REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE 12/3/2002	3. REPORT TYPE AND DATES COVERED Final 9/1/1996 – 8/31/2002

4. TITLE AND SUBTITLE

Low Energy Electronics Design for Mobile Platforms

5. FUNDING NUMBERS
DAAH04-96-0377

DAAH04-96-1-0377

6. AUTHOR(S)
J. East, A. Hero, L. Katehi, S. Lafortune, P. Mazumder, D. Neuhoff, K. Sarabandi, R. Smith, W. Stark, D. Teneketzis, K. Wasserman

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The University of Michigan, EECS
1301 Beal Avenue
Ann Arbor, MI 48109-2122

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

35890.1-EL-MUR

11. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT	12 b. DISTRIBUTION CODE
Approved for public release; distribution unlimited.	

13. ABSTRACT (Maximum 200 words)

In order to address the need for low-energy electronics design for mobile platforms in future Army communication systems a multidisciplinary effort is needed to investigate system and component design, simulation and optimization techniques. The emphasis in this research project is on the optimization, from a systems perspective, of energy requirements for a given performance level incorporating realistic models of device and circuit characteristics and energy consumption. The objectives of our project are to carry out detailed investigations to determine the best possible approaches and design methodologies to achieve significant energy reduction in a mobile platform performing various functions including communications, surveillance, detection, diagnostics and GPS direction finding.

14. SUBJECT TERMS	15. NUMBER OF PAGES 17
	16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

20030403 010

MASTER COPY: PLEASE KEEP THIS "MEMORANDUM OF TRANSMITTAL" BLANK FOR REPRODUCTION PURPOSES. WHEN REPORTS ARE GENERATED UNDER THE ARO SPONSORSHIP, FORWARD A COMPLETED COPY OF THIS FORM WITH EACH REPORT SHIPMENT TO THE ARO. THIS WILL ASSURE PROPER IDENTIFICATION. NOT TO BE USED FOR INTERIM PROGRESS REPORTS; SEE PAGE 2 FOR INTERIM PROGRESS REPORT INSTRUCTIONS.

MEMORANDUM OF TRANSMITTAL

U.S. Army Research Office
ATTN: AMSRL-RO-BI (TR)
P.O. Box 12211
Research Triangle Park, NC 27709-2211

- ☐ Reprint (Orig + 2 copies)
- ☐ Manuscript (1 copy)
- ☐ Technical Report (Orig + 2 copies)
- ☒ Final Progress Report (Orig + 2 copies)
- ☐ Related Materials, Abstracts, Theses (1 copy)

CONTRACT/GRANT NUMBER: DAAH04-96-0377

REPORT TITLE: Low Energy Electronics Design for Mobile Platforms

is forwarded for your information.

SUBMITTED FOR PUBLICATION TO (applicable only if report is manuscript):

Sincerely,

Wayne Stark

Wayne E. Stark

TITLE

Low Energy Electronics Design For Mobile Platforms

Final Report for Grant DAAH04-96-1-0377
For the period September 1, 1996 to August 31, 2002

Principal Investigators

Jack East, Alfred Hero, Linda Katehi, Stéphane Lafortune, Pinaki Mazumder, David L. Neuhoff, Kamal Sarabandi, Robert Smith, Wayne Stark, Demosthenis Teneketzis, Kimberly Wasserman

Submitted December 3, 2002 to
the US Army Research Office

Electrical Engineering and Computer Science
The University of Michigan
Ann Arbor, MI 48109

Cover Page

Executive Summary

In order to address the need for low-energy electronics design for mobile platforms in future Army communication systems a multidisciplinary effort is underway to investigate system and component design, simulation and optimization techniques. The emphasis in this project is on the optimization, from a systems perspective, of energy requirements for a given performance level incorporating realistic models of device and circuit characteristics and energy consumption. The objectives of our program are to carry out detailed investigations to determine the best possible approaches and design methodologies to achieve significant energy reduction in a mobile platform performing various functions including communications, surveillance, detection, diagnostics, and GPS direction finding.

In order to systematically attack the problem of minimum energy consumption electronic design of mobile platforms from a systems perspective we have defined four design layers. The four layers are: the distributed system layer, the local integration layer, the processing layer, and the device layer.

At the *distributed system layer* we have developed a methodology for simulation environment used to studying tradeoffs between the frequency of communication of position data and the position estimation accuracy in a situation awareness scenario involving a set of mobile platforms that includes energy consumption of the mobiles. We have studied the problems of supervisory control and diagnostics for systems with decentralized information. Our results lead to control and diagnostics strategies that are energy efficient in the sense that they minimize the amount of communication between the mobile nodes. We have developed energy and spectrally efficient media access control protocols for ad hoc wireless networks. The high performance attained by these protocols derives from exploiting the channel memory induced by shadowing, and appropriately combining corrupted packets with retransmitted packets. We have also investigated the relationship between deadlock-free information structures and concurrency. Such a relationship allows us to characterize the speed of response of mobile networks to various events, and provides guidelines on how to organize the information of mobile networks for routing purposes.

At the *local integration layer* we have developed a computationally efficient algorithm for selecting the energy-optimal configuration of sensors that achieves desired diagnosability properties. We have also developed a new technique for implementing the control logic that significantly reduces memory requirements at the price of a small amount of on-line computations.

At the *processing layer* we have investigated different signal and information processing algorithms used in a mobile platform for their energy efficiencies and system performance. For an equalizer we have determined the fundamental tradeoff between the performance (mean squared error) and power consumption of digital circuitry as the number of quantization levels in the received signal and tap coefficients vary. For a turbo decoder we have determined the tradeoff between performance (bit error probability) and power consumption as the number of quantization levels in a turbo decoder vary and as the number of iterations change. We have also investigated performance in various hostile environments such as multipath fading and partial-band interference. In addition we have developed algorithms for code combining with turbo codes and have analyzed the performance in a spread-spectrum systems. For a joint source and channel code we have determined the tradeoff in performance and power consumption as the number of computations assigned to the source code and channel code vary. Finally, we have found new error control codes that are better than all previously known codes for short packet sizes in terms of performance (minimum Euclidean distance) versus signal-to-noise ratio.

At the *device layer* we have developed models for high efficiency plannar antennas and methods to analyze the efficiency useful in optimizing overall system performance. We have developed numerical techniques to determine propagation of radio waves that will be used in performance evaluation of communication systems. We have developed experimental techniques to measure nonlinear device performance for a power amplifier used in a communication system and have developed numerically efficient techniques to simulation nonlinear circuits. Finally, we have been developing methodologies to reduce power consumption in digital circuits using spectral techniques and low power quantum CMOS circuitry.

Finally, in order to verify the design tradeoffs and their impact on the overall system, we have developed a methodology for a simulation-based optimization environment that incorporates various aspects of the communications part of a mobile platform. The optimization procedure that we have synthesized makes use of the structure in this complex system by decomposing the overall optimization tasks into three layers (network, processing, and device) that are interfaced by passing of key variables and tables. This optimization procedure employs different types of optimization at the different layers. Overall a simulated annealing algorithm for global optimization is used and shown to be computationally tractable. Furthermore we have shown the resulting decomposition of the simulation is still globally optimal.

1 Publications Suppored By the MURI

[1] P. Mazumder, "Multiple-valued logic circuits using resonant tunneling diodes," *Proceedings of the 1997 Advanced Workshop on Frontiers in Electronics*, 1997.

[2] P. Mazumder, "Ultrafast circuits and systems using quantum devices," *Proceedings of the 1997 Advanced Workshop on Frontiers in Electronics*, 1997.

[3] S.-J. Oh and K. M. Wasserman, "Spreading gain control in random access direct-sequence spread spectrum data networks," in *Proceedings of the 6th IEEE International Conference on Universal Personal Communications*, volume 1, pp. 48–52, 1997.

[4] J. D. Shumpert, T. Ellis, G. M. Rebeiz, and L. P. B. Katehi, "Millimeter-wave propagation in photonic band-gap structures," Technical report, Radiation Lab Report RL-953, The University of Michigan, 1997.

[5] I. Sharfer and A. O. Hero, "A maximum likelihood digital receiver using coordinate ascent and the discrete wavelet transform," *IEEE Transactions on Signal Processing*, April 1997.

[6] M. Sampath, S. Lafortune, and D. Teneketzis, "Active diagnosis of discrete event systems," *Proceedings of the 36th IEEE Conference on Decision and Control Conference*, pp. 2976–2983, December 1997.

[7] T. Chiu and K. Sarabandi, "Electromagnetic scattering from targets above rough surfaces," *Proceedings of IEEE Transactions on Antennas and Propagation- URSI Symposium*, July 1997.

[8] J. D. Shumpert, T. Ellis, G. M. Rebeiz, and L. P. B. Katehi, "Microwave and millimeter-wave propagation in photonic band-gap structures," *1997 IEEE Antennas and Propagation Society (AP-S) International Symposium and URSI Radio Science Meeting*, July 1997.

[9] D. Zahn, K. Sarabandi, and K. F. Sabet, "Numerical simulation of scattering from rough surfaces: A wavelet-based approach," *IEEE Transactions on Antennas and Propagation URSI Symposium*, July 1997.

[10] G. R. Barrett and S. Lafortune, "Using bisimulation to solve discrete event control problems," *Proceedings of the 1997 American Control Conference*, pp. 2337–2341, June 1997.

[11] J. Papapolymerou, J. C. Cheng, J. East, and L. P. B. Katehi, "A micromachined high-Q X-band resonators," *IEEE Microwave and Guided Wave Letters*, June 1997.

[12] T. Nolan and W. Stark, "Analysis of product codes for frequency-hopped spread-spectrum with partial band interference," *Military Communications Conference*, pp. 603–607, November 1997.

[13] V. Borich, J.-H. Jong, J. East, and W. Stark, "Nonlinear effects of power amplification on multicarrier spread specturm systems," *International Microwave Symposium*, 1998.

[14] S. Kiatsupaibul and R. Smith, "On the solution of infinite horizon optimization problems through global optimization," Technical Report 98-19, Department of Industrial and Operations Engineering, University of Michigan, 1998.

[15] H. Marchand, O. Boivineau, and S. Lafortune, "On the synthesis of optimal schedules in discrete-event control problems with multiple goals," *SIAM Journal on Control and Optimization*, vol. 39, no. 2, pp. 612–632, 1998.

[16] S.-J. Oh and K. M. Wasserman, "Integration of voice and data traffic in cdma networks using dynamic spreading gain control," in *Proceedings of the IEEE International Conference on Communications*, volume 2, pp. 968–972, 1998.

[17] S.-J. Oh and K. M. Wasserman, "Adaptive resource management for ds-cdma networks subject to energy constraints," in *Proceedings of the IEEE 17th Annual Conference on Computer Communications (INFOCOM'98)*, volume 2, pp. 556–563, 1998.

[18] K. Sarabandi and D. Zahn, "Numerical simulation of scattering from rough surfaces using an iterative physical optics approach," *Proceedings of IEEE Transactions on Antennas and Propagation and URSI Symposium*, 1998.

[19] P. Mazumder, S. Kulkarni, M. Bhattacharya, J. P. Sun, and G. I. Haddad, "Digital circuit applications of resonant-tunneling devices," *Proceedings of the IEEE*, vol. 86, no. 4, , April 1998.

[20] J. P. Sun, G. I. Haddad, P. Mazumder, and J. Schulman, "Resonant tunneling diodes: models and properties," *Proceedings of the IEEE*, vol. 86, no. 4, , April 1998.

[21] M. D. Casciato and K. Sarabandi, "High frequency radio wave diffraction from singly curved surfaces: A heuristic approach," *IEEE Transactions on Antennas and Propagation*, August 1998. Submitted for publication.

[22] T. Chiu and K. Sarabandi, "Field of a short dipole above a dielectric half-space with rough interface," *IEEE Transactions on Antennas and Propagation*, August 1998. Submitted for publication.

[23] R. Debouk, S. Lafortune, and D. Teneketzis, "A coordinated decentralized protocol for failure diagnosis of discrete event systems," *Proceedings of WODES 1998, the International Workshop on Discrete Event Systems*, pp. 138–143, August 1998.

[24] A. O. Hero and R. Gupta, "Optimal bit allocation strategies for reduced power adaptive channel equalization," *Proceedings of the 1998 International Symposium on Information Theory*, p. 183, August 1998.

[25] J. H. Kang and W. E. Stark, "Performance of turbo-coded FH-SS with partial-band interference," in *1998 IEEE International Symposium on Information Theory*, p. 456, August 1998.

[26] J. Lim and D. Neuhoff, "Allocating complexity between source and channel coding," *Proceedings of the Workshop on Data Compression Processing Techniques for Missile Guidance Data Links*, Dec 1998.

[27] G. R. Barrett and S. Lafortune, "Bisimulation, the supervisory control problem and strong model matching for finite state machines," *Journal of Discrete Event Dynamical Systems: Theory and Applications*, vol. 8, no. 4, pp. 377–429, December 1998.

[28] G. R. Barrett and S. Lafortune, "On the synthesis of communicating controllers with decentralized information structures for discrete-event systems," *IEEE Conference on Decision and Control*, December 1998. 1998 CDC Best Student Paper Award.

[29] R. Debouk, S. Lafortune, and D. Teneketzis, "Coordinated decentralized protocols for failure diagnosis of discrete event systems," *Proceedings of CDC 1998, the IEEE Conference on Decision and Control*, December 1998.

[30] J. Lim, D. L. Neuhoff, and T. Nolan, "Allocating complexity between source and channel coding," *Proceedings of the Workshop on Data Compression Processing Techniques for Missile Guidance Data Links*, December 1998.

[31] M. Bhattacharya and P. Mazumder, "Noise margins of threshold logic gates containing resonant tunneling diodes," *Proceedings of the 1998 8th Great Lakes Symposium on VLSI*, February 1998.

[32] P. Mazumder, S. Kulkarni, M. Bhattacharya, and A. F. Gonzalez, "Design and simulation of resonant tunneling diode circuits," *Proceedings of the 11th International Conference on VLSI Design*, January 1998.

[33] D. Zahn, K. Sarabandi, and K. F. Sabet, "Numerical simulation of scattering from rough surfaces: A wavelet-based approach," *IEEE Transactions on Antennas and Propagation*, January 1998. Submitted for publication.

[34] M. Sampath, S. Lafortune, and D. Teneketzis, "Active diagnosis of discrete event systems," *IEEE Transactions on Automatic Control*, pp. 908–929, July 1998.

[35] M. Casciato and K. Sarabandi, "A novel approach to high frequency diffraction from curved, perfectly conducting surfaces," *IEEE Antennas and Propagation URSI Symposium*, June 1998. Winner of second prize in IEEE AP-S'98 student paper contest.

[36] N. Deb, J. Xiong, M. Bhattacharya, S. Kulkarni, and P. Mazumder, "Switching speed and power consumption of bistable q-mos circuits," *Third IEEE Silicon Nanoelectronic Workshop*, June 1998.

[37] T. Ellis, J. D. Shumpert, L. P. B. Katehi, and G. M. Rebeiz, "Do two dimensional periodic structures exhibit photonic bandgap properties?," *1998 IEEE Antennas and Propagation Society (AP-S) International Symposium and URSI Radio Science Meeting*, June 1998.

[38] J. D. Shumpert, T. Ellis, G. M. Rebeiz, and L. P. B. Katehi, "Two-dimensional band-gap formation in finite substrates," *1998 IEEE Antennas and Propagation Society (AP-S) International Symposium and URSI Radio Science Meeting*, June 1998.

[39] K. Sarabandi and M. Casciato, "Radio wave diffraction from impedance surfaces with one dimensional general impedance variation," *IEEE Antennas and Propagation URSI Symposium*, June 21-26 1998.

[40] S. Kulkarni and P. Mazumder, "Full adder circuit design using rtds and mosfets," *Government Microcircuit Applications Conference*, March 1998.

[41] H. Hadinejad-Mahram and A. O. Hero, "Digital modulation classification using power moment matrices," *Proceedings of the IEEE International Conference on Speech, Acoustics and Signal Processing*, pp. 3285–3288, May 1998.

[42] S. Hong and W. E. Stark, "Low-complexity iterative block decoding algorithm for low-power wireless mobile communication applications," in *IEEE International Symposium on Wireless Communications*, p. 10, May 1998.

[43] J. Kang, W. Stark, and A. Hero, "Turbo codes for fading and burst channels," in *Global Communication Conference: Communication Theory Mini Conference*, pp. 40–45, November 1998.

[44] J. H. Kang and W. E. Stark, "Turbo codes for noncoherent FH-SS with partial-band interference," *IEEE Transactions on Communications*, pp. 1451–1458, November 1998.

[45] G. R. Barrett and S. Lafortune, "A novel framework for decentralized supervisory control with communication," *IEEE Conference on Systems, Man, and Cybernetics*, pp. 617–620, October 1998.

[46] M. J. Chu and W. E. Stark, "Asymptotic performance of a coded communication system with orthogonal signalling in partial-band interference," in *IEEE Military Communications Conference*, pp. 1003–1007, October 1998.

[47] A. O. Hero and R. Gupta, "Power vs performance tradeoffs for reduced resolution adaptive equalizers," *IEEE Conference on Military Communications (MILCOM)*, pp. 718–722, October 1998.

[48] S. Hong and W. E. Stark, "An efficient timing synchronization technique for FFT based multi-carrier direct-sequence spread-spectrum transceiver," in *IEEE Military Communications Conference*, pp. 713–717, October 1998.

[49] S. Hong and W. E. Stark, "VLSI circuit complexity and decoding performance analysis for low-power turbo-code and iterative block decoders design," in *IEEE Military Communication Conference*, pp. 708–712, October 1998.

[50] S. Hong, J. Yi, and W. E. Stark, "Low-complexity VLSI design and implementation of FFT based multi-carrier direct sequence spread spectrum transceiver," in *IEEE Workshops on Signal Processing Systems: Design and Implementation*, pp. 223–242, October 1998.

[51] S. Hong, J. Yi, and W. E. Stark, "VLSI design and implementation of low-complexity adaptive turbo-code encoder and decoder for wireless mobile communication applications," in *IEEE Workshops on Signal Processing Systems: Design and Implementation*, pp. 337–346, October 1998.

[52] J. H. Kang and W. E. Stark, "Performance of turbo-coded FH-SS with partial-band interference and Rayleigh fading," in *Proceedings of the 1998 IEEE Military Communications Conference*, pp. 977–981, October 1998.

[53] H. Marchand, O. Boivineau, and S. Lafortune, "On the synthesis of optimal schedules in discrete-event control problems with multiple goals," *Proceedings of IEEE Conference on Systems, Man, and Cybernetics*, October 1998.

[54] A. F. Gonzalez and P. Mazumder, "Multiple-valued signed-digit adder using negative differential-resistance devices," *IEEE Transactions on Computers*, vol. 47, no. 9, pp. 947–959, Sept. 1998.

[55] A. P. Andrew and W. E. Stark, "Low-density parity check codes for fading channels with memory," in *Proceedings of the 36th Annual Allerton Conference on Communications, Control, and Computing*, pp. 117–125, September 1998.

[56] A. F. Gonzalez and P. Mazumder, "Multivalued signed digit adder using rtds and cmos," *IEEE Transactions on Computers*, September 1998.

[57] A. O. Hero and R. Gupta, "Optimal bit allocation for the quantized LMS adaptive algorithm," *Proceedings of the 1998 IEEE Workshop on Statistical Signal and Array Processing*, pp. 128–131, September 1998.

[58] V. Borich, J. East, and G. Haddad, "A fixed-point harmonic balance approach for circuit simulation under modulated carrier excitation," *1999 International Symposium on Circuits and Systems*, 1999. Accepted for presentation.

[59] M. D. Casciato and K. Sarabandi, "A novel approach to high frequency diffraction from curved, perfectly conducting cylinders," *Proceedings of IEEE Antennas and Propagation and URSI Symposium*, vol. 2, pp. 1278–1281, 1999. Winner of 2nd prize in IEEE AP-S'98 student paper contest.

[60] R. Debouk, S. Lafortune, and D. Teneketzis, "Coordinated decentralized protocols for failure diagnosis of discrete event systems," *To appear in the Journal of Discrete Event Dynamical Systems: Theory and Applications*, 1999. An extended summary of this paper appeared in the Proceedings of SMC 1998, the 1998 IEEE Conference on Systems, Man and Cybernetics, pp. 3010-3011, October 1998.

[61] K. Sarabandi and M. D. Casciato, "Diffraction of radio waves from arbitrary one-dimensional surface impedance discontinuities," *IEEE Transactions on Antennas and Propagation*, vol. 47, no. 1, pp. 86–96, 1999.

[62] T. Uemura and P. Mazumder, "Transient analysis of bistable-monostable properties of quantum mos gates," *submitted to IEEE Transactions on Circuits and Systems*, 1999.

[63] K. Sarabandi and I. Koh, "Effect of canopy-air interface roughness on HF-VHF wave propagation in forest," *IEEE Transactions on Antennas and Propagation*, April 1999. Submitted for publication.

[64] J. D. Shumpert and L. P. B. Katehi, "On the use of higher order shanks' transforms in the numerical evaluation of the two-dimensional planar periodic free-space Green's functions," *Journal of Mathematical Physics*, Dec 1999. Submitted.

[65] J. D. Shumpert and L. P. B. Katehi, "Emulation of uniaxial substrate using doubly periodic dielectric substrate," *IEEE Transactions on Antennas and Propagation*, Dec 1999. Submitted.

[66] R. Debouk, S. Lafortune, and D. Teneketzis, "On an optimization problem in sensor selection for failure diagnosis," *Proceedings of the IEEE Conference on Decsion and Control*, pp. 4490–4495, Dec. 1999.

[67] C. Lott and D. Teneketzis, "Multi-channel allocation in single-hop mobil networks with priorities," *Proceedings of the 39th IEEE Conference on Decision and Control*, pp. 3550–3555, Dec. 1999.

[68] G. R. Barrett and S. Lafortune, "Some issues concerning decentralized supervisory control with communication," *To appear in the IEEE Conference on Decision and Control*, December 1999.

[69] R. Gupta and A. O. Hero, "Power vs performance tradeoffs for reduced resolution LMS adaptive filters," *IEEE Transactions on Signal Processing*, pp. 2772–2784, December 1999.

[70] K. Sarabandi and M. Casciato, "Diffraction of radio waves from arbitrary one-dimensional surface impedance discontinuities," *IEEE Transactions on Antennas and Propagation*, vol. 47, no. 1, pp. 86–96, January 1999.

[71] M. Casciato and K. Sarabandi, "Evaluation of diffracted fields for perfectly conducting cylinders from approximate surface currents," *IEEE Antennas and Propagation URSI Symposium*, July 1999.

[72] M. Casciato and K. Sarabandi, "Modeling surface currents on electrically large impedance cylinders - 2d, tm case," *IEEE Antennas and Propagation URSI Symposium*, July 1999.

[73] M. D. Casciato and K. Sarabandi, "Modeling surface currents on electrically large impedance cylinders - 2d, tm case," *Proceedings of IEEE Antennas and Propagation and URSI Symposium*, vol. 2, pp. 780–783, July 1999.

[74] K. Sarabandi and I. Koh, "Effect of canopy-air interface roughness on HF-VHF wave propagation in forest," *IEEE Antennas and Propagation URSI Symposium*, July 1999.

[75] D. Zahn and K. Sarabandi, "Numerical simulation of scattering from rough surfaces using a fast far-field iterative physical optics approach," *IEEE Antennas and Propagation URSI Symposium*, July 1999.

[76] M. Godavarti and A. O. Hero, "Stability bounds on the step size for the partial update lms algorithm," *Proceedings of the 1998 International Conference on Acoustics, Speech and Signal Processing*, pp. 1667–1680, March 1999.

[77] R. Gupta and A. O. Hero, "Theoretical aspects of power-reduction for adaptive filters," *Proceedings of the 1999 International Conference on Acoustics, Speech, and Signal Processing*, pp. 1245–1248, March 1999.

[78] T. Ji and W. E. Stark, "Modified Viterbi algorithm for predictive TCQ," in *Proceedings of the 1999 Data Compression Conference*, p. 532, Snowbird, Utah, March 1999.

[79] J. Kang and W. Stark, "Iterative estimation and decoding for FH-SS with slow Rayleigh fading," *IEEE Transactions on Communications*, March 1999. Submitted.

[80] T. Uemura and P. Mazumder, "Design and analysis of quantum-mos sense amplifier circuit," *submitted to the 9th Great Lakes Symposium on VLSI*, March 1999.

[81] S.-J. Oh and K. M. Wasserman, "Dynamic spreading gain control in ultiservice cdma networks," *IEEE Journal on Selected Areas in Commuinications*, vol. 17, no. 5, pp. 918–927, May 1999.

[82] J. D. Shumpert, *Modeling of Periodic Dielectric Structures (Electromagnetic Crystals)*, PhD thesis, The Unversity of Michigan, Nov 1999. Ph.D. thesis.

[83] J. D. Shumpert, W. J. Chappell, and L. P. B. Katehi, "Parallel-plate mode reduction in conductor-backed slots using electromagnetic band-gap substrates," *IEEE Transactions on Microwave Theory and Techniques*, vol. MTT-47, no. 11, pp. 2099–2105, Nov 1999.

[84] J. D. Shumpert, W. J. Chappell, and L. P. B. Katehi, "Parallel-plate mode reduction in conductor-backed slots using electromagnetic bandgap substrates," *IEEE Transactions on Microwave Theory and Techniques*, vol. 47, no. 11, pp. 2099–2014, November 1999.

[85] M. J. Chu, D. L. Goeckel, and W. E. Stark, "On the design of Markov models for fading channels," in *Proceedings of the 1999 IEEE Fall Vehicular Technology Conference*, October 1999. Accepted.

[86] T. Ji and W. E. Stark, "Turbo-coded ARQ schemes for DS-CDMA data networks over fading and shadowing channels," in *Proceedings of the 1999 IEEE Military Communications Conference*, Fort Monmouth, New Jersey, October 1999.

[87] A. P. Worthen, S. Hong, R. Gupta, and W. E. Stark, "Performance optimization of VLSI transceivers for low-energy communications systems," in *Proceedings of MILCOM'99*, October 1999.

[88] A. Garcia and R. Smith, "Existence of markov perfect equilibria (mpe) in undiscounted infinite horizon dynamic games," *Journal of Optimization Theory and Applications*, 2000. in press.

[89] S. Kiatsupaibul and R. Smith, "Discrete hit-and-run," Technical Report 00-05, Department of Industrial and Operations Engineering, University of Michigan, 2000.

[90] C. Lott and D. Teneketzis, "Stochastic routing in ad hoc wireless networks," in *Proceedings of the 39th IEEE Conference on Decision and Control, Sydney, Australia*, pp. 2302–2307, 2000.

[91] D. Reaume, E. Romeijn, and R. Smith, "Implementing Pure Adaptive Search for Global Optimization using Markov Chain Sampling," submitted to Mathematical Programming, 2000.

[92] D. Teneketzis and M. Andersland, "On partial order characterization of information structures," *Mathematics of Control Signals and Systems*, vol. 13, pp. 277–292, 2000.

[93] T. Yoo and S. Lafortune, "New results on decentralized supervisory control of discrete-event systems," *Proceedings of the 39th IEEE Conference on Decision and Control*, 2000.

[94] A. P. Worthen and W. E. Stark, "Interference mitigation in frequency-hopped spread-spectrum systems," in *Proceedings of the IEEE 6th International Symposium on Spread-Spectrum Techniques and Applications ISSSTA'00*, volume 1, pp. 58–62, New Jersey, USA, September 2000.

[95] A. P. Worthen and W. E. Stark, "On iterative receivers for non-coherent channels," To appear in *Proceedings of the IEEE International Symposium on Information Theory and Its Applications ISITA'00*, Honolulu, HI, November 2000.

[96] G. Barrett and S. Lafortune, "On the separation of estimation and control in discrete-event systems," *Proceedings of the 39th Conference on Decision and Control*, pp. 2258–2260, Dec. 2000.

[97] R. Debouk, S. Lafortune, and D. Teneketzis, "On the effect of communication delays in failure diagnosis of decentralized discrete event systems," *Proceedings of the 39th IEEE Conference on Decision and Control*, pp. 2245–2250, Dec. 2000.

[98] Y. L. Chen, S. Lafortune, and F. Lin, "Incremental model evolution and reusability of supervisors for discrete-event systems," *Automatica*, vol. 36, no. 2, pp. 243–259, Feb. 2000.

[99] M. Casciato and K. Sarabandi, "Fields of an infinitesimal dipole radiating near an impedance half-space by application of exact image theory," *IEEE Antennas and Propagation URSI Symposium*, July 2000.

[100] C. Lott and D. Teneketzis, "On the optimality of an index rule in multi-channel allocation for single-hop mobile networks with multiple service classes," *Probability in the Engineering and Informational Sciences*, vol. 14, no. 3, pp. 259–297, July 2000.

[101] K. Sarabandi and I. Koh, "Full-wave simulation of propagation channel parameters for a forest environment," *IEEE Antennas and Propagation URSI Symposium*, July 2000.

[102] K. Sarabandi and I. Koh, "Performance characterization of gps receivers under tree canopies," *IEEE Antennas and Propagation URSI Symposium*, July 2000.

[103] K. Sarabandi and I. Koh, "Multipole expansion of exact image theory and cosite interference simulation using mom," *IEEE Antennas and Propagation URSI Symposium*, July 2000.

[104] R. Gupta and A. O. Hero, "Transient behavior of fixed point LMS adaptation," in *Proc. IEEE Int. Conf. Acoust., Speech, and Sig. Proc.*, pp. 376–379, June 2000.

[105] S. Kiatsupaibul and R. Smith, "An analytically derived cooling schedule for simulated annealing," Technical report, Department of Industrial and Operations Engineering, University of Michigan, June 2000.

[106] J. Lim and D. Neuhoff, "Source-channel coding strategies: tandem coding vs. channel- optimized quantization," *2000 IEEE International Symposium on Information Theory*, June 2000.

[107] J. Lim and D. Neuhoff, "Source-channel coding strategies: tandem coding vs. channel- optimized quantization," *2000 IEEE International Symposium on Information Theory*, June 2000.

[108] N. Song and D. Teneketzis, "On a conjecture by coffman, flatto, and wright on stochastic machine minimization," *SIAM Journal on Computing*, vol. 30, no. 2, pp. 681–687, June 2000.

[109] M. Godavarti and A. O. Hero, "Stochastic partial update LMS algorithm for adaptive arrays," in *Proceedings of the 2000 Workshop on Sensors, Arrays, and Multi-channel Signal Processing*, pp. 322–326, March 2000.

[110] K. Sarabandi and M. Casciato, "Efficient calculation of the fields of a dipole radiating above an impedance surface," *IEEE Transactions on Antennas and Propagation*, March 2000. Submitted for publication.

[111] S. Hong, R. Gupta, W. Stark, and A. O. Hero, "Performance and complexity analysis of VLSI multi-carrier receivers for low-energy wireless communications," in *IEEE Vehic. Technol. Conf.*, pp. 1–5, May 2000.

[112] R. Gupta and A. O. Hero, "Power-performance tradeoffs and optimal bit allocation in reduced resolution adaptive filtering," *Signal Processing*, vol. 48, no. 10, pp. 2772–2784, Oct. 2000.

[113] W. E. Stark, H. Wang, A. Worthen, P. Liang, R. Gupta, J. East, A. Hero, S. Lafortune, and D. Teneketzis, "Low energy wireless communication system design," in *2000 Allerton Conf. on Comm., Cont. and Comput.*, Oct. 2000.

[114] G. R. Barrett and S. Lafortune, "Decentralized supervisory control with communicating controllers," *IEEE Transactions on Automatic Control*, vol. 45, no. 2, pp. 1620–1638, Sept. 2000.

[115] K. Sarabandi and I. Koh, "Full-wave simulation of propagation channel parameters for a forest environment," *IEEE Transactions on Antennas and Propagation*, September 2000. Submitted for publication.

[116] M. Godavarti and A. O. Hero, "Stability analysis of the sequential partial update lms algorithm," *Submitted to International Conference on Acoustics, Speech and Signal Processing*, vol. 6, pp. 3857–3860, 2001.

[117] M. Godavarti, A. O. Hero, and T. L. Marzetta, "Min-capacity of a multiple antenna wireless link in a static Rician fading environment," in *Proc. of IEEE International Symposium on Information Theory*, p. 57, 2001.

[118] T. Javidi, N. Song, and D. Teneketzis, "Expected makespan minimization on identical machines in two interconnected queues," *Probability in the Engineering and Informational Sciences*, vol. 15, pp. 409–443, 2001.

[119] T. Javidi and D. Teneketzis, "Sensitivity analysis for optimal routing policy in an ad hoc wireless network," Control Group Report CGR-02-01, University of Michigan, RM. 4230, EECS BLDG. Ann Arbor, MI 48109-2122 USA, 2001.

[120] N. O. Song and D. Teneketzis, "Discrete search with multiple sensors," Control Group Report CGR-01-10, University of Michigan, RM. 4230, EECS BLDG. Ann Arbor, MI 48109-2122 USA, 2001.

[121] T. Yoo and S. Lafortune, "On the computational complexity of some problems arising in partially-observed discrete-event systems," *Proc. 2001 Ameri. Contr. Conf.*, 2001.

[122] A. P. Worthen and W. E. Stark, "Unified design of iterative receivers using factor graphs," *IEEE Transactions on Information Theory*, pp. 843–849, February 2001.

[123] A. O. Hero and M. Godavarti, "Smart antennas for secure networks," in *Meeting of Intl. Union of Radio Sciences (URSI)*, Boulder, CO, January 2001.

[124] J. Lim and D. Neuhoff, "Joint and tandem source-channel coding with delay constraints," *2001 IEEE International Conference on Acoustics, Speech and Signal Processing*, May 2001. submitted on Nov. 2000.

[125] J. Lim and D. Neuhoff, "Joint and tandem source-channel coding with delay constraints," *2001 IEEE International Conference on Acoustics, Speech and Signal Processing*, May 2001. submitted on Nov. 2000.

[126] M.-F. Shih and A. O. Hero, "Unicast inference of network link delay distributions from edge measurements," in *Proc. IEEE Int. Conf. Acoust., Speech, and Sig. Proc.*, pp. 3421–3424, Salt Lake City, UT, May 2001.

[127] A.-G. Ziotopoulos, A. O. Hero, and K. Wasserman, "Estimation of network link loss rates via chaining in multicast trees," in *Proc. IEEE Int. Conf. Acoust., Speech, and Sig. Proc.*, pp. 2517–2520, Salt Lake City, UT, May 2001.

[128] C. Lott and D. Teneketzis, "On the optimality of an index rule in channel allocation for single-hop networks with multiple service classes and switching cost," submitted to *Probability in the Entineering and Informational Sciences*, Nov. 2001.

[129] T. Javidi and D. Teneketzis, "An approach to connection admission control in single-hop multi-service wireless networks with q0s requirements," Submitted, 2002.

[130] T. Javidi and D. Teneketzis, "Outage-based admission region in multi-class cellular systems," *IEEE Wireless Communications and Networking Conference*, pp. 124 –129, 2002.

[131] C. Lott and D. Teneketzis, "Stochastic routing in ad-hoc wireless networks i: Model and optimal policy structure," *IEEE/ACM Transactions on Networking*, 2002. submitted.

[132] C. Lott and D. Teneketzis, "Stochastic routing in ad-hoc wireless networks ii: Distributed algorithms," *IEEE/ACM Transactions on Networking*, 2002. submitted.

[133] T. Yoo and S. Lafortune, "Polynomial time verification of diagnosability of partially-observed discrete-event systems," *IEEE Transactions on Automatic Control*, 2002. To appear.

[134] T. Yoo and S. Lafortune, "Np-completeness of sensor selection problems arising in partially-observed discrete-event systems," *IEEE Transactions on Automatic Control*, 2002. Accepted for publication.

[135] T. Yoo and S. Lafortune, "A general architecture for decentralized supervisory control of discrete-event systems," *Discrete Event Dynamic Systems: Theory and Applications*, 2002. Accepted for publication.

[136] T. Yoo, S. Lafortune, and F. Lin, "An uniform approach for computing the supremal sublanguages arising in supervisory control theory," *Systems and Control Letters*, 2002. Submitted.

[137] W. E. Stark, H. Wang, A. Worthen, S. ane Lafortune, and D. Teneketzis, "Low energy wireless communication network design," *IEEE Wireless Communication Magazine*, pp. 60–71, August 2002.

[138] K. Sarabandi and I.-S. Koh, "Effect of canopy-air interface roughness on HF-VHF wave propagation in forest," *IEEE Transactions on Antennas and Propagation*, vol. 50, no. 2, pp. 111–121, Feb. 2002.

2 Scientific Personnel and Honors/Awards/Degrees

Senior Investigators

Jack East	Alfred Hero	Linda Katehi
Stéphane Lafortune	Pinaki Mazumder	David L. Neuhoff
Kamal Sarabandi	Robert L. Smith	Wayne E. Stark
Demosthenis Teneketzis	Kimberly Wasserman	

Students

Pablo Aghemo	Noel Baisa	George Barrett
William Benard	Oliver Boivineau	Mark Casciato
Houshou Chen	Richard Cheung	Mike Chu
Rami Debouk	Anurag Dod	Robby Gupta
Lee Harley	Sangjin Hong	Tara Javidi
Joseph Kang	Hyang Soo Kim	Sungkill Jim
Cheng-Po Liang	Jontae Lim	Chris Lott
Jeremy Muldavin	Thomas Panagiotis	John Shumpert
Rajiv Vijayakumar	Vuk Borich	Craig Wilsen
Jian-Jun Xiong	Daniel Zahn	Ketan Patel
Chia-Ning Peng	Mahesh Godavarti	

During the grant five senior investigators became IEEE Fellows (Alfred Hero, Stéphane Lafortune, Pinaki Mazumdar, Wayne Stark, Demos Teneketzis).

Ph.D. Candidate George Barrett received the Student Best Paper Contest for the 1999 IEEE Conference on Decision and Control. The paper is titled "On the Synthesis of Communicating Controllers with Decentralized Information Structures for Discrete-Event Systems."

Wayne Stark has served on the Army Strategic Planning Committee (1997). Linda Katehi and Wayne Stark served on the National Science Foundation/Dod Committee studying Foreign Technology in Wireless Communications (1999,2000) and received the 2002 IEEE Military Communications Conference Award for Technical Achievement recognizing long-term technical "Sustained Contributions to Military Communications". Al Hero served on a DARPA (2000) study pannel on multuser detection.

Faculty Names	Award	Date Awarded
Coffey, John		
East, Jack	EECS Research	1994
Hero, Alfred	IEEE Meritorious Service	1999
	IEEE Signal Processing Society Best Paper	1999
	IEEE Fellow	1998
	EECS Research	1996
	G.V.N. Lothrop Fellowship in Engineering	1983
	One U.S. Patent Pending	
Katehi, Linda	IEEE MTT-S 1st Prize Symposium Paper	1998
	IEEE MTT-S Judge's Award Symposium Paper	1998
	IMAPS Best Paper	1997
	IEEE Microwave Prize, MTT-S	1996
	IEEE Fellow	1995
	UM Faculty Recognition	1994
	EECS Research	1993
	URSI Young Scientist	1987
	NSF Young Investigator	1987
	IEEE A. Schelkunoff Award, AP-S	1985
	IEEE W.P. King Award, AP-S	1984
	Amelia Earhart Fellowship	1983
	One U.S. Patent	1998
	One U.S. Patent	1997
	Two U.S. Patents Pending	
Lafortune, Stéphane	IEEE Fellow	1999
	EECS Teaching	1998
	EECS Research	1995
	IEEE Control Systems Soc. Best Paper	1994
	NSF Presidential Young Investigator	1990
	NSF Engineering Research Initiation	1987
Mazumder, Pinaki	IEEE Fellow	1999
	EECS Research	1995
	Digital's Incentives for Excellence Award	
	DARPA Research Excellence Award	
	B.F. Goodrich National Collegiate Invention	
	NSF Research Initiation	
	Bell Northern Research Laboratory Faculty	
	Two U.S. Patents Under Review	

Faculty Names	Award	Date Awarded
Neuhoff, David	EECS Outstanding Achievement	1999
	IEEE Fellow	1994
	CoE Service	1992
	1938E Distinguished CoE Service	1978
	One U.S. Patent	1997
	Four U.S. Patents	1995
	One U.S. Patent	1994
Sarabandi, Kamal	German and American Council Disting. Lecturer	1999
	Co-author 2nd place IEEE AP-S Student Paper	1998
	(with Mark Casciato)	1998
	UM Henry Russel	1997
	EECS Teaching	1996
	Two U.S. Patents Under Review	1998
Stark, Wayne	IEEE Military Communications Conference Award for Technical Achievement recognizing Sustained Technical Achievement in Military Communications	2002
	EECS Research	1998
	IEEE Fellow	1998
	EECS Service	1993
	Co-author 2 of 7 most significant papers Spreadspectrum Comm. Res.	1986–88
	NSF Young Investigator	1985
	Two U.S. Patents	1998
	One U.S. Patent	1986
	Four U.S. Patents	1996
Teneketzis, Demos	CoE Teaching	1999
	EECS Service	1998
	EECS Teaching	1993
	Outstanding Instructor by MSA	1990
	Outstanding Instructor by MSA	1989
	Best Paper of Session at ACC	1987
	Co-author 2 of 7 most significant papers Spreadspectrum Comm. Res.	1986-88
Wasserman, Kimberly	NSF CAREER Award	1998
	Army Research Office Young Investigator	1996
	GTE Corp. Graduate Fellowship	1990

3 Accomplishments

- First to develop a methodology for integrating the performance of physical layer with the network layer in ad-hoc wireless networks that also uses models that depend on actual consumed energy.
- First to develop tradeoffs between received processing energy and code performance.
- First to show how memory can influence the performance of actual codes very close to capacity for finite block lengths.
- First methodology to minimize energy in wireless networks including effects of nonlinear amplifiers, efficiency of amplifiers, receiver processing power.
- First to develop algorithms for frequency-hopped radios that jointly and iteratively estimate the channel and the data. We showed that the performance improvement of these algorithms with turbo codes was on the order of 6dB is energy relative to conventional techniques with Reed-Solomon codes.
- First to derive optimal bit allocation strategies for reduced power mixed resolution adaptive filters (fixed point LMS) used in channel equalization, matched filtering, and spatial beamforming with smart antennas.
- Characterized performance and derived algorithms for optimal vector quantization under detection fidelity criteria.
- Established that all popular partial update strategies for LMS adaptive filtering can fail to converge for cyclostationary signals such as arise in communications. Proposed new partial update strategy which is guaranteed to converge and implemented this algorithm for channel equalization and beamforming.
- Optimal power allocation strategy demonstrated for tranmission antennas with smart receive antennas and space time coding under quasi-static flat Rayleigh fading model. First to prove that minimal-distance space-time coding attains computational cut-off rate as number of receive antennas increases.
- Obtained first tractable formulation of channel capacity and channel min-capacity for isotropically random Rician/Rayleigh space time channels. Proved min-capacity for rank one Rician channels is equivalent to capacity for Rayleigh channels.
- First theoretical modeling of a microstrip circuit mounted on 1-D periodic substrate using photonic band-gap concepts
- Improved the performance of conductor-backed half-wave slots by designing a new doubly periodic dielectric substrate
- Developed a new full-wave, integral equation (IE)/periodic moment method (PMoM) code to determine the three-dimensional scattering from singly- and doubly-periodic dielectric layered structures for use in radome/frequency selective surface (FSS) design
- First implementation of higher order Shanks' transforms in the numerical evaluation of the double sum in the 2-D planar periodic free-space Green's function for on-plane elements to improve series acceleration
- Determined scattering from simple dipoles over double periodic dielectric layer over a layered medium
- Emulation of an equivalent uniaxial layer by a doubly periodic dielectric layer
- Validation of the equivalent model for use in planar antenna array applications

4 Industrial Interactions and Collaborations

4.1 Raytheon

We worked with Raytheon on a proposal for the Collaborative Technology Alliance (CTA). The proposed research would have built on the research we have conducted so far under the MURI on low energy wireless communication system design and optimization.

Invited seminars on low power MURI topics

Besides presenting our research findings at various conferences we have also been invited to present our finding at companies and workshops including: Hughes Network Systems, Lucent Technologies, MIT Lincoln Laboratory , France Telecom, IEEE Communications Theory Worshop, IEEE Systems and Circuits Workshop, Allerton Conference

Students graduating, Place of employment

- Sangjin Hong: Assistant Professor SUNY (Stony Brook)
- Joesph Kang: Lucent
- Tingfang Ji: Lucent
- Vuk Borich: Applied Wave Research
- Mark Cascito: MIT Lincoln Laboratory
- George Barrett: Johns Hopkins
- J.D. Shumpert: ARF Aperture Systems: Northrup-Gruman
- Chris Lott: Qualcomm
- Paul Liang: Tropian
- Troy Nolan: Harris
- Andrew Worthen: MIT Lincoln Labs
- Do-Sik Yoo: University of Michigan

Industrial Internships

- Bell Labs, Lucent Technologies (Murray Hill) - Hero (1999)
- Bell Labs, Lucent Technologies (Murray Hill) - Godavarti (2000)
- Rockwell Inc. (LA) - Gupta (2000)