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Form Approved
OMB No. 0704-0188

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1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 12/02/96	3. REPORT TYPE AND DATES COVERED Semi-Annual 5/1/96 - 10/31/96
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4. TITLE AND SUBTITLE Numerical and Symbolic Algorithms for Application Specific Signal Processing	5. FUNDING NUMBERS N00014-93-1-0686
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Research Laboratory of Electronics Massachusetts Institute of Technology 77 Massachusetts Avenue Cambridge, MA 02139	8. PERFORMING ORGANIZATION REPORT NUMBER
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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research Ballston Tower One 800 North Quincy Street Arlington, VA 22217-5660	10. SPONSORING/MONITORING <b style="font-size: 2em;">19961205 034
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11. SUPPLEMENTARY NOTES
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12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.	12b. DISTRIBUTION CODE
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13. ABSTRACT (Maximum 200 words)

Work by Prof. Oppenheim and his collaborators is summarized here

14. SUBJECT TERMS	15. NUMBER OF PAGES
DTIC QUALITY INSPECTED 4	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL
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Semi-Annual Report
Numerical and Symbolic Algorithms for
Application Specific Signal Processing

May 1, 1996 - October 31, 1996

Research Organization: Digital Signal Processing Group
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Grant Number: N00014-93-1-0686
OSP Number: 60314

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I. Introduction

During the period of this grant, our detailed technical accomplishments are reported through journal articles and technical reports. Each of our semi-annual reports highlight certain technical areas.

II. Energy Efficient Implementation of DSP Systems

Over the last few months, we've been working on several new approaches and tools for the energy efficient implementation of DSP systems. Specifically we have focused on three areas which include approximate filtering techniques, power reduction in delay line structures, and power estimation at the Register Transfer Level (RTL) level.

We have proposed a low-power filtering technique in which the number of sections used in a IIR or FIR digital filter structure is adaptively changed in order to dynamically control the net stopband attenuation. This technique is based on an efficient measure of the input/output power differential, and has been shown empirically to be effective in reducing power consumption without noticeable quality degradation. Currently we are exploring the theoretical rationale and statistical properties of this technique, and have shown that under certain assumptions the technique converges to a suitably-defined optimal number of filtering sections. By developing a theoretical framework for analyzing the performance of the low-power filtering technique, we will be able to quantify its performance and limitations.

We have also been working on reducing power consumption in long delay line structures commonly found in signal processing and communications applications (e.g., matched filters). Data shifting in the delay lines can be power hungry due to high clock and register power consumption. We have been working on an approach to significantly reduce the switched capacitance at a fixed power supply voltage. The basic idea involves using N-level parallelism to reduce clock frequencies without loss in functional throughput (i.e., the I/O data rate is fixed). For $N=2$, two parallel shift registers are used each with half the original length and clock frequency. Without accounting for the multiplexor overhead, this results in a factor of 2 power reduction without loss in performance. In general, an N-fold reduction in power is achieved for N-level parallelism. Unfortunately, the overhead circuitry associated with parallelism (routing, multiplexors, control signal generation, etc.) limits the amount of power reduction possible and results in an "optimum" level of parallelism. We have performed layout of various matched filter architectures and simulated power consumption using switch level simulators.

Finally, we have been involved with developing a power estimation tool that works with a structural circuit description. The tool is capable of estimating circuit power dissipation by monitoring signal transitions on all circuit nets based on the validation test vectors used. Unlike commercial power estimators such as PowerMill, this tool does not work at the transistor level. It works at the gate/module level and as a result, large systems can be simulated for a big number of input vectors. The goal is, however, not to compromise estimation accuracy. The user can provide information about the internal capacitive nodes of low-level modules and link them to input transitions. In such a way, both simulation speed and estimation accuracy are preserved. Each net is annotated with three different capacitance values (gate, junction, and routing capacitance). The model accounts for the non-linear capacitance variations with voltage associated with the gate and junction components. Therefore accurate power estimates at different supply voltages can be obtained at an RTL level. The extra transitions due to glitching are also accounted for by using a reasonable timing model. Second order effects such as reduced swing on some nodes (e.g., pulling a node up using a NMOS device) are also included. This tool allows a

hybrid approach in which some modules in the design can be evaluated using simulation (e.g., a multiplier whose energy consumption is very strongly dependent on input patterns) and others using high-level black box models (e.g., a SRAM array where the energy per access is independent of data patterns). Preliminary simulation results are very encouraging. The power consumption of register and adder structures have been simulated and appear to be within 20% of SPICE simulations. Such a tool can be used to explore the design space at the RTL level, without having to map a design to layout for accurate power estimation. After validating this tool using larger design examples, we plan to use it to evaluate the power efficiency of various DSP filter architectures.

III. Algorithm-Based Fault Tolerance

This section describes our research progress in the area of Algorithm-Based Fault Tolerance. Our recent work in this area has investigated methods for introducing controlled or systematic redundancy into dynamic systems that implement signal processing operations. This line of investigation originated in the algebraic setting of state machines used to implement group or semigroup computations. In such structures, the composition of an input with a present state constitutes the computation, with the next state being the result, [1]. Using the algebraic framework that was developed in the thesis [2], we have been able to show that in order to introduce redundancy into a given group (or semigroup) machine, we need to design a larger machine that performs a computation in a larger group (or semigroup). The original (semi)group is mapped into this larger (semi)group through an algebraic homomorphism. The rich theory of decomposition for machines allowed us to take a closer look at the actual structure of the redundant machine. For instance, it is known that a group machine can be decomposed into a subgroup machine and a coset leader machine, [1]. In the case of separate parity checks for computations in groups, we have been able to show that fault tolerance is introduced by replicating the coset leader machine, whereas for non-separate checks we need to decompose the redundant machine using a subgroup other than the one in which the original computation is performed. Most of the above results can be extended to the class of group homomorphic systems studied in [3].

In order to obtain more detailed and constructive results, our recent focus has been on linear, time-invariant (LTI) state-space models, [4], [5]. We anticipate similar results for systems modeled by factored state-variable representations [6] or signal flow graphs, which are important in a variety of signal processing tasks. A redundant version of a given LTI state-space model is obtained by embedding it in a larger model using a "state homomorphic mapping." This mapping takes the states of the original non-redundant system into a larger redundant space, while encoding -- within this larger space -- the properties of the original system. The added redundancy can be used to obtain error detection and correction under hardware failures.

More specifically, the state of the redundant system at any given time allows us to calculate the original state vector through a linear mapping. We show that, in order for this to happen, it is necessary that all the original modes appear in the redundant system. In addition, the redundant system has modes that are observable but unreachable under fault-free conditions; these modes are initialized to zero and, because they are unreachable, manifest themselves only if a fault takes place. By detecting the presence of such unreachable modes, we can detect, locate and subsequently correct errors.

All fault-tolerant versions of a given non-redundant LTI state-space system can be put into a standard form through similarity transformations. In the standard form, the redundant modes are seen by inspection to be unreachable, and the coupling between the original and the redundant modes is unidirectional: the original modes can be affected by the redundant

ones, but not vice-versa. The coupling of the redundant modes to the original ones is unimportant under fault-free conditions, because the redundant modes are never excited under these conditions. However, the coupling can be an important factor when considering the error detecting and correcting capabilities of the fault-tolerant design.

Our framework is general enough to include previously developed fault-tolerant schemes for LTI state-space systems, such as modular redundancy, or the "checksum" scheme developed by Abraham in [7]. However, we are now also able to develop more advanced checksum schemes that resemble linear error-correcting codes. In such schemes, the parity checks (i.e., the set of linear equations that check whether the redundant modes have been excited or not) form a linear error correcting code. The code allows one to easily detect and locate one or more transient faults (depending on the number of modes that have been added in the redundant system). Error correction is straightforward, once we locate the erroneous state variables. Given any set of parity checks, one can always use an appropriate similarity transformation in order to transform these checks to a linear code. Assuming that a single fault corrupts a single state variable, we can provide single error correction at the expense of very few additional state variables. For example, by adding $O(\log(N))$ redundant variables, we provide single-error-correction to a system of order N .

We are currently investigating the possibility of extending our results to a class of dynamic systems in state form known as "max-plus systems." These systems are nonlinear, but have some analogies with traditional LTI state-space systems, in that they are described by analogous state evolution and output equations. The only difference is that regular addition is replaced by the MAX operation, and regular multiplication is replaced by + (i.e. regular addition). The resulting setting is that of minimax algebra, and has been studied extensively, [8]-[10]. For example, $\text{MAX}(3+x,5)=7$ can be thought of as a linear equation in minimax algebra --- corresponding to $3x+5=7$ in traditional linear algebra. With this type of substitution, a max-plus system looks like an LTI state-space model. Max-plus systems are used to model a large class of discrete-event processes, with documented or potential applications for scheduling and routing in various types of networks (e.g., for computing, signal processing, communication, transportation, or manufacturing), [8]-[10].

Due to the lack of an inverse for the MAX operation, the introduction of redundancy into a max-plus linear system aims mostly at detecting (rather than correcting) errors, and at maintaining a desired level of performance despite the existence of faults. For example, by ensuring that strategic tasks are duplicated by additional processors in a signal processing network, one could guarantee that the (main) functionality of the network would be maintained despite the breakdown of certain processors. As another example, in a railway network one hopes to ensure robust performance despite malfunctions in some trains (or stations) by introducing additional train links between the most important stations.

We have been able to show that all redundant max-plus systems that can be used to protect a given original system (again through a "state homomorphic mapping") are similar to a system in a certain standard form. The standard system contains the original state variables intact, along with a number of parity state variables. The choice of these parity variables is arbitrary; the coupling between them and the original ones, however, is not necessarily unidirectional (as was the case for LTI state-space systems) and has to be carefully chosen so that the original variables evolve in the same way as they would in the original system. Using this framework, we have developed new examples of fault-tolerant max-plus systems. Most of these examples are based on state variable replication, a scheme in which we selectively replicate some of the most important state variables.

We expect to be looking further at ways to achieve robust performance in max-plus linear systems and other dynamic systems, and are optimistic that our paradigm will be fruitful in these other contexts.

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V. Publications During the Reporting Period

Journal Articles

G.W. Wornell, "Emerging Applications of Multirate Signal Processing and Wavelets in Digital Communications," *Proceedings of the IEEE, Special Issue on Application of Wavelets*, April 1996.

G.W. Wornell and M.D. Trott, "Efficient Signal Processing Techniques for Exploiting Transmit Antenna Diversity on Fading Channels," to appear in *IEEE Transactions on Signals Processing, Special Issue on Signal Processing for Advanced Communications*, January 1997.

J.M. Ooi and G.W. Wornell, "Fast Iterative Coding Techniques for Feedback Channels," submitted to *IEEE Transactions on Inform. Theory*.

J.M. Ooi, S.M. Verbout, J.T. Ludwig and G.W. Wornell, "A Separation Theorem for Periodic Sharing Information Patterns in Decentralized Control," submitted to *IEEE Transactions on Automatic Control*.

J.M. Ooi, S.M. Verbout and J.T. Ludwig, "The Min-Sum Problem on Tanner Graphs with Cycles is NP-Complete," submitted to *European Transactions on Telecommunications*.

Conference Papers

K.M. Cuomo, A.V. Oppenheim and R.J. Barron, "Channel Equalization for Self-Synchronizing Chaotic Systems," IEEE International Conference on Acoustics, Speech, and Signal Processing, ICASSP-96, Atlanta, May 1996.

W.M. Lam and G.W. Wornell, "Multiscale Analysis of Fractal Point Processes and Queues," IEEE International Conference on Acoustics, Speech and Signal Processing, ICASSP-96, Atlanta, May 1996.

H.C. Papadopoulos and G.W. Wornell, "A Class of Stochastic Resonance Systems for Signal Processing Applications," IEEE International Conference on Acoustics, Speech, and Signal Processing, ICASSP-96, Atlanta, May 1996.

J.M. Winograd, S.H. Nawab and A.V. Oppenheim, "FFT-Based Incremental Refinement of Suboptimal Detection," IEEE International Conference on Acoustics, Speech, and Signal Processing, ICASSP-96, Atlanta, May 1996.

G.W. Wornell and M.D. Trott, "Signal Processing Techniques for Efficient Use of Transmit Diversity in Wireless Communications," IEEE International Conference on Acoustics, Speech, and Signal Processing, ICASSP-96, Atlanta, May 1996.

A. Narula, M.D. Trott, and G.W. Wornell, "Information-Theoretic Analysis of Multiple-Antenna Transmission Diversity for Fading Channels," International Symposium on Inform. Theory and Appl., Victoria, Canada, September 1996.

S.H. Isabelle and G.W. Wornell, "Recursive Multiuser Equalization for CDMA Systems in Fading Environments," Allerton Conference Commun. Contr., Signal Processing, Illinois, October 1996.

B. Chen and G.W. Wornell, "Efficient Channel Coding for Analog Services using Chaotic Systems," submitted for the IEEE GLOBECOM, London, November 1996.

J.M. Ooi and G.W. Wornell, "Decentralized Control of a Multiple Access Broadcast Channel: Performance Bounds," submitted for the International Conference on Dec. Control, Japan, December 1996.

J.M. Winograd and S.H. Nawab, "Probabilistic Complexity Analysis of Incremental DFT Algorithms," submitted for the International Conference on Acoustics, Speech, and Signal Processing, ICASSP-97, Munich, April 1997.

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