Resource Consumption in Dynamic Spectrum Access Networks: Applications and Shannon Limits

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Abstract

When a frequency band has been selected for a session in a dynamic spectrum access network, the initial choices for the modulation and coding must be consistent with the bandwidth that is available and the session's quality-of-service priorities. A measure of resource consumption is developed for use in the selection of the code-modulation combination. The resource-consumption metric accounts for the bandwidth, data-transmission time, and transmitted power for the session. Shannon capacity limits are employed to bound the resource consumption and permit tradeoffs between the time-bandwidth product of the signals and the amount of power that must be transmitted to achieve reliable communication.

I. Introduction

Several protocols are required for packet radios to be able to initiate and maintain reliable communications in a wireless ad hoc dynamic spectrum access network. In this paper, we focus on the modulation-selection protocol and the power-adjustment protocol. After a frequency band has been selected, a *modulation-selection protocol* must choose a modulation technique according to the capabilities of the radios, the established etiquette for transmission in the network, and the quality-of-service (QoS) priorities for the session. Because the propagation loss is typically unknown for a new frequency band, a *power-adjustment protocol* must adjust the transmitter power during the first few packets. A power level that is too low results in a large number of unsuccessful attempts to send packets to the destination. A power level that is too high wastes energy and causes excessive interference to other radios in the network. Although most of the paper is devoted to modulation selection, it is necessary to be aware of some features of power adjustment when we introduce a quantitative method for choosing the initial code-modulation combination.

The metric for modulation selection accounts for the three primary spectrum etiquette parameters: time, bandwidth, and power. The metric is a measure of resource consumption that permits tradeoffs between the power and the time-bandwidth product. The resource-consumption metric is evaluated for several code-modulation combinations. Shannon capacity limits are employed to bound the resource consumption, and comparisons are made between the Shannon limits and the resource consumption levels achieved for turbo product codes applied to biorthogonal modulation, quadriphase-shift keying (QPSK), and quadrature amplitude modulation (QAM).

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II. Code-Modulation Combinations

All the code-modulation combinations are examples of bit-interleaved coded modulation [2], and the modulation formats include biorthogonal modulation, QPSK, QAM, and complementary code keying (CCK). Helical interleaving [12] is used for most of the modulation formats, but S-random [3] interleaving is employed for QAM. Optional direct-sequence (DS) or frequency-hop (FH) spread-spectrum modulation may be applied to the data-modulated signal. Our numerical results are for a family of turbo product codes with iterative soft-decision decoding. The trends in the performance results are the same for standard convolutional codes with Viterbi decoding, but the required power levels are higher. Results are also given for five hypothetical capacity-achieving codes of the same rates as the turbo product codes.

The set of available modulation formats is $\{\mathcal{M}_j : 1 \leq j \leq n_m\}$ and the set of codes is $\{C_i : 1 \leq i \leq n_c\}$. The rate of code C_i is denoted by r_i, and the codes are indexed to give $r_1 < r_2 < \ldots < r_{n_c}$. The radios employ a set $\{\mathcal{D}_k : 1 \leq k \leq n\}$ of code-modulation combinations that are indexed with a single subscript whose maximum value is $n \leq n_c n_m$. In many applications, some of the $n_c n_m$ possible combinations are not used.

The *modulation chip* is the basic pulse used for the data modulated waveform. For example, suppose N is a power of 2 and $M = 2N$. The modulation symbols for M-biorthogonal modulation can be obtained from an $N \times N$ Hadamard matrix. Each of the M modulation symbols is a sequence of N rectangular pulses of duration T_c and each sequence of N pulse amplitudes that represents a modulation symbol corresponds to the elements in a row of the matrix or the complements of such elements. M^2 I-Q biorthogonal modulation has

M-biorthogonal modulation on the I and Q components, which implies that it has half the bandwidth of standard M-biorthogonal modulation for the same information rate. The high-data-rate version of IEEE 802.11b CCK [4], which we denote by 256-CCK, has the same bandwidth as 256 I-Q biorthogonal modulation. However, if the turbo product codes that we consider are employed for error control, then 256 I-Q biorthogonal modulation gives 1–2.5 dB better performance than 256-CCK for the additive white Gaussian noise (AWGN) channel. A pseudo-random sequence, referred to as a *signature sequence*, can be applied to some modulation formats to provide *spread-spectrum multiple-access capability* [7], which permits multiple sessions to occupy the same frequency band simultaneously. Frequency hopping can also provide multiple-access capability, and it can easily be included in the metric for resource consumption by use of the expressions in [9].

The set $\{C_i : 1 \le i \le 5\}$ of codes that are used to obtain numerical values for the resource consumption is a set of five turbo product codes. The block length is 4096 for C_2, C_3, and C_5, whose rates are approximately 0.325, 0.495, and 0.793, respectively. Each packet consists of $n_b = 4096$ binary code symbols, so there is one code word per packet if C_2, C_3, or C_5 is used. The block length for C_1 is 2048 and its rate is approximately 0.236. Code C_4 has block length 1024 and rate approximately 0.660. There are two code words per packet if C_1 is used and four code words per packet if C_4 is used. All five codes and their iterative decoders are available on a single chip [1]. The log-likelihood-ratio (LLR) metric [5] is used for all modulation formats except QAM. For QAM, we use a simpler distance metric [6] that gives approximately same performance.

III. Time-Bandwidth Product

A session must be established whenever one radio, the *source*, wishes to send a sequence of packets to another radio, the *destination*. Other radios within range of the source are referred to as *unintended receivers*; these radios may experience interference from the source's transmissions. The source and destination are part of a dynamic spectrum access network, so they must choose an available frequency band that meets their requirements. They must select modulation and coding that are usable by both radios and satisfy all constraints imposed by the frequency band that was chosen. For example, for some modulation formats and code rates, the packet transmissions may require more bandwidth than is available at the chosen frequency in order to complete the session within the allotted time. We propose the use of a spectrum etiquette measure in the selection of the initial modulation and coding for a new session. The spectrum etiquette measure is a function of the bandwidth, data transmission time, and power. The data transmission time is the total time that the source is actively transmitting data during the session. Headers and preambles are not included.

Let η_j be the number of signature sequence chips per modulation chip for modulation format $\mathcal{M}_j$. If there is no signature sequence, then $\eta_j = 1$. Let m_j denote the number of binary symbols per modulation symbol and let L_j denote the number of modulation chips per modulation symbol. Each packet contains the same number n_b of binary code symbols. If code C_i has rate r_i, there are $k_i = r_i n_b$ information bits per packet when code C_i is used. If the chip waveform is a rectangular pulse and the information rate is R_b b/s, then the null-to-null bandwidth for modulation format $\mathcal{M}_j$ and code C_i is $B_{i,j} = 2\lambda_{i,j} R_b$ Hz, where

$$\lambda_{i,j} = \frac{\eta_j L_j n_b}{m_j k_i} \tag{1}$$

represents the number of chips per information bit for a single packet that uses C_i and $\mathcal{M}_j$; in particular, $\lambda_{i,j} = 1$ for uncoded BPSK with no spread spectrum.

Suppose the session is required to deliver N_b bits of information regardless of which code-modulation combination is used. For code C_i and modulation $\mathcal{M}_j$, the number of packets that must be decoded correctly at the destination is $N_i = \lceil N_b/k_i \rceil \approx N_b/k_i$. The expected number of packet transmissions required to complete the session, including retransmissions of any failed packets, is $N_i/Q_{i,j}$, where $Q_{i,j}$ is the packet success probability. If $B_{i,j}$ is the null-to-null bandwidth that can be accommodated in the frequency band selected for the session, then the average data transmission time per session is closely approximated by

$$\mathcal{T}_{i,j} \approx \frac{2N_b \lambda_{i,j}}{Q_{i,j} B_{i,j}}, \tag{2}$$

and the parameter

$$\tau_{i,j} = \frac{\lambda_{i,j}}{Q_{i,j}} = \frac{\eta_j L_j n_b}{Q_{i,j} m_j k_i} \tag{3}$$

is approximately equal to the average number of transmitted chips per delivered information bit. Both approximations are exact if N_b/k_i is an integer. The time required for packet headers or preambles is not included in (2) or (3), but it is easy to account for such overhead times [9]. The *average time-bandwidth product* $\Psi_{i,j}$ for a session that employs code C_i and modulation format $\mathcal{M}_j$ is $\Psi_{i,j} = \mathcal{T}_{i,j} B_{i,j}$. From (2) and (3) we see that

$$\Psi_{i,j} \approx \frac{2N_b \lambda_{i,j}}{Q_{i,j}} = 2N_b \tau_{i,j}. \tag{4}$$

Because N_b is does not depend on C_i or $\mathcal{M}_j$ the parameter $\tau_{i,j}$ can be interpreted as the normalized time-bandwidth product. Thus far, we have accounted for the bandwidth and transmission time but not the power used by the source. It is desirable for the source to transmit only the minimum power needed to provide the required probability of success. The mechanism for ensuring the source uses this minimum power is the power-adjustment protocol that is described in the next section.

IV. Power Adjustment

Because of the unknown propagation loss in a new frequency band, the initial power level is likely to be above or below the minimum level that achieves the desired packet success probability. If each session has several hundred packets or more, then a session can tolerate excessive interference from the source for ten to twenty packets, but it cannot tolerate excessive interference for a significant fraction of the packets in the session. Because the source does not know the correct power level, the power-adjustment protocol must use feedback from the destination to adjust the source's transmitter power at the start of each session. For each packet that is received by the destination during the power-adjustment phase, the destination receiver derives a demodulator statistic that is used to determine the power level for the next packet that is sent from the source to the destination. For M-biorthogonal modulation, the demodulator statistic is a ratio statistic (see [8] and [11]). For PSK and QAM, the demodulator statistic is based on the Euclidean distance between each received symbol and its closest point in the signal constellation [6]. The statistic or a power-adjustment decision based on the statistic is included in the acknowledgment packet that is sent to the source. If the acknowledgment packet is received by the source, then the power level for the next packet is a function of the demodulator statistic for the previous packet. No matter where the power-adjustment decision is made, it is obtained by applying an interval test to the demodulator statistic. For each packet that is sent during the power-adjustment period but not acknowledged, the source automatically increases the power by a fixed amount (e.g., 5 dB). The termination of the power-adjustment phase is determined by a stopping condition applied to the demodulator statistics for the initial sequence of packets in the session.

For each modulation format, we simulated $10{,}000$ sessions with independent, random initial power levels that are uniformly distributed on the interval from 15 dB below the target level to 15 dB greater than the target level. The target level was based on the requirement for a packet error probability of 10^{-2}. The highest-rate turbo product code (C_5) was employed in each simulation. The power-adjustment protocol stopped within the first eight packets of each session, and the adjusted power level was not more than 1.3 dB above the target level for any session. For 64-biorthogonal modulation and QPSK, the adjusted power level was never more than 0.7 dB above the target level. For each modulation format, the adjusted power level was never less than the minimum power required to achieve a packet error probability of 10^{-2}.

V. Resource Consumption

In this section, we consider a fixed but arbitrary code-modulation combination $\mathcal{D} \in \{\mathcal{D}_k : 1 \leq k \leq n\}$ and a fixed value Q for the packet success probability, so we omit the subscripts i and j for the symbols that are used in (1)–(4). Also, for simplicity, we assume that N_b is a multiple of the number of information bits per packet, so the approximations in Section III are exact. The minor differences that arise if N_b is not a multiple of the number of information bits per packet are negligible.

Suppose the source and unintended receivers are randomly and independently located in the plane and the packet success probability for the session is to be no less than Q. The code-modulation combinations $\{\mathcal{D}_k : 1 \leq k \leq n\}$ are available to the source and destination for use in the session. The source's transmissions cause interference to unintended receivers that are nearby, so the frequency band is not available for sessions that involve those receivers. Suppose that a frequency band of width B Hz is unavailable to an average of $\mathcal{N}$ unintended receivers for an average of $\mathcal{T}$ seconds per session whenever the source uses combination $\mathcal{D}$ and the transmitted power density level is ζ. The power density ζ is determined by the power-adjustment protocol, so it is very close to the minimum power density that provides packet success probability Q at the destination. If one unit of resource consumption corresponds to the prevention of one radio from receiving for one second in a frequency interval of one Hz, then the resource consumption for the session with power density ζ is

$$\mathrm{RC} = \mathcal{T} B \mathcal{N}. \tag{5}$$

The *interference region* for the source's transmission is the set of all potential locations of unintended receivers for which the received power density exceeds a specified threshold. The area of the interference region is the *interference area*. $\mathcal{N}$ is the average number of unintended receivers that are in the interference region when the source employs code-modulation combination $\mathcal{D}$. The threshold is the minimum tolerable interference among the unintended receivers, and power is normalized in such a way that one unit of power density is equal to the threshold. For evaluations of the relative resource consumptions for different code-modulation combinations, multiplicative constants in the expressions are unimportant, so we let each such constant be unity.

Because of the uniform distribution of unintended receivers, $\mathcal{N}$ is proportional to the interference area $\mathcal{A}$, so we set $\mathcal{N} = \mathcal{A}$. The interference area depends on the range of the transmission. For a given combination $\mathcal{D}$, the range ρ and the transmitted power density ζ are related by $\zeta\rho^{-\alpha} = 1$, where α denotes the propagation loss exponent, which normally satisfies $2 \le \alpha \le 6$. The interference area $\mathcal{A}$ is proportional to the square of the range, so $\mathcal{A} = \rho^2 = \zeta^{2/\alpha}$. Recall that the constant of proportionality is not important, so it is set equal to one. For most situations, free-space propagation ($\alpha = 2$) gives the maximum area. The interference area for $\alpha = 2$ is $\mathcal{A} = \zeta$. The propagation environment is unknown, so in the assessment of the effects of interference, it is best to use a small value for α. We chose $\alpha = 2$ to make it very unlikely that the source's transmission will cause interference over a wider area than predicted by our model.

The average number of unintended receivers that experience interference above the threshold is proportional to the interference area, so $\mathcal{A} = \zeta$ implies $\mathcal{N} = \zeta$ and (5) implies

$$\mathrm{RC} = \mathcal{T} B \zeta. \tag{6}$$

It is convenient to normalize the resource consumption in order to convert the source's transmitted power density ζ to the received power density ξ at the destination. In the normalization, we also incorporate the number of information bits that are delivered during the session and the thermal noise density in the destination receiver.

For a session that delivers N_b information bits to a destination receiver with one-sided noise density N_0 over a channel with gain G (the propagation loss is $1/G$), the received power density is $\xi = G\zeta$ and the normalized resource consumption is

$$\mathcal{R} = \frac{G}{N_b N_0}\,\mathrm{RC} = \frac{\mathcal{T} B \xi}{N_b N_0}. \tag{7}$$

It follows from (4) that $\mathcal{T} B = 2 N_b \tau$, because the approximation in (4) is exact whenever N_b is a multiple of the number of information bits per packet, so (7) implies

$$\mathcal{R} = \frac{2\tau\xi}{N_0} = P\tau, \tag{8}$$

where $P = 2\xi/N_0$. Because N_0 is constant, P is proportional to the received power density at the destination. The relationship $\mathcal{R} = P\tau$ is used in the computation of some of the entries in Table I. To obtain another relationship that is used for the table, we return to (7) and observe that $B\xi$ is the received power and $\mathcal{T} B\xi$ is the average energy received per session. The average received energy per information bit is $\mathcal{E}_b = \mathcal{T} B \xi / N_b$, so

$$\mathcal{R} = \mathcal{E}_b / N_0. \tag{9}$$

For each code-modulation combination in Table I, we give the values for the normalized power density P, the normalized time-bandwidth product τ, and the normalized resource consumption $\mathcal{R}$ for $Q = 0.99$. The values of τ are computed from (3) and the values of $\mathcal{E}_b/N_0$ required to give $Q = 0.99$ are obtained from simulations of the iterative decoders for the five turbo product codes. The results for $Q = 0.999$ typically differ by no more than 0.3 dB from those shown in Table I.

Modulation	Code, Rate	P	τ	$\mathcal{R}$	SL	Δ
64-Biorth	C_1, 0.236	0.10	22.83	2.3	1.7	1.3 dB
64-Biorth	C_2, 0.325	0.12	16.58	2.0	1.5	1.3 dB
64-Biorth	C_3, 0.495	0.15	10.88	1.6	1.3	0.9 dB
64-Biorth	C_5, 0.793	0.24	6.79	1.6	1.4	0.7 dB
256 I-Q Biorth	C_3, 0.495	0.81	2.04	1.7	1.3	1.1 dB
256-CCK	C_3, 0.495	1.22	2.04	2.5		
QPSK	C_2, 0.325	0.83	1.55	1.3	0.9	1.6 dB
QPSK	C_3, 0.495	1.45	1.02	1.5	1.0	1.5 dB
QPSK	C_4, 0.660	2.57	0.77	2.0	1.3	2.0 dB
QPSK	C_5, 0.793	3.07	0.64	2.0	1.6	0.9 dB
64-QAM	C_2, 0.325	6.71	0.52	3.5	1.9	2.6 dB
64-QAM	C_3, 0.495	14.73	0.34	5.0	3.0	2.3 dB
64-QAM	C_4, 0.660	31.87	0.26	8.3	4.6	2.6 dB
64-QAM	C_5, 0.793	45.02	0.21	9.5	7.1	1.3 dB

TABLE I

Resource consumption for a packet error probability of 10^{-2}

Because the normalized resource consumption is the ratio of the average received energy per information bit to the one-sided thermal noise density, we can apply the Shannon capacity limit for $\mathcal{E}_b/N_0$ to obtain a lower bound on the resource consumption for the code-modulation combination $\mathcal{D}$. However, the capacity limit depends on the code rate and the modulation format, so we must determine the capacity as a function of the code rate for each modulation format in the set $\{\mathcal{M}_j : 1 \le j \le n_m\}$.

Let Λ be the minimum value of $\mathcal{E}_b/N_0$ that permits reliable communication with binary codes of rate r and modulation format $\mathcal{M}$. For example, if binary antipodal modulation (e.g., BPSK) is used with coherent demodulation and binary codes of rate r, the capacity is

$$C = 1 - \int_{-\infty}^{\infty} \frac{\exp\{-(u-\alpha)^2\}}{\sqrt{\pi}\,\ln 2} \ln[1 + \exp\{-4\alpha u\}]\,\mathrm{d}u,$$

where $\alpha = \sqrt{r\mathcal{E}_b/N_0}$. This equation and corresponding expressions for other modulation formats are of the form

$$C = \Gamma(\alpha) = \Gamma\left(\sqrt{r\mathcal{E}_b/N_0}\right). \tag{10}$$

If we wish to communicate at the capacity limit with a code of rate r, then $r = C$, $\mathcal{E}_b/N_0 = \Lambda$, and (10) give

$$r = \Gamma\left(\sqrt{r\Lambda}\right). \tag{11}$$

Numerical methods are applied to solve (11) for Λ to find the lower bound on $\mathcal{E}_b/N_0$ for modulation format $\mathcal{M}$ and binary codes of rate r. The results for BPSK and coherent demodulation for the AWGN channel are

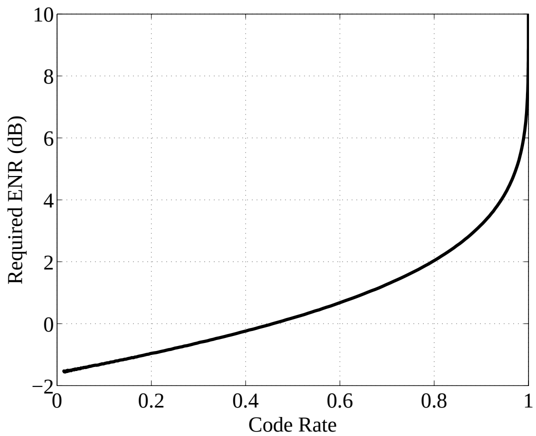

Fig. 1. Capacity limits for binary antipodal modulation with coherent demodulation.

illustrated in Figure 1, where $\mathrm{ENR} = 10\log_{10}(\mathcal{E}_b/N_0)$ is the information-bit-energy to noise-density ratio in decibels (dB).

We apply the solutions of the capacity equations for the modulation formats in $\{\mathcal{M}_j : 1 \leq j \leq n_m\}$ and the rates of the codes in $\{C_i : 1 \leq i \leq n_c\}$ to determine asymptotically tight lower bounds on the normalized resource consumption for the code-modulation combinations in $\{\mathcal{D}_k : 1 \leq k \leq n\}$. These bounds represent the smallest possible values for the resource consumption that permit reliable communication; that is, for reliable communication, $\mathcal{R}$ cannot be less than the Shannon capacity limit for the communication channel from the source to the destination. In Table I are the values of the normalized resource consumption, the corresponding values for the Shannon limit (SL), and the difference Δ in dB between the two. The resource consumption for the turbo product code and the Shannon limit are rounded to the nearest tenth in Table I, but more precise values for $\mathcal{R}$ and SL were used to compute Δ. For CCK modulation, there are no entries for SL or Δ because of the difficulty of evaluating the capacity for CCK modulation.

There are many potential uses for the concept of resource consumption and the specific resource-consumption metric that we have proposed. If users are required to pay for spectrum, then one application of the resource-consumption metric is to provide a basis for fee assessment in the dynamic spectrum access network. The metric also provides a quantitative measure that can be used in the selection of the initial modulation and coding for a new session. For instance, the protocol that selects the code-modulation combination could minimize $\mathcal{R}$ subject to constraints on delay or other QoS measures. Constraints could also be imposed on the resources themselves: time, bandwidth, and power. Guaranteed QoS is impossible in wireless communications because of the nature of the wireless communication channel, so it may be more realistic to establish QoS priorities rather than impose QoS constraints. The resource-consumption metric can be employed with QoS priorities to conduct tradeoffs among time, bandwidth, and power requirements for the session.

Tradeoffs can be performed for a specific class of codes by employing the resource-consumption metric $\mathcal{R}$. For optimal codes, we can conduct tradeoffs by using the Shannon limit SL as a metric. The results in Table I for these two metrics suggest that if good error-control codes are employed, then the smallest resource consumptions are obtained with code-modulation combinations that compromise between achieving low interference levels for unintended receivers and small time-bandwidth products.

For an ad hoc network in which the destination is not always within communication range of the source, some packets must be relayed to the destination by intermediate nodes in the network. Route selection in the network should be influenced by the amounts of resources that will be consumed by the alternative routes. This can be accomplished by combining the resource-consumption metric with other routing metrics [10] to provide link weights for the routing protocol.

VI. Conclusion

A protocol for initial power adjustment is presented in Section IV. We found that our protocol, which uses an appropriate demodulator statistic for each modulation format, can adjust the power to a satisfactory level within the first eight packets of a new session. Application of this protocol ensures that the transmitted power density is close to the minimum possible for the specified packet success probability. A framework for modulation selection based on a proposed measure of resource consumption is presented in Section V. A resource-consumption metric is derived in that section, and it is evaluated in Table I for several modulation formats. Shannon theory is used to obtain lower bounds on the resource consumption. It is shown that neither the code-modulation combinations with the lowest power spectral density nor the combinations with the least time-bandwidth product give the smallest resource consumption.

References

[1] Advanced Hardware Architectures, Inc., Product Specification for AHA4501 Astro 36 Mbits/sec Turbo Product Code Encoder/Decoder. Available: http://www.aha.com

[2] G. Caire, G. Taricco, and E. Biglieri, "Bit-interleaved coded modulation," *IEEE Transactions on Information Theory,* vol. 44, no. 3, pp. 927–946, May 1998.

[3] S. Dolinar and D. Divsalar, "Weight distributions for turbo codes using random and nonrandom permutations," *JPL TDA Progress Report 42-122,* pp. 56–65, August 1995.

[4] Institute of Electrical and Electronics Engineers, *Standard 802.11b-1999, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Higher-Speed Physical Layer Extension in the 2.4 GHz Band*, http://grouper.ieee.org/groups/802/11/, January 2000.

[5] S. Le Goff, A. Glaviuex, and C. Berrou, "Turbo-codes and high spectral efficiency modulation," *Proceedings of the 1994 IEEE International Conference on Communications*, pp. 645-649, 1994.

[6] W. G. Phoel, J. A. Pursley, M. B. Pursley, and J. S. Skinner, "Frequency-hop spread spectrum with quadrature amplitude modulation and error-control coding," *Proceedings of the 2004 IEEE Military Communications Conference* (Monterey, CA), Nov. 2004.

[7] M. B. Pursley, *Introduction to Digital Communications*, Upper Saddle River, NJ: Prentice Hall, 2005.

[8] M. B. Pursley and T. C. Royster IV, "Adaptation of modulation, coding, and power for high-rate direct-sequence spread spectrum," *Proceedings of the 2006 IEEE Military Communications Conference* (Washington, DC), October 2006.

[9] M. B. Pursley, T. C. Royster IV, and J. S. Skinner, "Protocols for the selection, adjustment, and adaptation of transmission parameters in dynamic spectrum access networks," *Proceedings of the 2005 IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks* (Baltimore), pp. 649–657, November 2005.

[10] M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "Energy-efficient routing of multimedia traffic in frequency-hop packet radio networks," *International Journal of Wireless Information Networks*, vol. 13, no. 3, pp. 193-205, July 2006.

[11] A. J. Viterbi, "A robust ratio-threshold technique to mitigate tone and partial band jamming in coded MFSK systems," *Proceedings of the 1982 IEEE Military Communications Conference* (Boston), vol. 2, pp. 22.4.1–22.4.5, October 1982.

[12] W. W. Wu, D. Haccoun, R. Peile, and Y. Hirata, "Coding for satellite communication," *IEEE Journal on Selected Areas in Communications*, vol. SAC-5, pp. 724–748, May 1987.