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Re:	Response to Call for Contributions to Session #4 of the IEEE 802.16 Working Group on BWA by the PHY Task Group for PHY proposals dated 1999-9-22.
Abstract	Rate two-thirds convolutionally-coded, 8-ary continuous phase modulation is proposed for implementing FDMA/TDM and multi-frequency TDMA air interfaces in BWA Systems. It is further proposed that symbol-synchronous, multi-frequency TDMA be implemented in the upstream direction in BWA Systems. The proposed methods are described and their advantages and limitations are summarized herein.
Purpose	To propose the use of rate two-thirds convolutionally coded, 8-ary continuous phase modulation for implementing FDMA/TDM and Multi-Frequency TDMA air interfaces in BWA Systems.
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Continuous Phase Modulation for BWA System Implementation

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Introduction

The use of rate two-thirds convolutionally-coded, 8-ary continuous phase modulation (CPM) for implementing FDMA/TDM and multi-frequency TDMA air interfaces in broadband wireless access systems (BWA Systems) is proposed herein. CPM in the form of 2-ary GMSK has been used commercially with considerable success worldwide in GSM systems (which use TDMA upstream signaling) during the past several years. Perhaps the most important attribute of GMSK is its relative insensitivity to power amplifier nonlinearities – as both the bit error probability (BEP) performance of and the signal's spectrum sidelobe levels for GMSK degrade moderately when the power amplifier is operated at or above its one-decibel output power compression point. The limitations of GMSK include a less-than-stellar spectrum utilization efficiency (SUE) for the *Eb/No* required to achieve a specified BEP and inflexibility in changing the SUE versus (required) *Eb/No* tradeoff. Advances made in modem technology during the past few years now enable the practical implementation of systems which use "higher"-ary CPM in concert with convolutional coding that provide both improved and selectable SUE versus *Eb/No* tradeoffs while retaining relative insensitivity to power amplifier nonlinearities.

Concatenation of rate two-thirds convolutional coding with block coding on a selective basis is proposed where the block code, when selected, is either a commonly used Reed-Solomon (R-S) code or the (extended) Golay (24, 12) code. The short, rate one-half Golay code would provide for robust interchange of overhead messages between terminals and for effective implementation of low-data-rate user circuits without introducing unacceptable block encoding (and interleaving) delays. It is further proposed that the transmit time bases in subscriber transceiver stations (STSs) within a BWA System be synchronized accurately so that time tracking of STS-sourced signals received at a base transceiver station (BTS) is not required, *i.e.*, that symbol-synchronous, multi-frequency TDMA be used to provide upstream signaling.

Overview

General description

A block diagram of the proposed PHY elements is shown in Figure 1. At the level of detail contained therein, the diagram applies for both BTSs and STSs. There are minor differences between TDM and TDMA signal structures and certain frequencies and time bases are reference frequencies and time bases in a BTS but are controlled frequencies and time bases in a STS – as addressed subsequently. The proposed TDM and TDMA frame structures are shown in Figures 2 and 3, respectively. Except for the use of CPM for signaling and MSK signals modulated by pseudo-noise (PN) sequences for implementing system synchronization, the proposed PHY elements and frame structures differ only moderately from their counterparts in existing standards.

The *Eb/No* performance of and signal spectral width for the proposed CPM depend, in part, on the value of the signal's modulation index, *h*, and on the properties of transmit and receive filters used to filter the signal. It is proposed that the system be implemented so that the SUE versus *Eb/No* tradeoff can be varied by statically and/or dynamically via modulation index value selection and that the modulation symbol rate be correspondingly varied so that the signal's spectral occupancy remains nominally constant. The *Eb/No* versus SUE performance for SUE values ranging from one to about 1.7 is documented in a subsequent section.

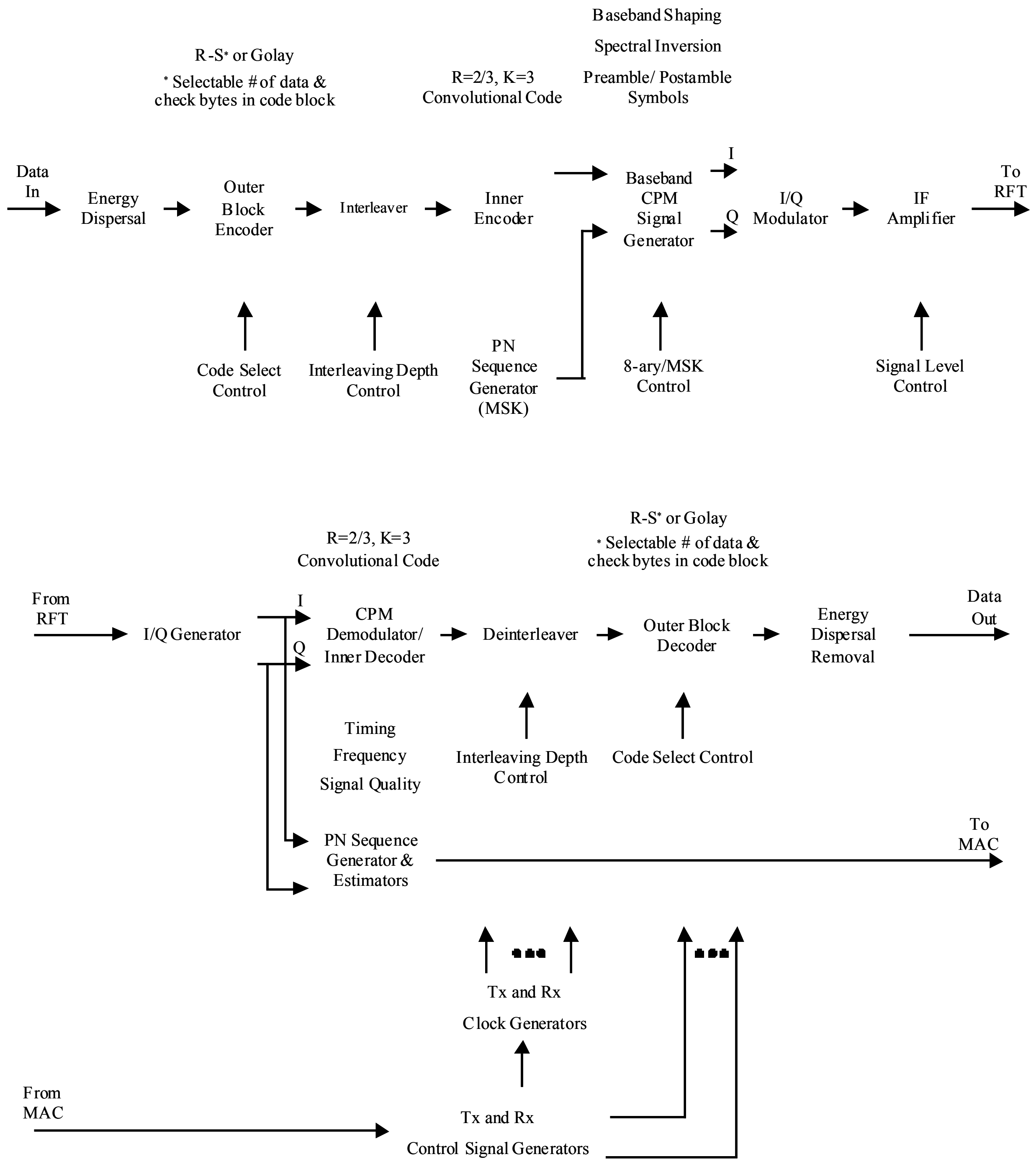

Figure 1. Block diagram of PHY elements proposed.

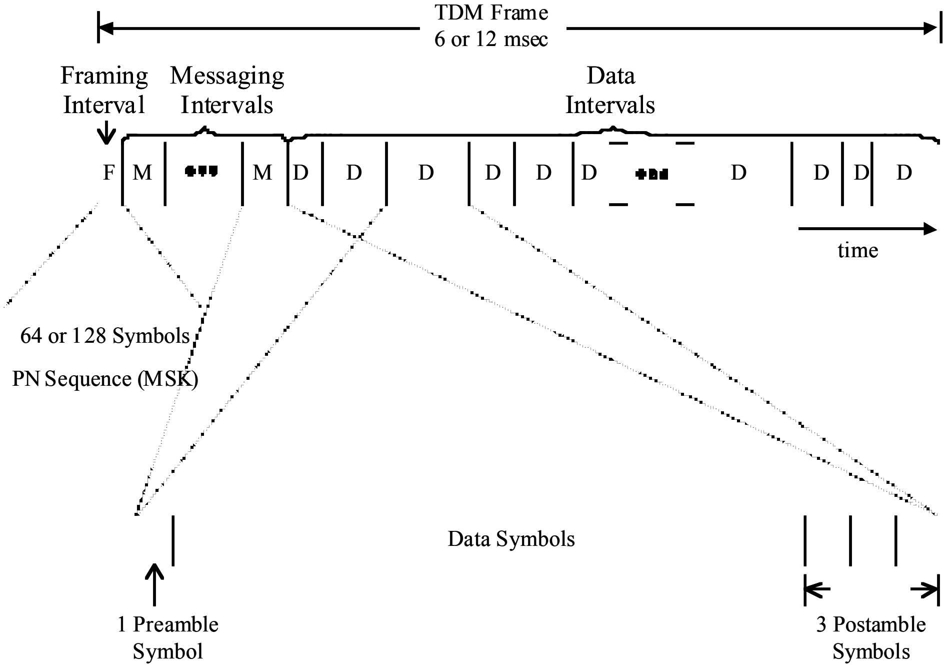

Figure 2. Proposed TDM frame structure.

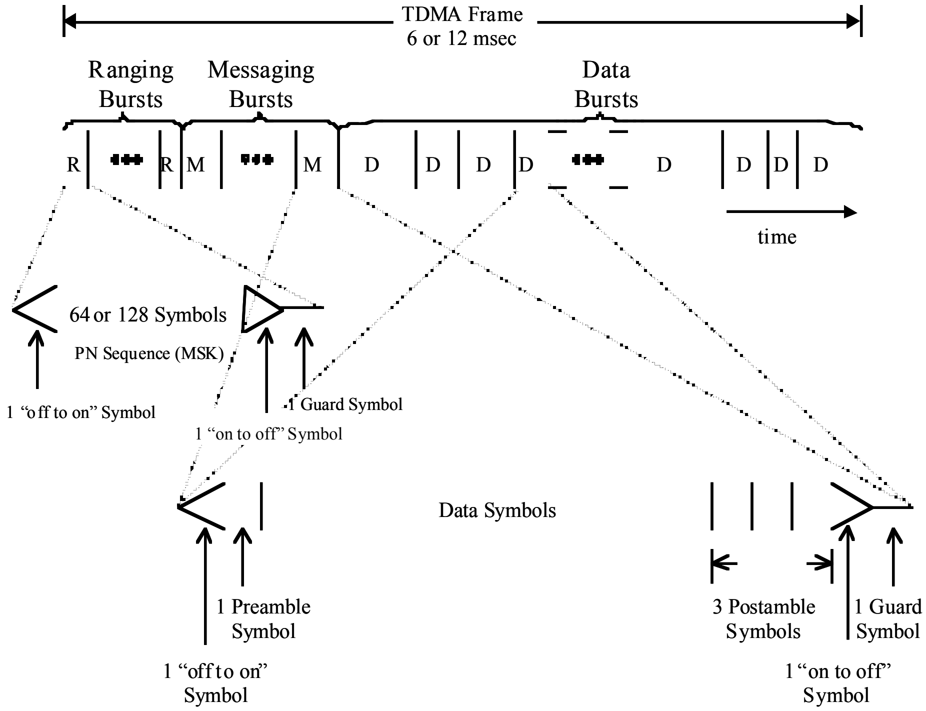

Figure 3. Proposed TDMA frame structure.

Block coding

For R-S block coding, the numbers of message bytes and check bytes in a code block would be selectable as indicated in Figure 1. The use of a (208, 192) R-S code over GF(256) is particularly convenient for implementing average circuit rates that are integer multiples of eight kilobits per second in TDM/TDMA systems. Using such a code improves the *Eb/No* performance of rate two-thirds convolutionally-coded, 8-ary CPM by about three decibels while reducing the SUE by only about eight percent provided code blocks are interleaved over four blocks. Since overhead messages communicated between a BTS and STSs are typically much shorter than 192 bytes, such overhead messages would be rate one-half (Golay) block coded and, typically, interleaved over multiple code blocks since most overhead messages (including CRC bits appended for error detection) will span several code blocks when only twelve message bits are transmitted per block. Extremely robust overhead message processing would thus be provided in exchange for a reduction in SUE for overhead-message transmission. Also, Golay block coding and multiple block interleaving would be used to implement circuits that have a low average data rate, a sensitivity to encoding/interleaving delay and a high availability requirement, *e.g.*, voice over IP circuits with stringent QoS requirements. For such circuits, enabling/disabling of block coding in real time could be implemented to provide coarse control of the SUE versus *Eb/No* tradeoff and/or the circuit availability. Since the *forte* of BWA Systems is “broadband,” the impact of using rate one-half block coding for overhead messages and selected low-rate circuits on the overall system SUE should be small.

Symbol-synchronous TDMA

For a symbol-synchronous, multi-frequency TDMA implementation, each STS accurately controls its transmit time base, transmit frequency and transmit power level (when the available output power level allows) so that corresponding values need not be determined at the BTS to effect data-burst demodulation. When appropriately combined with CPM, symbol-synchronous operation allows the use of a preamble for each (TDMA) data burst that spans only one modulation symbol as shown in Figure 3. For k equal to three convolutional coding, the postamble for each data burst would span three modulation symbols. Transitioning the signal from “off to on” and from “on to off” would each be allocated a time interval that spans one modulation symbol – and a one modulation-symbol guard time between bursts would accommodate changing the signal’s carrier frequency from burst to burst (using a digitally-implemented frequency synthesizer). A total of seven modulation symbols would be spanned by burst overhead for each data burst. Thus, signal bursts that convey short messages from the STS to the BTS for implementing overhead functions and data bursts for circuits that operate at a low average data rate can each be transmitted with a high burst utilization efficiency (BUE) without imposing unacceptable TDMA multiplexing delays that result from long frame durations (provided the data in such bursts are either not block encoded/interleaved or block encoded/interleaved using a short block code, *e.g.*, the extended Golay code as described above).

For symbol-synchronous operation, STS transmit frequency control would be implemented open-loop based on a receive-frequency offset determined by frequency-tracking a downstream signal received at the STS from the BTS. Each STS would transmit ranging (channel estimation) bursts at a rate of about one burst per second in pre-assigned time slots, see Figure 3, from which the BTS would estimate signal arrival-time error relative to a reference receive (demodulator) clock, signal amplitude and signal quality; the BTS reference receive clock would be synchronized to the BTS transmit clock. As a check, the frequency error for ranging bursts received from each STS would also be estimated at the BTS. In turn, for each STS, the estimated errors in signal arrival time and signal amplitude would be transmitted from the BTS to the STS as overhead messages via downstream signaling at an appropriate rate, see Figure 2, and used at the STS to correct the transmit time base and the transmit power level, respectively. Each ranging burst would be an MSK signal burst modulated by a pseudo-noise (PN) sequence where the (extended) PN sequence length would equal 64 or 128, and the aforesaid parameter estimates would be generated at the BTS using robust correlation processing methods.

Downstream TDM

For a BTS-sourced downstream TDM signal, the time continuum would be organized into contiguous frames of equal duration and an extended PN sequence of 64 or 128 symbols would be transmitted using MSK modulation at the beginning of each frame as shown in Figure 2. Each STS would process a received downstream signal as appropriate to “acquire” and synchronize its receive time base with respect to the PN sequences embedded therein, implement receive-frequency tracking, estimate the received signal's amplitude, implement AGC and generate signal quality estimates through the use of suitable robust correlation processing methods; time tracking would be provided by a sampled-data delay-lock loop. Rate two-thirds convolutionally-coded, 8-ary CPM would be used to convey overhead messages and user-circuit data to the STSs during contiguous time intervals of varying lengths (see Figure 2). For each signaling interval associated with a distinct overhead message or user circuit, the signal's modulation index value and a block coding option, including no block coding, would be selected by the BTS consistent with the circuit type, the required circuit availability and QoS and, for selected circuit types, signal quality estimates for the STS(s) to which the data is destined (which are generated as described above and conveyed to the BTS as overhead data). The modulation index value and block coding option would be selected for a circuit when the circuit is established, and for some types of circuits, changed in real time in response to changes in path attenuation. Each distinct signaling interval would have one preamble symbol transmitted at the beginning of the interval and three postamble symbols transmitted at the end of the interval (for k equal to three convolutional coding). That is, the TDM signal structure is like the TDMA signal structure except that no guard symbols or on/off transitioning symbols are present in the TDM signal, see Figures 2 and 3, and the TDM signal's phase would be continuous at signaling interval boundaries.

ATM-cell accommodation

For the modulation and coding methods described above, ATM cell transmission can be accommodated in a straightforward manner when the average user-circuit data rate is an integral multiple of 64 kilobits per second and the TDM/TDMA frames have a duration that is an integral multiple of 6 milliseconds. For a user-circuit data rate of 64 kilobits per second and a frame duration of 6 milliseconds, the user data in one ATM cell, 384 data bits, could be transmitted in each frame as two interleaved (208, 192) R-S code blocks (interleaving over two code blocks only would result in an *Eb/No* performance degradation of less than 0.5 decibels) or as 32 (24, 12) interleaved Golay-code blocks. If the transmission of ATM-cell overhead bytes is required, the number of message bytes in a R-S code block could be set equal to four times the number of ATM cell bytes transmitted per cell – a maximum value of four times 53: 212. If cell overhead-byte transmission is required, the implementation of ATM circuits at rates less than 32 kilobits per second may be difficult to accomplish in a straightforward manner without increasing the frame duration to an appropriate integral multiple of 6 milliseconds – and correspondingly increasing the multiplexing delay.

Eb/No versus SUE Performance

AWGN performance for the linear channel with adjacent-channel signals

Performance data for rate two-thirds convolutionally-coded, 8-ary CPM combined with (208, 192) R-S block coding that apply when the channel is linear and the CPM signal is received in the presence of AWGN are presented in Figure 4. In this figure, the value of *Eb/No* required to achieve a BEP of 10-9 is plotted as a function of spectrum utilization efficiency (SUE) for a design believed to be realizable where *Eb* represents the energy in the signal demodulated per bit output by the R-S decoder, *No* represents the single-sided power spectral density of the AWGN and SUE is rate at which information bits are output by the R-S decoder in bits per second divided by the bandwidth allocated for signal transmission in Hertz. As noted in the preceding section, the value of SUE depends primarily on the signal's modulation index value – but moderate changes in SUE can be effected by changing the designs, particularly the bandwidths, of transmit and receive filters. In determining the SUE values, it was assumed that the desired signal is received in the presence of adjacent-channel signals that have carrier frequencies lower and higher than the desired signal's carrier frequency by the same amount and are modulated by independently-generated random bit streams, but are otherwise like the desired signal. The amplitude of each adjacent-channel signal was set six decibels higher than the desired signal's amplitude and the adjacent-channel frequency offset for which an increase of 0.2 dB in *Eb/No* was required with the adjacent channel signals present to maintain a BEP of 10-9 was determined. The bandwidth allocated for signal transmission is taken to be equal to the aforesaid adjacent-channel frequency offset value. The 0.2 dB performance degradation is not included in the plotted values of *Eb/No* because the performance degradation is negligibly small when all signals have the same amplitude. Values for *C/N* required to achieve a BEP of 10-9 are also plotted as a function of SUE in Figure 4 where *C* represents the power level of the received signal and *N* represents the noise power in the allocated channel bandwidth.

For TDM and TDMA signaling, the curves in Figure 4 apply provided the percentage of time during which "useful" data (overhead messages and user-circuit data) are not transmitted is much smaller than the percentage of time spanned by modulation symbols that convey useful data – as will nominally be the case for the modulation and coding means proposed herein when the average user-circuit data rate is on the order of 64 kilobits per second or higher. The four-symbol per time interval overhead for TDM signaling and seven-symbol per burst overhead for TDMA signaling cause the SUE values to be increasingly less than shown in Figure 4 for average user-circuit data rates increasingly less than about 64 kilobits per second. The reduction in SUE that results from overhead symbol transmission is, however, markedly smaller for the proposed TDMA signaling concepts than for conventional "preamble per burst" TDMA systems.

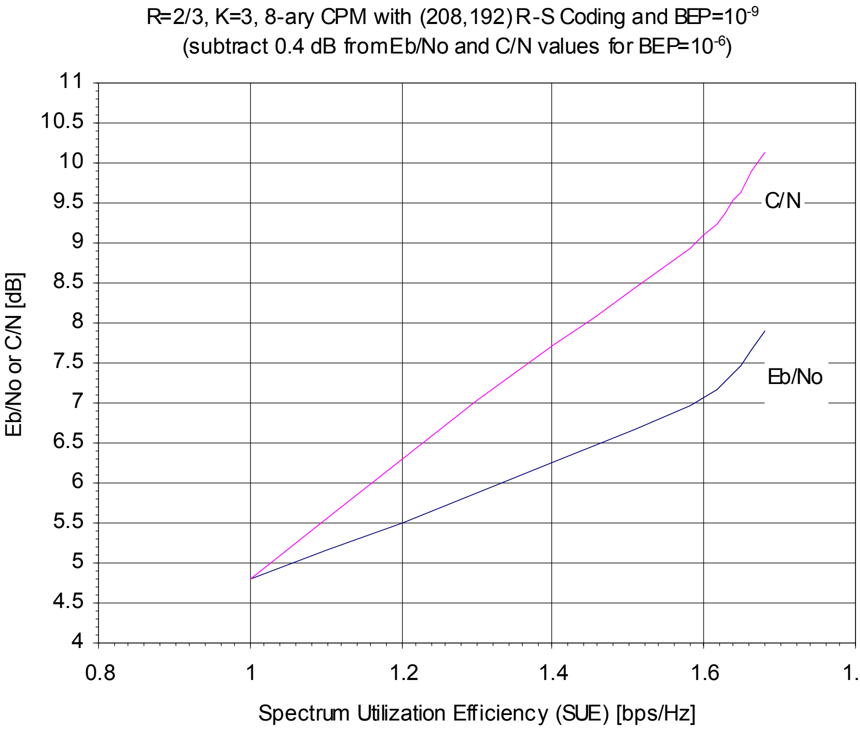

Figure 4. E_b/N_o versus SUE for linear-channel operation.

Co-channel signal sensitivity

The BEP performance of the CPM and block coding method described at the beginning of the preceding subsection when the desired signal is received in the presence of one or more co-channel signals of the same type as the desired signal and low-level AWGN (*Eb/No* = 30 db) has also been determined for SUE values of 1.0 and 1.6. The carrier frequencies of the desired and co-channel signals are modeled as differing by small amounts relative to the channel bit transmission rate, as would usually be the case. To a close approximation, the ratio of desired-signal received power to total co-channel signal power that results in a BEP of 10-9 equals the required *C/N* value plotted in Figure 4. That is, the BEP performance in nominally the same irrespective of whether the undesired signal is AWGN or multiple co-channel signals that have the same total power level as the AWGN. When only one co-channel signal contributes most of the co-channel signal power, the desired signal to co-channel signal power ratio for a 10-9 BEP and SUEs of 1.0 and 1.6 are approximately 0.9 dB and 0.6 dB smaller (better), respectively, than the *C/N* values plotted in Figure 4. Note that performance degradations attributable to imperfect “tracking” of carrier-signal phase variations due to the presence of co-channel signals are included in the results reported; since time synchronization is implemented robustly, the performance degradation caused by time synchronization errors is considered to be negligibly small.

Multipath sensitivity

The BEP performance of the subject CPM and block coding method for single-ray multipath operation has also been determined for multipath delays ranging from zero to one symbol duration in steps of one-eighth of a symbol duration. Worst-case performance results when the multipath delay equals zero and the desired and undesired signals differ in phase by 180 degrees. Thus, there does not appear to be any justification for implementing equalization for the subject CPM and block coding method.

Performance for nonlinear power amplification

For terminals that transmit only a single signal (at a time) – as is expected to be the case for STSs, the proposed CPM accommodates operation of each terminal's transmit power amplifier at or above its one-decibel output power compression point. The performance degradation that results from nonlinear power amplification depends on many factors that are beyond the scope of what can reasonably be addressed herein. However, said degradation is expected to be not greater than about 0.5 dB, even if the power amplifiers have not been "linearized," provided power amplifier input levels are prevented from being markedly larger than the input levels for which the output power is compressed by one decibel. That is, adding 0.5 dB to the *Eb/No* and *C/N* values plotted in Figure 4 accommodates nominal worst-case degradation to result from nonlinear power amplification. Of course, if multiple signals are transmitted concurrently – as may be the case for BSTs, power-amplifier output power back off will be required to prevent intermodulation signals from having unacceptable levels, and distortion of the desired signals will be sufficiently small for Figure 4 to apply without correction (provided the intermodulation signals have a suitably low level).

Summary of Benefits and Limitations of the Proposed PHY Elements

The primary benefits of the proposed PHY elements are

1. Stellar *Eb/No* versus SUE performance for SUEs ranging from 1.0 to 1.65 bits per second per Hertz of allocated bandwidth when CPM is employed in conjunction with R-S block coding
    a. Network capacity (aggregate data rate) is up to 40 percent larger than for coded QPSK for equal required values of *Eb/No* (and linear-channel operation)
2. Capability for independently setting the *Eb/No* versus SUE tradeoff for each user half-circuit either statically or dynamically based on required circuit BEP, QoS and availability and on signal to noise levels for each signal received in the system
3. Robust system synchronization
4. Robust accommodation of co-channel and multipath signals
    a. Enables frequency re-use by BSTs in adjacent cells
    b. Enables use of multiple sector antennas at a BST for which beams that cover adjacent sectors are orthogonally polarized
        i. The frequency re-use factor within a cell can equal the number of sector antennas plus the number of narrow beam antennas, if any, at the BST
    c. Equalization for multipath accommodation will not be required

5. Each TDMA signal burst is burdened with only seven overhead symbols
    1. Allows user circuits that have relatively-low data rates to be implemented effectively using a relatively-short TDMA frame length (6 or 12 milliseconds) thus avoiding an unacceptable-large TDMA multiplexing delay
    2. Allows efficient transmission of overhead messages from STSs to a BST
        - i. Enables efficient implementation of upstream signaling for always-on STS operation provided the aggregate upstream data rate is on the order of or greater than one kilobit per second times the number of STSs in the coverage area, *e.g.*, one megabit per second for 1,000 STSs
        - ii. Allows uplink signaling to be implemented as a “geographically-distributed statistical multiplexer” through effective allocation of uplink signaling capacity in real time
    3. Allows data for a half-circuit (transmitted at a rate equal to or greater than 16 kilobits per second) to be conveyed via multiple, non-contiguous bursts in a frame with reasonable efficiency
        - i. Dynamic allocation of time intervals to accommodate modulation index changes made adaptively to adjust to changing link conditions and to provide variable bit rate service is simplified markedly when data for a half-circuit is not required to be transmitted during a single interval in each frame
6. Power amplifiers which amplify a single RF transmit signal at a time – STS power amplifiers – can be operated at or above their one-decibel output power compression point without significantly degrading system performance and need not be “linearized”
    - a. The most expensive component in an STS will probably be its RF power amplifier
    - b. Design complexities or output power rating margin requirements that derive from ensuring that the output power back-off is never less than a required value are avoided
    - c. QPSK signaling requires about two to three (or more) decibels of output power back-off depending on power amplifier characteristics and the means used to ensure that the output power back-off is never less than the required value
    - d. For 16-QAM signaling, the average output power level is less than the one-decibel compression point output power rating by about seven to eight (or more) decibels depending on power amplifier characteristics and the means used to ensure that the output power back-off is never less than the required value
7. The TDM and TDMA signals proposed have nominally the same structure
    - a. Quasi-symmetrical point-to-point links, *e.g.*, a bi-directional interconnection of two BTSs, can easily be implemented
    - b. Downstream and upstream half-circuits can be similarly robust
    - c. Transmit to receive loop-back test configurations can be provided without unduly complicating the design

8. Recently-developed technology for jointly demodulating and rate two-thirds decoding TDMA signal bursts generated as proposed herein "accommodates" changes in the undesired component of the received signal's phase without using a phase-lock loop (PLL) to acquire and track said undesired phase component
    a. For said recently-developed technology, there are no known counterparts of PLL "hang-up" and cycle slipping that make a 10-9 BEP difficult to provide using conventional technologies – especially in "preamble per burst" TDMA systems
    b. For said recently-developed technology, digitized versions of the received signal's I and Q components are processed to implement nearly-ideal maximum-likelihood demodulation and decoding

The primary limitations of the proposed PHY elements are

1. For linear channel operation and a SUE value of 1.08, rate three-fourths turbo-coded QPSK outperforms the proposed coded CPM by about 0.5 dB
2. Higher values of SUE for point-to-point links can be provided by QAM
3. The technology required to implement the proposed PHY elements – particularly the TDMA demodulator/decoder – is new and, insofar as we know, yet to be proven in operational equipment for 8-ary signaling (however, a 4-ary CPFSK TDMA modem for implementing IP-based satellite communication systems that provides dynamic selection of four modulation index values, R-S coding and symbol-synchronous operation has been implemented successfully by Comtier), and such technology may not be available from multiple sources.

Intellectual Property Statement

Comtier owns intellectual property applicable to implementing selected PHY elements proposed herein. If said PHY elements are incorporated in the standard, Comtier would agree to license the applicable intellectual property under reasonable terms and conditions for the purpose of implementing the standard as required by the IEEE.