High-Performance Wireless Ethernet

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ABSTRACT

This article considers the recently successful IEEE 802.11b standard for high-performance wireless Ethernet and a proposed extension that provides for 22 Mb/s transmission. The IEEE 802.11 sets standards for wireless Ethernet or wireless local area networks. The article describes the history of the IEEE 802.11 standards and the market opportunities in the wireless Ethernet field. The article gives a brief description of the media access control layer and then presents details about the physical layer methods, including coding descriptions and performance evaluations. The article also discusses the role and limitations of spread spectrum communications in wireless Ethernet.

INTRODUCTION TO WIRELESS ETHERNET

In fall 1999 a new high-speed standard for wireless Ethernet was ratified by the IEEE 802.11 standards body [1]. This standard extended the original 1 and 2 Mb/s direct sequence physical layer transmission standard [2] to break the 10 Mb/s barrier. The standard, IEEE 802.11b, established two forms of coding that each deliver both 5.5 Mb/s and 11 Mb/s data rates. Currently, the IEEE 802.11 standards body Task Group G is considering an even higher rate extension that will supply a payload rate in excess of 20 Mb/s. This standard will become IEEE 802.11g.

This article describes these exciting standards and an extension developed by Alantro Communications, now a part of Texas Instruments Inc. It was the announcement of the Alantro technology that prompted the creation of the IEEE Task Group G activity. The Alantro PBCC system maintains a 22 Mb/s data rate in the same environment as the basic 11 Mb/s system of the current IEEE 802.11b standard as schematically described in Fig. 1.

THE HISTORY AND STATE OF THE STANDARDS AND MARKETPLACE

The origins of wireless networking standardization can be traced to the late 1980s, motivated by FCC spread spectrum regulations that provided for unlicensed transmission in the 2.4 GHz range. The initial standards activity was very contentious and progress was slow; in October 1997, the first completed standard from the IEEE 802.11 body was ratified. The standard set in 1997 defined both a common *media access control* (MAC) mechanism as well as multiple *physical access methods* (PHYs). The two PHYs involved two radio transmission methods for the 2.4 GHz band: *frequency hopping* (FH) and *direct sequence spread spectrum* (DSSS). Both of these PHYs operated at a 1 and 2 Mb/s data rate.

As the first standard was wrapping up, the creation of a new standards activity in IEEE 802.11 was begun. This new activity consisted of two initiatives. The first resulted in the IEEE 802.11a PHY for the 5 GHz band; this standard incorporates a coded multicarrier scheme known as OFDM. The second effort produced a standard commonly known as the IEEE 802.11b standard. This standard offers a DSSS backward-compatible transmission definition that added two new data rates, 5.5 Mb/s and 11 Mb/s, as well as two forms of coding. The mandatory coding mode is known as CCK modulation and is described in detail in a later section of this article. The optional code, known as PBCC and referred to as the *high-performance mode* of the standard, is described later. This standard is clearly the most successful standard of IEEE 802.11 to date; today there are millions of 11b-compliant devices in the hands of consumers.

Recently, the main standards setting activities of the IEEE 802.11 committee involve enhancements to the MAC, 11e (quality of service, QoS) and 11i (security), and even higher-rate extensions to the existing standard, 11g. The latter activity was motivated by the work of Alantro Communications (now a part of Texas Instruments), which is a central topic of this article (see some later sections). The main objective of this activity is to define a backward-compatible extension to the existing 11b networks in a way that improves the data rate (> 20 Mb/s) and overall user experience and satisfaction with wireless Ethernet.

As organizations such as the IEEE 802 Committee continue to push the envelope on the technology front, other organizations are also playing a key role in the adoption of Wireless Ethernet technology. The *Wireless Ethernet Compatibility Alliance* (WECA) is the most notable such organization. Both the IEEE and WECA have been instrumental in advocating innovation and enhancements to the standard, which has helped fuel rapid industry adoption.

WIRELESS ETHERNET BACKGROUND

MEDIA ACCESS CONTROL, SECURITY AND PACKET STRUCTURE

The IEEE 802.11 WLAN standard, commonly referred to as wireless Ethernet, is part of a family of IEEE local and metropolitan networking standards, of which 802.3 (Ethernet)is a well-known, widely deployed example. The IEEE 802 standards deal with the physical and data link layers in the ISO *open systems interconnection* (OSI) basic reference model. IEEE 802 specifies the data link layer in two sublayers, *logical link control* (LLC) and *medium access control* (MAC). The IEEE 802 LAN MACs share a common LLC layer (IEEE standard 802.2) and link layer address space utilizing 48-bit addresses.

It is relatively straightforward to bridge between IEEE 802.11 wireless LANs and IEEE 802 wired LANs and to construct extended interconnected wired and wireless 802 LAN networks. Through this means all the services typically offered on wired LANs, such as file sharing, email transfer, and internet browsing, are made available to wireless stations.

Wireless Ethernet Topology — Fundamental to IEEE 802.11 architecture is the concept of the wireless LAN cell, or Basic Service Set (BSS). The 802.11 MAC protocol supports the formation of two distinct types of BSSs. The first is an "ad hoc" BSS. As the name implies, ad hoc BSSs are typically created and maintained as needed without prior administrative arrangements for specific purposes (such as transferring a file from one personal computer to another).

The second type of BSS is an infrastructure BSS; this is the more common type used in practice. This type supports extended interconnected wireless and wired networking. Within each infrastructure BSS is an *Access Point* (AP), a special central traffic relay station that normally operates on a fixed channel and is stationary. APs may be placed such that the BSSs they service overlap slightly in order to provide continuous coverage to mobile stations. Commercially available APs include an embedded Ethernet portal, and they are therefore essentially wireless LAN to Ethernet bridges.

End stations, or *clients*, (non-APs) in an infrastructure BSS establish MAC layer links with an AP. Furthermore, they only communicate directly to and from the selected AP. Clients utilize the 802.11 architected scan, authentication, and association processes in order to join an infrastructure BSS and connect to the wireless LAN system. Scanning allows clients to discover existing BSSs that are within range. APs periodically transmit beacon frames that, among other things, may be used by clients to discover BSSs. Prior to joining a BSS, a client must demonstrate through authentication that it has the credentials to do so.

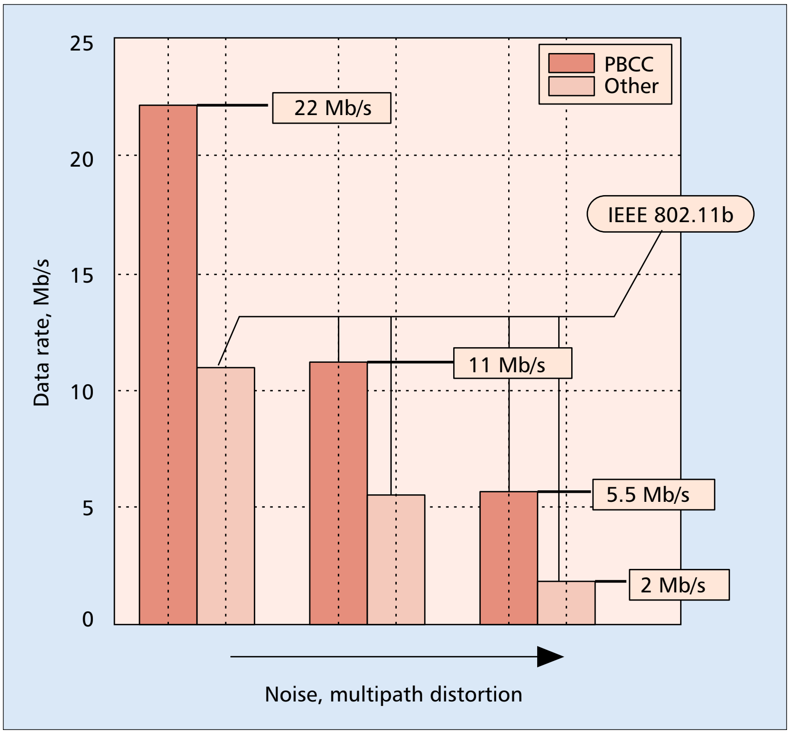

Figure 1. *Performance of wireless Ethernet.*

Medium Access Control — The IEEE 802.11 MAC is similar to wired Ethernet in that both utilize a "listen before talk" mechanism to control access to a shared medium. However, the wireless medium presents some unique challenges not present in wired LANs that must be dealt with by the 802.11 MAC. The wireless medium is subject to interference and is inherently less reliable. The medium is susceptible to possible unwanted interception. Wireless networks suffer from the "hidden client" problem; a client transmitting to a receiving client may be interfered with by a third "hidden" client which is within range of the receiver but out of range of the transmitter and therefore does not defer. Finally, wireless clients cannot reliably monitor the idle / busy state of the medium while transmitting.

The 802.11 MAC protocol is designed to provide robust, secure communications over the wireless medium. The basic access mechanism is *Carrier Sense Multiple Access/Collision Avoidance* (CSMA/CA) with truncated binary exponential back off. Multiple MAC layer mechanisms contribute to collision avoidance and efficient use of the wireless medium.

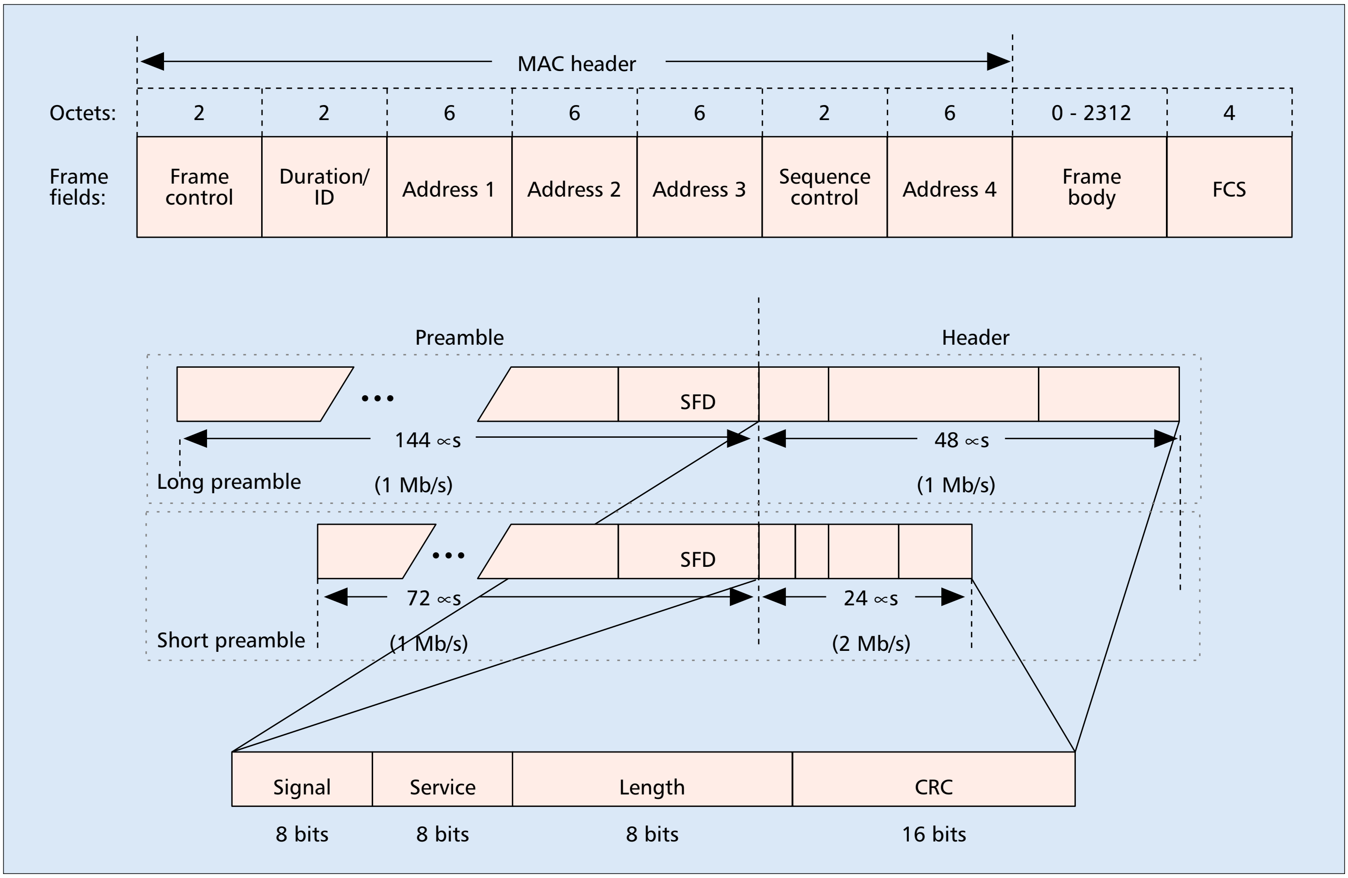

Figure 2. *The wireless Ethernet frame and the physical layer preamble.*

Wt/$2E_S$:	0	4	6	8	10	12	16
Number (CCK-11):	1	24	16	174	16	24	1
Number (CCK-5.50:	1			14			1
Number (CCK-6.875):	1			30			1

Table 1. *CCK weight distribution.*

Security — Wireless LANs are subject to possible breaches from unwanted monitoring. For this reason IEEE 802.11 specifies an optional MAC layer security system known as *wired equivalent privacy* (WEP). As the name implies, WEP is intended to provide to the wireless Ethernet a level of privacy similar to that enjoyed by wired Ethernets. WEP involves a shared key authentication service with RC4 encryption. By default each BSS supports up to four 40-bit keys that are shared by all the clients in the BSS. Keys unique to a pair of communicating clients and direction of transmission may also be used (i.e., unique to a transmit/receive address pair).

The 802.11 MAC Frame Format — Shown in Fig. 2 is the general 802.11 MAC frame format. The address fields, if present, contain one of the following 48-bit IEEE 802 link layer addresses: destination address, source address, receiver address, transmitter address, *basic service set ID* (BSSID). For infrastructure networks, the BSSID is the link layer address of the AP. The Sequence Control field is 16 bits in length and contains the Sequence Number and Fragment Number sub-fields. The Frame Body is an optional field that contains the MAC frame payload.

THE PHYSICAL LAYER: CODING AND MODULATION

THE PHYSICAL LAYER PREAMBLE

The IEEE 802.11b standard defines a PHY preamble that is transmitted before the wireless Ethernet frame depicted in Fig. 2. The PHY preamble, as shown in Fig. 2, consists of a preamble and a header. The header consists of three fields: the *Signal* field, the *Service* field and the *Length* field. These three fields are protected with a 16-bit cyclic redundancy check (CRC) used to detect transmission errors in the header.

The original DSSS (1 and 2 Mb/s) standard defined a PHY preamble with a length of 192 µs; this preamble is encoded using the 1 Mb/s encoding method described in a later section. The 802.11b standard added an optional "short preamble" with a duration half as long, 96 µs. The short preamble uses a short 1 Mb/s encoded preamble followed by a 2 Mb/s encoded header.

THE LOW-RATE DS STANDARDS: THE PAST

The original low-rate *direct sequence* (DS) modulation forms a basis for the high-rate extension. This method of coding and modulation is used

Wt/2E_S:	0	9	10	11	12	13	14	15	16	…
Number (PBCC-11):	1	1	6	11	12	45	117	259	629	…

Table 2. *PBCC-11 Euclidean weight distribution.*

Wt/2E_S:	3.56	3.74	3.98	4.14	4.32	4.55	…
99.Wt/2Es:	352	370	394	410	428	450	…
Number:	2	47	1	53	437	12	…

Table 3. *PBCC-22 weight distribution bound.*

for preamble generation in all rates and coding combinations. The low-rate system is a DSSS signal with a chip rate of 11 MHz and a data rate of 1 Mb/s (binary phase shift keying, BPSK) or 2 Mb/s (quaternary PSK, QPSK).

Barker 1 and 2 Mb/s — The basis for the original 1 and 2 Mb/s transmission is the incorporation of an 11-bit Barker code (or sequence) $B_{11} = [-1, +1, -1, -1, +1, -1, -1, -1, +1, +1, +1]$ with QPSK or BPSK modulation. This code has the desirable property that the auto-correlation function is minimal (0 or –1) except at the origin (where it is 11). This means the modulated waveform essentially occupies the same spectrum as an 11 MHz uncoded chip signal and that a matched filter receiver, matched to the Barker sequence, will experience a processing gain of 11 = 10.41 dB.

From a coding point of view [3], the Barker code can be described in terms of a *linear block code* over the set of integers modulo 4, $Z_4 = \{0,1,2,3\}$. Consider the 1 × 11 repetition *generator matrix* G = [1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1] and the length 11 *cover vector* [2, 0, 2, 2, 0, 2, 2, 2, 0, 0, 0]. Then the four Barker codewords for the 2 Mb/s case are generated as a Z_4 multiple of the generator plus the cover vector (modulo 4). The transmitted signal is generated with the QPSK mapping, which translates Z_4 to QPSK symbols.

Notice that the 2 Mb/s Barker code is 90° rotationally invariant (i.e., the rotation of a codeword vector **x** by 90° is another codeword). This follows from the fact the addition of 1 (modulo 4) to a message symbol $m \in Z_4$ will add the all 1's vector (modulo 4) to the codeword **c** and that incrementing by 1 (modulo 4) in the QPSK mapping corresponds to rotation by 90° (counter-clockwise). This rotational invariance is exploited in the standard by using a differential encoding method that involves "precoding" at the transmitter and "differential" decoding at the receiver (the sliding window nature of the differential decoder limits error propagation).

The 1 Mb/s mode is defined by using a repetition generator matrix G = [2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2] which incorporates a binary message symbol, $Z_2 = \{0,1\}$, and produces a BPSK signal. This produces a code that is 180° rotationally invariant.

The *minimum squared distance* of QPSK is $2E_s$ (where E_s) is the average symbol energy); both the 1 and 2 Mb/s transmissions schemes show an energy improvement in minimum distance squared, at the cost of rate. In the case of 2 Mb/s, the minimum distance squared is $22E_s$ which results in an energy gain of 11 = 10.41 dB over QPSK. However, from a coding gain perspective, there is no coding gain w.r.t. QPSK since the minimum distance squared normalized by the data rate is the same as QPSK. The asymptotic coding gain (ACG) of a coded system (C) relative to an uncoded system (U) is defined as the ratio of the minimum distances of the two schemes (C and U) normalized by the rate and the average signal energy. In the 2 Mb/s case, the minimum distance is 22 times the signal energy and the rate is 2/11 (b/symbol). For uncoded QPSK, on the other hand, the minimum distance is twice times the signal energy and the rate is 2 (b/symbol); in this case the ACG is 0 dB. Similarly, in the 1 Mb/s case, there is an energy gain of 22 = 13.42 dB (over QPSK) but 0 dB of coding gain.

THE "HIGH-RATE" STANDARDS: THE PRESENT

The standard calls for two choices of coding each involving a "symbol rate" of 11 MHz and data rates of 5.5 Mb/s and 11 Mb/s. One code uses a short block length code, known as *complementary code keying* (CCK), that codes over eight QPSK symbols; the other choice incorporates a 64-state packet-based binary convolutional code (PBCC). The main difference between the two involves the much larger coding gain of the PBCC over CCK at a cost of computation at the receiver.

CCK 5.5 and 11 Mb/s — The CCK code can be considered a block code generalization of the low-rate Barker code. For CCK-11, the code is an (n = 8, k = 4) linear block code over Z_4. At the 11 Mb/s rate, 8 bits (4 Z_4 symbols) of information is encoded via the $k \times n = 4 \times 8$ CCK-11 *generator matrix* G added to a length 8 cover vector [0, 0, 0, 2, 0, 0, 2, 0]. Applying the QPSK mapping produces the signal vector.

Wt/2E_S:	3.56	3.58	3.60	3.62	3.74	3.76	3.78	3.98	4.00	4.02	4.14	4.16
99.Wt/2Es:	352	354	356	358	370	372	374	394	396	398	410	412
Ave. Number:	.0913	.2783	.2677	.0927	1.479	3.017	1.528	.2497	.5	.2503	1.293	2.786
Wt/2E_S:	4.18	4.20	4.32	4.34	4.36	4.55	4.57	4.59	4.61	4.63	…	
99.Wt/2E_S:	414	416	428	430	432	450	452	454	456	458	…	
Ave. Number:	2.796	1.327	3.843	7.786	3.933	0.282	1.894	3.267	1.848	.2693	…	

Table 4. *PBCC-22 average weight distribution.*

> *The IEEE 802.11b standard specifies an optional choice of coding and modulation and is considered the "high performance" mode for 11 and 5.5 Mb/s transmission. The optional mode, termed packet binary convolutional coding, involves a BCC combined with a symbol scrambling method.*

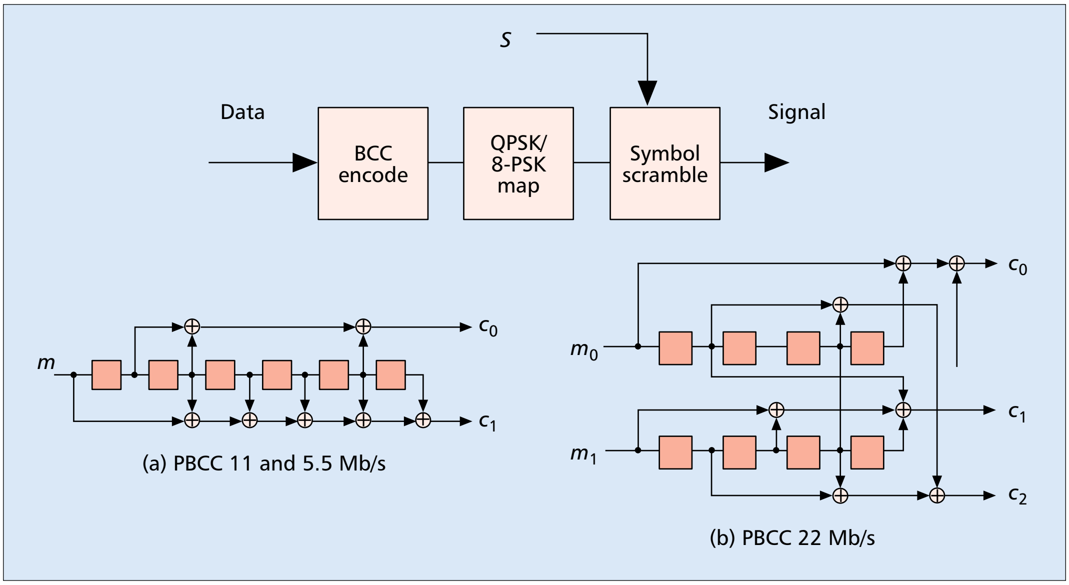

Figure 3. *Packet binary convolutional coding.*

At the 5.5 Mb/s rate, 4 bits of information is encoded via the $k \times n = 3 \times 8$ CCK-5.5 generator matrix G with the length 8 *cover vector* given by [1, 0, 1, 2, 1, 0, 3, 0].

The CCK code is rotationally invariant since the first row of the generator matrix G is the all 1s vector. This implies that a rotation by a multiple of 90° at the receiver will affect only the first symbol of the message vector. This is exploited in the standard by differential encoding/decoding on the first symbol, using the same method as in the low-rate case.

It is interesting to note that a 6.875 Mb/s CCK code, with the same minimum distance of 16Es, is possible by using a 4×8 generator G; this code is not part of the standard.

The asymptotic coding gain for CCK is 3 dB (ACG = 2) over uncoded QPSK. However, the practical coding gain is about 2 dB (as shown in Fig. 4a). The reduction in coding gain from the asymptote is due to the number of "nearest neighbors" at the minimum distance as shown in Table 1. This table shows that at the minimum distance of the code ($8E_s$ for CCK-11 and $16E_s$) for CCK-5.5/6.875) there are 24/14/30 codewords. This large number of nearest neighbors (compared to two nearest neighbors for the 2 Mb/s Barker) accounts for the 1 dB reduction in practical coding gain.

Table 2 shows PBCC-11 Euclidean weight distribution.

PBCC 5.5 and 11 Mb/s — The IEEE 802.11b standard specifies an optional choice of coding and modulation and is considered the high-performance mode for 11 and 5.5 Mb/s transmission. The optional mode, termed *packet binary convolutional coding* (PBCC), involves a BCC combined with a symbol scrambling method as shown in Fig. 3. This structure is also used for the higher-rate 22 Mb/s encoding described in this figure.

The 802.11b PBCC mode (11 Mb/s and 5.5 Mb/s) uses a 1×2 generator matrix over $Z_2[D]$, $G(D)$ as shown in Fig. 3a (in octal notation $G =$ [46, 175]).) For 11 Mb/s operation, this 64-state encoder is followed by a mapping onto QPSK modulation directly. For 5.5 Mb/s, the two binary outputs are bit serialized and mapped onto BPSK.

The last operation of the encoder is symbol scrambling. A specified 256-bit periodic binary sequence is used to control the symbol scrambler. When the binary s value into the symbol scrambler is 0, the QPSK/BPSK symbol out of the symbol mapper is sent directly, while s = 1 tells the symbol scrambler to rotate the mapped symbol by 90° (counterclockwise) as shown in Fig. 4a.

THE "HIGHER-RATE" STANDARDS: THE FUTURE

The Alantro/TI proposal increases the data rate of the IEEE 802.11b standard in a backward-compatible way.

PBCC 22 Mb/s — The high-rate case (22 Mb/s) has a 2×3 generator matrix over $Z_2[D]$ $G(D)$ (in octal notation $G =$ [21, 2, 12; 10, 25, 12].) This BCC encoding function is combined with the digital 8-PSK shown in Fig. 4b to produce a coded eight-level modulation signal.

This coded modulation was discovered via computer search using a bounding technique illustrated in Table 3. The weight values in the table provide a lower bound on the distance between points in the signal constellation. Using this weight function to compare the accumulated distance on a pair of sequences is the basis for the computer search.

The bound predicts the free distance of the code $d_{free} = 352$, but overestimates the growth in nearest neighbors. Table 4 shows the average nearest neighbor growth near the free distance of the code.

PERFORMANCE

AWGN PERFORMANCE

The performance of the various combinations of modeling and modulation is presented in Fig. 5. In Fig. 5a, the *bit error rate* (BER) of the various choices is shown as a function of the received signal to noise ratio Es/No. Figure 5b shows the *packet error rate* (PER), for 1000-byte (8000 bits) packets, as a function of the received signal-to-noise ratio E_s/N_0. Figure 5c shows the PER as a function of the energy-per-bit-to-noise ratio E_b/N_0; these curves are useful for computing and comparing the practical coding gains of the systems. Finally, Fig. 5d shows the PER as a function of the received signal-to-noise ratio E_s/N_0 for the 22 Mb/s system with the multipath receiver that is the basis of the Alantro/TI baseband receiver product. The multipath is modeled using a method developed by the IEEE 802.11 committee and indexes the multipath by a factor known as the *delay spread* [4]. In this model, an increase in delay spread corresponds to a more severe multipath environment.

SPREAD SPECTRUM TRANSMISSION

In wireless communications and other shared media systems, information is often encoded using spread spectrum signaling methods. The *spectral efficiency* of a digital transmission system is defined as the ratio of the *user data rate* (in bits per second) to the *bandwidth* (in hertz) of the power spectral density (suitably defined) of the ensemble of transmission signals. As argued in the very thought-provoking [5] Jim Massey considered an information-theoretic definition of spread spectrum, and studied some of the consequences of his view.

Massey demonstrated that in systems with low spectral efficiency, the use of spread spectrum is a reasonable means of communications that has only a modest, acceptable, loss in Shannon capacity. He also showed that in high spectral efficiency systems, mathematically precise notions of spread spectrum imply a very significant, uneconomical, loss in capacity. In the Massey framework, if the spectral efficiency is not a small fraction of 1, spread spectrum is not practical.

In the process of significantly increasing the data rate, the spread spectrum nature of the signal, in the narrow sense of Massey, is sacrificed. However, the flexible FCC definition allowed the FCC to certify the existing IEEE 802.11b 11 Mb/s systems under DSSS rules. This practical approach to regulation is based on the fact that as an interferer, the high-rate IEEE 802.11b signals are the same as the classical low-rate Barker signals. This is true in both the frequency characteristics as well as the time domain or the temporal characteristics of the transmitted signals.

Furthermore, IEEE 802.11 specifies three disjoint frequency bands for wireless Ethernet systems. This means that the legacy 2 Mb/s systems send a total of 6 Mb/s in the entire industrial, scientific, and mecial (ISM) band, while the 11 Mb/s ones supply 33 Mb/s in the band; the 22 Mb/s systems double the total capacity to 66 Mb/s.

Radio spectrum is a rare and valuable resource, and it is the responsibility of the FCC to ensure that the resource is used for the public good and in an efficient way. One compelling issue is the demands from the public for higher-performance data transmission. Another important issue is the need to avoid the introduction of new signals with spectral and temporal characteristics that were formerly disallowed under the existing rules. Such a change threatens the large base of current products that were built under existing rules with interference not previously allowed or anticipated; from a fairness position, this is unjust.

With the huge success of the IEEE 802.11b standard, one can see the wisdom of the FCC. It

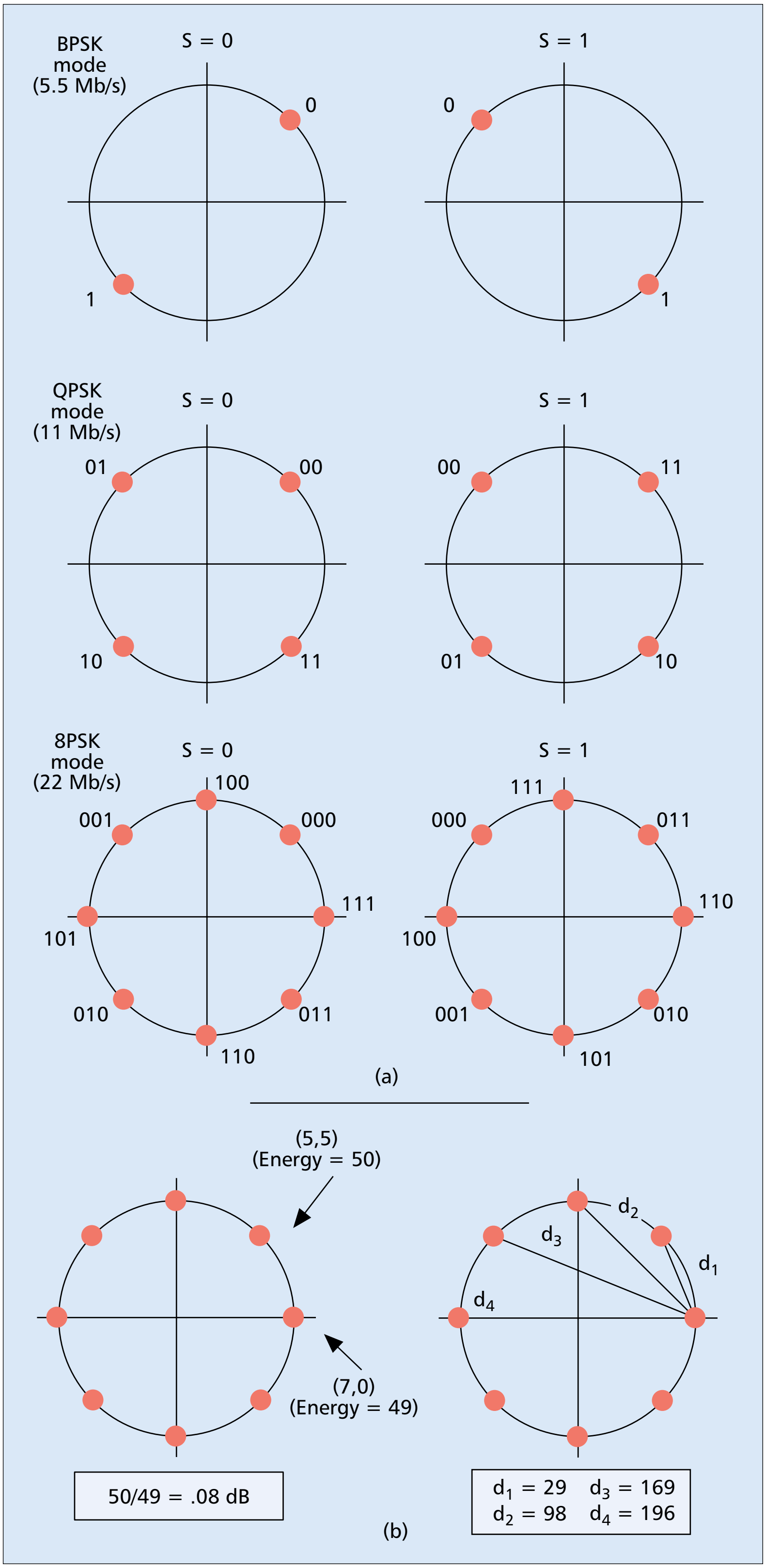

Figure 4. *Modulation symbols.*

In the signal design problem, various parameters are considered in order to optimize the transmission systems. Such parameters include transmission power, Fourier bandwidth, power spectrum and data rate, and a host of others, including the dimensionality of the signal set.

is anticipated that the future regulations will continue to satisfy the demands for higher performance while maintaining a level playing field. The beauty of the PBCC-22 modulation approach is that the data rate is doubled while maintaining backward compatibility with existing networks using a signal with the same interference characteristics as the existing signal sets.

MASSEY'S DEFINITION OF SPREAD SPECTRUM

Massey defined two notions of bandwidth and argued that the indication of spectrum spreading was related to the size of the ratio of the two. The first definition of bandwidth relates to the spectral occupancy of a given signal or a collection of signals. This form of bandwidth, B_F, is known as the *Fourier bandwidth* and relates to the span of frequencies occupied by the signal(s). As is often the case in communications theory, the exact numerical value of the Fourier bandwidth for a given signal or set of signals depends on a measurement criteria such as 3 dB bandwidth or 95 percent power bandwidth. Such required criteria are often needed to define other quantities of interest in communications theory; examples include the definition of signal-to-noise ratio and power spectral density. The Fourier bandwidth is directly related to the Nyquist bandwidth [6], which relates to periodic sampling of a signal (or sets of signal) and is of fundamental importance in the study of digital signal processing (DSP).

Massey's second notion of bandwidth is related to the fundamental problem of information transmission and is meaningful to define only for a collection or a set of signals. Fundamentally, the problem of information transmission is one of signal design and signal detection. Massey logically argues that the definition of spread spectrum should only involve the signal design issue and not signal detection (i.e., the determination of spread spectrum character of a transmission scheme should not change with a change in the receiver).

Signal design involves the creation of a collection of signals used by a transmitter to represent the multitude of messages the transmitter is trying to convey. In the signal design problem, various parameters are considered in order to optimize the transmission systems. Such parameters include transmission power, Fourier bandwidth, power spectrum and data rate, and a host of others, including the dimensionality of the signal set.

The *data rate* parameter of a signal set relates to the size of the collection or number of signals in the signal set; a system transmits at a rate of R b/s if, over a time interval of length T s, the designed signal set defines 2^{RT} distinct signals. With such a collection of signals, $k = RT$ bits of information can be transmitted by assigning a correspondence between the list of signals in the signal set and the 2^k possible values for a k-bit message.

The *dimensionality* of a signal set involves the standard notion of basis as defined in the area of linear algebra. Roughly speaking, the *dimension* of a signal set relates to the minimum number of *independent* parameters (i.e., numbers) required to describe the collection of signals.

The second definition of bandwidth, B_S, relates to the dimensionality of a signal set and describes the linear complexity of the scheme; a system transmits using a bandwidth of B_S Hz if, over a time interval of length T s, the designed signal set has a basis with $B_S T$ elements. Due to the strong relationship between this notion of bandwidth and information theory, Massey called this second definition the *Shannon bandwidth*.

Note that the Fourier bandwidth, the Shannon bandwidth, and the data rate are distinct ideas that all describe attributes of a signal set. For example, the spectral efficiency of a system is the ratio of the data rate to the Fourier bandwidth R/B_F. Another important parameter is the *spreading ratio* $\rho = B_F/B_S$, which relates the two notions of bandwidth.

The first observation Massey noted was the theorem stating that the Fourier bandwidth is never less than the Shannon bandwidth, $B_F \geq B_S$. This means that the spreading ratio satisfies the inequality

$$\rho = \frac{B_F}{B_S} \geq 1.$$

Furthermore, Massey argued that the spreading ratio is the logical measure of the degree in which a communications system spreads the spectrum. If a given system has a large value for ρ, say 10 or 100, it should be considered a spread spectrum system; conversely, a system with a spreading ratio ρ near the minimum of 1 would not be labeled a spread spectrum system. It would be debatable if a system with a spreading ratio of, say, $\rho = 4$ is spread spectrum or not; this is the "gray" area.

In Shannon's original 1948 paper [7], a famous formula for the capacity of a bandlmited additive white Gaussian channel was presented. This formula relates the capacity of the channel to the Fourier bandwidth and signal-to-noise ratio available for transmission. The interpretation of the Shannon capacity is that reliable transmission is possible, for a given signal-to-noise ratio and Fourier bandwidth B_F, *if and only if* the rate of transmission is no more than the Shannon capacity C. In practical terms, the Shannon limit defines an objective data rate goal for a given signaling environment. For the past 53 years, communications engineering have been striving to approach this goal. If one is to impose the requirement that the transmission system operate with a required spreading ratio of ρ, the formula is modified as in Fig. 6.

SPREAD SPECTRUM IN WIRELESS ETHERNET

It is interesting to see how Massey's notion of spreading relates to the DSSS wireless Ethernet standard and the higher-rate extensions. In terms of the coding level, the Barker systems introduce a nontrivial spreading ratio of $\rho = 11$ (2 Mb/s) and $\rho = 22$ (1 Mb/s). All the high-rate (> 2 Mb/s) cases have $\rho = 1$, with the exception of PBCC-5.5, which has $\rho = 2$. In practice, the wireless Ethernet signals use a nontrival excess bandwidth pulse shape so that the occupied bandwidth is larger than the 11 MHz symbol rate. It is important to note that, in terms of Massey's spread ratio, all the high-rate systems have the same value (with the exception of

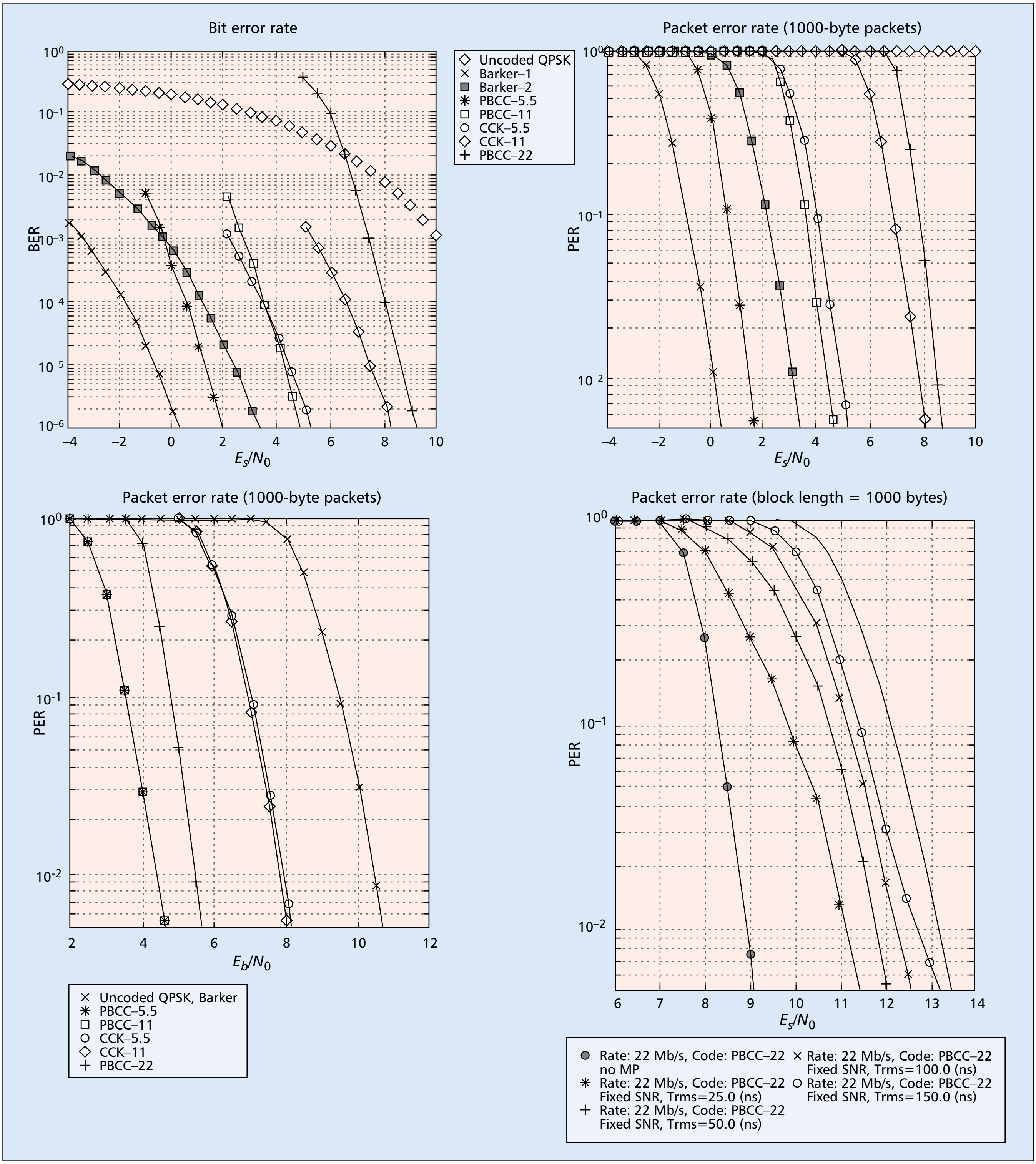

Figure 5. *The error rate performance compared: a) bit error rate vs. channel SNR (E_s/N_o); b) packet error rate vs. channel SNR (E_s/N_o); c) packet error rate for coding gain (E_b/N_0); d) packet error rate in multipath (22 Mb/s).*

PBCC-5.5). Thus, for example, from the viewpoint of information theory, the CCK-11 and PBCC-22 signals show the same degree of signal spreading.

In Fig. 6 the offered data rate and signal-to-noise ratio requirements for the IEEE 802.11b standard and the Alantro 22 Mb/s extension are displayed. On the x-axis is the signal-to-noise ratio defined as the symbol-energy-to-noise ratio E_s/N_0,[1] while the y-axis is the data rate of the system assuming the 11 MHz symbol frequency common to the standard. The upper solid curve is the Shannon limit as described by the equation shown. The dotted curve shows the Shannon limit assuming a spreading ratio of $\rho = 11$ (the spreading ratio of the 2 Mb/s Barker system). The individual points on the graph describe the various data rates and SNR require-

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[1] $E_s = P/B_S = P \cdot \rho/B_F$.

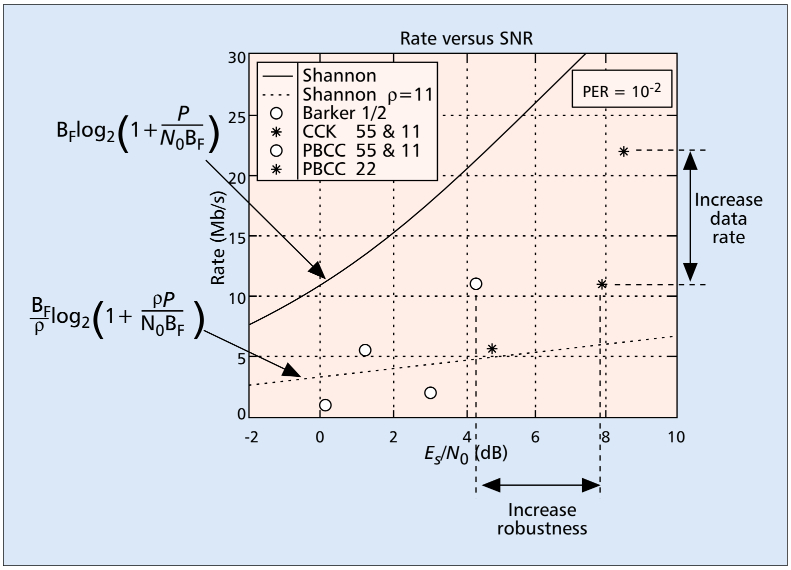

Figure 6. *The performance of wireless Ethernet relative to the Shannon limit.*

ments of the host of systems. Note that the SNR requirement is defined as the SNR required to maintain a PER of 10^{-2} with a 1000-byte (8000-bit) packet; this 1 percent PER threshold is a standard measure of "robustness" used by the IEEE 802.11 committee in deliberations leading to the selection of standards.

Figure 6 shows how the superior error control properties of the PBCC method of signal generation can be used to improve robustness (i.e., SNR requirements) or user data rate. It is also interesting to see that the existing IEEE 802.11b standard, which is widely deployed in FCC certified products, violates the Massey spread spectrum result in terms of Shannon theory. The reason for this discrepancy is explained by the pragmatism of the FCC regulatory body, the FCC's broader definition of spread spectrum, as well as the strictness of Massey's theoretical result. Without such flexibility on the part of the FCC, there would be no high-performance wireless Ethernets.

CONCLUSIONS

This article considers the history, development, and future of high-speed wireless Ethernet in the 2.4 GHz ISM band. Networks that allow users to connect to networks without wires and with high throughput have recently become popular and show the potential for exponential growth in the coming years.

The birth of wireless Ethernet began over a decade ago with the work of the IEEE 802.11 wireless networking standards body. This group developed the technology behind the very successful IEEE 802.11b standard that has shown explosive growth over the last couple of years.

This article considers the origins of the 11b standard and includes an introduction to the media access control technology including a description of the MAC header structure.

The article describes the physical layer technology specified in the 11b standard including the CCK and PBCC modes. An extension of the 11b technology developed by Alantro Communications (now a part of Texas Instruments) is described; this extension provides a "double the data rate" (22 Mb/s) mode that is fully backward compatible with existing 11b networks.

The article also discusses the role and limitations of spread spectrum communications in wireless Ethernet.

As of the writing of this conclusion, a compromise proposal, that includes the PBCC-22 extension, is under consideration by the current IEEE 802.11g task group. It is the expectation of the authors that some form of this compromise will be adapted this fall. Currently, Texas Instruments is shipping wireless Ethernet chips that fully implement the 11b standard with both CCK and PBCC modes, and include the PBCC-22 extension.

Note that an expanded version of this article will appear in an upcoming book [8].

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BIOGRAPHIES

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PETER A. MURPHY received his B.S. in electrical engineering from the University of Massachusetts at Amherst in 1989, and his M.S. and Ph.D. degrees in electrical engineering from the University of California at Davis in 1993 and 1998, respectively. In 1999 he joined Alantro Communications in Santa Rosa, California, where he worked on 802.11a and 802.11b wireless LAN products. In 2000 he became a communications systems engineer with Texas Instruments (following their acquisition of Alantro Communications) where he continues to work on wireless LAN products. From 1997 to 1999 he was a member of the technical staff at U.S. Wireless Corporation of San Ramon, California, where he worked on the early development of an E-911 array-based geolocation system. From 1989 to 1991 he was a software engineer working for Sterling Software, Palo Alto, California, where he designed and developed software applications under contract for the NASA Ames Research Center in Mountain View, California.

RON PROVENCIO is marketing manager for Texas Instruments Wireless Networking Business Unit. His business unit is part of TI's Semiconductor Group, chartered to provide complete silicon solutions for the Wireless Ethernet market. He has joined TI through TI's acquisition of Alantro Communications (Sept. 8, 2000). a small startup providing state-of-the-art technology in wireless Ethernet (802.11). Prior to joining Alantro Communications he had a successful 10 year career with Hewlett-Packard, where he worked in several technology and product areas covering HP scanners, All-in-One Officejets, and HP Omnibooks. During his involvement with HP Omnibooks, he helped drive HP's wireless strategy for their Omnibook product line. His experience covers a well rounded portfolio of marketing responsibilities in product management, business development, and marketing management. In many of these roles he has been instrumental in helping HP develop new product concepts and define product strategies for future generations of products.

ERIC J. ROSSIN received his B.S.E.E., M.Eng., and Ph.D. degrees in electrical engineering from Cornell University, Ithaca, New York, in 1983, 1984, and 1995, respectively. He is currently with the Wireless LAN Business Unit of Texas Instruments in Santa Rosa, California. Previously he was a cofounder and president of Alantro Communications from 1997 to 2000. He has also held engineering and management positions at Next Level Communications and Applied Signal Technology, in addition to consulting for several corporations.

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MATTHEW B. SHOEMAKE is research manager for Wireless Networking at Texas Instruments. He also is the chairperson for IEEE 802.11 Task Group G, the committee tasked with extending the IEEE 802.11b standard to higher data rates. Prior to TI he was member of technical staff for Alantro Communications, a company specializing in WLAN semiconductor technology, which was acquired by TI in late 2000. He co-invented packet binary convolutional coding (PBCC), the high-performance modulation mode of the IEEE 802.11b standard, and is a key designer of TI's 802.11b-compliant chips. He received doctorate and Master's degrees in electrical engineering from Cornell University and a Bachelor's degree in electrical engineering and computer science from Texas A&M University.

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