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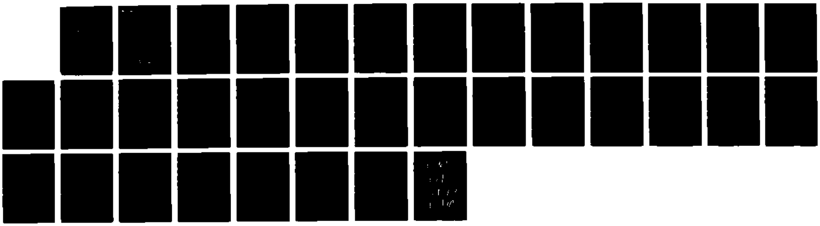

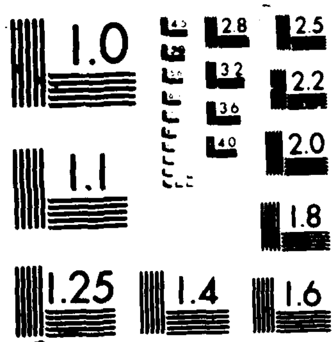
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ADAPTIVE SPREAD SPECTRUM NETWORKS

DAAG29-84-K-0084

FINAL REPORT

1 July, 1984 - June 30, 1987

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PAPERS SUBMITTED/IN PROCESS/PUBLISHED DURING THIS PERIOD

1984

* John Silvester, "Performance of Spread Spectrum Networks", Proceedings of the Allerton Conference, 1984.

* 20 reprints 12/84

ABSTRACT

In this paper we describe throughput/delay performance results for Spread Spectrum Communication Networks. In previous work we have used a strong independence assumption and an iterative algorithm to generate approximate performance models for (non-spread) multiple access broadcast networks using random access protocols. The model incorporates the effect of buffering and finite populations. In this paper we extend these results to Spread Spectrum Networks capable of Code Division Multiple Access and study the effect of the multi-user threshold and capture.

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RESEARCH RESULTS AND FURTHER INFORMATION

We have developed a unified model for evaluating the key performance measures (i.e., throughput/delay or user BER/delay) of Random Access, Packet Switched Spread Spectrum Links, based on a symmetry condition among the concerned users. The model is general enough to encompass and generalize previously published results in the open literature and is well suited for studying a wide variety of traffic patterns, network topology, and channel conditions. In particular, jamming impact on the link level can be neatly incorporated as a specific form of channel conditioning along with any reactive measures (adaptivity) undertaken by the communicator. The key feature of the theory is the identification of a single parameter, which quantifies the impact of all of the above on the link operation. Thus, once this parameter has been evaluated, performance on a link level is uniquely defined. We are currently in the process of assessing the effects of various forms of jamming coupled with possible adaptivity measures.

One of the problems with our previous models for multi-hop networks of buffered nodes was that only the Delayed First Transmission (DFT) protocol was modelled. DFT is not a protocol that would be used in a a real network however and we were therfore interested to extend the results to the Immediate First Transmission protocol (IFT). We have, therefore, modified our simulation to include this case and have succeeded in developing an analytical model, which unfortunately lacks the simple structure of the DFT case. We are continuing work on this case since if we can generate a simple model we will be able to study network optimisation and adaptivity with respect to delay rather than throughput as has been done previously.

Acknowledgemt channels are a straightforward way to implement the feedback necessary to make effective use of adaptivity. We have, therefore, started to investigate Acknowledgement protocols that make use of the Spread Spectrum multi-access capabilities. In particular, the approach we consider reserves the beginning of each slot for the acknowledgement traffic. We are investigating various different strategies for deciding whether to allow transmission or not in a slot when an acknowledgement is anticipated.

We are also investigating the use of random graphs as models of Spread Spectrum Communication networks. Initial studies indicate that performance models generated under these assumptions are reasonable approximations to reality and result in simple models that can be used to study network level adaptivity issues.

1985

* Elvino S. Sousa and John A. Silvester, "Channel Access Protocols for Distributed Spread Spectrum Packet Radio Networks," presentation at the SURAN Workshop, Washington, DC, March 24-25, 1985, (Abstract only)

* Elvino S. Sousa and John A. Silvester, "Determination of Optimum Transmission Ranges in a Multi-Hop Spread Spectrum Network," presented at the SURAN Workshop, Washington, DC, March 24-25, 1985, (Abstract only)

* Andreas Polydoros and John A. Silvester, "A General Model for Performance Evaluation of Single-Hop Packet Radio Networks," presented at the SURAN Workshop, Washington, DC, March 24-25, 1985, (Abstract only)

* Elvino S. Sousa and John A. Silvester, "Determination of Optimum Transmission Ranges in a Multi-Hop Spread Spectrum Network," to be presented at MILCOM '85, Boston, MA, October 1985.

ABSTRACT

In this paper we obtain the optimum transmission ranges to maximize throughput for a multi-hop spread spectrum network. In the analysis we model the network self-interference as a random variable which is equal to the sum of the interference power of all other terminals. For a spread spectrum network with an *effective* capacity equal to K simultaneous transmissions and an inverse fourth power propagation law we found that a terminal should transmit with a range so that on the average there are approximately $1.3\sqrt{K}$ terminals closer to the transmitter than the receiver. We found that for the inverse fourth power propagation law, the probability density of the interference power at a given terminal is the inverse Gaussian probability density. More generally, if the propagation law is an inverse γ^{th} power ($\gamma > 2$), then the probability law of interference power is the stable law of exponent $2/\gamma$.

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* Andreas Polydoros and John Silvester, "An Analytic Framework for Slotted ALOHA/SSMA Links", *Proceedings of MILCOM '85*, Boston, Massachusetts, October 1985.

ABSTRACT

An analytic framework is proposed for the study of Random Access, Packet-Switched, Spread Spectrum Links under various network topologies and channel conditions. The key feature of the theory is the identification of a set of probabilistic

parameters which, based on a symmetry argument, serve to efficiently summarize the effect of various network considerations on the link performance such as transmitter/receiver configuration, spread spectrum code allocation, error correction and detection mechanisms, spreading format, jamming condition, etc. The concept is illustrated through examples which show how (a) previous results can be included as special cases and (b) can be generalized to a multitude of scenarios.

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* Elvino S. Sousa and John A. Silvester, "Spreading Code Protocols for Distributed Spread Spectrum Packet Radio Networks," to appear in IEEE Transactions on Communications.

* 1 preprint 7/85

ABSTRACT

Spreading code protocols for a distributed spread spectrum packet radio network are presented. We assume distributed single hop system (i.e., each terminal can hear all other terminals) with the users approximately synchronized, together with a set of prespecified spreading codes. The spreading code protocol is then a policy for choosing a spreading code to be used given that a terminal has a packet to send, and a policy for monitoring spreading codes given that a terminal is idle. We consider a slotted system where a packet occupies a number of slots, and present two protocols which involve changing the spreading code of transmission after an initial header is transmitted. In one protocol the header is transmitted on a common code and in the other it is transmitted on a transmitter-based code. In the receiving mode, a terminal monitors either a common code, in the first case, or a receiver-based code in the latter. Upon recognizing its own address and the source address, the receiver dynamically switches to a despreading code corresponding to the source. Throughput results are obtained the case of geometrically distributed packet lengths. For the idealized case of infinite processing gain we give two fundamental limiting throughput results which correspond to a utilization of .343 and .398 per terminal pair for an unslotted system with exponential packet length and slotted system respectively.

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* S.S. Lee and J.A. Silvester, "The Effect of Acknowledgement on the Performance of Distributed Spread Spectrum Packet Radio Networks," *Proceedings of the Allerton Conference*, 1985.

ABSTRACT

In this paper, we present the effect of acknowledgements on the throughput/delay performance for distributed spread spectrum packet radio networks. We consider a system that uses a receiver-based code for data and transmitter-based code for acknowledgement packets, respectively. We also assume that the transmitter does not have a dedicated receiver. Therefore, packets are unsuccessfully received if two or more transmitters address the same receiver, or if the receiver is in transmit mode. We propose two acknowledgement schemes: non split-slot scheme; split-slot scheme, and analyze throughput/delay performances for different amounts of acknowledgement overhead.

1986

* Andreas Polydoros, "Analytical Models for Slotted, Wideband, Random-Access Networks", to be presented at *URSI*, August 1986, Budapest, Hungary. (abstract only)

ABSTRACT

The area of multiple-access radio networks is still of great activity in the research community. One of the first such networks was the ALOHA network at the University of Hawaii [Abra70], which was subsequently analyzed in detail in [Klei75]. Since that time much work has been done on network performance of these networks. More recently we have seen the introduction of Spread Spectrum as a modulation technique for use in these networks [Kahn78]. This has been motivated mainly by military applications since it provides anti-jam communication capability. As a by-product we can also use the spread spectrum properties to provide multi-user capability. Until recently, analysis of these systems has focussed on the physical level of communication with a few papers treating link level issues and very few treating the network issues. Notable exceptions to this are the paper by Davis and Gronemeyer, [Davi80] which looks at capture issues in a centralized Spread Spectrum netwOrk; the paper by Raychaudhuri, [Ray81], which looks at multiple spread spectrum links in a common environment; and the papers by Sousa and Silvester, [Sous84, Sous85] which look at spreading code assingment strategies and specifically consider the network aspects of the problem, i.e., is the destined receiver able to receive the packet or is he already busy with some other communication?

In this talk, an analytic framework is proposed for the study of Random Access, Packet-Switched, Spread Spectrum Links under various network topologies and channel conditions. The key feature of the theory is the identification of a set of probabilistic parameters which, based on a symmetry argument, serve to efficiently summarize the effect of various network considerations on the link performance such as transmitter/receiver configuration, spread spectrum code allocation, error correction and detection mechanisms, spreading format, etc. The concept is illustrated through examples which show how past results (a) can be included as special cases and (b) can be generalized to a multitude of scenarios.

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* [Kahn78] R. Kahn, S. Gronemeyer, J. Burchfiel and R. Kunzeman, "Advances in Packet Radio Technology," *Proceedings of the IEEE*, vol. 66, no. 11, November 1978, pp. 1468-1496.

* [Davi80] D.H. Davis and S.A. Gronemeyer, "Performance of Slotted ALOHA Random Access with Delay Capture and Randomized Time of Arrival," *IEEE Transactions on Communications*, vol. COM-28, no. 5, May 1980, pp. 703-710.

* [Ray c81] D. Raychaudhuri, "Performance Analysis of Random Access Packet Switched Code Division Multiple Access Systems," *IEEE Transactions on Communications*, vol. COM-29, no. 6, June 1981, pp. 895-901.

* [Sous84] E.S. Sousa and J.A. Silvester, "A Spreading Code Protocol for a Distributed Spread Spectrum Packet Radio Network," *Proceedings of GLOBECOM '84*, December 1984.

* [Sous85] E.S. Sousa and J.A. Silvester, "A Code Switching Technique for Distributed Spread Spectrum Packet Radio Network," *Proceedings of the International Conference on Communications*, Chicago, June 1985.

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* Samuel S. Lee and John A. Silvester, "The Effect of Acknowledgements on the Performance of Distributed Spread Spectrum Packet Radio Network", *ICC '86*.

ABSTRACT

In this paper, we study the effect of acknowledgements on the throughput/delay performance of distributed single-hop packet radio networks using spread spectrum modulation and the Slotted-Aloha access protocol.

The considered system uses a receiver directed spreading code for data transmission and a transmitter based code for acknowledgements, and nodes can either

transmit or receive but not both at the same time. Therefore, packets are unsuccessfully received if two or more transmitters address the same receiver, or if the receiver is in transmit mode. Several acknowledgement schemes are studied and the throughput/delay performance for differing amounts of acknowledgement overhead is analyzed.

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* Elvino S. Sousa and John A. Silvester, "Determination of Optimum Transmission Ranges in a Multi-Hop Spread Spectrum Network", submitted to *IEEE Transactions on Communications*.

* 1 preprint 5/86

ABSTRACT

In this paper we obtain the optimum transmission ranges to maximize throughput for a multi-hop spread spectrum network. In the analysis we model the network self-interference as a random variable which is equal to the sum of the interference power of all other terminals. For a spread spectrum network with an *effective* capacity equal to K simultaneous transmissions and an inverse fourth power propagation law we found that a terminal should transmit with a range so that on the average there are approximately $1.3\sqrt{K}$ terminals closer to the transmitter than the receiver. We found that for the inverse fourth power propagation law, the probability density of the interference power at a given terminal is the inverse Gaussian probability density. More generally, if the propagation law is an inverse γ^{th} power ($\gamma > 2$), then the probability law of the interference power is the stable law of exponent $2/\gamma$.

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* Elvino S. Sousa and John A. Silvester, "A Graphical Package for Experimentation with Packet Radio Network", *Proceedings of MILCOM '86*, Monterey, CA, October 1986.

* 20 reprints 7/86

ABSTRACT

This paper is concerned with the graphical modeling of multi-hop spread spectrum packet radio networks. We show various network graphs, obtained using a graphics program, that illustrate typical connectivities that may be achieved for nominal values of the processing gain. The effects of the propagation power loss function and terminal transmission probability are also displayed. We introduce the notion of a *soft* link where the number of links included in the network depends on a link quality parameter.

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* Peter R. Pawlowski and Andreas Polydoros, "Adaptive Nonparametric Acquisition of FH-SS Signals in Jamming", *Proceedings of MILCOM '86*, Monterey, CA, October 1986.[1]

* 20 reprints 1/87

ABSTRACT

A matched filter receiver for frequency-hopped spread spectrum code acquisition in jamming is analyzed. The receiver uses an adaptive, nonparametric distribution-free Median Test detector requiring no knowledge or "side-information" about the signal, jammer, and thermal noise parameters to implement an asymptotically constant false alarm rate test. The median of a reference sample set, empirically describing the code-absent probability distribution, determines the threshold used in the nonparametric detector. By updating the reference set every hop epoch, the threshold adapts to the channel condition. Adaptive threshold setting introduces memory so that tests are no longer independent, making exact closed-form analysis difficult. Performance approximations are developed and compared to simulation results illustrating acquisition performance.

[1] Acknowledgement of ARO-effort was overlooked in error when this paper was submitted to MILCOM '86

1987

* Leonard Kleinrock and John Silvester, "Spatial Reuse in Multihop Packet Radio Networks," *Proceedings of the IEEE*, January 1987.

* 1 preprint 7/86

ABSTRACT

Multihop packet radio networks present many challenging problems to the network analyst and designer. The communication channel, which must be shared by all of the network users, is the critical system resource. In order to make efficient use of this shared resource, a variety of channel access protocols to promote organized sharing have been investigated. Sharing can occur in three domains: frequency, time and space. This paper is mostly concerned with sharing and channel reuse in the spatial domain. A survey of the results on approaches to topological design and associated channel access protocols that attempt to optimize system performance by spatial reuse of the communication channel is presented.

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* Andreas Polydoros and John A. Silvester, "Slotted Random Access Spread Spectrum Networks - An Analytical Framework," *IEEE Journal on Selected Areas in Communications*, vol. SAC-5, no. 6, July 1987, pp. 989-1001.

* 20 copies 8/87

ABSTRACT

An analytic framework is proposed for the study of Random Access, Packet-Switched, Spread Spectrum Links under various network topologies and channel conditions. The key feature of the theory is the identification of a set of probabilistic parameters which, based on a symmetry argument, serve to efficiently summarize the effect on link performance of various network considerations such as transmitter/receiver configuration, spread spectrum code allocation, error correction and detection

mechanisms, spreading format, jamming condition, etc. Examples investigating capture effects, coding tradeoffs and scheduling optimization are presented. Various previously known results are shown to be special cases of the framework that we describe.

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* S.S. Lee and John Silvester, "Analysis of Acknowledgement Effect on the Performance of Spread Spectrum Packet Radio Networks," submitted to the *IEEE Transactions on Communications*).

ABSTRACT

In this paper, we propose several different acknowledgement schemes and study their performance. The environment we consider is a distributed single-hop packet radio network using spread spectrum modulation and the Slotted-Aloha access protocol. A receiver directed spreading code is used for data transmission and a transmitter based code is used for acknowledgements.

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* Jonathan L. Wang and John A. Silvester, "On Some Optimization Problems in Packet-Switched Radio Networks - Part I," report prepared for the Ph.D. Qualifying Examination *CSI-86-12-07*.

* 1 copy 1/87

ABSTRACT

Networks using packet radios are an effective means of data communication. Many aspects of them have been under intense research during the past decade, such as multi-access protocols, reliability issues, flow and congestion control, etc. In this report, we have identified and formulated some optimization problems that exist in packet radio networks. The first problem we looked into is design of protocols for the response traffic of broadcast messages. To minimize the time for the source node to receive the required responses, a two level protocol is proposed and the corresponding optimization problem is set up and solved by a dynamic programming technique. The second problem we examined is determination of the maximum throughput that can be supported between a

pair of nodes in a multi-hop packet radio network. By the use of a proper link activation protocol, we found that the throughput will always be one if there exists at least four independent paths between the source and the destination nodes. Finally, some future research direction is proposed and discussed.

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* Jonathan L. Wang and John A. Silvester, "On the Response Traffic for Broadcast Messages in Packet-Switched Radio Networks," *Proc. of the Third International Conf. on Data Communication Systems and Their Performance*, pp. 137-149, Rio de Janeiro, Brazil, June 1987.

* 1 preprint 8/87

ABSTRACT

The performance characteristics of the response traffic for broadcast messages in a packet-switched radio network are studied. The situation we consider here involves a source node sending a broadcast message to all destinations and collecting positive response packets from these destinations in a fully-connected packet radio network. The exact value of the number of destination nodes is unknown. A contention-based two level protocol is described. Based on the protocol, an optimization problem is formulated in order to minimize the time for the source to receive all the responses. Several schemes are presented and numerical results of the corresponding optimization problems are obtained.

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* Jonathan L. Wang and John A. Silvester, "Optimal Adaptive ARQ Protocols for Point-to-Multipoint Communications," submitted to *IEEE INFOCOM*, 1988.

* 1 preprint 8/87

ABSTRACT

This paper studies some data link layer error control protocols suitable for point-to-multipoint communication where data are delivered to the destinations in the order they are sent. We study a series of protocols differing in the way that the sender uses the outcomes of the previous transmissions. The protocols are based on the go-back-N schemes discussed by Gopal and Jaffe. We generalize their proposed protocols to the case where multiple copies of a message are sent (instead of just a single copy). The optimum number of copies is determined, which depends on how many receivers have yet not received the message. A dynamic programming technique is used to solve this optimization problem. The throughput comparison shows that by sending the optimum number of copies of a data frame instead of just a single copy, the performance will be significantly improved.

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* Jonathan L. Wang and John A. Silvester, "Algorithms for Optimization of Broadcast Message Response Traffic Performance with Application to Packet-Switched Radio Networks," submitted to *Algorithmica*.

* 1 preprint 8/87

ABSTRACT

Algorithms to optimize the performance of response traffic for broadcast messages in a packet-switched radio network are studied. The situation considered here involves a source node sending a broadcast message to all destinations and collecting positive response packets from these destinations in a fully-connected packet radio network. The exact value of the number of destination nodes is unknown. A contention-based two level protocol is described. Based on the protocol, an optimization problem is formulated in order to minimize the time for the source node to receive all the responses. Several algorithms are presented and numerical results of the corresponding optimization problems are obtained. These optimization problems are treated by the methods of dynamic programming. Extensions of the basic scheme are proposed by allowing relaxation of the assumptions made earlier such as random noise in forward channel, capture effect, and multicast instead of full broadcast message are also studied.

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* N.B. Pronios and A. Polydoros,"Slotted ALOHA-type Fully Connected Networks in Jamming, Part I: Unspread ALOHA," *Proceedings of MILCOM '87*, October 1987, Washington, DC.

* 20 reprints 8/87

ABSTRACT

The throughput-delay performance of slotted, un-spread ALOHA-type mono-hop networks is considered under different types of stochastic slot-synchronous jamming. Trade-offs and optimal values of certain parameters for both the communicator (user) and jammer are determined.

In Progress

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* John A. Silvester and Syu-Je Wang, "An Approximate Performance Model of Slotted ALOHA Multihop Packet Radio Networks," in preparation for submission to *ICC* 1988.

* preprint not available

ABSTRACT

Due to the dependency between the different queues at the nodes of the network and the difficulty of keeping track of packets as they are relayed to their destinations the exact queueing analysis of multihop packet radio networks is mathematically intractable In this paper, an approximate performance model of slotted ALOHA multihop packet radio networks with a finite number of buffered nodes is presented. This model improves and generalizes the ones by Segall and Sidi [6] and Silvester and Lee [9]. The delay/throughput results obtained from this model are then compared to simulation and exact analysis for some simple network configurations.

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* Jeffrey Dill and J.A. Silvester, "Throughput Analysis of Random Multihop Packet Radio Networks Using Receiver Directed CDMA", in preparation.

* preprint not available.

ABSTRACT

In this paper we present a receiver directed code division multiple access (RD-CDMA) scheme for use in multihop packet radio networks. This scheme takes advantage of the inherent multiple access capabilities of spread spectrum antijam communications systems to allow efficient channel sharing and thus a significant increase in achievable network throughput. We first derive an analytical upper bound on average network throughput for random networks with uniform message traffic, assuming that the network is homogeneous. A slotted-ALOHA like access protocol is then developed, using code division to uniquely address the desired receiver, in conjunction with a simple minimum hop routing algorithm. Finally, simulation results are presented which agree quite closely with the predicted throughput over a wide range of input conditions.

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* Jeffrey C. Dill & John A. Silvester, "A Dedicated Channel Acknowledgement Protocol for Multihop CDMA Packet Radio Networks," in preparation.

* preprint not available.

ABSTRACT

In this paper we present an acknowledgement scheme for Receiver Directed Code Division Multiple Access (RD-CDMA) networks, which takes advantage of the inherent CDMA capabilities of the radio to ensure the success of acknowledgement transmissions with very high probability, by placing acknowledgements on a dedicated code channel, which is guaranteed to be contention free. This is a dramatic improvement over the performance of acknowledgements on the normal data transmission channel. Throughput expressions are developed for the cases of perfect acknowledgement, normal acknowledgement, and dedicated channel acknowledgement.

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* Jonathan L. Wang and John A. Silvester, "A New Measure in Network Reliability - Radio Connectivity", for submission to *ICC '88*, in preparation.

* preprint not available

ABSTRACT

In this paper, we are interested in determining the network reliability for a multi-hop packet radio network in the presence of a hostile jammer. A new connectivity parameter called *radio connectivity* is defined as the maximum number of disjoint communication paths that are still usable between given nodes s and d after the jammer is on. Time complexity of obtaining the radio connectivity is analyzed. Unfortunately, it is shown that the problem is *NP*-hard except for some special cases. Following that, a couple of greedy heuristics to get an approximate answer for general networks are described.

****

* N.B. Pronios and A. Polydoros, "An Approximate Method for Throughput/Delay Analysis of Slotted Random-Access Networks," submitted to *INFOCOM '88*, New Orleans, LA, April 1988.

* 1 preprint 8/87

ABSTRACT

We develop an approximate method for performance evaluation of a general class of slotted ALOHA-type Random Access networks. Approximation is used in three levels; the diffusion approximation of the process Q(t) a variant of the number of backlogged users, the approximation of the Random Access channel and the existing receivers by a single server with equivalent queue-size-dependent service rate and the approximation of the state dependent composite traffic distribution by a Gaussian random variable with equivalent mean and variance. Applications and comparisons with the precise solutions are given.

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* N.B. Pronios and A. Polydoros, "Spread-Spectrum Slotted-ALOHA Fully-Connected Networks in Jamming", submitted to *INFOCOM '88* New Orleans, LA, April 1988, and the *IEEE Transactions on Communications*.

* 1 preprint 8/87

ABSTRACT

We examine the throughput/delay performance of Random Access Networks, of the fully-connected slotted-ALOHA type, under various temporal jamming configurations. Jamming is probabilistic and independent of the user's state. User protection includes Spread-Spectrum modulation and error-correcting codes. Trade-offs and optimal values of certain parameters for both the communicators (users) and jammer are determined through exact and approximate analysis. The relationship between the user's coding rate r and the jammer's duty-cycle ρ is further exphasized.

****

* T. Ketseoglou and A. Polydoros, "Slotted Spread-Spectrum Random Access Networks with Adaptive Coding Rates and Power," to be presented at *CDC '87*, Los Angeles, CA, December 1987.

* preprint not available

ABSTRACT

The idea of a general coding adaptivity is introduced in SSMA networks. This is achieved by allowing transmissions of signals of different redundancy amount through the MA channel in an adaptive way. We consider both DS/SS and FH/SS systems operating in a slotted random-access mode while, the data transmission is asynchronous. Performance analysis including throughtput/utilization and average delay is presented. It is shown that, this scheme can improve essentially the (link) performance of SSMA networks. In addition, the expressions found in this paper can be used for performance evaluation purposes of any SSMA network if certain assymetries exist. From this perspective, the paper generalizes the existing analysis of SSMA networks by allowing the transmitters to use different coding rates in combination with different spreading ratios (DS/SS) or number of channels (FH/SS). Power level adaptivity is considered, as well.

Ph.D. Thesis

* Elvino S. Sousa, "On Distributed Spread Spectrum Packet Radio Networks", Department of Electrical Engineering, University of Southern California, Los Angeles, CA, November 1985.

* 1 copy 1/86

ABSTRACT

In this thesis we study various aspects of spread spectrum packet radio networks. The second chapter deals with throughput per unit bandwidth bounds for a system with a large number of users simultaneously transmitting. In chapter 3 we propose 2 spreading code protocols and give throughput results for a single-hop system. The spreading code protocols are the terminal's protocols for choice of transmitting code and, when the terminal is idle, the monitoring code. With spread spectrum signaling, since multiple simultaneous successful transmissions are possible, the throughput is not only dependent on the channel but also on the tendency of the terminals to pair-up as transmitter-receiver pairs. For a system of large processing gain we give the limiting throughputs, which correspond to utilizations, of .343 and .398 for unslotted and slotted systems respectively with a large number of users. Finally chapters 4 and 5 deal with multi-hop networks. In chapter 4 we derive the probability density of the interference power at a given point of a large random network and find optimum transmission ranges. The probability laws of the interference power are the stable laws; in particular for a signal which attenuates as an inverse fourth power the probability law is the stable law of exponent 1/2, the density is known as the inverse Gaussian density. The optimum transmission ranges are proportional to a fractional power of the processing gain. In chapter 5 we draw some random networks using a graphics program and observe network connectivities as some of the network parameters are varied.

* **Peter Pawlowski**, "On the Acquisition of Frequency-Hopped Spread Spectrum Signals in Jamming", Ph.D. Dissertatio Department of Electrical Engineering University of Southern California, Los Angeles, CA, May 1986.

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ABSTRACT

Spread Spectral Modulation is a digital data transmission technique whose characteristics Scholtz [35] has defined as follows: "Spread spectrum is a means of transmission in which the signal occupies a bandwidth in excess of the minimum necessary to send the information; the band spread is accomplished by means of a code which is independent of the data, and a synchronized reception with the code at the receiver is used for despreading and subsequent data recovery." The code described in the previous definition is some known, periodic, pseudorandom (or pseudonoise, "PN") symbol sequence which is used to modify the transmitted data sequence. In a Direct Sequence (DS) spread spectrum system, the code generally has a rate much larger than the data symbol rate. The code multiplies the data sequence directly, as shown in Fig. 1.1. By the convolution theorem, bandwidth spreading is accomplished through the convolution of the data sequence spectrum with the PN code sequence spectrum. In a Frequency-Hopped (FH) system, the PN code is used to generate a pseudorandom sequence of carrier frequencies. This sequence is mixed with the data signal which may be either at baseband or some IF frequency, as shown in Fig. 1.2. The bandwidth spreading is accomplished by designing the pseudorandom carrier sequence to agree apriori upon the spreading sequence used. However, direct knowledge of the received code phase is generally not available at the receiver. Therefore, the receiver must perform a synchronization process whereby the phase of the received code sequence is estimated (Acquisition) and this phase synchronization is maintained (Tracking). Acquisition is the process where a local code replica stored within the receiver is brought into coarse alignment with the received PN code, where coarse alignment means within one code symbol or hop duration.

Andreas Polydoros' efforts on behalf on this thesis research, were supported in part by ARO.

* **Soo Kyung Lee**, "On the Performance of Distributed Spread Spectrum Packet Radio Networks With and Without Acknowledgements" Ph.D. dissertation, Department of Electrical Engineering, University of Southern California, Los Angeles, CA, August 1986.

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ABSTRACT

In this thesis, the performance of centralized and distributed spread spectrum packet radio network is analyzed. The first scenario modeled is a centralized network. Capture probabilities and interference effects are computed as a function of traffic allowing comparison between systems with different spreading factors and signal to noise ratios. The next scenario is a distributed network in which a node may communicate with any other node (in a random manner). The significant factors for this case are the traffic patterns (i.e., which nodes are transmitting/receiving or idle). The second part of the thesis considers how acknowledgement traffic should be handled in a distributed network. Several schemes are proposed and a performance comparison is made.

John Silvester's efforts on behalf on this thesis research, were supported in part by ARO.

COMMUNICATION SCIENCES INSTITUTE

ANNUAL REVIEW

Thursday, February 6, 1986

Room 1, Davidson Conference Center
University of Southern California

MORNING SESSION

A G E N D A

8:30 A.M.	**REGISTRATION**
9:00 A.M.	**Leonard M. Silverman**, *Dean of Engineering* - Welcoming Remarks
9:15 A.M.	**Dr. Charles L. Weber** - "Recent Results in: (1) Principles of Wideband Radar (2) A New Class of Algorithms for Soft Decisions of Linear Block Codes"
9:45 A.M.	**Dr. Irving S. Reed** "Adaptive Processing with Application to Optical Detection"
10:15 A.M.	**COFFEE BREAK**
10:45 A.M.	**Dr. Robert A. Scholtz** "Comments on a Variety of Jamming Problems"
11:15 A.M.	**Steve Mecherle** "Coding for the Semiconductor Optical PPM Communication System"
	Dr. Robert M. Gagliardi "Performance of Optical PPM Systems with Power Combining"
11:45 A.M.	**Dr. William C. Lindsey** "Network Synchronization and Applications"
12:15 P.M.	**L U N C H** - Faculty Center, Rooms B & C

AFTERNOON SESSION

A G E N D A

1:45 P.M.	**Dr. Solomon W. Golomb & Dr. Herbert Taylor** "Tuscan Squares - Theory & Applications"
2:15 P.M.	**Dr. Elvino Sousa** "On Distributed Spread Spectrum Packet Radio Networks"
2:45 P.M.	**COFFEE BREAK**
3:15 P.M.	**Dr. Victor Li** "Performance Comparisons of Acknowledgement Protocols for Multihop Spread Spectrum Networks"
3:45 P.M.	**Dr. Andreas Polydoros** "Research Summary of: (1) Code Synchronization (2) Wideband LPI Detection (3) Spread Spectrum Networks"
4:15 P.M.	**CONSULTATIONS**
6:00 P.M.	**COCKTAILS- University Hilton Hotel**
7:00 P.M.	**DINNER - University Hilton Hotel**

ATTENDEES - CSI Review

John Armstrong	GTE
Stephen D. Stearns	GTE
Philip Fire	GTE
Patrick Wong	GTE
Roland Handy	Gould, Inc.
Richard Booton, Jr.	TRW
John Maul	TRW
J. Jay Jones	Ford Aerospace
Frank Chethik	Ford Aerospace
Edwin Key	MITRE Corp.
Ronald D. Haggarty	MITRE Corp.
Dean Carhoun	MITRE Corp.
Jawad Salehi	Bell Communications Research
Alex Netch	General Dynamics
James Spilker Jr.	Stanford Telecommunications, Inc.
William Sander	ARO
John F. Dillon	NSA
Eliza Wotaszik	RAND Corp.
Gilbert Devey	NSF
Barney Reiffen	MIT Lincoln Labs.
Fred Bond	Aerospace Corp.
Edward Bedrosian	RAND Corpn.
Roy Cideciyan	USC, Ph.D. Student

Robert Gagliardi	USC
Solomon Golomb	USC
Lloyd Griffiths	USC
P. Vijay Kumar	USC
Victor Li	USC
William Lindsey	USC
Steve Mecherle	USC Ph.D. Student
Jerry Mendel	Chairman, EE-Systems, USC
Andreas Polydoros	USC
Irving Reed	USC
Robert Scholtz	USC
Leonard Silverman	Dean of Engineering, USC
John Silvester	USC
Elvino Sousa	USC Ph.D. Student
Herbert Taylor	USC
Charles Weber	USC
Lloyd Welch	USC

COMMUNICATION SCIENCES INSTITUTE

ANNUAL REVIEW

Thursday, February 12, 1987

Room 1, Davidson Conference Center

University of Southern California

MORNING SESSION

A G E N D A

8:30 a.m.:	**R E G I S T R A T I O N**
9:00 a.m.:	**Dr. Leonard Silverman**, *Dean of Engineering* - Welcoming Remarks
9:15 a.m.:	**Dr. Robert Scholtz** "Developments at the Communication Sciences Institute"
9:30 a.m.:	**Dr. Irving Reed** "Recent Thoughts on Detection Theory and its Applications"
10:00 a.m.	**Dr. Vijay Kumar** "On the Welch Bound"
10:30 a.m.:	**COFFEE BREAK**
11:00 a.m.:	**Dr. Lloyd Welch** "Automorphism Groups of BCH Codes & Simplified Decoding"
11.30 a.m.:	**Dr. John Silvester** "Recent Results in Packet Radio Networks"
NOON:	**L U N C H - Commons, Room B (upstairs)**
1.30 p.m.:	**Dr. James Yee** "Distributed Routing Algorithms for Communication Networks"
2.00 p.m.:	**Dr. Herbert Taylor** "Compatible Permutation Arrays with Good Correlation"
2.30 p.m.:	**B R E A K**
3.00 p.m.:	**Dr. William Lindsey** "Scintillation Effects on Communications"
3.30 p.m.:	**Dr. Paul Feintuch** "Some Current Sonar Issues"
4.00 p.m.:	**POSTER SESSION On Ph.D. Candidate Research**
6:00 p.m.:	**COCKTAILS - University Hilton, Room 1880**
7:00 p.m.:	**DINNER & ENTERTAINMENT**

POSTER SESSION

Student	Presentation Title
Alexovich, John	The Effect of Wideband High-Resolution Frequency Synthesizers on FSK-FH Communications
Chiou, Shen-Neng	Diversity Routing in a Communication Network with Unreliable Links
Ching, Chuang	On Power Spectral Densities of Modulated and Coded Digital Signals Via Markov Modeling
Chung, Habong	On the One-Dimensional Generalized Bent Function
Franz, Charles	An Analysis of Aperture Distortion Problems in an Airborne Real-Array Imaging Radar
Huey, Henry	Convolutional Codes Defined by Irreducible Polynomials
Kim, Kiseon	Wideband Detection in the Correlation of Correlation Domain
Kinman, Peter	Laser Doppler and Range Measurements with Active Transponders
Lee, Tsern-Hui	Communications with Multiple Data Rates in a Hostile Environment
Liu, Kuo-Hui	Binary Sequences with Very Small Local Partial Period Correlations and Local Orthogonal Sequences
Mayhew, Gregory	Statistical Properties of Modified de Bruijn Sequences
Pronios, Nikos	Slotted Random-Access Single-Hop Networks in Jamming
Rude, Michael	The P-Vector Algorithm: A Linearly Constrained Point of View
No, Jeong-Seon	On GMW Sequences
Tseng, Ching-Yih	VLSI Implementation on Generalized Sidelobe Canceller
Wang, Jonathon	On Some Optimization Problems in Packet Radio Networks
Wicker, Steve	The Geometry of Error Correcting Codes
Yang, Kun-Min	Adaptive Detection Algorithms for Optical Targets in Clutter
Yovanof, Gregory	Searching for Counterexamples to S. Piccard's "Theorem"
Yuan, Chin	Distributed Multiaccess Protocols for Integrated Voice/Data Traffic

CSI REVIEW - ATTENDEES

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TRAVEL

1. John Silvester travelled to Champaign, Illinois to attend the Allerton Conference, October 2-3, 1984, and present a paper.

2. John Silvester travelled to Atlanta, Georgia, to attend GLOBECOM '84, November 26-29, 1984.

3. Elvino Sousa travelled to to Atlanta, Georgia, to attend GLOBECOM '84, November 26-29, 1984, and deliver a presentation.

4. John Silvester travelled to Vancouver, Canada, to attend and participate in the ARO-Sponsored workshop "Research Trends in Spread Spectrum Systems", August 2-7, 1985.

5. John Silvester travelled to Boston, MA, to attend MILCOM '85, and present 2 technical papers at this meeting, October 19-23, 1985.

6. John Silvester travelled to New Orleans, Louisiana, to attend GLOBECOM '85 as a session organizer and to present a technical paper, December 2-5, 1985.

7. John Silvester travelled to Washington, DC, March 23-26, 1985, to attend technical sessions at INFOCOM '85, and the Suran Workshop,and deliver a presentation at the SURAN workshop. (abstract above)

8. John Silvester travelled to Chicago, Illinois, June 23-26, 1985,to attend the International Conference on Communications.

9. John Silvester travelled to Miami, Florida, April 7-10, 1986, to attend and participate in technical sessions at INFOCOM '86.

10. Andreas Polydoros travelled to Miami, Florida, April 7-10, 1986, to attend and participate in technical sessions at INFOCOM '86.

11. Andreas Polydoros travelled to Palm Springs, CA, April 28-30, 1986, to attend and participate in the IEEE Communication Theory Workshop, also as organizer of this meeting.

12. John Silvester travelled to Miami, Florida, April 7-10, 1986, to attend and participate in technical sessions at INFOCOM '86.

13. Andreas Polydoros travelled to Miami, Florida, April 7-10, 1986, to attend and participate in technical sessions at INFOCOM '86.

14. Andreas Polydoros travelled to Palm Springs, CA, April 28-30, 1986, to attend and participate in the IEEE Communication Theory Workshop, also as organizer of this meeting.

15. John Silvester travelled to Warner Springs, CA, September 24-26, 1986, to attend the Ist Annual Computer Communications Workshop, chaired and organized by himself. Partial travel support was received from this ARO contract.

16. John Silvester travelled to Monterey, CA, October 5-6, 1986, to attend and deliver a paper at MILCOM '86.

17. John Silvester travelled to Houston, Texas, December 1-4, 1986, where he attended technical sessions and delivered a presentation. Partial travel support was received from this ARO contract.

18. John Silvester travelled to San Francisco, CA, April 1-2, 1987, to attend and deliver a paper at the 1987 IEEE INFOCOM.

19. Andreas Polydoros travelled to San Francisco, CA, March 28 - April 1, 1987, to attend and participate in the 1987 IEEE INFOCOM.

20. John Silvester travelled to Seattle, Washington, June 6-10, 1987, to attend technical sessions and deliver a presentation at ICC '87.

Personnel

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Char-Dir Chung	Part-time Research Assistant
Jeffrey Dill	Part-time Research Assistant
Thomas Papavassiliou	Part-time Research Assistant
Nikos Pronios	Full-time Research Assistant
Elvino Sousa	Part-time Research Assistant
Jonathan Wang	Part-time Research Assistant
Syu-Je Wang	Full-time Research Assistant
Chin Yuan	Full-time Research Assistant

Faculty

John A. Silvester	Principal Investigator
Andreas Polydoros	Principal Investigator

END
Feb.
1988
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