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The fundamental theme for the research performed under the subject grant is the exploitation of receiver statistics that are obtained as packets are being demodulated and decoded in tactical cognitive radio networks. We employ receiver statistics to provide control information for adaptive protocols, improve soft-decision decoding, permit spectrum sensing while communicating, and form silencing sets in media access control. To accelerate protocol design and development, we derived methods to generate receiver statistics directly, which avoids time-consuming embedded simulations of the physical layer in performance evaluations of cross-layer protocols such as adaptive transmission, media access control, and routing protocols.

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Final Technical Report

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Title: Receiver Statistics for Cognitive Radios in Dynamic Spectrum Access Networks

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Abstract

The fundamental theme for the research performed under the subject grant is the exploitation of receiver statistics that are obtained as packets are being demodulated and decoded in tactical cognitive radio networks. We employ receiver statistics to provide control information for adaptive protocols, improve soft-decision decoding, permit spectrum sensing while communicating, and form silencing sets in media access control. To accelerate protocol design and development, we derived methods to generate receiver statistics directly, which avoids time-consuming embedded simulations of the physical layer in performance evaluations of cross-layer protocols such as adaptive transmission, media access control, and routing protocols.

Key Words and Phrases: Cognitive radio, receiver statistics, adaptive transmission, dynamic spectrum access, packet radio networks

Research Results

Effective adaptive protocols for packet radio networks require information that can be obtained from statistics that are derived in the receiving radio during the reception of each packet. The design and evaluation of cross-layer protocols that use such statistics typically require numerous simulations of the network, and each simulation of the network has numerous embedded simulations of each radio's demodulator and decoder. The embedded simulations of the decoder are especially computationally intensive if the radios employ iterative decoding. We developed methods for the direct generation of receiver statistics that avoid the time-consuming embedded simulations and accelerate the process of designing, developing, and evaluating adaptive cross-layer protocols [3]. The required statistics are modeled as random variables that can be generated quickly, yet their distributions approximate the distributions of the actual receiver statistics. The method is illustrated in [3] for an adaptive transmission protocol in a network of packet radios that employ turbo product codes with soft-decision iterative decoding. Our method for the direct generation of receiver statistics provides even greater benefits in the design and evaluation of higher-layer protocols that employ physical-layer information.

In a dynamic spectrum access network that has primary or high-priority users and secondary or low-priority users, the secondary users must monitor the frequency band in which they are communicating so that they can determine when the primary user has begun transmission. Traditional sensing methods require the transmitters of the secondary users to be silent while spectrum monitoring is performed, which greatly decreases the communications efficiency of the secondary network. In [5], we employ receiver statistics to perform spectrum monitoring while the receiver is demodulating and decoding a packet, so that it is not necessary to silence the secondary transmitters. The new techniques for spectrum monitoring while communicating also offer the promise of more prompt detection of an emerging transmission by a primary user, thereby reducing disruption to the primary network.

Estimates of the signal-to-noise ratio (SNR) are employed by many protocols and processes in direct-sequence (DS) spread-spectrum packet radio networks, including soft-decision decoding, adaptive modulation protocols, and power adjustment protocols. For DS spread spectrum, we have introduced and evaluated SNR estimators that employ receiver statistics that are obtained during demodulation (see [1], [2], and [4] for details). One of our estimators [1] combines the well-known signal-to-noise-variance (SNV) estimator, which works well for large values of SNR, with a new estimator based on the post-detection signal quality (PDSQ) statistic, which works especially well for smaller values of SNR.

In [6] we described and evaluated new decoding techniques that will increase the probability of successful decoding in packet radio systems. The proposed soft-decision decoding metric is derived from receiver statistics that are obtained during demodulation in a binary CDMA receiver. We investigated several methods to apply the proposed metric to the demodulator's soft-decision decision outputs prior to decoding. Our soft-decision decoding techniques are designed to mitigate the effects of interference from other signals in the frequency band. We compare the performance of our proposed metric with the performance of the log-likelihood ratio (LLR) metric, which requires that the mean signal level and noise variance are known for each bit position. Rather than attempt to estimate these parameters directly, our metric uses demodulator statistics and thus does not require the pilot symbols or training sequences that are typically necessary for parameter estimation in an LLR-based metric.

We presented in [7] a low-complexity adaptive multicast transmission protocol that compensates for time-varying propagation losses in a packet radio network by adjusting the modulation and coding. Simple receiver statistics furnish the necessary control information for the adaptive protocol, so channel estimation, training, and pilot symbols are not required. We evaluated the protocol's throughput performance on time-varying channels and we showed that the throughput of our practical protocol is nearly as good as the throughput of hypothetical ideal protocols that are given perfect channel-state information. Adaptive multicast transmission in a packet radio network requires that the source be provided with feedback from all destinations; however, it is not feasible for all destinations to send packet-by-packet replies. Our low-complexity adaptive multicast transmission protocol gives good performance, even if it must rely on round-robin reporting from only one destination per packet.

Spectrum access protocols permit secondary users to utilize frequency bands when the bands are not in use by the primary owners. To determine if a frequency band is in use, spectrum sensing techniques (e.g., energy detection or feature detection) are employed by the secondary radios. Such techniques require that the secondary radios cease transmitting in the band during spectrum sensing periods. In [8] we proposed and evaluated a technique whereby cognitive radios that are secondary users of a frequency band monitor the band for the emergence of primary signals while they are communicating with other secondary radios. Our approach permits more efficient use of spectrum by the secondary network, which results in increased channel utilization and spectral efficiency.

New protocols for channel access and adaptive spreading are described and evaluated for use in direct-sequence spread-spectrum (DS-SS) packet radio networks in [9]. A channel-access protocol is developed to provide efficient use of the frequency band by multiple DS-SS signals, and we investigated the tradeoff between the additional capacity obtained from frequency reuse and the detrimental effects of co-channel interference caused by multiple simultaneous transmissions in the frequency band. We also developed a protocol that adapts the spreading factor of each DS-SS signal to compensate for changes in channel conditions that occur from packet to packet. Although the two protocols operate in different layers of the protocol stack, each relies on the same receiver statistic, which is a demodulator statistic. We demonstrate that the protocols work together to achieve significant performance gains over protocols that do not employ adaptive spreading or do not control spectrum reuse efficiently.

In orthogonal frequency division multiplexing (OFDM) systems, a transmission method known as power loading can improve performance. Power loading algorithms process channel state information to determine the power distribution that optimizes or improves the performance of OFDM reception. Most previous investigations of power loading are for OFDM systems that do not use error-control coding. However, their objective of minimizing the bit error probability at the demodulator output does not minimize the packet error probability when error-control codes are used, and the packet error probability is the error probability of importance in packet transmission systems. Especially since modern OFDM systems use error-control coding, the utility of the previous results is questionable. Furthermore, the power loading algorithms that minimize the bit error probability use approximations for the error probability that are not accurate for the signal-to-noise ratios of interest in packet radio systems that employ error-control coding. In [10], we investigated half-duplex tactical packet communications with OFDM modulation, error-control coding, and iterative decoding. We examined the adaptation of the code rate and subcarrier modulation (without power loading) as an alternative to reliance on power loading. We employed a combination of analysis and simulation to determine the effect of power loading on the binary symbol error probability at the demodulator output, the packet error probability at the decoder output, and the throughput of the packet radio system. Our conclusion is that adaptation of the coding and modulation provides a higher throughput and gives more robust performance than can be obtained from power loading. We also determined that power loading does not improve performance if it is added to a system that uses adaptive coding and modulation.

In [11] we provide techniques that permit secondary radios to monitor the spectrum that is shared with primary users without having the secondary radios cease transmission. Traditional spectrum sensing requires the secondary radios to refrain from communicating while they check for the emergence of primary signals. We proposed and evaluated methods by which the secondary radios can continue their communications while simultaneously monitoring the band to detect any transmissions that are initiated by the primary radios. Our methods for spectrum monitoring supplement traditional spectrum sensing and improve the communications efficiency of the secondary radios. Greater spectral efficiency is obtained by the secondary network, because our protocols reduce the frequency with which traditional spectrum sensing must be performed. If the receiver statistics suggest that a transmission from a primary user may have emerged, then the secondary user's session is suspended temporarily while more accurate traditional spectrum sensing is employed. The use of our spectrum monitoring protocol also decreases the time required to detect the emergence of the primary signal.

Our results indicate that spectrum monitoring based on the receiver's error count by a single secondary receiver will not be adequate if the primary signal is very weak. Instead, either cooperative monitoring among multiple geographically distributed secondary receivers or a combination of spectrum monitoring and traditional spectrum sensing must be employed. Because of the very low complexity of our methods for spectrum monitoring and the potential benefits they provide in terms of earlier detection of a primary signal and increased throughput in the secondary network, we believe that spectrum monitoring should be employed even in systems that rely primarily on traditional spectrum sensing. This suggests that the integration of spectrum monitoring and spectrum sensing is an important area for future research. Some preliminary results on the integration of monitoring and sensing are given in [8].

Our protocols in [11] for spectrum monitoring have backup modes for unanticipated circumstances. For example, if poor or highly variable channel conditions cause spectrum monitoring to produce several consecutive false alarms, then the protocol resorts to traditional spectrum sensing until the channel improves. Large variations in the receiver's error count, iteration count, or other receiver statistics provide one indication of time-varying disturbances on the channel, and they suggest that the backup mode should be employed temporarily. A return to smaller variations in the receiver statistics is an indication that spectrum monitoring during packet reception can be resumed in the secondary network.

Publications Sponsored by this Grant:

[1] S. W. Boyd and M. B. Pursley, "Enhanced SNR estimates from direct-sequence spread-spectrum demodulator statistics," *IEEE Communications Letters*, vol. 13, no. 5, pp. 289–291, May 2009.

[2] S. W. Boyd and M. B. Pursley, "Maximum-likelihood SNR estimators for direct-sequence spread-spectrum receivers," *Proceedings of the 2009 International Symposium on Communication Theory and Applications* (Ambleside, UK), July 2009.

[3] 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.

[4] S. W. Boyd and M. B. Pursley, "SNR estimation in direct-sequence spread-spectrum multiple-access systems," *Proceedings of the 2009 IEEE Military Communications Conference* (Boston), October 2009.

[5] S. W. Boyd, J. M. Frye, M. B. Pursley, and T. C. Royster IV, "Receiver statistics for spectrum monitoring while communicating," *Proceedings of the 2009 IEEE Global Communications Conference* (Honolulu), November 2009.

[6] S.W. Boyd and M. B. Pursley, "Demodulator statistics for enhanced soft-decision decoding in CDMA packet radio systems," *Proceedings of the 2010 IEEE International Conference on Communications*, (Cape Town, South Africa), May 2010.

[7] 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.

[8] S. W. Boyd and M. B. Pursley, "Enhanced spectrum sensing techniques for dynamic spectrum access cognitive radio networks," *Proceedings of the 2010 IEEE Military Communications Conference* (San Jose, CA), pp. 41–46, November 2010.

[9] S. W. Boyd, M. B. Pursley, and H. B. Russell, "Demodulator statistics for channel access and adaptive spreading in direct-sequence spread-spectrum packet radio networks," *IEEE Transactions on Communications,* vol. 59, no. 2, pp. 560–568, February 2011.

[10] 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), pp. 572–577, November 2011.

[11] S. W. Boyd, J. M. Frye, M. B. Pursley, and T. C. Royster IV, "Spectrum monitoring during reception in dynamic spectrum access cognitive radio networks," *IEEE Transactions on Communications,* vol. 60, no. 2. pp. 547–558, February 2012.

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