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14. ABSTRACT
Research has been completed on adaptive modulation and coding for multicast transmission in a tactical packet radio network. Our adaptive multicast transmission compensates for changes in propagation conditions that occur from packet to packet during a session with one sender and multiple receivers. We also completed our research investigation of adaptive coding for frequency-hop communications over tactical communications channels that have time-varying fading and partial-band interference. New protocols were developed that combat fading and

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Report Title

Cognitive Radio for Tactical Wireless Communication Networks

ABSTRACT

Research has been completed on adaptive modulation and coding for multicast transmission in a tactical packet radio network. Our adaptive multicast transmission compensates for changes in propagation conditions that occur from packet to packet during a session with one sender and multiple receivers. We also completed our research investigation of adaptive coding for frequency-hop communications over tactical communications channels that have time-varying fading and partial-band interference. New protocols were developed that combat fading and interference while providing throughput levels that are near the theoretical upper bounds. New distributed protocols for channel access and adaptive spreading were devised and evaluated for use in direct-sequence spread-spectrum packet radio networks that have no central controllers, access points, or base stations. Information theoretic bounds and tools have been derived that give performance benchmarks for practical protocols, provide analytical techniques for the minimization of resource consumption in tactical networks, and simplify the design of protocols for the adaptation of coding and spreading in direct-sequence spread-spectrum packet radios.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
2011/09/29 1	3	T.C. Royster, M.B. Pursley. CCK modulation: beyond Wi-Fi, IEEE Communications Letters, (01 2009): 0. doi: 10.1109/LCOMM.2009.080740
2011/09/29 0	2	Steven W. Boyd, Michael B. Pursley, Harlan B. Russell. Demodulator Statistics for Channel Access and Adaptive Spreading in Direct-Sequence Spread-Spectrum Packet Radio Networks, IEEE Transactions on Communications, (02 2011): 0. doi: 10.1109/TCOMM.2011.122110.090364
2011/09/29 0	1	Michael B. Pursley, Michael R. Masse, Jason S. Skinner. Adaptive Coding for Frequency-Hop Transmission over Fading Channels with Partial-Band Interference, IEEE Transactions on Communications, (03 2011): 0. doi: 10.1109/TCOMM.2010.011811.100227

TOTAL: 3

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None

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Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
2011/10/03 1:	17	M.A. Juang, M.B. Pursley. Power loading for OFDM in tactical packet radio systems, Proceedings of the 2011 IEEE Military Communications Conference (Baltimore MD). , . : ,
2011/10/03 1	16	J.D. Ellis, M.B. Pursley. Adaptive incrementa-redundancy transmission for tactical packet radio systems, Proceedings of the 2011 IEEE Military Communications Conference (Baltimore, MD). , . : ,
2011/10/03 1	14	J.M. Frye , M.B. Pursley. Simplified methods for performance evaluations of adaptive transmission, Proceedings of the 2009 International Symposium on Communication Theory and Applications (Ambleside, UK) . , . : ,
2011/09/30 1	13	S.W. Boyd, M.B. Pursley. Information-theoretic methods for the design and evaluation of adaptive protocols for direct-sequence spread spectrum transmissions, Proceedings of the 2010 IEEE Global Communications Conference (Miami FL) . , . : ,
2011/09/30 1	12	M.B. Pursley, T.C. Royster IV. An information-theoretic approach to resource consumption minimization for dynamic spectrum access networks, Proceedings of the 2010 IEEE Global Communications Conference (Miami FL) . , . : ,
2011/09/30 1	11	J.M. Frye, M.R. Masse, M.B. Pursley. Acceleration of performance evaluations for adaptive coding protocols in frequency-hop communications, Proceedings of the 2009 IEEE Military Communications Conference. , . : ,
2011/09/29 1	10	Michael A. Juang, Michael B. Pursley . Adaptation of modulation and coding for OFDM packet transmission, MILCOM 2010 - 2010 IEEE Military Communications Conference. 2010/10/31 00:00:00, San Jose, CA, USA. : ,
2011/09/29 1	9	S. W. Boyd, J. D. Ellis, M. B. Pursley,. A protocol for adaptive multicast transmission in packet radio networks, Proceedings of the 2010 IEEE Military Communications Conference. 2010/11/08 00:00:00, . : ,
2011/09/29 1	8	S. W. Boyd, M. B. Pursley. Demodulator Statistics for Enhanced Soft-Decision Decoding in CDMA Packet Radio Systems, ICC 2010 - 2010 IEEE International Conference on Communications. 2010/05/23 00:00:00, Cape Town, South Africa. : ,
2011/09/29 1:	7	Jason D. Ellis, Michael B. Pursley. Comparison of soft-decision decoding metrics in a QAM system with phase and amplitude errors, MILCOM 2009 - 2009 IEEE Military Communications Conference. 2009/10/18 00:00:00, Boston, MA, USA. : ,
2011/09/29 1:	6	Steven W. Boyd, Michael B. Pursley. Initial power adjustment and link adaptation from direct-sequence spread-spectrum demodulator statistics, MILCOM 2009 - 2009 IEEE Military Communications Conference. 2009/10/18 00:00:00, Boston, MA, USA. : ,
2011/09/29 1	5	Michael B. Pursley, Thomas C. Royster. Adaptive-rate nonbinary LDPC coding for frequency-hop communications, MILCOM 2008 - 2008 IEEE Military Communications Conference (MILCOM). 2008/11/16 00:00:00, San Diego, CA, USA. : ,
2011/09/29 1	4	Steven W. Boyd, Michael B. Pursley, Thomas C. Royster, Harlan B. Russell. A soft-decision scaling metric employing receiver statistics for direct-sequence spread-spectrum packet radio networks, MILCOM 2008 - 2008 IEEE Military Communications Conference (MILCOM). 2008/11/16 00:00:00, San Diego, CA, USA. : ,

TOTAL: **13**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
2011/10/03 1·	15	S.W. Boyd, J.D. Ellis, M.B. Pursley. Adaptive coding and modulation for multicast transmission in packet radio networks, IEEE Transactions on Communications (01 2010)

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Books

Received	Paper

TOTAL:

Patents Submitted

None

Patents Awarded

None

Awards

Michael Pursley, Named Outstanding Electrical Engineer by Purdue University, 2008

Michael Pursley, IEEE Communications Society Distinguished Lecturer, 2008–present

Steven Boyd, AFCEA Fellow, 2010

Jason Ellis, MIT Lincoln Lab Fellow, 2010–11

Michael Juang, Barry M. Goldwater Scholar, 2010

Michael Juang, 2010 Samuel B. Earle Award for the most outstanding senior in all engineering degree programs at Clemson University

Michael Juang, MIT Lincoln Lab Fellow, 2010–11

Michael Juang, NDSEG Fellow, 2011–14

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Steven Boyd	0.20	
James Michael Frye, Jr.	0.20	
Jason Ellis	0.20	
Michael Masse	0.20	
Michael Juang	0.20	
FTE Equivalent:	**1.00**	
Total Number:	**5**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Michael B. Pursley	0.18	No
FTE Equivalent:	**0.18**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Michael Juang	0.20	Electrical Engineering
FTE Equivalent:	**0.20**	
Total Number:	**1**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 1.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 1.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 1.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 1.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 1.00

Names of Personnel receiving masters degrees

NAME
Jason Ellis
Michael Masse

Total Number: **2**

Names of personnel receiving PHDs

NAME
Steven W. Boyd
James Michael Frye, Jr.

Total Number: **2**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Scientific Progress and Accomplishments

An adaptive transmission protocol for a cognitive radio network requires a library of code-modulation (CM) combinations, which is a collection of modulation formats and error-control codes that can be combined to give reliable, efficient communications for the range of channel conditions the radio will encounter. As channel conditions change, the cognitive radio chooses the CM combination to optimize performance for the next packet transmission. The choice of CM combination for a packet depends on statistics that were derived from the most recent packet reception. For each packet, a tradeoff is made between the success probability for the packet and the amount of information the packet will carry. The CMs with higher success probabilities carry fewer information bits per modulation chip and those that have higher information rates in bits per chip have lower success probabilities. The average throughput for a CM is proportional to the product of the CM's success probability and the number of bits per chip carried by the CM. Especially for tactical communication channels that may have cochannel interference or jamming, the CM library should include some robust combinations. In general, a CM combination is said to be robust if it provides an acceptable success probability for communications in the presence of strong interference.

Among the modulation formats that are valuable in a CM library are orthogonal, quasi-orthogonal, and biorthogonal modulation, each of which is a robust modulation format. In [PuR09], we show that 256-ary complementary code keying (CCK), which is used in the full-rate IEEE 802.11b standard for wireless local area networks, is similar to a 256-ary modulation that can be derived from biorthogonal signals. Military applications require the use of error-control coding, which is not permitted in the IEEE 802.11b standard; moreover, the bit-to-symbol mappings in the IEEE 802.11b standard CCK modulation degrade the performance of most standard binary codes. Better bit mappings are provided in [PuR09] for a CM combination that uses CCK and standard binary convolutional coding. We also show that additional performance can be obtain by chip scrambling, which is a form direct-sequence modulation of CCK that gives no increase in bandwidth.

Another valuable modulation format for a CM library is a modulation method that is commonly referred to as quadrature amplitude modulation (QAM) but is more accurately called quadrature amplitude shift key (QASK). QAM is less robust than orthogonal, quasi-orthogonal, and biorthogonal modulation, and it is also less robust than standard QPSK. Among other problems with QAM is the requirement for accurate estimates of the phase and amplitude of the received signal [ElP09]. In contrast, orthogonal modulation can be demodulated without estimation of the phase or the amplitude, and coherent demodulation of orthogonal, quasi-orthogonal, biorthogonal, or QPSK modulation does not require amplitude estimation. In [ElP09] we examine the sensitivity of QAM to errors in the phase and amplitude estimates and we show that the sensitivity is reduced by appropriate combinations of error-control coding and soft-decision decoding. Turbo product codes and binary convolutional codes are evaluated with soft-decision decoding based on log-likelihood ratio (LLR) metrics and distance metrics.

In [BPR08], [BoP09], and [BPR11], we investigated direct-sequence spread-spectrum (DS-SS) modulation formats, which are among the most robust formats for tactical cognitive radio networks. DS-SS modulation with adaptive soft-decision decoding is examined in [BPR08], where we derive a new metric from post-detection signal quality statistics that are developed in the demodulator of the tactical radio. The metric is used to scale to the demodulator’s soft-decision outputs before they are sent to the decoder. Our method requires no overhead, such as the addition of pilot symbols to the data symbols, and it requires no channel measurements. We compare the performance of our adaptive scaling metric with an adaptive LLR metric that requires channel measurements and with a fixed (nonadaptive) soft-decision metric. For channels with time-varying propagation loss or multiple-access interference, we show in [BPR08] that our adaptive scaling metric, which requires no channel measurements, gives approximately the same performance as the more complex LLR metric and better performance than fixed metrics. DS-SS modulation is also examined in [BoP09] for dynamic spectrum access networks in which initial power adjustments are required at the start of each session and adaptation to time-varying propagation conditions is required throughout the session.

Protocols for combined channel access and adaptive spreading in DS-SS tactical radio are described and evaluated in [BPR11]. The channel-access protocol provides efficient sharing of the frequency band by multiple DS-SS signals and the adaptive transmission protocol controls the spreading factor of the transmitted signal to compensate for changes in channel conditions from one packet to the next. The combination of the two protocols gives a cross-layer protocol that uses demodulator statistics derived in the receivers of the tactical radios. Significant performance gains are obtained by the combination of adaptive channel access and adaptive spreading [BPR11].

Our research on direct-sequence spread-spectrum (DS-SS) tactical radio networks [BoP09], [BPR11], [BoP10a] has produced results on initial power adjustment, adaptive coding, and adaptive spreading, and it has integrated the physical-layer adaptation with the media access (MAC) protocol. For adaptive coding and spreading in DS-SS radio transmissions, we rely on a demodulator statistic to provide the necessary information for the adaptation, so our protocol does not need pilot signals, training sequences, channel measurements, or parameter estimates. We show that the throughput of our adaptive coding and spreading protocol performs almost as well as a hypothetical protocol that has perfect channel state information, and it also gives throughput that is close to the capacity limit obtained from information theory.

Frequency hopping is another candidate for a CM library, especially for a tactical cognitive radio network. In [PuR08] and

[FMP09], adaptive transmission is employed to combat time-varying propagation conditions and interference in a frequency-hop (FH) packet radio network. Performance results are given in [PuR08] for irregular low-density parity-check (LDPC) codes in FH spread-spectrum systems with nonbinary orthogonal modulation. Two adaptive LDPC coding protocols are devised and evaluated. Each employs statistics that are obtained by the iterative decoder during the decoding of each packet to select the code rate for the next packet. One protocol uses the iteration count and the other uses the hard-decision error count [PuR08]. The adaptive coding protocols provide good performance, even on channels for which some of the individual codes exhibit nonmonotonic throughput. We also investigated protocols that provide adaptive error-control coding for tactical channels with fading and partial-band interference (e.g., jamming). Our recent research results [MPS11] focus on the ability of the protocol to handle fading distributions with time-varying parameters, such as Rician fading with a time-varying fading coefficient. Possible causes for variations in the Rician fading coefficient include fluctuations in the specular component of the received signal as a result of time-varying shadowing. Because our protocols are implemented in subsystems that are external to the demodulator and decoder, they can be employed with a wide range of error-control codes and decoding algorithms.

The design and evaluation of cross-layer protocols that use receiver statistics or other physical-layer information typically require numerous simulations of the network, and each simulation of the network has numerous embedded simulations of the demodulators and decoders in the individual radios. The embedded simulations of the decoder are especially computationally intensive in tactical radios that employ iterative decoding to combat noise and interference. In [FMP09] and [FrP09], we present a methods for the direct generation of receiver statistics in tactical cognitive radio networks. These methods for direct generation avoid the time-consuming embedded simulations of the demodulators and decoders, which greatly accelerates the design, development, and evaluation of adaptive cross-layer protocols. Results are given on the quality of the approximations and the reductions in simulation time that they provide. In [FMP09], the method is illustrated for an adaptive coding protocol in a network of frequency-hop (FH) radios. In [FrP09], corresponding results are given for an extensive CM library that uses biorthogonal modulation, QPSK, and QAM. In both [FMP09] and [FrP09], turbo product codes of several different rates are employed with soft-decision iterative decoding. We have demonstrated savings in simulation time between one to two orders of magnitude for performance evaluations and tradeoff studies of adaptive protocols that rely on the physical layer to provide the control information [FMP09]. This is very important because it is unrealistic to evaluate the performance of higher-layer protocols (e.g., network routing) for tactical wireless networks in a simulation that must include embedded simulations of physical-layer subsystems in the receivers, especially for tactical radios that employ modern iterative decoding methods for turbo codes and low-density parity-check codes.

In our research on orthogonal frequency-division multiplexing (OFDM) for tactical packet radio networks, we have devised a novel protocol for adapting the modulation and coding to compensate for channel variations caused by time-varying fading [JuP10]. Our protocol not only achieves superior performance, but it has lower complexity than previous adaptive OFDM protocols, which typically require extensive channel measurements or parameter estimates and often adapt only the power levels of the subcarriers. In contrast, our protocol uses simple receiver statistics obtained during the demodulation and decoding of a packet to adapt the modulation and coding for the next packet but maintain a constant power level for each subcarrier. Increases in the power levels of the subcarriers are especially undesirable if is desired to avoid detection by unauthorized receivers or if the frequency band is to be shared with other radios in the network or with the networks employed by friendly forces. In our approach, the protocol first determines the code rate and then selects the modulation formats for the individual OFDM subcarriers. We have obtained both analytical and simulation results that demonstrate the performance of our protocol, and we also have performance bounds to use as benchmarks in the design of future OFDM systems for tactical networks. Comparisons with power loading, which is often proposed for commercial applications, are given in [JuP11], where we show that our protocol for adaptive modulation and coding provides higher throughput and more robust performance.

In [BEP10] we describe and evaluate a low-complexity protocol for adaptation of the modulation and coding that are employed for multicast transmission in half-duplex packet radio networks. The adaptive multicast transmission protocol is designed to compensate for changes in propagation conditions that occur from packet to packet during a session with one sender and multiple receivers. The protocol relies on the receivers' error counts [BEP10] to obtain the control information for adapting the modulation and coding, and it also provides scheduling to avoid collisions among acknowledgments from the receivers. The research is extended in [BEP11] to permit the use of alternative receiver statistics, such as the iteration count, and to accommodate a larger number of destinations. Tradeoffs among reporting strategies for the destinations are also included in [BEP11]. The throughput provided by the protocol is compared with upper bounds that are obtained from hypothetical ideal protocols that are given perfect channel-state information. We show that the protocol's performance is nearly as good as the performance of the ideal protocols.

Information-theoretic limits on resource consumption are employed in [PuR10] to obtain analytical methods for conducting tradeoffs between power, bandwidth, and time for cognitive radio transmissions in ad hoc dynamic spectrum access networks. A quantitative measure of resource consumption is applied to the design and evaluation of protocols for adaptive modulation and coding. The application of information theory to the minimization of resource consumption in cognitive radio networks is illustrated for binary phase-shift-key modulation with coherent demodulation.

Adaptation of the code rate and spreading factor for DS-SS tactical packet radio transmissions provides much higher throughput than if the code rate and spreading factor are fixed.
We have devised a low-complexity protocol for packet-by-packet adaptation, but the design and evaluation of such a protocol typically requires extensive simulations, especially for receivers that use iterative methods. In [BoP10b] we show that analytical methods based on Shannon capacity results greatly simplify the design of the adaptive protocol and provide good estimates of its throughput performance.

A low-complexity protocol for adaptive incremental-redundancy transmission is described and evaluated in [ElP11]. The protocol responds to variations in fading and interference by adjusting the number of binary code symbols that are punctured in the first transmission for a packet and kept for subsequent transmissions in case the initial transmission fails. The protocol relies on simple statistics from the receiver to provide the necessary control information for adapting the puncturing level or code rate. No channel measurements, parameter estimates, pilot symbols, or training are needed. The protocol's throughput performance is evaluated for time-varying channels for which we used finite-state Markov models. Hypothetical ideal protocols are employed to provide bounds on throughput. The ideal protocols have perfect channel-state information. We show in [ElP11] that our adaptive incremental-redundancy protocol gives throughput levels that are almost as high as those achieved by the hypothetical ideal protocols, but of course our adaptive incremental-redundancy protocol is given no channel-state information and no information about the channel characteristics or its parameters.

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[PuR09] M. B. Pursley and T. C. Royster IV, "CCK modulation: Beyond Wi-Fi," IEEE Communications Letters, vol. 13, no. 1, pp. 31–33, January 2009.

[ElP09] J. D. Ellis and M. B. Pursley, "Comparison of soft decision decoding metrics in a QAM system with phase and amplitude errors," Proceedings of the 2009 IEEE Military Communications Conference (Boston), October 2009.

[BPR08] S. W. Boyd, M. B. Pursley, T. C. Royster IV, and H. B. Russell, "A soft-decision scaling metric employing receiver statistics for direct-sequence spread-spectrum packet radio networks," Proceedings of the 2008 IEEE Military Communications Conference (San Diego), November 2008.

[BoP09] S. W. Boyd and M. B. Pursley, "Initial power adjustment and link adaptation from direct-sequence spread-spectrum demodulator statistics," Proceedings of the 2009 IEEE Military Communications Conference (Boston), October 2009.

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[PuR08] M. B. Pursley and T. C. Royster IV, "Adaptive-rate nonbinary LDPC coding for frequency-hop communications," Proceedings of the 2008 IEEE Military Communications Conference (San Diego), November 2008.

[FMP09] J. M. Frye, M. R. Masse, and M. B. Pursley, "Acceleration of performance evaluations for adaptive coding protocols in frequency-hop communications," Proceedings of the 2009 IEEE Military Communications Conference (Boston), October 2009.

[FrP09] J. M. Frye and M. B. Pursley, "Simplified methods for performance evaluations of adaptive transmission protocols," Proceedings of the 2009 International Symposium on Communication Theory and Applications (Ambleside, UK), July 2009.

[MPS11] M. R. Masse, M. B. Pursley, and J. S. Skinner, "Adaptive coding for frequency-hop transmission over fading channels with partial-band interference," IEEE Transactions on Communications, vol. 59, no. 3, pp. 854-862, March 2011.

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[JuP10]M. A. Juang and M. B. Pursley, "Adaptation of modulation and coding for OFDM packet transmission," Proceedings of the 2010 IEEE Military Communications Conference (San Jose, CA), pp. 1613–1618, November 2010.

[BEP10] S. W. Boyd, J. D. Ellis, and M. B. Pursley, "A protocol for adaptive multicast transmission in packet radio networks," Proceedings of the 2010 IEEE Military Communications Conference (San Jose, CA), pp. 117–122, November 2010.

[BEP11] S. W. Boyd, J. D. Ellis, and M. B. Pursley, "Adaptive coding and modulation for multicast transmission in packet radio networks," submitted for publication in the IEEE Transactions on Communications.

[PuR10] M. B. Pursley and T. C. Royster IV, "An information-theoretic approach to resource consumption minimization for dynamic spectrum access networks," Proceedings of the 2010 IEEE Global Communications Conference (Miami, FL), December 2010.

[BoP10b] S. W. Boyd and M. B. Pursley, "Information-theoretic methods for the design and evaluation of adaptive protocols for direct-sequence spread-spectrum transmissions," Proceedings of the 2010 IEEE Global Communications Conference (Miami, FL), December 2010, in press.

[JuP11] M. A. Juang and M. B. Pursley, "Power loading for OFDM in tactical packet radio systems," Proceedings of the 2011 IEEE Military Communications Conference (Baltimore, MD), November 2011 (in press).

[ElP11] J. D. Ellis and M. B. Pursley, "Adaptive incremental-redundancy transmission for tactical packet radio systems," submitted for publication in the Proceedings of the 2011 IEEE Military Communications Conference (Baltimore, MD), November 2011 (in press).

Technology Transfer