of California, Los Angeles, 1974

Professor Leonard Kleinrock, Chairman

This dissertation considers a packet switching technique applicable to packet communication using a satellite or ground radio channel. The objective of this research is to develop analytic models for the evaluation and optimization of the system performance in terms of stability, throughput and delay.

Advantages of packet switched satellite and ground radio systems over conventional wire communications for large computer-communication networks are discussed. The emphasis of this research is on a high-speed channel shared by a large population of "small" users. The channel behavior is typical of "contention" systems in which the throughput vanishes to zero as the load on the system increases. This phenomenon is called channel saturation. The channel may go into saturation as a result of (a) time fluctuations, and (b) stochastic fluctuations in the channel input. The channel response to time varying inputs is first studied using a deterministic approximation analysis. The effect of (b) is then studied through probabilistic models. In this case, contributions of this research may be classified into three categories:

- (1) a coherent theory of channel behavior in which the key result is the characterization of stable and unstable channels
- (2) evaluation of channel performance such as equilibrium throughput-delay tradeoffs for stable channels and stability-throughput-delay tradeoffs for unstable channels
- (3) dynamic channel control and estimation procedures for optimal control of unstable channels.

This study has several implications. First, a coherent theory of channel behavior has been developed, system design variables have been identified and operational strategies for the optimization of channel performance have been evaluated. These results suggest a system design methodology. Second, the techniques employed in characterizing the stability behavior and evaluating dynamic channel control schemes may profitably be applied to probabilistic models of other contention systems.