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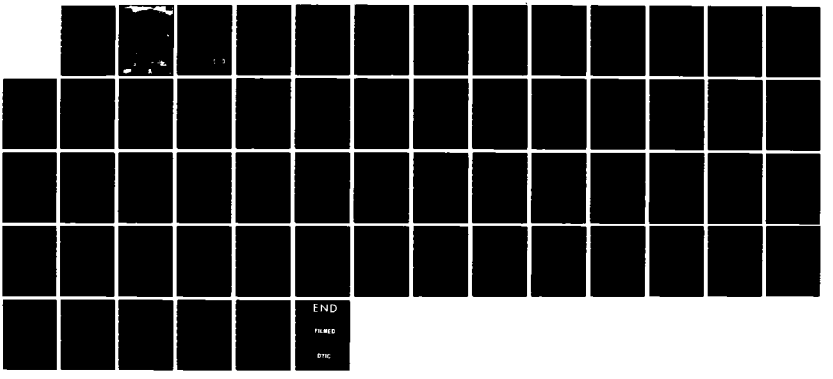

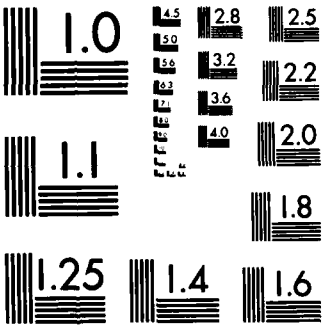

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ELECTRICAL ENGINEERING - SYSTEMS
LOS ANGELES, CALIFORNIA 90089-0272

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ADVANCED DIGITAL COMMUNICATION RESEARCH

FINAL REPORT

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The research proposed for this contract included the following topics: spread-spectrum systems (synch acquisition and performance), the design of pseudorandom sequences, digital signal design, spectral shaping via redundancy, retrodirective array processing, VLSI implementation of number-theoretic transforms, and approximation theory.

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ADVANCED DIGITAL COMMUNICATION RESEARCH

R.A. Scholtz & L.M. Silverman
Principal Investigators

Department of Electrical Engineering
University of Southern California
Los Angeles, CA 90089-0272

A FINAL REPORT ON

CONTRACT NO. DAAG29-82-K-0142

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~~14 March, 1982~~ - 31 May, 1985

JULY 1985

TABLE OF CONTENTS

I. INTRODUCTION

In March of 1979 a group of investigators at the University of Southern California began work in digital communications under a large research contract from the Army Research Office. On September 1, 1982, with minor changes in personnel and new objectives, efforts began on Contract DAAG29-82-K-0142.

The research proposed for this contract includes the following topics: spread-spectrum systems (synch acquisition and performance), the design of pseudorandom sequences, digital signal design, spectral shaping via redundancy, retrodirective array processing, VLSI implementation of number-theoretic transforms, and approximation theory. Progress on all of these fronts, as well as new areas of research, is reflected in the publication abstract lists of Part III of this report. The work on this Contract officially terminated May 31, 1985.

Several events related to the above research effort are worth mentioning here. The first is the formation in the summer of 1982 of the Communication Sciences Institute (CSI) at USC. This certainly was due in part to the success of our first block grant with the Army Research Office and to the realization that there were significant administrative and identification advantages to giving our research group a name.

The second event of interest was the success of CSI in obtaining a DoD University Instrumentation Program Grant to obtain a dedicated computer system for research in communications. This has led, with the aid of additional funds from our ARO Contract, to a CSI research computer facility built around three VAX 750 computers and TEK graphics equipment, with a VT100-type terminal available in every research office. This has dramatically improved our computational capabilities.

On May 4, 1983, with the sponsorship of ARO, CSI sponsored a workshop on "Research Trends in Military Communications." Attended by a highly qualified group of researchers from DoD, industry, and academia, this group tried to sort out areas in which significant research remained to be accomplished within the realm of spread-spectrum communications. The program and attendee list from this workshop are included in Part V of this report.

The Communication Sciences Institute conducted its ARO Research Review on October 25-26, 1984. This attracted considerable interest from local industry, as well as from DoD. A program and list of attendees are included in Part VI of this report.

II. PERSONNEL

Research Assistants

Min-In Chung	Part-time Research Assistant (Graduated August 1983)
Roy D. Cideciyan	Part-time Research Assistant
Nai-Kwan Huang	Full-time Research Assistant (Graduated December 1983)
Yu-Cheun Jou	Part-time Research Assistant
Seong Y. Kang	Full-time Research Assistant (Graduated May 1983)
Kiseon Kim	Full-time Research Assistant
Aysin Kitapci	Full-time Research Assistant (Graduated August 1985)
Tsern-Huei Lee	Full-time Research Assistant
Tze-Hwa Liu	Part-time Research Assistant (Graduated May 1984)
Kuo-Hui Liu	Part-time Research Assistant
Chung-Chin Liu	Part-time Research Assistant
Philippe C. Opdenacker	Part-time Research Assistant (Graduated August 1985)
Wei-Chung Peng	Full-time Research Assistant
Arie Reichman	Full-time Research Assistant (Graduated July 1984)
Jawad A. Salehi	Full-time Research Assistant (Graduated July 1984)
Samir Soliman	Full-time Research Assistant (Graduated August 1983)
Yu-Teh Su	Part-time Research Assistant (Graduated April 1983)

Betty Tang	Full-time Research Assistant during the summer of 1983
Herbert Taylor	Part-time Research Associate
Dale Woods	82-83 school year ARO Fellow
Allan Greatorex	83-84 school year ARO Fellow
John Johl	84-85 school year ARO Fellow

Faculty

S.W. Golomb	Co-Investigator
S.Y. Kung	Co-Investigator
I.S. Reed	Co-Investigator
R.A. Scholtz	Principal Investigator
L.M. Silverman	Principal Investigator
C.L. Weber	Co-Investigator
L.R. Welch	Co-Investigator

III. RESEARCH RESULTS

References appearing here without abstracts are to work which was performed primarily on the previous contract and described in its final report.

A. Sequences, Direct-Sequence and Frequency-Hopping Signal Design

* U. Cheng and S.W. Golomb, "On the Characterization of PN Sequences", IEEE Transactions on Information Theory, vol. IT-29, No. 4, p. 600, 4 July, 1983.

A B S T R A C T

Balanced binary sequences of period 2^n-1 with the run property and the two-level autocorrelation property are not necessarily PN sequences.

****

* Cheng U, and Golomb S.W., "On the Recursion $a_n=a_{n-1}{}_{n-1}$", submitted to Information and Control, presently under additional revision.

A B S T R A C T

Properties of the recursion $a_n=a_{n-a_{n-1}}$ are studied. A Simple algorithm for the construction of its cycles is given. The cycles for which the maximum term is smaller than the period are of special interest. Examples of such cycles are given. In fact, the period May exceed the largest term of the sequence by an arbitrarily large factor.

****

* U. Cheng and S.W. Golomb, "Relations Between Run Distributions and Periodic Auto-Correlations", Submitted to IEEE Trans. on Information Theory.

A B S T R A C T

General relations between run distributions and periodic autocorrelations are developed. Run distributions are described in terms of entities called suites which are subsequences consisting of consecutive runs. For periodic autocorrelations, only the lengths of the suites and the number of runs in them are important. The occurrences of various n-tuples in a given sequence are not mutually independent. In fact, half of them are already enough to determine the others.

****

* R.A. Scholtz, and L.R. Welch, "GMW Sequences," IEEE Transactions on Information Theory, vol. IT-30, no. 3, May 1984, pp. 548-553.

* ---(Abstract only published in Proceedings of the International Symposium on Information Theory, September 1983)

A B S T R A C T

The difference set design of Gordon, Mills, and Welch is adapted for use as a pseudo-random number generator. Statistical properties of the generated binary sequences, including periodic correlation, linear span, and k-tuple statistics, are derived. One mechanization of a GMW sequence generator is suggested. and the number of sequences which can be generated with a fixed number of shift-register stages and ROM size, is evaluated.

****

* Al-Quaddoomi, R.A., Scholtz, R.A., and Welch, L.R., "On the Non-Existence of Two-Dimensional Binary Barker Arrays", accepted for publication at the IT Symposium, September 1983.

A B S T R A C T

Evidence to support the conjecture that W by N Barker arrays (arrays with an out-of-phase doubly-aperiodic autocorrelation of +1, −1, or 0, with elements from the binary sets of{+1,−1} do not exist for $W \geq 2$ and $N > 2$. Hence it is conjectured that $B = \begin{smallmatrix} 1 & 1 \\ 1 & -1 \end{smallmatrix}$ and equivalent 2x2 binary arrays under a set of correlation preserving transformations are "two-dimensional" Barker.

It is proven that W by N arrays, where N is odd prime, are non-Barker for all $W \geq 2$. By exhaustive computer search it is verified that no 2 by N Barker array exists for all $3 \leq N \leq 105$. Furthermore W by N arrays, when W is even and N is odd composite, generated by taking the Kronecker product of the top rows and the Kronecker product of the bottom rows of two smaller arrays which satisfy a "partial" (or "tail") Barker condition, are shown to be non-Barker. Consequently, W+1 by N arrays are also non-Barker. It is conjectured that the above Kronecker product construction method produces all W by N arrays which satisfy the aperiodic Barker tail condition.

****

* Scholtz, R.A., and Kumar, P.V., "Bounds on the Linear Span of Bent Sequences," Proceedings of the International Symposium on Information Theory, September 1983. (abstract only)

A B S T R A C T

Recently, Olsen, Scholtz and Welch presented families of binary sequences called bent-function sequences which can be generated through nonlinear operations on m-sequences. These families of sequences possess asymptotically optimum correlation properties and large equivalent linear span (ELS). In this paper, upper and lower bounds to the ELS of bent-function sequences are derived. The upper bound improves upon Key's upper bound and the lower bound, obtained through construction exceeds $\binom{n/2}{n/4} \cdot 2^{n/4}$ where n is the length of the shift register generating the m-sequence. An interesting general result contained in the derivation is the exhibition of a class of nonlinear sequences whose ELS is guaranteed to be large.

****

* Scholtz, R.A., "Pseudonoise Generator Designs", Proceedings of the National Radio Science Meeting, Boulder, Colorado, January 11-13, 1984. (Abstract only.)

A B S T R A C T

Spread spectrum systems use pseudonoise generators for a number of different purposes. Each of these objectives suggests certain nice properties which the PN generator's output sequence should possess. This paper reviews these properties and indicates the extent to which several well-known PN generator designs achieve these goals. Two new families of PN generators employing nonlinear feedforward logic will be described and comparisons made. Unsolved problems in PN sequence design will be posed.

****

* P.V. Kumar, R.A. Scholtz, and L.R. Welch, "Generalized Bent Functions and their Properties," to appear in the Journal on Combinatorial Theory.

A B S T R A C T

Let J denote the set of m-tuples over the integers modulo q and set $i = \sqrt{-1}$, $w = e^{i(2\pi/q)}$. As an extension of Rothaus' notion of a bent function, a function f, f: $j_q^m \rightarrow J_q^1$ is called bent fi all the Fourier coefficients of w have unit magnitude. An interesting result shows that it is immaterial as to which particular complex, primitive, q^{th} root w, of unity is used in defining a bent function. The nature of the Fourier coefficients of a bent function is examined as a proof for the non-existence of bent functions over J_q^m, m odd, q=2(mod 4), given. For every other possible value of q and m, constructions of bent functions are provided.

****

* C.L. Weber and U. Cheng, "Address Sequences for Frequency Hopping Multiple Access," Proceedings of the National Radio Science Meeting, Boulder, Colorado, January 11-13, 1984. (Abstract only)

A B S T R A C T

The criteria for developing good sets of Address Sequences for Frequency Hopping Multiple Access (FHMA) depend upon the signal format. Nonoverlapping, Partial Overlapping and Multi-level MFSK signal formats are considered. Lower bounds on the maximum number of hits are developed in all of the above cases in a non-synchronized environment; they are dependent on the number of address sequences in the set, the period of the sequences, and the alphabet size, i.e., the number of candidate carrier frequencies.

The utility of Reed-Solomon (RS) codes in the nonsynchronized frequency hopping multiple access environment is discussed, in particular RS codes can be partitioned so that excellent sets of FHMA address sequences result.

****

We present new high-resolution methods for the problem of retrieving sinusoidal processes from noisy measurements. The approach taken is by use of the so-called principal-components method, which is a singular-value-decomposition-based approximate modeling method. The low-rank property and the algebraic structure of both the data matrix and the covariance matrix (under noise-free conditions) form the basis of exact modeling methods. In a noisy environment, however, the rank property is often perturbed, and singular-value decomposition is used to obtain a low-rank approximant in factored form. The underlying algebraic structure of these factors leads naturally to least-squares estimates of the state-space parameters of the sinusoidal process. This forms the basis of the Toeplitz approximation method, which offers a robust Pisarenko-like spectral estimate from the covariance sequence. Furthermore, the principle of Pisarenko's method is extended to harmonic retrieval directly from time-series data, which leads to a direct-data approximation method. Our simulation results indicate that favorable resolution capability (compared with existing methods) can be achieved by the above methods. The application of these principles of two-dimensional signals is also discussed.

****

* S.Y. Kung, D.V. Bhaskar Rao and K.S. Arun, "Spectral Estimation: From Conventional Methods to High Resolution: From Conventional Methods to High Resolution Modeling Methods." To appear in VLSI and Modern Signal Processing, S.Y. Kung, H.J. Whitehouse and T. Kailath, eds., Prentice-Hall, Inc. 1985.

****

F. Decoding of Convolutional Codes

* I.S. Reed and T.K. Truong, "Simplified Syndrome Decoding of (n,1) Convolutional Codes," submitted to IEEE Transactions on Communications.

A B S T R A C T

This paper presents a new syndrome decoding algorithm for the (n,1) convolutional codes (CC) that is simpler than the previous syndrome decoding algorithm of Schalkwijk and Vinck [1]. The new algorithm uses the general solution of the polynomial linear Diophantine solutions is a coset of the CC weight error vector E(D) in this error coset. An example, illustrating the new decoding algorithm is given for the binary nonsymmetric (2,1) CC.

****

* I.S. Reed and T.K. Truong, "New Syndrome Decoding Techniques for Convolutional Codes Over GF(q)", submitted to the IEEE Transactions on Information Theory.

A B S T R A C T

the model to an initial state, and to use an existing deterministic realization algorithm for the model parameter estimation. The power of state space parameterization and the numerical properties of the Singular Value Decomposition (SVD) based realization algorithms together make the new method (the Direct Data Approximation (DDA) method) very appealing. Simulations performed on the DDA demonstrate its numerical robustness compared to existing methods and the high performance achievable.

****

* Kung, S.Y., and Arun, K.S., "State Space Modeling and Approximate Realization Methods for ARMA Spectral Estimation", Proc. of the IEEE International Conf. on Cybernetics and Society, India, January 1984.

A B S T R A C T

The problem addressed in this paper is that of obtaining an ARMA spectral estimate for a stochastic process, from noisy measurements or estimates of its covariance lags. A state space and SVD based approach is adopted to derive a new algorithm for robust ARMA identification from the perturbed covariance. In contrast to existing methods that use canonical correlation analysis to approximate the information interface between the past and the future of the time series, the new algorithm optimizes the approximation of this interface in terms of the predictive efficiency of the past for the future. This is equivalent to a principal component approximation of the predictor subspace via a Karhuen Loeve expansion. Reasons for preferring the new approximation criterion to canonical correlation coefficients, are presented with supporting simulations.

****

* Kung, S.Y., and Arun, K.S., "A New SVD Based Algorithm for ARMA Spectral Estimation",Proceedings of the IEEE ASSP Workshop on Spectral Estimation II, Tampa, Fla., November 1983

A B S T R A C T

The problem addressed in this paper is that of obtaining an ARMA spectral estimate for a stochastic process, from noisy measurements or estimates of its covariance lags. A state space and SVD based approach is adopted to derive a new algorithm for robust ARMA identification from the perturbed covariance. The new algorithm optimizes the covariance approximation in terms of the predictive efficiency of the current state vector for the future of the time series. Reasons for preferring the new approximation criterion to canonical correlation analysis and the so called overdetermined higher order Yule-Walker equations approach, are presented. Simulations indicate that the method is capable of very high resolution compared with these existing methods.

****

* S.Y. Kung, K.S. Arun, and D.V. Bhaskar Rao, "State Space and Singular Value Decomposition Based Approximation Methods for the Harmonic Retrieval Problem," J.O.S.A., Vol. 73, No. 12, December 1983, pp. 1799-1811.

A B S T R A C T

estimate has to be based on short data records (in radar, for example, only a few data samples are available in each radar pulse), and yet, low bias, low variance, high resolution estimates are desired. The frequency resolution in conventional Fourier transform methods, is roughly equal to the reciprocal of the data record length. So some additional constraints (or prior information) have to be imposed to improve the resolution capability. To this end, in modern methods the data is modeled (or assumed) as the output of a linear system driven by white noise. Popular models used are moving average (MA), autoregressive (AR), autoregressive moving average (ARMA), and sinusoids plus noise (S+N), etc. When The model is appropriate, these methods will lead to enhanced performance. The price paid for this improvement is usually in the form of increased computational complexity as compared to conventional methods that utilize FFT. The advent of VLSI, however, has reduced the cost of computation hardware, providing a major impetus towards the utilization and development of computationally more sophisticated spectral estimation methods for improved performance.

In this paper, we first discuss the conventional methods for power spectrum estimation. Then in the latter sections we shall focus our attention on the modern methods with special emphasis on those modelling methods that are suited for resolving narrow band signals.

****

* Kung, S.Y., and Arun, K.S., "A New Algorithm for Approximate Stochastic Realization", submitted to the IEEE Trans. on Auto. Control.

A B S T R A C T

The problem addressed in this paper is that of obtaining a Markovian representation of a stochastic process, from noisy measurements of its covariance lags. A new algorithm for the approximate realization of a state space model from perturbed covariance information is proposed. In contrast to existing methods that use canonical correlation analysis to approximate the information interface between the past and the future of the time series, the new algorithm optimizes the approximation of this interface in terms of the predictive efficiency of the past for the future. This is equivalent to a principal components extraction of the predictor subspace via a Karhuen-Loeve expansion. Reasons for preferring the new approximation criterion to canonical correlation coefficients, are presented. Finally, it is shown that the new algorithm is a stochastic generation of an existing deterministic realization algorithm.

****

* Kung, S.Y., Arun, K.S., and Bhaskar Rao, D.V., "A Realization Approach to Spectral Line Estimation," Proceedings IEEE International Conf. on Cybernetics and Society, India, January 1984.

A B S T R A C T

In this paper we present a new high resolution method for the important problem of retrieving sinusoidal processes from noisy measurements. We present a special state space model for representing sinusoidal signals and display the algebraic structure present in the problem. This allows us to treat the time series as the noisy response of

* S.Y. Kung, K.S. Arun, and D.V. Bhaskar Rao, "State Space and Singular Value Decomposition Based Approximation Methods for the Harmonic Retrieval Problem", JOSA, 1983.[2]

A B S T R A C T

In this paper we present new high-resolution methods for the problem of retrieving sinusoidal processes from noisy measurements. The approach taken is via the so-called principal components method, which is a singular value decomposition (SVD) based approximate modeling method. The low rank property and algebraic structure of both the data matrix and the covariance matrix (under noise free conditions) forms the basis of exact modeling methods. In a noisy environment, however, the rank property is often perturbed, and singular value decomposition is used to obtain a low rank approximant in factored form. The underlying algebraic structure of these factors, naturally leads to least-squares estimates of the state space parameters of the sinusoidal process. This forms the basis of the Toeplitz Approximation Method (TAM), which offers a robust Pisarenko-like spectral estimate from the covariance sequence. Furthermore, the principle of Pisarenko's method is extended to harmonic retrieval directly from time-series data, which leads to a Direct Data Approximation (DDA) method. Our simulation results indicate that very favorable resolution capability (compared to existing methods) can be achieved by the above methods. The application of these principles to two dimensional signals is also discussed.

****

* S.Y. Kung, D.V. Bhaskar Rao and K.S. Arun, "Spectral Estimation: From Conventional Methods to High Resolution Modeling Methods", in VLSI and Modern Signal Processing, S.Y. Kung, eds., Prentice-Hall, Inc., January 1984.[3]

A B S T R A C T

Spectral Analysis often forms the basis of a major part of signal processing, typically for distinguishing and tracking signals of interest, and for extracting information from the relevant data. Given a finite number of noisy measurements of a discrete-time stochastic process, or its first few covariance lags, the classical spectral estimation problem was that of estimating the shape of its continuous power spectrum. For a majority of modern applications of signal processing, such as radar, sonar and phased arrays, the spectrum of interest is a line spectrum, and the spectral estimation problem is that of estimating the locations of these spectral lines. As a result, the notions of bias and variance that once referred to estimates of spectral shape, now refer to estimates of frequency. Another measure of performance is frequency resolution. In the classical spectrum estimation problem, resolution defines how finely a spectrum can be examined. In the modern context, resolution is the ability to distinguish and identify spectral lines that are closely spaced in frequency. In many modern signal processing applications, the

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[2] See footnote 1.

[3] See footnote 1.

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D. Low Probability of Intercept

* A.Polydoros and C.L. Weber, "Optimal Detection Considerations for Low Probability of Intercept," Proceedings of MILCOM 82 Boston, Mass., October 1982.

A B S T R A C T

Variety of receivers which can be used to detect the presence of a wideband (spread) signal in additive white Gaussian noise (AWGN) is explored. The optimality of these receivers is founded upon the knowledge (or lack thereof certain key signal parameters. Suboptimal receivers are used based upon the removal of knowledge of some of these parameters.

****

E. Approximation Theory and Spectral Estimation

* S.Y. Kung and K.S. Arun, "Approximate Realization Methods for ARMA Spectral Estimation", 1983 International Conference on Circuits and Systems, Newport Beach, CA, May 1983.[1]

A B S T R A C T

The problem addressed in this paper is that of estimating the power spectrum of a discrete-time stochastic process, given noisy measurements of its covariance sequence over a finite segment. For achieving high resolution in frequency, in the power spectrum estimate, the modern approach is to model the process as the output of a linear rational system driven by white noise. This reduces the spectral estimation problem to a problem of covariance realization. While today's popular methods use transfer function models, in this paper we advocate the use of state space models. New approximate covariance realization methods based on state space models, are proposed for high resolution spectral estimation. Approximation is the key to high resolution, as the given covariances are usually perturbed, and approximate realizations are expected to be insensitive to perturbations.

****

[1]Due to an oversight, this research acknowledged support under Contract DAAG29-79-C-0054, rather than the current contract DAAG29-82-K-0142.

October 1984.

A B S T R A C T

The variable dwell time (VDT) PN acquisition algorithm has been proposed to reduce the mean PN acquisition time. Previous analyses pertaining to VDT systems have used either approximation method or simulation to evaluate related system performance parameters, namely P_D, P_{FA} and $\bar{n}$, mean dwell time per cell. This paper reports two related algorithms to compute these parameters. Exact results, instead of approximations, are obtained by these algorithms. Furthermore, two performance parameters: P_{FA} and $\bar{n}$ can be evaluated more efficiently.

****

* C.L. Weber and E. Siess, "Acquisition of Direct Sequence Spread Spectrum Signals with Modulation and/or Tone Jamming," submitted for publication in the IEEE Transactions, Special Issue on Military Communications.

A B S T R A C T

The analyses of narrowband interference in direct sequence (DS) spread spectrum systems in the open literature have either determined the effect of interference on performance after synchronization or have presented approaches of combating the interference. Acquisition of DS systems when under the influence of narrowband interference has heretofore not been considered.

Acquisition performance has been documented when the carrier is modulated by data and the spreading code for a correlator/square-law acquisition receiver. The recently presented noncoherent I-Q detector has been shown to surpass the correlator/square-law detector in performance, but the effect of data on performance has only been qualitatively addressed.

For most of the spreading codes of interest, the variable to be detected in the I-Q receiver is Gaussian with known statistics. Data modulation decreases the mean and tone jamming increases the variance of the detection variable. The statistics of the decision variable with the data and/or jamming significantly influence the probabilities of detection and false alarm of the receiver. The effects of data and/or jamming on acquisition time are assessed when particular acquisition schemes are selected. Finally, the results of these analyses are used to propose receivers which mitigate the deleterious effects of the data or jamming.

The result of the analyses demonstrate that the I-Q detector, modified for a data modulated carrier, is superior to the correlator/square-law detector despite the latter's robustness to data. When the average pulsed jammer power is constrained, the analyses illustrate that the jammer's duty factor does not impact acquisition time when the pulse repetition frequency (PRF) is high and that a duty factor of unity maximally degrades acquisition performance when the PRF is low. The most important result of the analyses is the need for the acquisition receiver to sense and adapt to jamming. A proposed adaptive receiver provides considerable jamming protection and the acquisition performance obtained with such a receiver bounds the performance of all adaptive acquisition receivers.

Additional but nominal improvement is gained when more than two dwells are employed.

****

* A. Polydoros and C.L. Weber, "Analysis and Optimization of Correlative Code Tracking Loops in Spread Spectrum Systems," to appear in the IEEE Transactions on Communications.

* -- Also Proceedings of MILCOM '82, Boston, Ma.

A B S T R A C T

The purpose of this paper is to apply the renewal theory approach for analyzing aperiodic finite *S*-curve code-tracking loops developed by Meyr to the case of a noncoherent, arbitrary offset, early-late, delay-locked loop ("noncoherent δ-DLL"). The exact (renewal) approach of using the periodic *S*-curve or phase-locked loop theory, as well as to the linear theory developed herein for the aforementioned code-tracking loop. Finally, loop optimization with respect to the offset δ is carried out according to certain performance criteria. The results indicate that, for low SNR, the exact and approximate theories could deviate significantly while, for high SNR, all three theories yield identical performance, as expected. Furthermore, it is shown that the optimal δ for both low and high SNR could differ from the commonly accepted choice δ=1/2.

****

* C.L. Weber and E. Siess, "Spread Spectrum Acquisition with Data Modulation", Proceedings MILCOM '84, Los Angeles, CA, October 1984.?

A B S T R A C T

Direct sequence spread spectrum acquisition performance has been documented when the carrier is modulated by data and the spreading code for the correlator/square-law acquisition receiver. The recently presented noncoherent I-Q detector has been shown to surpass the correlator/square-law detector in performance, but the effect of data on performance has only been qualitatively addressed.

For most of the spreading codes of interest, the variable to be detected in the I-Q receiver is Gaussian with known statistics. Data modulation decreases the mean of the detection variable. The statistics of the decision variable with the data significantly influences the probabilities of detection and false alarm of the receiver. The effects of data on acquisition time are assessed when particular acquisition schemes are selected. Finally, the results of these analyses are used to propose receivers which mitigate the deleterious effects of the data.

The result of the analyses demonstrate that the I-Q detector, modified for a data modulated carrier, is superior to the correlator/square-law detector despite the latter's robustness to data.

****

* C.L. Weber, and Y.T. Su, "On the Performance Evaluation of the Variable Dwell Time PN Acquisition System," Proceedings of MILCOM '84, Los Angeles, CA,

A B S T R A C T

The purpose of this two-part paper is threefold: (1) Part I discusses the code-acquisition problem in some depth and (2) also provides a general extension to the approach of analyzing serial-search acquisition techniques via transform-domain flow graphs; (3) Part II illustrates the applicability of the proposed theoretical framework by evaluating a matched-filter (fast-decision rate) noncoherent acquisition receiver as an example.

The theory is formulated in a general manner which allows for significant freedom in the receiver modeling. The statistics of the acquisition time for the single-dwell and N-dwell systems are shown to be special cases of this unified approach.

****

* A. Polydoros and C.L. Weber, "A Unified Approach to Serial Search Spread-Spectrum Code Acquisition - Part II: A Matched-Filter Receiver," IEEE Trans. on Communications, Vol. COM-32, No. 5, May 1984, pp. 550-560.

A B S T R A C T

The unified theory developed in Part I is employed here in the analysis of a noncoherent, matched-filter (fast-decision-rate) code acquisition receiver in a direct-sequence spread-spectrum system. The results illustrate the dynamic dependence of the *mean* acquisition time on system parameters, such as the predetection signal-to-noise ratio, the decision threshold settings and the ratio of the decision rate to the code rate.

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* DiCarlo, D.M., and Weber, C.L., "Multiple Dwell Serial Acquisition of Direct Sequence Code Signals", IEEE Trans. on Comm., Vol. COM-31, No. 5, May 1983, pp. 650-659.

A B S T R A C T

The technique of multiple dwell serial search is described and analyzed. The advantage of the multiple dwell procedure is that the examination interval need not be fixed, allowing incorrect cells to be quickly discarded, which in turn results in a shorter search time than is possible with a fixed dwell time procedure. This type of search scheme is particularly useful for direct sequence code acquisition in a spread-spectrum communication system.

An expression for the generating function is obtained from a flow graph representation of the multiple dwell technique. The generating function is used to develop expressions for the mean and variance of the search time in terms of the following parameters: the dwell times, the detection probability, the false alarm probability, and the false alarm penalty time. Coherent detector characteristics are then used to investigate the performance of the multiple dwell technique for direct sequence code acquisition. It is shown that the multiple dwell procedure can significantly reduce the expected acquisition time from that obtained with a single dwell system.

The most significant improvement is obtained by using a two-dwell system.

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* A Reichman and R.A. Scholtz, "Adaptive Spread Spectrum Systems Using Least-Squares Lattice Algorithms", submitted to the IEEE Transactions, Special Issue on Military Communications.

A B S T R A C T

Practical communication systems must cope with many uncertainties in addition to determining the transmitted data; e.g., the direction, timing, and distortion of the desired signal, and the spectral and spatial distribution of the interference, all of which may change with time. In this paper we will apply the exact least-squares (L.S.) recursive lattice algorithm to resolve these uncertainties in a direct-sequence spread-spectrum digital communication system. The L.S. algorithm is recursive both in order and time, the fast converging adaptively to the uncertain parameters. This time-discrete algorithm may be mechanized by a receiver containing integrate-and-dump circuits operating at the chip rate of the PN sequence, one in each in-phase and each quadrature channel of each sensor array element's output. The resultant signal to be processed by the LS algorithm, is regarded as a sequence of complex vectors representing the modulation received by an array of antennas.

Different configurations of an optimal time-discrete receiver are presented and transformed into adaptive receivers using the spectral properties of the different kinds of LS filters. Simulation results are presented and some guide lines are given for the architecture of a direct-sequence spread-spectrum system.

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* G.K. Huth and C.L. Weber, "The Performance of Direct Sequence Systems in the Presence of Jammers," Proceedings of MILCOM 82, Boston, Mass., October 1982.

A B S T R A C T

An enumeration of the types of interference pertinent to direct-sequence systems is given. The candidates are categorized as narrowband or wideband. The performance of direct-sequence 9DS) systems in the presence of a variety of types of interference is also presented. When the jammer has a choice of parameters, the optimal value is then determined.

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C. Spread-Spectrum Signal Acquisition

* A. Polydoros and C.L. Weber, "A Unified Approach to Serial Search Spread-Spectrum Code Acquisition Part I: General Theory," IEEE Trans. on Communications, Vol. COM-32, No. 5, May 1984, pp. 542-549.

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B. Interference Rejection in Spread Spectrum Systems

* Scholtz, R.A., "Notes on Spread Spectrum History", IEEE Trans. on Comm., COM-31, No. 1, January 1983, pp. 82-84.

A B S T R A C T

This paper presents additional historical information relating to the spread-spectrum history described in [1]. Included here are ties with speech scrambling technology, wide-band matched filter design, stimulus of the WHYN system design by British research, ITT's efforts to protect vital information during World War II, and other miscellaneous notes and references.

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* Sampaio Neto, Raimundo and Scholtz, R.A., "Pseudonoise Tracking in the Presence of Spectrally-known Interference", Proceedings MILCOM '83, Washington, DC, October 1983

A B S T R A C T

This paper describes the design of a direct-sequence code tracking loop employing generalized correlators for tracking-error estimation. The signal to be tracked is assumed to be PSK modulated by data, and carrier-phase incoherent. The correlators consist of the usual correlator circuit with realizable filters inserted in each input arm. In the proposed design technique, the tracking loop's effective signal-to-noise ratio is optimized by filter design for operation in the presence of strong colored interference of known spectral content. Performance results are given.

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* A. Reichman and R.A. Scholtz, "Equalization in a Direct Sequence Spread Spectrum System Using a Least Squares Lattice Filter," Proceedings of MILCOM '84, Los Angeles, October 84.

A B S T R A C T

A direct sequence spread-spectrum system, employing a least-squares equalizer is shown to perform nearly as well as the optimal receiver under certain conditions. The system presented here requires neither the knowledge of the noise statistics and of the impulse response of the channel, nor a training sequence of known data bits. The reference for the equalizer is provided by the decoding circuit with negligible delay.

Simulation results for the probability of error are close to the theoretical results of an optimal receiver. To adapt to changes in noise statistics and channel, a restriction on the memory of the equalizer is required, which causes some degradation in performance.

An exhaustive list of binary sequences with non-positive out-of-phase autocorrelation for lengths 4,8,12,16,20,24,28,32,36,40 was obtained by computer search and presented at the end of this paper.

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* L.R. Welch, "Useful Criteria for Frequency Hopping Sequences", (*This work has not been published, but a talk on it was given at the 1984 Communication Theory Workshop, Taos, New Mexico, June 10-13, 1984.*)

A B S T R A C T

For sequences used in spread spectrum systems, whether binary sequences used in the direct sequence mode or q-ary sequences used in phase or frequency hopping, the ideal sequences are those for which the conditional distribution of X(t) given {X(t-1), X(t-2),...} is uniform over the q symbols. Such sequences are impossible to generate at both transmitter and receiver. What is needed is a criterion which can be met in practice and which provides sequences which are useful in spread spectrum systems.

In this reporting period, such a criterion was developed when the sequence is generated by a finite state machine and the 'alphabet' is a finite field of characteristic 2.

Define the function $N(a,b,\tau)$ to be the number of solutions to the equation $a = X(t)$, $b = X(t+\tau)$ when 't' ranges over one period of the sequence. Clearly, for ideal sequences, the values of this function should be exactly

$$N(a, b, \tau) = p/(q*q)$$

when τ is not a multiple of the period. We propose, as the measure of how well a sequence comes to being ideal, the quantity

$$\max_{\tau \neq 0} \{ \sum_{a,b \text{ in } GF(q)} [n(a,b,\tau) - p/(q*q)] \}$$

Given this measure, the criterion is just that for a sequence to be 'good' this quantity should be small. In the binary case, this reduces to the usual maximum cross-correlation measure.

Another criterion, applicable to the characteristic 2 case, is as follows: The trace function maps GF(q) into GF(2). In addition, multiplication by a non-zero element in GF(q) followed by the trace function also maps GF(q) into GF(2). In the case of an ideal sequence, this produces a family of binary sequences which could be used in direct sequence, spread spectrum, CDMA systems.

We have developed a theorem which states that if a sequence over GF(q) meets the above goodness criterion then the resulting family of binary sequences meet the usual 'goodness' criterion for direct sequence, CDMA applications.

This result, together with the known properties of the GOLD codes was then used to generalize the GOLD codes to a class of frequency hopping sequences.

A. For the totally synchronized case, Level B, the bounds all increase by a factor of L with respect to Levels A and C.

2. The Hamming, Plotkin, and Elias bounds can also be extended to sets of sequences employing the maximum partial overlap signal format. These bounds apply for all values of M, including multi-level MFSK, where M=Q.

3. A prime candidate for construction of excellent sets of FHMA sequences is to begin with the Reed Solomon (RS) code. A construction process is described, which applies to both the maximum partial overlap and multi-level MFSK signal formats, as well as all synchronization levels. The process partitions the row vectors of the generator matrix for the RS code into two sets; one is used for representation of the data, and the other for representation of the address sequence of the user. It can be tailored to account for different levels of acquisition uncertainty, both in time and frequency. As a result, these FHMA sequences can be used without an acquisition preamble (i.e., no synchronization overhead). That is, these sequences can be employed for acquisition when there exists an uncertainty in both time and frequency even in the presence of data. The number of sequences generated meets the Plotkin bound for the maximum partial overlap signal formats, including the special case of multi-level MFSK; in that sense the resulting sets of FHMA sequences are optimum.

4. This construction technique without modification can also be used with BCH codes to obtain longer sequences, although the resulting sets of sequences may not be optimum.

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* Wang Ke and L.R. Welch, "Binary Sequences with Non-Positive Autocorrelation Values," Acta Electronics Sinica, No. 10, October 1982, People's Republic of China.

ABSTRACT

Baumert developed the theory of binary sequences with the property of transorthogonality and orthogonality for cyclic shifts. Turyn investigated the existence of binary sequences with small autocorrelation values in terms of min max $|a_j|$ where a_j is the periodic correlation and minimization is over binary sequences of fixed length. In this paper we restrict the investigation to cyclic correlation and drop the absolute value sign in the minmax expression. There are a number of channels in which large magnitude negative correlations are not objectionable. (Signal design for a laser channel where the initial detector is an energy pulse detector can be formulated into the present context.)

In this study many binary sequences were found with autocorrelation properties in between transorthogonality and orthogonality. The most interesting sequences were those we named Yin-Yang sequences whose out of phase correlations are zero except for T equals to one half the period when the value is negative. Within this class, an infinite family is constructed.

hypothetical decisions must first be made, each of which effects the approach that is taken in the construction process, as well as the measure of performance, namely a correlation bound.

First is the choice of frequency hopping signal format. The choices are: (i) MFSK or (DPSK) without overlap, wherein each candidate carrier frequency and associated set of M frequency slots for the MFSK modulation does not overlap the set of M slots for any other candidate carrier frequency. These sets need not be contiguous. (ii) MFSK with partial overlap, which is different from the nonoverlap case in that candidate RF's can be more dense than one every M slots. (iii) MFSK with maximum partial overlap. This is the limiting case of (ii) in which every frequency slot is a candidate RF. (iv) Multi-Level MFSK. This is a limiting case of (iii) to the extent that the number of MFSK tones is increased to be equal to the alphabet size, Q, of the candidate RF's.

Second is the choice of long sequences versus short sequences. By a short sequence, we mean that one period of the sequence occurs during each information symbol. For a long sequence, we assume a very large number of information symbols occur during each period. Here, we emphasize only short codes with the above signal formats, noting that an attractive sequence design for a very long sequence is a random sequence.

Third is the level of available a priori synchronization. We distinguish between three situations. (i) Synchronization Level A represents the broadcast channel, wherein there are N receivers which operate in a receive only mode, and one transmitter which transmits N different FH signals; these signals are initially synchronized at the transmitter. (ii) Synchronization Level B assumes there are N transmitters and N receivers all of which are a priori totally synchronized. This is typically an unrealistic situation, but serves as a basis for designing sequences for the other levels of synchronization (iii) Synchronization Level C also has N transmitters and N receivers, but exhibits no a priori synchronization at all which is the more realistic scenario.

The design criteria is to minimize the number of hits between any pair of FHMA sequences under any relative time shift that may be encountered. If a linear cyclic block code is used as a basis for designing sets of FHMA sequences, then, under Synchronization Level B, periodic extensions of all codewords can be used in the design. Under Levels A and C, however, only one codeword from each cyclic equivalence class can be used, and still preserve the distance properties of the code - or equivalently, the maximum number of hits/period.

Given a scenario via the above hypothetical decisions, we have the following bounds and algorithms:

1. For the nonsynchronized (Level C) environment, the Hamming, Plotkin, and Elias block code bounds are extended so that they provide an upper bound on the number, N, of sequences of period L over an alphabet of size Q without overlap, and maximum number of hits, H, over all out-of-phase autocorrelation values and all cross-correlation values. For all three bounds, when three of four parameters are specified, a bound is provided for the remaining parameter. Usually the Plotkin bound is tighter than the Elias and the Hamming bounds for finite parameters. These bounds also apply to Level

* U. Cheng, C.L. Weber and C.K. Huth, "On the Design of Efficient FDMA Sequences", presented at URSI in Canada. (Abstract only)

A B S T R A C T

The design of a set of frequency hopping multiple access (FHMA) sequences depends upon the choice of frequency hopping signal format, the choice of long sequences versus short sequences, and on the available a priori synchronization. Each of these alters the construction process as well as the measure of performance, namely a correlation bound.

First is the choice of frequency hopping signal format. The choices herein considered are: (i) MFSK (or DPSK) without overlap, (ii) MFSK with partial overlap, (iii) MFSK with maximal partial overlap, (iv) Multi-Level MFSK.

Second is the choice of long sequences versus short sequences. By a short sequence, we mean that one period of the sequence occurs during each information symbol.

Third is the level of available a priori synchronization. We distinguish between three situations. (i) Synchronization Level A represents the broadcast channel, wherein there are N receivers which operate in a receive only mode, and one transmitter which transmits N different FH signals; (ii) Synchronization Level B assumes there are N transmitters and N receivers all of which are a priori totally synchronized; (iii) Synchronization Level C also has N transmitters and N receivers, but exhibits no a priori synchronization at all.

The performance measure is to minimize the number of hits between any pair of FHMA sequences under any relative time shift that may be encountered.

A given operational environment will specify the above hypothetical decisions, for which we have the following bounds and algorithms: (1) For the nonsynchronized (Level C) environment, the Hamming, Plotkin, and Elias block code bounds are extended so that they provide an upper bound on the number, N, of sequences of period L over an alphabet of size Q without overlap, and maximum number of hits, H, over all out-of-phase autocorrelation values and all cross-correlation values. (2) The Hamming, Plotkin, and Elias bounds can also be extended to sets of sequences employing the maximum partial overlap signal format. These bounds apply for all values of M, including multi-level MFSK, where M=Q. (3) A prime candidate for construction of excellent sets of FHMA sequences is to begin with the Reed-Solomon (RS) code. A construction process is described, which applies to both the maximum partial overlap and multi-level MFSK signal formats, as well as all synchronization levels. The number of sequences generated meets the Plotkin bound for the maximum overlap signal format, including the special case of multi-level MFSK; in that sense the resulting sets of FHMA sequences are optimum.

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* U. Cheng, C.L. Weber, and G.K. Huth, "Design Considerations for FHMA Sequences", International Information Theory Symposium, Brighton, England, June, 1985. (Abstract only.)

A B S T R A C T

In order to design a set of frequency hopping multiple access sequences, several

This paper presents a new syndrome decoding algorithm for the (n,k) convolutional codes which differs completely from an earlier syndrome decoding algorithm of Schalkwijk and Vinck. The new algorithm is based on the general solution of the syndrome equation, a linear Diophantine equation for the error polynomial vector E(D). The set of Diophantine solutions is a coset of the CC. In this error coset a recursive, Viterbi-like, algorithm is developed to find the minimum weight error vector $\hat{E}(D)$. An example, illustrating the new decoding algorithm is given for the binary nonsystematic (3,1) CC.

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* Reed, I.S., and Truong, T.K., "New Syndrome Decoding Techniques for the (N,k) Convolutional Codes", accepted for publication in the IEE Proceedings - F Communications, Radar, and Signal Processing, England.

A B S T R A C T

This paper presents a new syndrome decoding algorithm for the (n,k) convolutional codes (CC). The construction of Trellis diagram of this algorithm is simpler than a syndrome decoding algorithm of Schalkwijk, Vinck and Di Paepa. The new algorithm is based on the general solution of the syndrome equation, a linear Diophantine equation for the error polynomial vector E(D). The set of Diophantine solutions is a coset of the CC. In this error coset a recursive, Viterbi-like algorithm is developed to find the minimum weight error vector E(D). An example, illustrating the new decoding algorithm is given for the binary nonsystematic (3,1) CC.

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G. Edge Detectors for Image Processing

* N.K. Huang, L.R. Welch and R.A. Scholtz, "Markov Texture Model for Automatic Segmentation", submitted to the IEEE Transactions on Pattern Analysis and Machine Intelligence.

A B S T R A C T

An estimation-theoretic method is developed to locate textural boundary. Textures are modeled as finite state Markov chains, where the number of states is the number of gray levels of the quantized digital image. Textural regions in the image are separately equalized before the experiment so that their difference is not detectable from the first order statistics. An algorithm is introduced to compute the state distribution at each pixel. An edge between textures is detected when there is a drastic change in these probabilities. Experiments are performed with both natural and artificial textures. Boundary between random microtextures is easily recognizable from the detected edges.

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* Huang, N.K., Welch, L.R., and Scholtz, R.A., "An Image Segmentation Algorithm

with Learning Ability", Information Theory Symposium, Ste. Jovite, Quebec, Canada, September 1983.

A B S T R A C T

This research develops a way to segment images, using textural information, without prior texture descriptions. A built-in learning capability, which helps a computer to train itself on the job and improve its efficiency, also makes this method good for textural discrimination/recognition, textural analysis and synthesis. An iterative algorithm, that reestimates the parameters of an underlying Markov chain and the associated probabilistic observation functions, is used to detect textural edges in monochromatic digital images in which textures are modeled as Markov sources. For example, in a picture composed of two different textural regions, we can initialize the parameters (e.g., distributions of the probabilistic observation functions and transition matrix of the Markov chain) by a weighted count. These parameters are continually reestimated until little change is noticed, and then the probability of being from either state is computed at each pixel. A jump in probability indicates a textural edge. More complicated cases were investigated with reasonable success. The powerful reestimation algorithm employed here has greatly simplified the usual co-occurrence models which need more matrices of joint distributions to characterize a specific texture. Mathematical theory and experimental results are presented. Applications to other areas of artificial intelligence are suggested.

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H. Synchronization over Fading Dispersive Channels

* S.S. Soliman, and R.A. Scholtz, "Synchronization over Fading Dispersive Channels," Proceedings of GLOBECOM '84, Atlanta, Georgia, November 26-29, 1984, pp. 29.1.1-29.1.6.

A B S T R A C T

This paper investigates the acquisition mode of the synchronization process for digital communication over fading dispersive channels. The mean propagation delay and doppler of the channel and the offset between the transmitter's and the receiver's clock and oscillators are combined in one unknown vector parameter. A performance measure for the synchronizer in the acquisition mode is defined. Upper and lower bounds on the performance measure are derived under Gaussian assumptions. The effect of various parameters, such as signal-to-noise ratio, pulse width and modulation, number of pulses, spread of the channel, and the size of the resolution cell on the performance of the synchronizer are investigated.

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I. Adaptive Wavefront Reception and Retrodirectivity

* A. Netch, and R.A. Scholtz, "Pair-Wise Phase-Locked Loop Coupling for Self-Focusing and Retrodirective Array Antennas", International Information Theory Symposium, Brighton, England, June 1985. (Abstract only)

A B S T R A C T

The study addresses the ability of a Retrodirective Array (RDA) to form a beam in the direction of a received pilot signal via the phase conjugacy principle. Methods of layered pairwise phase-locked loop (PLL) coupling are developed and analyzed for beamforming improvement and pointing jitter reduction with static and dynamically distorting arrays. The techniques are most effective when the pilot signal is weak and angular resolution or gain requirements dictate a large array aperture, not having the structural integrity required for good beamforming.

Two new types of coupled PLL tracking networks are developed, based on the maximum likelihood principle. The Delta coupling scheme is designed to track differential electrical phase angle increments. The Geometry coupled approach exploits differences in the rates of array distortion and pilot signal directional motion by tracking the changing array geometry and constructing the electrical phase from the estimated geometric variables. Both tracking networks are realized with generic pairwise coupling modules, common in form to all coupling nodes, and resulting in networks having a layered binary tree structure. A linearized tracking error analysis shows a significant improvement in beamforming with coupling, if the array structural distortion is slowly varying relative to the dynamics of the carrier phase. A large geometrically coupled antenna array (64 elements) is simulated and time-varying simulated beam patterns are compared for coupled and uncoupled RDAs.

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J. Systems Theory

* Shokoohi S., Silverman L.M., and Van Dooren P., "Linear Time-Variable Systems: Stability of Reduced Models", IEEE Trans. on Automatic Control, August 1983, Vol. AC-28, No. 8, pp. 810-822.

* ---- Automatica, Vol. 20, No. 1, pp. 59-67.

A B S T R A C T

The authors previously introduced the notion of a "uniformly balanced" realization for time-variable systems. This representation is characterized by the fact that its controllability and observability grammians are equal and diagonal. Such a framework has many remarkable properties and leads to a setting where the subsystems can be taken as reduced model for time-variable systems. It turns out that once the stability of a subsystem is guaranteed, then the subsystem preserves many of the properties of the

original system. In this paper, the stability of subsystems is fully explored.

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* B. Lashgari and L.M. Silverman, "A New Algorithm for Recursive Estimation of Two-Dimensional Processes," submitted to IEEE Trans. on Acoustics, Speech and Signal Processing.

A B S T R A C T

A low dimensional quarter-plane-causal recursive model is presented to represent the class of 2-D stationary Gaussian processes with power spectra matrices factorable into the quarter-plane-causal and anticausal parts. This model is used to develop a technique for obtaining optimal 2-D recursive estimators. The approach taken here is similar to Attasi's while new results must be developed to utilize this model. The white noise assumptions on the process and observation noise are later relaxed so that more general situations can be handled. The estimation procedure is then applied to the image restoration problem where the degradation is caused by blur in addition to noise. Finally, some simulated results are presented to illustrate the technique.

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* Harshavardhana P., Jonckheere E.A., and Silverman L.M., "Open and Closed Loop Approximation Techniques - An Overview", 1983 IEEE International Symposium on Circuits and Systems, Newport Beach, CA, May 1983, pp. 126-129.[4]

A B S T R A C T

In this paper we review several different types of system balancing and the associated model reduction procedures.

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* Harshavardhana P., Jonckheere E.A. and Silverman L.M., "Stochastic Balancing and Approximation - Stability and Minimality", Symposium on the Mathematical Theory of Networks and System MTNS, Beer Sheva Israel, June 20-24, 1983.[5]

A B S T R A C T

A new method of balancing, called stochastic balancing, has recently been introduced. This paper focuses on the stability aspects of the associated stochastic model reduction scheme. It is shown that in both the continuous-time and discrete-time cases the reduced order model is asymptotically stable and dissipative. Further, it is shown that

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[4]Due to an oversight, prior contract DAAG29-79-C-0054 was acknowledged rather than our current contract DAAG29-82-K-0142.

[5]See previous footnote.

in the continuous-time case the reduced order model is minimal.

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* Lashgari B., and Silverman L.M., "Cascade Realization of 2-D Separable in Denominator Filters", Circuits, Systems and Signal Processing, Vol. 2 No. 2, 1983, pp. 193-201.

A B S T R A C T

After selecting the most suitable model for the class of two-dimensional quarter-plane-causal, recursive, and separable in denominator (CRSD) filters, a procedure for realizing a cascade system of such filters is developed. The realization utilizes the individual CRSD models constituting the cascade system. An example is given to further illustrate the technique.

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* Silverman, L.M., and Jonckheere, E.A., "A New Set of Invariants for Linear Systems -- Application to Reduced Order Compensator Design", IEEE Trans. on Automatic Control, vol. AC-28, no. 10, October 1983, pp. 953-964.

A B S T R A C T

A new set of invariants for linear systems, weighting the contribution of each state component to the inherent closed-loop LQG behavior of the system is presented, together with applications to model order reduction and reduced order compensator design.

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* Silverman, L., Harshavardhana, P., and Jonckheere, E.A., "Stochastic balancing and approximation", Symposium on the Mathematical Theory of Network and Systems [MTNS], Beer Sheva, Israel, June 20-24, 1983.

A B S T R A C T

A new method of stochastic model reduction has recently been introduced by Desai et al. The stability of the reduced order model has not previously been considered. In this paper, we show that the stability of the reduced order model follows directly from the results of Pernebo and Silverman. It is also shown that the reduced order model is minimal, in the controllability/observability sense. The relevance of this notion of minimality to stochastic minimality is made clear.

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* Silverman, L., Opdenacker, P., and Jonckheere, E.A., "Stochastic Balancing and Approximation - Stability and Minimality", Proc. IEEE Conference on Decision and Control, San Antonio, Texas, Vol. 3 of 3, pp. 1260-1265, December 1983.

A B S T R A C T

A new method of balancing, called stochastic balancing, has recently been

introduced. This paper focuses on the stability aspects of the associated stochastic model reduction scheme. It is shown that in both the continuous-time and discrete-time cases the reduced order model is asymptotically stable and dissipative. Further, it is shown that in the continuous-time case the reduced order model is minimal.

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* Silverman, L., Kitapci, A., "System Structure at Infinity", Systems & Control Letters, No. 3, August 1983, pp. 123-131.

* -- Presented at the National CNR Colloquium, and 21st CDC, Orlando, Florida, December 8-10, 1983.

A B S T R A C T

The structure at infinity of a rational matrix (Smith-McMillan factorization at infinity) has been the subject of a number of recent papers. Several different algorithms have been proposed to compute this structure and various relationships with other structural properties of linear systems have been brought out. In this paper we will follow up an approach initiated by Hautus, which makes use of the Structure Algorithm. It will be shown that a particular version of this algorithm (nested) provides all the structural information needed to obtain the Smith-McMillan factorization at infinity.

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K. Finite Fields

* L.R. Welch, "Fast Algorithms for Finding Roots of Cubic Polynomials Over Finite Fields", submitted for presentation at the International Information Theory Symposium, June 1985. (Abstract only)

A B S T R A C T

In error correction systems using Reed-Solomon codes, once the error locator polynomial is found, the next step is to determine if all of its roots are in the appropriate field and find them. In the case that there are two errors, several authors [Berlekamp, Sloane and MacWilliams] have developed fast algorithms for finding the roots of quadratic polynomials. For machines that have finite field arithmetic hardware for $GF(2^m)$ and the roots are in $GF(2^m)$ these algorithms execute in time proportional to m. The most elegant version occurs when field representation is in a normal basis [Sloane and MacWilliams p. 278].

For general polynomials, the most efficient root finding methods involve splitting the polynomial into smaller degree factors by computing the greatest common divisor of a polynomial with a trace polynomial,

$$T(\alpha X) = \sum_{i=0}^{m-1} \alpha^{2^i} X^{2^i}$$

[Ref: Berlekamp 111, 113, 117, 121, 131, Chien 288, Golomb 523, McEliece 937, Mills and

Zierler 961[6]]. For a given α it is matter of luck as to the degrees of the two factors produced. However, in the optimum case when every GCD calculation splits a polynomial into two polynomials of equal degree, the total amount of work to find all roots in $GF(2^m)$ of a polynomial of degree d is of the form $d^2(Am+B)$ where A and B are small constants.

In the case of a cubic, Berlekamp [113] "linearizes" the polynomial to the form $X^4+X^2+AX = P(X)$ by a transformation $X \rightarrow aX+b$ and multiplication by X. He shows that finding the roots is equivalent to solving a matrix equation

$$m\underline{X} = \underline{0}$$

where the components are in {0,1}. The easiest way to do this is to introduce a basis $\{x_1,x_2,\ldots,x_m\}$ for $GF(2^m)$ over GF(2) and define

$$Z_i = P(x_i)$$

The problem is then to find linear dependencies among the $\{Z_i\}$, $\sum_1^m k_i Z_i = 0$, $k_i \epsilon \{0,1\}$. For each such dependency $\sum_1^m k_i x_i$ is a root of P. Given hardware for $GF(2^m)$ arithmetic and bit testing, the average computation time is proportional to m^2.

In this paper, I describe a method of finding the roots of a cubic, such that, while the worst case computation time is proportional to m^2, the average time is proportional to m. In error correction systems which use buffers many codewords long, the average time of computation is more relevant than worst case time. Therefore this algorithm should be useful in such systems.

Suppose we want to find those roots of $P(Z) = Z^4+Z^2+AZ = 0$ in $GF(2^m)$ which also satisfy $Tr(\alpha Z)=a$, a=0 or 1 for specified α in $GF(2^m)$. Define the squaring operator D on $GF(2^m)$ by $DX = X^2$. Then the equation and the condition can be written

$$(D^2 + D + A)Z = 0$$

$$\left[\sum_{i=0}^{m-1} \alpha^{2^i} D^i\right]Z = T_\alpha(D)Z = a$$

The algebra of operators which are polynomials in D with left coefficients in $GF(2^m)$ is non-commutative but easy to perform. In particular it is easy to compute

$$T_\alpha(D) \mod(D^2 + D + A) = bD + c = T_\alpha(D) - Q(D)(D^2 + D + A)$$

as I will show in a minute. The previous two operator equations then imply

$$bZ^2 + cZ = a.$$

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[6]Reference notation is taken from Sloane and MacWilliams, The Theory of Error Correcting Codes.

Since the sum of the three non-trivial roots of P is 0 and Trace is linear, the equation $bZ + c = 0$ must have either 1 or 3 solutions if all the roots of P lie in $GF(2^m)$. In the first case $bZ^2 + cZ = 1$ must have 2 roots, in the second case $b = c = 0$. Again in the first case, it must be true that

$$(bZ^2 + cZ)(bZ^2 + cZ + 1) = b^2P(Z)$$

If b,c does not satisfy either of these conditions then P does not have all of its roots in $GF(2^m)$, and conversely. It can be shown that if the three non-trivial roots of P are chosen at random in $GF(2^m)$ with $x_1 + x_2 + x_3 = 0$ then the probability that $b = c = 0$ is 1/4. It follows that the probability of finding a root, c/b is 3/4. If $b = c = 0$ then α can be replaced by another element and the process repeated. The expected number of trials to success is 4/3.

Returning to the computation of $T_\alpha(D) \bmod (D^2 + D + A)$, define $B_1 = \alpha^2$, $C_1 = \alpha$. Then recursively define

$$B_{i+1} = B_i^2 + C_i^2$$

$$C_{i+1} = B_i^2 A + \alpha$$

It can be shown that $B_{m-1} = b$, $C_{m-1} = c$.

The amount of work *in one iteration is therefore* two squarings, one multiplication and one addition. The amount of work in one trial is $(m-2)2$ squarings, $m-2$ multiplications and $(m-2)$ additions. Multiplying these counts by 4/3 gives the expected amount of work to find a factor. Once a factor is found, the standard techniques for finding roots of quadratics can be applied to $(bZ^2 + cZ + 1) = 0$.

Ph.D. THESES

* Yu-Teh Su, "Advances on Multiple Dwell and Sequential Serial Synchronization of Pseudonoise Signals", April 1983.

A B S T R A C T

The process of PN signal acquisition is decomposed, by repeated applications of the theorem on total probability, into a semi_Markov process. The method of generating function is then utilized to obtain statistical information on the acquisition process, notably the mean and variance of acquisition time. The exploitation of the semi-Markov *nature of the acquisition process* with a simple probability theorem in fact unifies the seemingly different approaches of Braun, Weinberg and Polydoros & Weber.

The main body of this thesis is devoted to the other phase of the PN acquisition problem, namely, the design of an optimal detector. Our criterion of optimality is to achieve the minimum possible acquisition time under the worst possible time offset condition. Two major families of tests - MDT and the ST (or, VD systems) - are proposed, their behaviors analyzed, performances evaluated and compared. It is found that the performance of the MDT improves as N, the number of dwells, increases so long as N is

not too large. The ST, if properly designed are capable of outperforming the MDT. Both MDT and ST are discussed in two distinct environments, namely, the coherent code synchronization (CCS) case and the noncoherent code synchronization (NCS) case.

All the numerical results are confined to the situation when no a priori information are available and a so-called straight line search strategy is adapted. But our analyses can be readily applied to obtain performances in other environments once the corresponding generating functions are found.

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* **Seong Young Kang**, Frequency-Offset Retrodirective Arrays" May 1983.

A B S T R A C T

There exist phase ambiguities at the output signals of the frequency-offset retrodirective arrays. A method to eliminate these phase ambiguities is described. A phase-locked loop type frequency multiplier can be employed in the frequency-offset retrodirective array. In this case, the output phases can be changed from one stable state to the next stable state by applying proper signals to the input of voltage-controlled oscillator. A performance measure of the retrodirective arrays is the steady-state probability density function (p.d.f.) p(V) of the envelope V of the resultant received signal at the pilot tone's source. The p.d.f. p(V) is related to the steady-state p.d.f. of the phase error of the phase-locked loop multiplier. The p.d.f p(V), mean of the envelope m_V and the variance of the envelope σ_V^2 are obtained numerically under various conditions when the number of elements is large. The operation of three element frequency-offset retrodirective array is simulated on a digital computer. An extension of Runge-Kutta algorithm to solve stochastic differential equations is employed in the simulation. Various results of the simulation are described.

****

* **P. Vijay Kumar**, "On Bent Sequences and Generalized Bent Functions", August, 1983.

A B S T R A C T

Bent functions are Boolean functions whose Fourier (Hadamard) coefficients have uniform magnitude. The linear span of a sequence is the degree of the shortest linear-recursion relation that the sequence satisfies. Recently, Olsen, Scholtz and Welch employed bent functions to construct families of sequences (called bent-function sequences) having asymptotically-optimum periodic-correlation properties and large linear spans, properties of interest in spread-spectrum multiple-access (SSMA) communication systems. The construction of these sequences involves non-linear operations upon m-sequences.

Here, bent functions are generalized with a view toward generalizing bent sequences and providing the practicing engineer with code sequences for possible deployment in a SSMA system employing non-binary phase-shift keying. Bounds indicating the maximum-achievable linear span of bent sequences are derived and a count is obtained (under restricted conditions) of the number of distinct families of bent

sequences that one can possibly generate using a single bent function.

Rothaus' definition of a bent function is extended to include functions defined over vector spaces comprised of m-tuples with elements drawn from the integers mod q, m and q being arbitrary integers. For every possible value of q and m, constructions of bent functions are provided, with one exception. In the exceptional case m is odd and q=2(mod 4) and the author is currently uncertain as to the existence or otherwise of bent functions over such vector spaces, having proven nonexistence only in a special case. Given the generalization of bent functions, the generalization of bent sequences is shown to follow trivially. An important point, to use in constructing generalized bent sequences, is that generalized bent functions are not restricted to be functions defined over vector-spaces of even dimension.

While the generalized and binary versions share many properties in common, they have their differences. Some properties of generalized bent functions are unique to the general case in the sense that the corresponding binary results are uninteresting. For example generalized bent functions over vector spaces of dimension 1 possess "ideal" periodic autocorrelation properties while binary one-dimensional bent functions are clearly of only trivial interest. On the other hand, some properties of binary bent functions are not readily extended to the general case. For example, a trivial argument shows the Fourier coefficients of binary bent functions as being ± 1 , whereas the problem of identifying values of q and m for which the Fourier coefficients of generalized bent functions are necessarily roots of unity is far more difficult and the subject of considerable attention in this dissertation.

On the topic of linear span, an interesting result (Lemma 3.3) provides a simple means of generating binary sequences having guaranteed large linear span. This result is used to provide a lower bound to the maximum achievable linear span of binary bent sequences. In addition, a certain characteristic of these sequences is used to derive an upper bound, tighter than Key's more general bound. A count of the number of binary bent sequences that can be obtained from a given maximum-degree class I bent function (as defined by Rothaus) is obtained. Such sequences are of interest as sequences derived from bent functions of larger degree have, in general a larger linear span.

Lemma 3.3 and the generalization of bent functions contained in Chapter 5 are perhaps the principal contributions of this dissertation.

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* **Min-In Chung**, "Generalized Network Structure of Transversal Filter Suitable for VLSI Implementation", August 1983.

A B S T R A C T

Rapid Progress in Very Large Scale Integration (VLSI) integrated circuit technology has called for fundamental changes in theoretical and practical aspect of the hardware implementation and computer architecture. This thesis represents an unconventional approach on a VLSI system.

As an ubiquitous component of the communication and signal processing system, the transversal filter has many very important applications in various fields. Conceiving that it will play an even much more important role in future VLSI systems, we study the

transversal filter's network structure and its generalized form in this thesis.

Motivated by the belief that the very large scale physical structure should prevail down from the lowest device level and up to system level for a VLSI system, we select Galois field GF(2) and its extension field as the arithmetic system to investigate.

It is shown that through repetitive finite dimensional field extension over Galois field GF(2), an infinite number of generalized transversal filter can be constructed. The generalized transversal filter exhibits obvious hierarchical structure in timing signal, geometric physical structure and interconnection (communication) pattern. It is further demonstrated that under multiple-level connection environment the connection pattern of these generalized transversal filter meet Mead's criterion for achieving minimum propagation delays which are logarithmic in wire lengths.

Another new transversal filter structure called double Galois configuration is also derived. This network structure reveals that similar to Berlekamp-Massey algorithm, continued fraction algorithm can also physically be interpreted as a shift register synthesis process. The natural correspondence between continued fraction's recursion formula and the synthesized shift register is studied. The study shows that continued fraction can be interpreted as joint operation of three transversal filter (double Galois configuration).

A digital Metal Oxide Semiconductor (MOS) Large Scale Integration (LSI) chip that implements the generalized Galois configuration over $GF(2^m)$, where m may be any nonnegative integer, is presented.

It is suggested in the conclusion that transversal filter and its generalized form should be the building block of the next generation computer's memory.

The work presented in this thesis is directly applicable to the VLSI implementation of error correcting code encoder and decoder (such as Reed-Solomon code).

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* **Samir Salib Soliman**, "Synchronization over Fading Dispersive Channels", August 1983.

A B S T R A C T

This dissertation investigates the acquisition mode of the synchronization process for digital communication over a fading dispersive channel. The mean propagation delay and doppler of the channel and the offset between the transmitter's and the receiver's clock and oscillators are combined in one unknown vector parameter. The maximum likelihood estimator of this vector parameter, for both single pulse transmission and pulse sequence transmission, is derived. The effect of various parameters, such as signal-to-noise ratio, pulse width and modulation, number of pulses, spread of the channel, and spacing between detectors on the performance of the synchronizer are investigated.

A mathematical model for a time and frequency dispersive channel is first presented, and then channel classification and examples are given. Methods of measuring the scattering function of the channel and related quantities are discussed.

A probabilistic model for the eigenvalue is developed, and a technique for

approximating the eigenvalues of any Hermitian kernel is presented. As a sidelight, this original technique leads to an interpretation of a pseudonoise sequence as the moment sequence for an appropriately defined random variable.

A new autocorrelation ambiguity function is defined and its properties are derived. Some comments on the use of this autocorrelation ambiguity function in signal design are discussed.

To complete this study of the acquisition problem, a performance measure for the synchronizer in the acquisition mode is defined. Upper and lower bounds on the performance measure are derived. For a specific shape of both the scattering function of the channel and the transmitted waveform, a set of curves are provided to illustrate the effect of the different parameters on the performance of the synchronizer for both over-spread and under-spread channels.

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* **Raimundo Sampaio Neto** "Spread-Spectrum Code Tracking in the Presence of Interference", September 1983 .

A B S T R A C T

This dissertation studies the problem of code-delay tracking in direct-sequence systems operating in an interference environment.

Receiver-noise interference is considered first, and several closed-loop structures for both coherent and noncoherent code tracking are developed, based on the maximum likelihood principle. The structures originated by such development - among which most of the traditional loops were included - are extended via the notion of a generalized correlation, which leads to a unifying approach to the analysis and design of code tracking loops subjected to spectrally white and/or non-white interferences.

The generalized correlation is created by introducing arbitrary linear transformations (filtering) of the incoming waveforms and locally generated references prior to the usual correlation operation. Optimal sufficient conditions are derived, based on the minimization of the linearized tracking jitter, which allow the designer to specify the transformations in a suitable way. The fulfillment of the pertinent conditions is shown to yield structures that, simultaneously with minimum-jitter tracking, provide the data detection circuitry with a maximized despread signal-to-interference power ratio.

Expressions for linearized jitter performance of optimal and sub-optimal tracking configurations in the presence of arbitrary interference are derived.

The true nonlinear behavior of the tracking systems is described and analyzed in a renewal process framework. General expressions for the stationary distribution of the tracking error process and the mean time to lose lock are obtained in terms of the loop's normalized S-curve and the spectral level of the loop's effective noise. The results are used to investigate nonlinear performance of a selected loop configuration in receiver noise and strong colored interference environments, and illustrate the effects of placing whitening filters, as suggested by the design results, in the loop.

Numerical results illustrating the impact of interference power and bandwidth on different measures of system performance are presented and discussed.

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* **Naikuan Huang**, "Markov Probabilistic Function Models for Texture-based Image Segmentation", December 1983.

A B S T R A C T

Textural information provides important clues to analyze the structure of a scene. Such features are extracted by dividing the image into regions of different textures. Existing approaches fall into two categories: The local methods inherently ignore the relative layout of the regions. The global methods overlook smaller parts in the composition, and involve logical difficulty in the general case. An image model that treats the structure and the textures in an integrated manner is therefore required.

In this dissertation, textures are modeled as probabilistic output of a finite state Markov chain. Welch-Baum's parameters reestimation algorithm is adapted to obtain the probability distribution of each primitive picture element being a member of a certain texture. An edge is defined when there is a jump in probability. Boundaries are connected by following the detected edges between textures. Prior knowledge of the scene is not required to initiate the processing, except the assumption that textural boundaries are present and reasonably smooth. No training samples nor human supervision are necessary. The computer learns the structure of the source by ruminating on the output.

The processing is one-dimensional in nature, though simulations have been done on both one-dimensional and two-dimensional images of simple configurations. Perfect results are obtained on a set of non-equalized one-dimensional artificial textures. With a two-dimensional image composed of two separately equalized textures, there are nearly fifty percent randomly distributed out-of-place edge estimates, but strong information on the shape of the boundary can be inferred from clusters of correctly located edges, and a connected boundary can then be followed. Extension to more complex situations is described, and limitations are discussed. Future works along this line are suggested.

Similar mathematical models can be applied to other problems. The learning ability of this algorithm, which is built-in with the reestimation of the system parameters, is attractive to various artificial intelligence problems. There are cases, such as in all recognition problems, in which the decisions are more frequently made on a probabilistic basis rather than exact calculations or exhaustive searches -- an ability sometimes called intuition. Instead of an extremely large data base, a relatively small set of system parameters (which are nothing but probabilities) that summarizes the inter-relationship of possible events can then be used as the knowledge base. Proposals of applications to seismic data processing, style analysis, speech understanding and channel characterization are collected in the last chapter, though the first and last are usually not mentioned in connection with artificial intelligence.

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* **Eric William Siess**, "Acquisition of Direct Sequence Spread Spectrum with Modulation and Tone Jamming", December 1983.

A B S T R A C T

The analyses of narrowband interference in direct sequence (DS) spread spectrum systems in the open literature have either determined the effect of interference on performance after synchronization or have presented approaches of combating the interference. Acquisition of DS systems when under the influence of narrowband interference has heretofore not been considered.

Acquisition performance has been documented when the carrier is modulated by data and the spreading code for a correlator/square-law acquisition receiver. The recently presented noncoherent I-Q detector has been shown to surpass the correlator/square-law detector in performance, but the effect of data on performance has only been qualitatively addressed.

For most of the spreading codes of interest, the variable to be detected in the I-Q receiver is Gaussian with known statistics. Data modulation decreases the mean and tone jamming increases the variance of the detection variable. The statistics of the decision variable with the data and/or jamming significantly influence the probabilities of detection and false alarm of the receiver. The effects of data and/or jamming on acquisition time are assessed when particular acquisition schemes are selected. Finally, the results of these analyses are used to propose receivers which mitigate the deleterious effects of the data or jamming.

The result of the analyses demonstrate that the I-Q detector, modified for a data modulated carrier, is superior to the correlator/square-law detector despite the latter's robustness to data. When the average pulsed jammer power is constrained, the analyses illustrate that the jammer's duty factor does not impact acquisition time when the pulse repetition frequency (PRF) is high and that a duty factor of unity maximally degrades acquisition performance when the PRF is low. The most important result of the analyses is the need for the acquisition receiver to sense and adapt to jamming. A proposed adaptive receiver provides considerable jamming protection and the acquisition performance obtained with such a receiver bounds the performance of all adaptive acquisition receivers.

C.L. Weber's efforts on behalf of this thesis research, were supported in part by ARO.

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* **Arie Reichman**, "Adaptive Spread Spectrum Systems Using a Least-Squares Lattice Algorithm", July 1984.

A B S T R A C T

Practical communication systems must cope with many uncertainties in addition to determining the transmitted data; the direction, timing, and distortion of the desired signal, and the spectral and spatial distribution of the interference, all of which may change with time. In this paper, we will apply the exact least-squares (LS) recursive lattice algorithm to resolve these uncertainties in a direct-sequence spread-spectrum digital communication system.

The LS lattice algorithm is recursive both in filter order and time, and fast-coverging adaptively to the uncertain parameters. These parameters are assumed to change slowly relative to the data rate, necessitating the selection of an appropriate

VI. USC-ARO RESEARCH REVIEW

University of Southern California

October 25-26, 1984

Thursday, October 25, 1984

Room 224, Davidson Conference Center

8:30 AM **R E G I S T R A T I O N**

9:00 AM **Dr. Leonard M. Silverman - Welcoming Remarks**

9:15 AM **Solomon W. Golomb - THE CHARACTERIZATION OF PN SEQUENCES**

* Shift register sequences, both linear and nonlinear, are being used in an ever-increasing number of important applications. There is a hierarchy of randomness properties satisfied by all of the linear sequences and some of the nonlinear sequences. The interrelationship of these randomness properties, and the minimum set of pseudo-randomness assumptions necessary to characterize the linear sequences, will be discussed.

9:45 AM **P. Vijay Kumar - ON GENERALIZED BENT FUNCTIONS AND FREQUENCY HOPPING CODE DESIGNS**

* Bent functions are a class of Boolean functions having the interesting property that all of their Fourier coefficients have constant magnitude. In the first part of this talk, past work carried out relating to the generalization of bent functions and an examination of their properties will be reviewed.

* An application to frequency hopping (FH) will be presented in the second half of the talk. This will be followed by an identification of three research problems relating to the design of FH code sequences having large linear span.

10:15 AM **C O F F E E B R E A K**

Code 62 Nn
Monterey, CA 93940 (408) 646-2535

47. Dr. Joseph P. Yuen
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91030

48. Dr. Rodger E. Ziemer (Professor)
Electrical Engineering Department
University of Missouri-Rolla
Rolla, MO 65401 (314) 341-4514

Visitors

Tsun-Yee Yan
Jet Propulsion Lab
4800 Oak Grove Drive
Pasadena, CA 91030

Kesh Bakhru
Cubic Corporation
San Diego, CA (619) 277-6780 x2548

William L. Floyd (Senior Engineering Specialist)
General Dynamics Electronics
P.O. Box 85310, MZ 7212-H
San Diego, CA 92138 (619) 692-7613

Ronald F. Mathis (Sr Engineering Specialist)
P.O.Box 85310 MZ 7212-H
San Diego, CA 92138 (619) 692-7521

University of Southern California
Department of Electrical Engineering
Los Angeles, CA 90089-0272 (213) 743-5546

38. Dr. John A. Silvester (Assistant Professor)
Electrical Engineering Systems
University of Southern California
Los Angeles, CA 90089-0781 (213) 743-8189

39. Dr. Marvin K. Simon (Senior Research Engineer)
Jet Propulsion Laboratory
Mail Stop 161-228
4800 Oak Grove Ave.
Pasadena, CA 91109 (213) 354-3955

40. Dr. Seymour Stein (President)
SCPE, Inc.
56 Great Meadow Road
Newton Center, MA 02159 (617) 527-5551

41. Dr Fouad Tobagi (Professor)
Electrical Engineering Department
Stanford University
Stanford, CA 94305 (415) 497-1708

42. Dr. Robert A. Travis (Staff Officer DoD)
3289 Sudlersville So.
Laurel, Maryland 20707 (301) 725-2747

43. Dr. Charles L. Weber (Professor)
USC Communication Sciences Institute
Department of Electrical Engineering
University of Southern California
Los Angeles, CA 90089-0272 (213) 743-2407

44. Dr. Lloyd R. Welch (Professor)
USC Communication Sciences Institute
Department of Electrical Engineering
University of Southern California
Los Angeles, CA 90089-0272 (213) 743-2699

45. Dr. Jeff Wieselthier (Electronics Engineer)
Code 7521
Naval Research Laboratory
Washington, DC 20375 (202) 767-3043

46. Dr. John M. Wozencraft (Professor)
Naval Postgraduate School

University of Illinois
1101 West Springfield Ave.
Urbana, IL 61801 (217) 333-2966

29. Dr. Lawrence L. Rauch (Chief Technologist
Jet Propulsion Laboratory Telecommunication Science &
Mail Stop 238-540 Engineering Division)
4800 Oak Grove Drive
Pasadena, CA 91109 (213) 354-6334

30. Dr. Irving S. Reed (Professor)
USC Communication Sciences Institute
University of Southern California
Los Angeles, CA 90089-0272 (213) 743-2991

31. Dr. Barney Reiffen (Head, Communications Division)
MIT Lincoln Laboratory
P.O. Box 73
Lexington, MA 02173 (617) 863-5500 x7600

32. Dr. Bart F. Rice (Chief, Signal Theory Division)
Department of Defense (R52)
9800 Savage Road
Fort George G. Meade, MD 20755 (301) 859-6193

33. Dr. M.P. Ristenbatt (Research Scientist &
245 Cooley Bldg. Lecturer in E.C.E.)
University of Michigan
Ann Arbor, MI 48109 (313) 764-5202

34. Dr. Lowell Rosen (Engg. Staff Scientist)
General Dynamics
MS 42-6210
P.O.Box 85357
San Diego, CA 92138 (619) 277-8900 x3127

35. Dr. William A. Sander, III
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709 (919) 549-0641

36. Dr. Paul F. Sass (Electronic Engineer)
U.S. Army CECOM
DRSEL-COM-RF-2
Ft. Monmouth, NJ 07703 (201) 544-5680

37. Dr. Robert A.Scholtz (Professor)
USC Communication Sciences Institute

19. Dr. Robert J. McEliece (Professor)
Electrical Engineering Department (116-81)
California Institute of Technology
Pasadena, CA 91103 (213) 356-3891

20. Dr. Laurence B. Milstein (Professor)
Dept. of Electrical Engineering & Computer Science
University of California, San Diego
La Jolla, CA 92093 (619) 452-3096 or 3620

21. Dr. Joseph P. Odenwalder (Engineering Director)
M/A-COM Linkabit, Inc.
3033 Science Park Road
San Diego, CA 92121 (619) 457-2340 x1355

22. Dr. John D. Olsen (Head)
Hughes Aircraft Company
1901 W. Malvern Ave. (Communications & Network Technology Section)
P.O. Box 3310
Fullerton, CA 92634 (714) 732-2637

23. Dr. Jim K. Omura (Professor)
5100 Mayflme Lane (UCLA)
Culver City, CA 90230 (213) 558-0885

24. Dr. Roger L. Peterson (Principal Staff Engineer)
Motorola, Inc. GEG. M.S.-2220
8201 E. McDowell Rd.
Scottsdale, AZ 85234 (602) 949-2910

25. Dr. Andreas Polydoros (Assistant Professor)
USC Communication Sciences Institute
Department of Electrical Engineering
University of Southern California
Los Angeles, CA 90089-0272 (213) 743-7257

26. Dr. Robert Price (Staff Consultant)
Sperry Research Center
100 North Road
Sudbury, MA 01776 (617) 369-4000

27. Dr. Edward C. Posner (Professor)
California Institute of Technology, EE (& JPL)
116-81
Pasadena, CA 91125 (213) 356-4852

28. Dr. Michael B. Pursley (Professor)
Coordinated Science Laboratory

10. Lt. Col Jurgen Gobien DARPA Tactical Technology Office 1400 Wilson Blvd Arlington, VA 22209	(Program Manager) (703) 694-8379
11. Charles Graff Commander U.S. Army - CECOM DRSEL-COM-RF-2 Ft. Monmouth, NJ 07703	(Electronic Engineer) (201) 544-5619
12. Dr. Gaylord Huth AXIOMATIX 9841 Airport Blvd., Suite 912 Los Angeles, CA 90045	(President) (213) 641-9600
13. Dr. Pravin C. Jain Defense Communication Agency Code J810 Washington, DC 20305	(Asst. for Communications Technology) (202) 692-1949 or 6297
14. Dr. Norman Krasner Probe Systems 655 N. Pastoria Ave. Sunnyvale, CA 94086	(Senior Staff Scientist) (408) 732-6550 x257
15. Donald K. Leimer Magnavox Advanced Products & Systems Company 2829 Maricopa Street Torrance, CA 90504	(Senior Staff Engineer) (213) 618-1200 x1018
16. Dr. Barry M. Leiner DARPA/IPTO 1400 Wilson Blvd. Arlington, VA 22209	(Program Manager) (202) 694-4002
17. Dr. Barry Levitt Jet Propulsion Laboratory 4800 Oak Grove Drive Pasadena, CA 91109	(Technical Group Leader) (213) 354-2756
18. Dr. Victor Li USC Communication Sciences Institute University of Southern California Los Angeles, CA 90089-9272	(Assistant Professor) (213) 743-5543

ATTENDEES

1. Dr. John Bailey (Vice President
216 Pico Blvd. Adaptive Sensors, Inc.)
Suite 8
Santa Monica, CA 90405 (213) 396-5997

2. Dr. Edward Bedrosian (Senior Scientist)
The Rand Corporation
1700 Main Street
Santa Monica, CA 90406 (213) 393-0411 x503

3. Dr. Elwyn R. Berlekamp (President)
Cyclotomics, Inc.
2120 Haste St.
Berkeley, CA 94704 (415) 548-1300

4. Dr. John H. Cafarella (Assistant Leader)
Analog Device Technology Group
MIT Lincoln Laboratory
Box 73 Room C-117
Lexington, MA 02173 (617) 863-5500 x7864

5. Dr. John F. Dillon (Mathematician)
Department of Defense
9800 Savage Road
Fort George G. Meade, MD 20755 (301) 859-6461

6. Dr. Robert J. Dinger (Research Physicist)
Code 3814
Naval Weapons Center
China Lake, CA 93555 (619)939-2000

7. Dr. James DuPree (Staff Scientist)
TRW, Inc.
Mail Code 03-2627E
One Space Park
Redondo Beach, CA 90278 (213) 535-7303

8. Dr. Paul L. Feintuch
635 S. Chaparro Road
Covina, CA 91722 (714) 670-3059

9. Dr. Harold Fredricksen (Associate Professor)
Math Department - Code 53Fs
Naval Postgraduate School
Monterey, CA 93940 (408) 646-2235

Tuesday (3 May 1983)

1:30 PM: Spread Spectrum Networks

Chairman: Dr. Barry Leiner, DARPA/IPTO
Dr. Charles Graff, U.S. Army CECOM
Dr. John Olsen, Hughes Aircraft Co.
Dr. John Wozencraft, Naval Post-graduate School

Evening Cookout: Great Food and western hospitality. Sign up for the afternoon horseback ride, if you would like to arrive at dinner via the scenic route.

Wednesday (4 May 1983)

9 AM: Individual Presentations and Wrap-up Session

12 NOON: WORKSHOP CLOSED

V. WORKSHOP: RESEARCH TRENDS IN MILITARY COMMUNICATIONS

PROGRAM

Sunday (1 May 1983):

6 PM : Workshop Mixer

Monday (2 May 1983)

9 AM: Array Signal Processing in a Spread Spectrum Enviroment

Chairman: Dr. Paul Feintuch, Hughes Aircraft Co.
Dr. John Bailey, Adaptive Sensors, Inc.
Dr. Robert Dinger, Naval Weapons Center, Chinalake.
Dr. James DuPree, TRW, Inc.
Dr. Irving Reed, University of Southern California.
Dr. Marlin Ristenbatt, University of Michigan.

2 PM: Spread Spectrum Communication in Jamming

Chairman: Dr. Gaylord Huth, Axiomatix, Inc.
Lt. Col. Jurgen Gobien, DARPA/TTO.
Dr. Parvin Jain, Defense Communication Agency.
Dr. Barry Levitt, Jet Propulsion Laboratory.
Dr. Robert McEliece, California Institute of Technology.
Dr. Seymour Stein, SCPE, Inc.

9 PM: Cinema Treats from the USC Film Library.

Tuesday (3 May 1983)

9 AM: Applications of Coding to Spread Spectrum Communications

Chairman: Dr. Lloyd Welch, University of Southern California.
Dr. Elwyn Berlekamp, Cyclotomics, Inc.
Dr. Joseph Odenwalder, Linkabit Corp.
Dr. Jim Omura, University of California at Los Angeles

for Spread Spectrum Systems," in the session on Spread Spectrum.

15. Wei-Chung Peng attended MILCOM '84 at the Marriott in Los Angeles, October 22 - 24, 1984.

16. Dr. Scholtz attended MILCOM '84 at the Marriott in Los Angeles, October 22-24, 1984, where he chaired a session, and gave a presentation in one session.

17. Dr. Kung travelled to Tampa, Florida, March 25-28, 1985, to attend technical sessions at the ICASSP, and deliver a presentation in one session.

IV. TRAVEL SUMMARY

1. Drs. Scholtz and Weber attended MILCOM '82 in Boston. Dr. Weber presented papers there and Dr. Scholtz's 5-hour video-taped "History of Spread Spectrum Communications" was shown continuously at the conference.

2. Dr. Weber attended NTC '82 in Galveston, Texas where he chaired a panel on "Civil Applications of Spread Spectrum Communication Systems."

3. Dr. Silverman attended the IEEE Conference on Decision and Control in Orlando, Florida, where he presented a paper.

4. Drs. Reed, Scholtz, and Weber attended the ARO-sponsored workshop, "Research Trends in Military Communications". Drs. Scholtz and Weber were the general chairmen and Dr. Reed served as a panelist.

5. Dr. Scholtz travelled to Boston to attend sessions at ICC'83, and to receive the Leonard G. Abraham Prize Paper Award for the ARO sponsored paper, "The Origins of Spread Spectrum Communications".

6. Dr. Scholtz travelled to Ste. Jovite,, Quebec, Canada, Sept. 25-30, 1983 to attend the International Symposium on Information Theory and deliver 2 papers.

7. Dr. Silverman travelled to San Antonio, Texas, December 12-16, 1983, to attend the 22nd IEEE Conference on Decision and Control.

8. Dr. Weber travelled to Washington, DC, Nov. 1-4, to attend MILCOM '83.

9. Dr. Scholtz and Dr. Taylor travelled to San Diego, CA, to attend GLOBECOM '83 sessions and meetings, November 28-29, 1983.

10. Dr. Scholtz travelled to Boulder, Colorado, Jan.11-12, 1984 to attend the National Radio Science Meeting, and deliver a talk.

11. Dr. Scholtz travelled to Boston, Massachusetts, May 13-16, 1984 to attend sessions at ELECTRO and to receive an award for ARO-sponsored research.

12. Dr. Weber travelled to Taos, New Mexico, June 10-13, 1984 to attend the IEEE Communication Theory Workshop. He was the coordinator of the Technical Sessions.

13. Dr. Scholtz travelled to Taos, New Mexico, June 10-13, 1984 to attend the IEEE Communication Theory Workshop and participate as panel chairman in a discussion on coding theory.

14. Dr. Welch travelled to Taos, New Mexico, June 10-13, 1984 to attend the IEEE Communication Theory Workshop and deliver a presentation on "Signal Design

Finally, a design example for an experimental flexible space structure developed at TRW is worked out, showing the applicability of balanced model order reduction to controller design for LSS, and providing experimental confirmation of the validity of the techniques developed in this thesis.

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* **Aysin Kitapci**, "System Structure and Singular Control Problems," August 1985.

A B S T R A C T

Linear quadratic singular control and estimation as well as the stochastic singular control are investigated. The necessary results on related system structure are developed. The singular control and estimation problems naturally arise when some controls are not included in the quadratic cost or some measurements are not corrupted by noise both happen very frequently in practice. For minimum phase and left invertible systems, the linear quadratic stochastic problem is solved when the input cost matrix is singular and measurements are exact.

The geometry theory of linear systems is extensively used in the solution of singular problems. Using the left Structure Algorithm, some of the known results are extended to obtain finer details about system structure. The deeper results on infinite zero structure, Morse's Canonical Form, maximum output nulling controlled invariant and minimum input containing conditioned invariant subspaces, etc., are obtained to provide enough hint for the solution of the singular problems.

The deterministic optimal control problem has been solved by Hautus and Silverman for left invertible, minimum phase systems. In this thesis, the singular optimal control problem with zero terminal state cost is solved for the class of systems with no zeros on the imaginary axis. The optimal control input is found by using a reduced order algebraic Ricatti equation.

The solution of the singular optimal state estimation problem is also obtained. Using a reduced order algebraic Riccati equation, existence of a stable singular optimal filter is shown in case the imaginary axis modes of the system are in the smallest input containing conditioned invariant subspace.

Finally, the results of deterministic singular optimal control and singular state estimation are combined in a separation theorem for the stochastic singular optimal control problem with exact measurements.

The problem of Spread Spectrum multiple access systems, using hybrid of direct sequence and frequency hopping has been studied. A randomized multiple access scenario is introduced. Statistical properties of interference signals due to the presence of other asynchronous users are thoroughly investigated. Upper Chernoff bounds on probability of error per bit for above multiple access systems in two different channels, namely AWGN, and Rayleigh fading, are obtained. The notion of superiority and advantages of two different spread spectrum modulation techniques, i.e., direct sequence and frequency hopping are addressed. An expression for prediction of the optimum number of diversities in slow non-selective Rayleigh fading channel has been formulated.

The problem of Code Division Multiple Access (CDMA) spread spectrum in slow non-selective Rayleigh fading channel with presence of thermal noise is readdressed. The interference signal due to presence of other asynchronous user is shown to be Gaussian like processes. As a result, a closed form solution to probability of error per bit is obtained. An equivalent signal to noise ratio (SNR) is achieved, and it is shown in the absence of fading, above equivalent SNR reduces to that of [24] (M.B. Pursley, "Performance Evaluation for Phase Coded Spread Spectrum Multiple-Access Communication - Part I: System Analysis," IEEE Trans. Comm., vol. COM-25, pp. 795-799, Aug. 1977).

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* **Philippe Opdenacker**, "Balanced Model Order Reduction Techniques and Their Applications to Large Space Structure Problems," August 1985.

A B S T R A C T

Linear model order reduction has been the object of revived interest over the past few years. This technique allows for the simplification of overly complicated models of complex systems as well as the reduction of robust feedback controllers to a size that can be computer implemented. In this thesis, several model order reduction methods are introduced and examined in detail, and their relevance to the design of low order controllers for Large Space Structures (LSS) is emphasized.

Open-loop Balancing and Hankel norm approximation of LSS are reviewed. LQG balancing of symmetric passive systems, which constitute the special class of LSS with collocated rate sensors/actuators, is carefully studied and a proof of stability is given for reduced order LQG compensation. The tetrahedron of Draper Labs serves a case study, confirming the validity of the technique.

Passivity of linear systems, a crucial concept in LSS with collocated rate sensors/actuators, is characterized in terms of the similarity invariants that direct the reduction procedure, i.e., LQG characteristic values for strictly proper transfer matrices and canonical correlation coefficients for proper transfer matrices.

Two stochastic approximation methods, Stochastic Balancing and Phase Matching of the power spectral density matrix spectral factor are compared. A new state-space algorithm is provided for the latter one.

A new balancing method is introduced for the reduction of bounded real matrices and several infinity norm bounds on the approximants are derived. This method is also shown to be a valid alternative to the previous two for stochastic model reduction.

"memory" for the LS algorithm, i.e., an appropriate exponential decay factor λ(λ=1 for infinite memory).

The algorithm is time-discrete. Hence, we assume that the receiver contains integrate-and-dump circuits operating at the chip rate of the PN sequence, one in each in-phase and each quadrative channel of each sensor array element's output. Hence, the signal being processed is regarded as a sequence of complex vectors representing the modulation obtained from an array of antennas. For the discrete-time received signal, the optimal receiver is presented in various configurations assuming synchronization and knowledge of the noise statistics.

The LS filter's coefficients converge, when λ=1, to the coefficients of the Linear Minimum Mean Square Error (LMMSE) filter. The spectral properties of the LMMSE forward predictor, backward predictor, smoother and joint process estimator are used to transform the optimal receiver into 4 types of adaptive receivers which do not require priori knowledge of noise statistics. The first three receivers make use of different kinds of LS predictors to cancel the noise, while the fourth receiver uses the LS joint process estimator for both noise detection and channel equalization. The Viterbi algorithm can be used for improving the latter receiver.

For λ=1, the performance of the adaptive receivers are close to those of the optimal receiver. For λ<1, there is a degradation of performance which increases with order of the filter. A method for adaptively choosing the order of the filter is proposed. The synchronization process estimates the parameters of the signal required for data detection: direction, code timing, and carrier phase. Using the maximum likelihood approach, different configurations are derived for acquisition and tracking of the parameters. The synchronization process becomes adaptive to the noise using the LS filters.

Finally, some guidelines are given to combine the proposed methods in a complete adaptive receiver.

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* **Tze-Hwa Liu**, "A New Decoding Algorithm for Reed-Solomon Code", May 1984.

A B S T R A C T

Much work has been done to find an efficient way to decode the Reed-Solomon Code. In this thesis, we present a new algorithm which can bypass the syndrome computation and process the remainder polynomial directly. A new key equation is derived and solved. The new algorithm is illustrated by examples. The order of complexity is compared with other well-known algorithms and finally a generalized check positions decoding scheme is presented.

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* **Jawad Ahmad Salehi**, "Spread Spectrum Multiple Access Systems Performance Analysis", July 1984.

A B S T R A C T

10:45 AM **Lloyd R. Welch - GMW SEQUENCES**

* A certain class of designs, arising in the theory of difference sets give rise to binary sequences with the same correlation properties as m-sequences. These sequences, the GMW sequences, for a given period provide a far larger collection than the m-sequences of the same period. The properties and mechanization of these sequences will be discussed.

Lloyd R. Welch -SEQUENCE DESIGN FOR ACQUISITION OF FREQUENCY HOPPING SIGNALS

* In direct sequence spread spectrum systems, the signal must be observed for a large number of dwell times before synchronization can be obtained. For the same processing gain, relatively few dwell times need be examined in a frequency hopping system. This opens up the possibility that some sort of time-local patterns, known to the transmitter and receiver but not revealed to a jammer can be designed. This possibility will be discussed.

11:30 AM **Irving S. Reed - ERROR-TRELLIS DECODING WITH APPLICATIONS TO VITERBI DUAL-K CONVOLUTIONAL CODES**

* Error-trellis decoding involves the replacement of the standard coding trellis or what is called an error-trellis. The finite correcting capability of convolutional codes make possible the pruning of states or paths from the error-trellis. Decoding with improved error-trellis makes possible the use of convolutional codes with a larger error correcting capability than now considered practical.

12:15 PM **L U N C H at the Commons, Dining Room B (Upstairs)**

2:00 PM **Robert M. Gagliardi - FREQUENCY SYNTHESIZER FOR FREQUENCY HOPPED DESIGN COMMUNICATIONS**

* The design of the frequency synthesizer in a frequency hopped (FH) communication system directly effects decoding performance. These effects are being analyzed in terms of key synthesizer parameters, such as frequency range, loop bandwidths, frequency resolution, loop response time, for different types of FH modulation formats (coherent and non-coherent). A proposed study to further examine phase noise effects and nonlinear synthesizer models will be presented. The result would produce optimal design procedures for basic FH systems.

2:30 PM **Eric W. Siess/Charles L. Weber - ACQUISITION OF DIRECT SEQUENCE SPREAD SPECTRUM SIGNALS WITH MODULATION AND JAMMING**

* Receivers are developed and their acquisition performance is predicted for modulated DS signals in the presence of CW and packed time jamming. The need for the acquisition receiver to sense and adapt to jamming is demonstrated. A proposed adaptive receiver provides considerable jamming protection; its acquisition performance bounds the performance of all adaptive acquisition receivers.

3:00 PM **C O F F E E B R E A K**

3:30 PM **Andreas Polydoros - WIDEBAND DETECTION OF LPI WAVEFORMS**

* The purpose of this talk will be to briefly review the theoretical framework for the receiver operating characteristics of wideband LPI receivers, point out some questions and ambiguities, and finally establish certain topics of future research.

4:00 PM **Sun Y. Kung - VLSI ARRAY PROCESSORS FOR COMMUNICATION AND SIGNAL PROCESSING**

* To realize the potential impact of VLSI on communication and signal processing technologies, it is crucial to have a cohesive understanding of its applicational, algorithmical and architectural implications. For example, VLSI is already offering real-time processing for the currently prevailing computations such as FFT or 1-D and 2-D convolutions. Forthcoming VLSI computing hardware packages are likely to include modern linear algebraic and adaptive techniques, such as Kalman filtering, adaptive transversal or lattice filtering, SVD based spectrum analysis, two-dimensional processing, etc. In this presentation, we shall discuss how such processing requirements may be very efficiently handled by VLSI systolic/wavefront type arrays.

4:30 PM **CONSULTATIONS**

6:00 PM **COCKTAILS (Faculty Center, Patio)**

7:00 PM **DINNER (Faculty Center, Room C)**

Friday, October 26, 1984

Auditorium, Seaver Science Center

8:00 AM **Robert A. Scholtz - FLEXIBLE ARRAYS, PRECORRELATION FILTERING, AND ADAPTIVE SPREAD SPECTRUM SYSTEMS**

* This presentation traces the evolution of a line of research from elementary discussions of the Microwave Power Satellite to direct sequence code tracking and adaptive interference rejection. Two interesting results are presented: (a) the design of a high-performance nested control algorithm for flexible retrodirective arrays, and (b) the optimization of precorrelation interference-rejection, filter design in a spread spectrum receiver. Further work on the conversion of these structures to adaptive systems will be described, and possible future research areas will be mentioned.

8:45 AM **Lloyd J. Griffiths - ADAPTIVE ARRAYS HAVING FEW ELEMENTS**

* This talk is concerned with the implementation of adaptive nulling techniques and broadband direction finding in arrays having a small ($n<5$) number of elements. The degree to which methodologies developed for large arrays are applicable to small arrays is discussed. Element location and the efficient utilization of time windows from each element are shown to be important aspects of the problem.

9:15 AM **C O F F E E B R E A K**

9:30 AM **Wei-Chung Peng - ADAPTIVE TWO-WAY COMMUNICATION IN THE PRESENCE OF JAMMING**

* With the mean-time-to-success of a packet as the performance measure, we set up a two way communication link model and compare the performance of different adaptive strategies in the presence of jamming from the game theory point of view.

9:45 AM **John A. Silvester - ADAPTIVITY IN SPREAD SPECTRUM NETWORKS**

* Proposed research in SS network adaptivity and code selection protocols will be discussed. Preliminary results concerning the accuracy of our approximate analytical models of delay as compared to simulation will be presented.

10:15 AM **Victor O.K. Li - PERFORMANCE ANALYSIS OF CODE DIVISION MULTIPLE ACCESS (CDMA) SPREAD SPECTRUM NETWORKS**

* A model is developed to analyze the performance of a multihop Code Division Multiple Access (CDMA) network using the frequency-hopped spread spectrum technique. Each transmission is preceded by a preamble used by the receiver for acquisition. The preamble is encoded in the receiver's code while the message part is encoded in the PN code which is unique to the particular transmitter. Steady state results for the one-hop and end-to-end throughputs are obtained. This model will be illustrated by examples.

10:45 AM **ADJOURNMENT**

ATTENDEES - ARO REVIEW

Dr. Richard C. Booton, Jr., TRW
Phone: (213) 535-2103

Dr. Larry Hatch (NSA)
Phone: (301) 859-6438

Dr. Gaylord Huth (AXIOMATIX)
Phone: (213) 641-8600

Dr. Richard Leibler (NSA)
Phone:

Dr. S. Brent Morris (NSA)
Phone: (301) 859-6659

Dr. Douglas Nelson (DoD)
Phone: (301) 859-6559

Dr. Charles J. Powers (DoD)
(301) 859-6206

Dr. William Sander (ARO)
Phone: (919) 549-0641

Dr. Paul Sass (ARO)
Phone: (201) 544-5680

Dr. James Robert Sowers (US Army)
Phone: (703) 347-6666

Dr. Steve Stearns (GTE)

Dr. Sheldon Carroll (GTE)
Dr. Ken Gray (Motorola)

Dr. Marvin Simon (JPL)
(818) 354-3955

Dr. Tom Carter (TRW)

Jerry Wong (IBM)

Ed Ruth (IBM)

Jim Curry (IBM)

Mack Johnson (IBM)

Bob Schellhorn (IBM)

John Lynch (IBM)

USC ATTENDEES

Robert Gagliardi
Solomon Golomb
Lloyd Griffiths
P. Vijay Kumar
Sun-Yuan Kung
Victor Li
Andreas Polydoros
Irving Reed
Robert Scholtz
Leonard Silverman
John Silvester
Charles Weber
Lloyd Welch

USC STUDENTS

Sabah Alquaddoomi (Graduated 1982)
Thomas Carter (Graduated 1983)
Unjeng Cheng (Graduated 1981)
Mary Ann Kiefer
Kiseon Kim
Peter Pawlowski
Wei-Chung Peng
Nikos Pronius
Arie Reichman (Graduated 1984)
John Robbins
Eric Siess (Graduated 1983)
Elvino Sousa
Gregory Yovanof

END

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