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Title	**Synchronous, DS-CDMA/FDMA PHY Proposal for IEEE 802.16.3**
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Re:	This contribution is submitted in response to a call for contributions on initial PHY proposals for IEEE 802.16.3 Task Group initiated in September 2000.
Abstract	This document outlines a PHY proposal for IEEE 802.16.3 using a combined synchronous DS-CDMA (S-CDMA) and FDMA scheme. The proposed PHY features adaptive QAM modulation, high-rate trellis and/or turbo coding, linear equalization along with power and timing control.
Purpose	To provide a description of a proposed physical layer specification for consideration by the IEEE 802.16.3 Task Group.
Notice	
Release	
Patent Policy and Procedures	

Synchronous DS-CDMA/FDMA PHY Proposal for IEEE 802.16.3

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1 Introduction

In this document, we detail a preliminary PHY proposal for IEEE 802.16.3. The proposal uses a hybrid synchronous DS-CDMA (S-CDMA) and FDMA scheme with adaptive quadrature amplitude modulation (QAM) and trellis and/or turbo coding. While the focus of this proposal is on frequency division duplexing (FDD) operation, a time division duplexing mode is also possible for unpaired frequency allocations.

2 Overview

The bulleted list below provides an overview of the characteristics and features of the proposed PHY.

- Synchronous direct-sequence code division multiple access (S-CDMA) for both up and downstream [1][2]
  - Spread RF sub-channel bandwidths from 1.75-7 MHz depending on channelization of interest
  - Constant chip rate from 1-6 Mcps within each RF sub-channel with common I-Q spreading [chip rate depends on channelization of interest (e.g. 3.5 MHz or 6 MHz)]
  - Orthogonal, variable-length spreading codes using Walsh-Hadamard designs with spread factors (SF) from 1 to 128 chips/symbol
  - Unique spreading code sets for adjacent, same-frequency cells/sectors
  - Upstream and downstream power control and upstream link timing control
  - Variable data rate S-CDMA channels ranging from 32 kbps up to 32 Mbps depending on SF, chip rate, modulation format and channel coding rate
  - S-CDMA channel aggregation for highest data rates
- FDMA for large bandwidth allocations with S-CDMA in each FDMA RF sub-channel
- S-CDMA/FDMA channel aggregation for highest data rates
- Code, frequency and/or time division multiplexing for both up and downstream
- Frequency division duplex (FDD) or time division duplex (TDD) [TDD option not discussed]
- Coherent 4-QAM (i.e. QPSK) and 16-QAM modulation with optional support for 64-QAM
- End-to-end raised-cosine Nyquist pulse shape filtering
- Adaptive coding, using high-rate punctured, convolutional coding (K=7) and/or Turbo coding
- Data randomization using spreading code sequences
- Linear equalization in downstream with possible transmit pre-equalization for upstream
- Space division multiple access (SDMA) using adaptive beamforming antenna arrays at the base station (BS) [1-16 elements possible]

3 Reference Model

Figure 3.1 shows the wireless access reference model per the IEEE 802.16.3 FRD [3]. Within this model, the proposed PHY provides access between one or more subscriber stations (SS) and a base station (BS) to support the user and core network interface requirements. In Figure 3.2, the PHY reference model is shown. This reference model will be useful in discussing the various aspects of the proposed PHY in Sections 5 and 6.

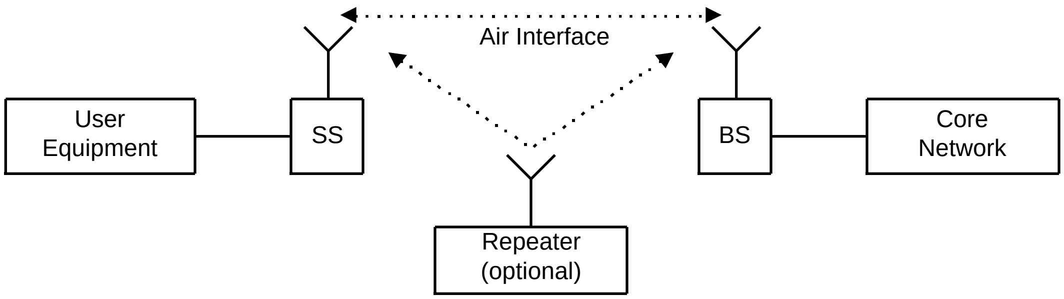

Figure 3.1: Wireless Access Reference Model

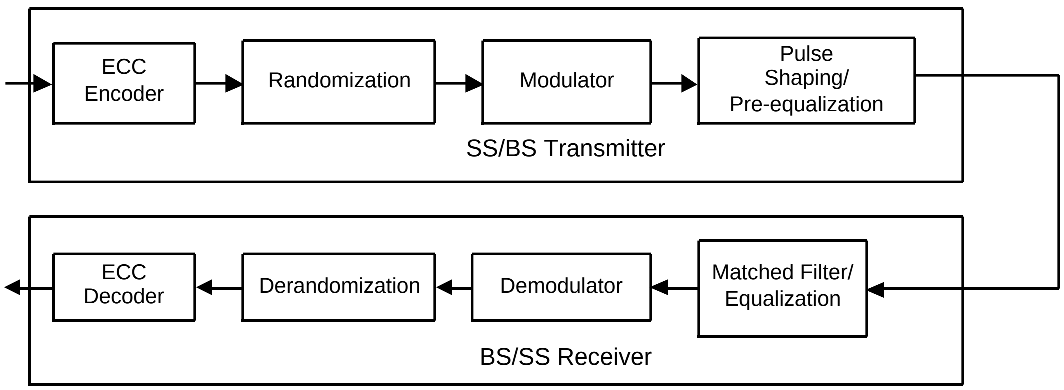

Figure 3.2: PHY Reference Model Showing Data Flow

The proposed PHY must interface with the MAC, carrying MAC packets and enabling MAC functions based on QoS requirements and Service Level Agreements (SLAs). As a S-CDMA system, the PHY must interact with the MAC for purposes of power and timing control. Both power and timing control should originate from the BS, with feedback from the SS needed for forward link power control. The PHY must also interact with the MAC for link adaptation (e.g. bandwidth allocation and SLAs), allowing adaptation of modulation formats, error control coding, data multiplexing, etc.

4 Frequency Bands and RF Channel Bandwidths

The primary frequency bands of interest for this PHY proposal include the ETSI frequency bands from 1-3 GHz and 3-11 GHz ([4] and [5]) along with the MMDS/MDS frequency bands. In [4], the radio characteristics for DS-CDMA systems in the fixed frequency bands around 1.5, 2.2, 2.4 and 2.6 GHz are given, allowing channelizations of 3.5, 7, 10.5 and 14 MHz. From [4], FDD is required with the FDD separation specific to the center frequency and ranging from 54 to 175 MHz. In [5], the radio characteristics of DS-CDMA systems with fixed frequency bands centered around 3.5, 3.7 and 10.2 GHz are specified, allowing channelizations of 3.5, 7, 14, 5, 10 and 15 MHz. FDD is required with separation again frequency band dependant and ranging from 50 to 200 MHz. Also targeted in this proposal are the MMDS/MDS/ITSF frequency bands between 2.5 and 2.7 GHz with 6 MHz channelizations.

5 Multiple Access, Duplexing and Multiplexing Schemes

We propose a frequency division duplex (FDD) PHY using a hybrid S-CDMA/FDMA multiple access scheme with SDMA for increased spectral efficiency. In our approach, each FDMA RF sub-channel has an RF channel bandwidth from 1.75 to 7 MHz. The choice of FDMA RF sub-channel bandwidth is dependent on the frequency band of interest with 3.5 MHz and 6 MHz being typical [3]. Within each FDMA RF sub-channel, S-CDMA is used with users transmitting in the up and downstream using a constant chipping rate from 1 to 6 million chips/second (Mcps). TDD could be used in a single RF sub-channel but we only discuss an FDD mode of operation in this document. With FDD, one or more FDMA RF sub-channel is used in the downstream while at least one FDMA sub-channel is required for the upstream. The approach is flexible to asymmetric data traffic, allowing more downstream FDMA RF sub-channels than upstream FDMA sub-channels when traffic patterns and frequency allocations warrant. Based on the target frequency bands, typical upstream/downstream FDD separation will range from 50 to 200 MHz.

5.1 Synchronous DS-CDMA (S-CDMA)

Within each FDMA sub-channel, S-CDMA is used in both the up and downstream [1]. The chipping rate is constant for all SS with rates ranging from 1 to 6 Mchips/second depending on the FDMA RF sub-channel bandwidth. Common I-Q spreading is performed using orthogonal, variable-length spreading codes based on Walsh-Hadamard designs with spread factors ranging from 1 up to 128 chips per symbol [See [8] for a review of spreading code design for CDMA]. For multi-cell deployments with low frequency reuse, unique spreading code sets are used in adjacent cells to minimize interference. It should be noted that a symmetric waveform is envisioned within each FDMA sub-channel, where both the upstream and downstream utilize the same chipping rate (and RF channel bandwidth), spreading code set, modulation format, channel coding, pulse shaping, etc.

5.2 Code and Time Division Multiplexing and Channel Aggregation

With a hybrid S-CDMA/FDMA system, it is possible to multiplex data over codes and frequency sub-channels. Furthermore, for a given code or frequency channel, time division multiplexing could also be employed. In our approach, we suggest the following multiplexing scheme. For the downstream transmission with a single FDMA sub-channel, the channel bandwidth (i.e. capacity measured in bits/second) is partitioned into a single TDM pipe and multiple CDM pipes. The TDM pipe could be created via the aggregation of multiple S-CDMA channels (e.g. spreading codes). The purpose of this partition is based on the desire to provide Quality of Service (QoS). Within the bandwidth partition, the TDM pipe would be used for best effort service (BES) and some assured forwarding (AF) traffic for packet services. The CDM channels would be used for expedited forwarding (EF) services, such as VoIP connections or other stream applications, where the data rate of the CDM channel is *matched* to the bandwidth requirement of the service.

Of course, the downstream could be configured as a single TDM pipe, without use of CDM. Here, time slot assignment would be used for bandwidth reservation, with typical slot sizes ranging from 4 –16 ms in length. While a pure TDM downstream is possible with our approach, we favor a mixed TDM/CDM approach since long packets can induce jitter into EF services in a pure TDM link. Having a CDMA channels (single or aggregated) dedicated to a single EF service (or user) reduces jitter without the need for packet fragmentation and reassembly. Furthermore, these essentially “circuit-switched” CDM channels would enable better support of legacy circuit-switched voice communications equipment and public switched telephone networks. As an example, full or partial T1/E1 lines could be provided via CDM channels.

For the upstream, we envision a similar partition of TDM/CMD channels. The TDM channel(s) would be used for random access, using a slotted-Aloha protocol. In keeping with a symmetric waveform, we recommend burst lengths on the order of the slot times for the downlink, ranging from 4-16 ms with multi-slot bursts possible. The BS monitors bursts from SS and allocates upstream CDM channels to SSs upon recognition of impending bandwidth requirements or based on service level agreements (SLAs). As an example, a BS recognizing a VoIP connection could move the call from the TDM channel to a dedicated CDM channel with a channel bandwidth matched to the rate of the VoIP connection (e.g. 32 kbps or 64 kbps).

When multiple FDMA sub-channels are present in the up and/or downstream, similar partitioning could be used. Here, extra bandwidth exists meaning more channel aggregation is possible. With a single TDM channel, data would be multiplexed across CDMA codes and across frequency sub-channels.

5.3 Space Division Multiple Access (SDMA) Extensions

The final aspect of our proposed multiple access scheme involves the use of space division multiple access (SDMA) implemented with adaptive beamforming antenna systems [See [6] for details of beamforming with CDMA systems]. We envision an adaptive antenna array at the BS, with narrow, fixed-beam SS antennas. In the approach, S-CDMA/FDMA channels can be directed or formed to individual SS. The isolation provided by the beamforming allows the CDMA spreading codes to be reused within the same cell, greatly increasing spectral efficiency. Beamforming is best suited to CDM rather than TDM channels. In the downstream, TDM would require beamforming on a per slot (or packet) basis, increasing complexity. In the upstream, beamforming would be difficult since the BS would have to anticipate transmission from SS in order to form the beams appropriately. In either case, reuse of CDMA spreading codes in a TDM-only environment would be difficult. With CDM, the BS could allocate bandwidth (i.e. CDMA channels) to SS based on need or SLAs. Once allocated, the BS would form a beam to the SS to maximize signal-to-interference ratios (SIR). Once formed, the BS could reallocate the same CDMA channel to other SSs in the same cell. It is theoretically possible for the spectral efficiency of the cell to scale linearly with the number of antennas in the BS array.

SDMA greatly favors the approach of “fast circuit-switching” over pure, TDM packet-switching in a CDMA environment. By “fast circuit-switching”, we mean packet-services handled using temporary, dedicated connections, which are allocated and terminated based on bandwidth requirements and/or SLAs. To provide effective packet-services using this approach, the BS must be able to rapidly 1.) determine and/or anticipate bandwidth requirements and 2.) allocate and terminate connections matched to the bandwidth required. With fast channel allocation and termination, SDMA combined with the low frequency reuse offered by S-CDMA is the best option in terms of spectral efficiency and providing QoS for BWA applications.

6 Waveform Specifications

The waveform includes the channel coding, scrambling, modulation, pulse shaping and equalization functions of the air interface. Also included are waveform control functions, including power and timing control. In our proposed PHY, each CDMA channel (i.e. spreading code) uses a common waveform, with the spreading factor dictating the communications channel rate (e.g. bits per second or symbols per second).

6.1 Error Control Coding (ECC)

The error control coding should be high-rate and adaptive. High rate codes are needed to maximize the spectral efficiency of S-CDMA systems that are code-limited. High rate codes are also appropriate for S-CDMA since in-cell interference is virtually eliminated. Thus, in S-CDMA, capacity is limited, not by the interference level, but rather by the code set cardinality (e.g. number of available orthogonal spreading codes). Adaptive coding is needed to provide robust performance and graceful degradation of system capacity in multipath fading environments. For the coding options, the baseline code is a punctured, convolutional code (CC). The constituent code is the industry standard, rate 1/2, constraint length 7 code with generator $(133/171)_8$. Puncturing is used to increase the rate of the code, with rates of 3/4, 4/5, 5/6 or 7/8 supported using optimum free distance puncturing patterns. The puncturing rate of the code may be adaptive to mitigate fading conditions. For decoding, a Viterbi decoder should be used. [See [2] for analysis of trellis-coded S-CDMA]

Turbo coding, including block turbo codes and/or traditional parallel and serial concatenated convolutional codes, should be supported as an option at the coding rates suggested above. In this document, we do not propose a specific turbo code design.

Each CDMA channel should be coded independently. Independent coding of CDMA channels furthers the symmetry of the upstream and downstream waveform and enables a similar time-slot structure on each CDMA channel. The upstream and downstream waveform symmetry aids in cost reduction allowing the SS and BS to share baseband hardware. The independent coding of each S-CDMA/FDMA channel is a key distinction between our approach and other multi-carrier CDMA techniques as discussed in the literature [7].

6.2 Randomization

Randomization should be implemented on the coded bit stream. Rather than using a traditional randomizing circuit, we propose the CDMA spreading sequences as randomizing codes in the transmitting station. Using the spreading codes allows different randomizing sequences to be used by different users, providing more robust randomization and eliminating problems with inter-user correlated data due to periodically transmitted sequences (e.g. preambles and start-of-frame delimiters). Since the receiving station has knowledge of the spreading codes, de-randomization is trivial at the receiving station. Randomization may be disabled on a per channel or per symbol basis. In Figure 6.2.1, the proposed channel coding and scrambling method is illustrated.

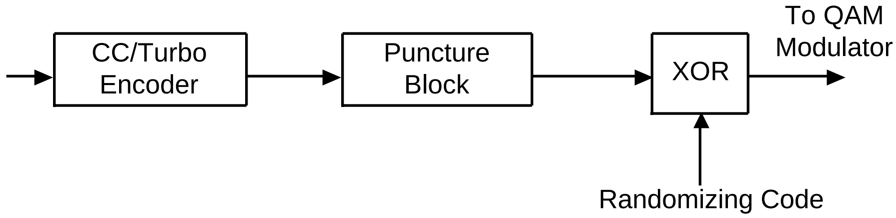

Figure 6.2.1: Proposed ECC and scrambling method for a single CDMA channel

6.3 Modulation Formats

Coherent 4-QAM (i.e. QPSK) and square 16-QAM modulation formats must be supported, with optional support for square 64-QAM. Using a binary channel coding technique, Gray-mapping should be used for constellation bit-labeling to achieve optimum decoded performance. This combined coded modulation scheme allows simple Viterbi decoding hardware designed for binary codes to be used. Differential detection for all modulation formats may be supported as an option. Depending on the channel coding, waveform spectral efficiencies from 1 to 6 information bits/symbol will be supported.

The modulation format should be adaptive based on the channel conditions (SIR) and bandwidth requirements. Both up and downstream links must be achievable using the 4-QAM waveform provided adequate SNR. In environments with higher SNR, up and downstream links may utilize 16-QAM and /or 64-QAM modulation formats for increased capacity and spectral efficiency. The allowable modulation format will depend on the channel conditions, hardware limitations (e.g. phase noise) and the channel coding being employed on the link.

6.4 Pulse Shape Filtering

End-to-end raised-cosine Nyquist pulse shaping should be applied. Pulse shape filtering should be designed to meet relevant spectral masks, mitigate inter-symbol interference (ISI) and adjacent FDMA sub-channel interference.

6.5 Equalization

To mitigate multipath fading, a linear equalizer is suggested for the downstream. Equalizer training could be done using a preamble, with decision-direction used following initial training. With S-CDMA, equalizing the aggregate signal in the downlink effectively equalizes all CDMA channels, thus restoring orthogonality between codes in frequency selective fading environments. Multipath delay spread less than 3 μs is expected for Non-Line Of Sight (NLOS) deployments using narrow-beam (10-20°) subscriber station antennas [12][13]. This low delay spread allows simple, linear equalizers with 8-16 taps that effectively equalize most channels. For the upstream, pre-equalization may be used as an option, but requires feedback from the subscriber station due to frequency division duplexing and thus is not recommend.

Rake processing to exploit the multipath environments is left as an option. However, we argue linear equalization to restore code orthogonality is a more appropriate technique for mitigating multipath for non-mobile systems.

6.6 Timing and Power Control

Timing control is required for upstream orthogonal S-CDMA. In the downstream, timing control is trivial. In the upstream, timing control is controlled by the BS. Timing-control results in reduce in-cell interference levels. While infinite in-cell signal-to-interference ratios (SIRs) are theoretically possible with orthogonal S-CDMA, timing errors, multipath fading and pulse shape filtering result in loss of code orthogonality leading to realistic in-cell SIRs from 30-40 dB. Asynchronous DS-CDMA (A-CDMA) systems have higher in-cell interference levels exist resulting in less tolerance of out-of-cell interference and higher frequency reuse factors [9]. The ability of timing-control to limit in-cell interference in the upstream is the key to frequency reuse of one in a S-CDMA system.

Power control is required for S-CDMA systems. Power control acts to mitigate in-cell and out-of-cell interference while also ensuring appropriate signal levels at the SS or BS to meet bit error rate requirements and QoS requirements. For SS that are close to the BS, less transmitted power is required for a given SIR, while for a distant SS, more transmit power is required in both the up and downstream to attain the same SIR. As with timing control, power control is a key technique towards achieving a frequency reuse of one with S-CDMA.

7 Capacity, Spectral Efficiency and Data Rates

7.1 Single-Cell Performance

For a single, spread FDMA channel, the proposed S-CDMA waveform is capable of providing channel bandwidths from 1 to 32 Mbps in both the up and downstream depending on the RF channel bandwidth. Using variable-length spreading codes and a constant chipping rate, each CDMA channel can be configured to operate at a variety of rates ranging from tens of kbps up to tens of Mbps. As illustrated in (1), the communications channel bandwidth of a single CDMA channel depends on the modulation format, channel coding rate, chipping rate and the spread factor, with higher data rates resulting from lower spreading factors [fewer chips/symbol].

With S-CDMA channel aggregation, high data rates are possible without requiring a SF of one and 64-QAM. In general, the use of S-CDMA along with our proposed interference mitigation techniques will allow the system to be code-limited. Mobile cellular A-CDMA systems are always interference-limited, resulting in frequency reuse and lower spectral efficiency. In code-limited systems, the capacity is limited by the code set cardinality rather than the level of the multi-user interference. In a code-limited environment, the communications channel bandwidth of the system is equal to the communications channel bandwidth of the waveform assuming SF of one. In Table 1, we show sample parameters for a hypothetical system using different coded modulation schemes and assuming a code-limited DS-CDMA environment.

	Modulation and Channel Coding		
Parameter	**4-QAM w/ R=4/5 Coding** **(1.6 bits/sym)**	**16-QAM w/ R=4/5 Coding** **(3.2 bits/sym)**	**64-QAM w/ R=4/5 Coding** **(4.8 bits/sym)**
RF Channel Bandwidth	3.5 MHz	3.5 MHz	3.5 MHz
Chip Rate	2.56 Mcps	2.56 Mcps	2.56 Mcps
Communication Channel Bandwidth	4.096 Mbps	8.192 Mbps	12.288 Mbps
Peak Data Rate	4.096 Mbps	8.192 Mbps	12.288 Mbps
CDMA Channel Bandwidth (SF=1)	4.096 Mbps	8.192 Mbps	12.288 Mbps
CDMA Channel Bandwidth (SF=16)	256 kbps	512 kbps	768 kbps

CDMA Channel Bandwidth (SF=128)	32 kbps	64 kbps	96 kbps
Modulation Factor	1.17 bps/Hz	2.34 bps/Hz	3.511 bps/Hz

Table 7.1.1: Hypothetical parameters for a 3.5 MHz RF channelization

Table 7.1.1 illustrates potential performance assuming a single 3.5 MHz channel in both the up and downstream. The numbers reported in Table 7.1.1 apply to both the upstream and downstream, meaning that upwards of 24 Mbps full duplex is possible in 3.5 MHz [12 Mbps upstream and 12 Mbps downstream]. With additional FDMA RF channels or wider RF channels [e.g. 6 MHz], additional communication bandwidth is possible with the same modulation factors from Table 7.1.1. As an example, allocation of 14 MHz could be serviced using 4 FDMA RF channels with the parameters described in Table 7.1.1. In 14 MHz, peak data rates to a SS up to 48 Mbps would be achievable, with per CDMA channel data rates scaling up from 32 kbps. With a 6 MHz channel allocation, a chipping rate of 4.48 Mcps could be used giving communication channel bandwidths of 14 Mbps with 16-QAM and upwards of 20 MHz with 64-QAM using a single 6 MHz RF channel. The proposed channel aggregation method is very flexible in servicing symmetric versus asymmetric traffic, as well as providing reserved bandwidth for QoS and SLA support.

7.2 Multi-Cell Performance

To this point, capacity and spectral efficiency have been discussed in the context of a single, isolated cell. In a multi-cell deployment, S-CDMA will allow for a true frequency reuse of one eliminating the need for frequency planning, improving spectral efficiency and reducing costs. With a frequency reuse of one, the total system spectral efficiency is equal to the modulation factor of a given cell. Comparing S-CDMA to a single carrier TDMA approach with a typical frequency reuse of 4, TDMA systems must achieve much higher modulation factors in order to compete in terms of overall system spectral efficiency. Assuming no sectorization and a frequency reuse of one, S-CDMA systems can achieve system spectral efficiencies from 1 to 6 bps/Hz with improvements possible using SDMA with adaptive beamforming.

While frequency reuse of one is theoretically possible for DS-CDMA, the true allowable reuse of a specific deployment is dependent on the propagation environment (path loss) and user distribution. For mobile cellular systems, it has been shown that realistic reuse factors range from 0.3 up to 0.7 for A-CDMA; factors that are still much higher than for TDMA systems [9]. In a S-CDMA system, in-cell interference is mitigated by the orthogonal nature of the S-CDMA, implying that the dominant interference results from adjacent cells. For the fixed environments using S-CDMA, true frequency reuse of one can be achieved for most deployments using directional SS antennas and up and downstream power control to mitigate levels of adjacent cell interference. In a S-CDMA environment, true frequency reuse of one implies that a cell is code-limited, even in the presence of adjacent cell interference.

For sectorized deployments with S-CDMA, a frequency reuse of two will be required to mitigate the adjacent channel interference contributed by users on sector boundaries. In light of this reuse issue, we recommend implementing SDMA with adaptive beamforming rather than sectorization to improve cell capacity.

Since spectral efficiency translates directly into cost for IEEE 802.16.3 systems, frequency reuse of one achieved with S-CDMA is an important, perhaps the most important, argument for developing the BWA PHY based on S-CDMA.

7.3 Performance with SDMA

The use of SDMA in conjunction with S-CDMA offers the ability to dramatically increase system capacity and spectral efficiency. SDMA uses an antenna array at the BS to spatially isolate same code users in the cell. The number of times that a code may be reused within the same cell is dependent upon the number of antenna elements in the array, the array geometry, the distribution of users in the cell, the stability of the channel, and the available processing power. Theoretically, in the absence of noise, with an M element antenna array it is possible to reuse each code sequence M times, thereby increasing system capacity by a factor of M. In practice, the code reuse is slightly less than M due to implementation loss, frequency selective multipath fading, and receiver noise. Regardless, significant capacity gains are achievable with SDMA. With appropriate array geometry and careful grouping of users sharing CDMA codes, it is possible to achieve a code reuse of $0.9M$ or better [6].

In real deployments, the number of antenna elements is limited by the available processing power, the physical tower constraints, and system cost [e.g. additional RF front ends (RFFE)]. Selected array sizes will vary depending upon the required capacity of the given cell on a cell-by-cell basis. Table 7.3.1 shows achievable aggregate capacity and modulation factors with typical array sizes assuming a code reuse equal to the number of antenna elements. The aggregate capacity is defined as the total data rate of the BS. Modulation factors exceeding 56 bps/Hz are achievable with 64-QAM and a sixteen-element antenna array.

Number of Elements in Antenna Array	4-QAM		16-QAM		64-QAM	
	Aggregate Capacity (Mbps)	Modulation Factor (bps/Hz)	Aggregate Capacity (Mbps)	Modulation Factor (bps/Hz)	Aggregate Capacity (Mbps)	Modulation Factor (bps/Hz)
1	4.096	1.17	8.192	2.34	12.288	3.511
2	8.192	2.34	16.384	4.68	24.576	7.022
4	16.384	4.68	32.768	9.36	49.152	14.044
8	32.768	9.36	65.536	18.72	98.304	28.088
16	65.536	18.72	131.072	37.44	196.608	56.176

Table 7.3.1: Aggregate capacity and modulation factors versus modulation type and array size.

It should be noted that while SDMA can dramatically increase the capacity of cell, it does not increase the peak data rate to a given SS. SDMA will allow an S-CDMA system to increase capacity, thus meeting growing user demands, without new spectral allocation. With SDMA, the peak data rate will not increase, but the number of users supported at a given rate can be dramatically increased.

8 Implementation and Deployment Issues

8.1 Flexibility

From previous discussion, our proposed PHY is very flexible. Using narrowband S-CDMA channels, our proposal can adapt to a variety of frequency allocations, easily handling non-contiguous frequency allocations. The proposed data multiplexing scheme allows great flexibility in servicing traffic asymmetry and support of traffic patterns created by higher-layer protocols such as TCP/IP. The use of variable rate CDMA channels allows efficient QoS support, with rate matching to meet bandwidth requirements.

8.2 Scalability

Deployments using our proposed PHY are very scalable. When traffic demands increase, new frequency allocation can be used. In our proposal, this amounts to adding additional FDMA channels, which may or may not be contiguous with the original allocation. Without additional frequency allocation, cell capacity can be increased using SDMA with an adaptive antenna array.

8.3 Complexity

Implementation complexity of the proposed PHY is fairly low. From mobile cellular systems and standards, CDMA is a proven technology. S-CDMA has also been proven in fielded systems. We envision significant complexity required at the MAC layer, regardless of the PHY, for efficient support of QoS and efficiency utilization of the PHY.

8.4 Cost

The high spectral efficiency of our waveform leads to cost benefits. First, low frequency reuse reduces costs associated with licensing spectrum. Secondly, high spectral efficiency allows providers to service more billable users in a given frequency allocation. Service providers with small spectral allocations will be capable of handling a larger customer base per cell.

Using a symmetric waveform (same in up and downstream) is a cost saving feature, allowing common baseband hardware in the SS and BS. The use of proven CDMA technology also aids in cost reduction, leveraging the CDMA development efforts and components used for mobile cellular systems.

9 Robustness

9.1 Robustness to Interference

As a spread spectrum signal, the proposed waveform offers inherent robustness to interference sources. Interference sources will be reduced by the spreading factor, which ranges from 1 to 128 (interference suppression of 0 to 21 dB.) At the SS, equalization further suppresses narrowband jammers by adaptively placing spectral nulls at the jammer frequency. Additional robustness to interference is achieved by the directionality of the SS antennas, since off-boresight interference sources will be attenuated by the antenna pattern in the corresponding direction. At the BS, the antenna array used to implement SDMA will offer the additional benefit of adaptively steering nulls towards unwanted interference sources.

9.2 Robustness to Channel Impairments

The proposed waveform has several properties that make it robust to channel impairments. The use of a spread spectrum makes the waveform robust to frequency selective fading channels through the inherent suppression of inter-chip interference. Further suppression of inter-chip interference is provided by equalization at the SS.

The proposed waveform is also robust to flat fading channel impairments. The proposed adaptive channel coding provides several dB of coding gain. The antenna array used to implement SDMA also functions as a diversity combiner. Assuming independent fading on each antenna element, diversity gains of M are achieved, where M is equal to the number of antenna elements in the array. Finally, since the S-CDMA system is code-limited rather than interference limited the system may run with a large amount of fade margin. Even without equalization or diversity, fade margins on the order of 10 dB are possible. Therefore, multipath fades of 10 dB or less will not increase the BER beyond the required level. Fade margins allow very high link availabilities in S-CDMA systems. Availabilities of 99.9% above 10^{-9} are not uncommon with S-CDMA, whereas availabilities of 95% with 10^{-3} bit error rate are common for A-CDMA and other multiple access alternatives.

9.3 Robustness to Radio Impairments

Adaptive modulation provides robustness to radio impairments. For receivers with larger phase noise, the QPSK modulation offers more tolerance to receiver phase noise and filter group delay. The adaptive equalizer at the SS of will reduce the impact of linear radio impairments. Finally, clipping may be used in the SS and BS to reduce the peak-to-average power ratio of the transmitted signal and help to avoid amplifier saturation, for a given average power output.

10 Relation to Existing Standards

The proposed PHY is most similar to mobile cellular standards including IS-95, W-CDMA and cdma2000. While similar to mobile cellular A-CDMA standards, it is important to note that many key differences exist which reflects optimization of the CDMA technology for the fixed, BWA environment. The most important difference is the use of a synchronous upstream, which allows a true frequency reuse of one. Due to some similarity with mobile cellular standards, cost savings are possible using existing, low-cost CDMA components and test equipment. Our proposed PHY is quite different from cable modem and xDSL industry standards as well as IEEE 802.11 and ETSI BRAN standards. However, with a spreading factor of one chip/symbol, our PHY supports a single-carrier QAM waveform similar to DOCSIS 1.1 and IEEE 802.16.1 draft PHY [10][11].

11 Statement of Intellectual Property Rights

L-3 Communications may have intellectual property rights (IPR) in the proposed PHY. If L-3 Communications has any applicable essential patents, it will comply with the IEEE IPR rules regarding disclosure and licensing.

12 Conclusions

We feel that a S-CDMA based PHY is optimum for the fixed, BWA application. Below we list the most important benefits along with the associated drawbacks of our proposed PHY. We feel that the most important aspect of the PHY should be spectral efficiency, as this will translate directly to cost measured in cost per line or cost per carried bit for BWA systems. With a frequency reuse of one, higher-order adaptive modulation and efficient support of SDMA for increased spectral efficiency, we feel S-CDMA combined with FDMA is the correct technology for the BWA market.

12.1 PHY Benefits

- High spectral efficiency - 1-6 bps/Hz system-wide without SDMA
- Perfectly compatibility with smart antenna systems implementing SDMA
  - 1-50 bps/Hz system-wide with SDMA and adaptive beamforming
- True frequency reuse of one possible (increased spectral efficiency and no frequency planning)
- S-CDMA gives:
  - Robustness to channel impairments (e.g. multipath fading)
  - Robustness to co-channel interference (allows frequency reuse of one)
  - Robustness to interference (e.g. receiver noise, clipping and quantization, etc.)
  - Security from eavesdropping
- Bandwidth flexibility and efficiency support of QoS requirements
- Support most frequency allocations using a combination of narrowband S-CDMA and FDMA
- Adaptive coding and modulation yield robustness to channel impairments and traffic asymmetries
- Leverages mobile cellular technology for reduced cost and rapid technology development and test
- Cost savings using a symmetric waveform and identical SS and BS hardware

12.2 PHY Drawbacks

- Power and timing control overhead and complexity
- Inconsistent with IEEE 802.16.1 PHY

References

[1] R. De Gaudenzi, C. Elia and R. Viola, "Bandlimited Quasi-Synchronous CDMA: A Novel Satellite Access Technique for Mobile and Personal Communication Systems," IEEE Journal on Selected Areas in Communications, Vol. 10, No. 2, February 1992, pp. 328-343.

[2] R. De Gaudenzi and F. Gianneti, "Analysis and Performance Evaluation of Synchronous Trellis-Coded CDMA for Satellite Applications," IEEE Transactions on Communications, Vol. 43, No. 2/3/4, February/March/April 1995, pp. 1400-1409.

[3] IEEE 802.16.3-00/02r4, "Functional Requirements for the 802.16.3 Interoperability Standard."

[4] ETSI EN 301 055, Fixed Radio Systems; Point-to-multipoint equipment; Direct Sequence Code Division Multiple Access (DS-CDMA); Point-to-point digital radio in frequency bands in the range 1 GHz to 3 GHz.

[5] ETSI EN 301 124, Fixed Radio Systems; Point-to-multipoint equipment; Direct Sequence Code Division Multiple Access (DS-CDMA) point-to-multipoint DRRS in frequency bands in the range 3 GHz to 11 GHz.

[6] J. Liberti and T. Rappaport, Smart Antennas for Wireless CDMA, Prentice-Hall, NJ, USA, 1997.

[7] S. Hara and R. Prasad, "Overview of Multicarrier CDMA," IEEE Communications Magazine, December 1997, pp. 126-133.

[8] E. Dinan and G. Jabbari, "Spreading Codes for Direct Sequence CDMA and Wideband CDMA Cellular Networks," IEEE Communications Magazine, September 1998, pp. 48-54.

[9] T. Rappaport, Wireless Communications: Principles and Practice, Prentice-Hall, NJ, USA, 1996.

[10] SP-RF1v1.1-I05-000714 "Data-Over-Cable Service Interface Specifications: Radio Frequency Interface Specification".

[11] IEEE 802.16.1-00/01r4, "Air Interface for Fixed Broadband Wireless Access Systems", September 2000.

[12] J. Porter and J. Thweat, "Microwave Propagation Characteristics in the MMDS Frequency Band," Proceedings of IEEE International Conference On Communications (ICC) 2000, New Orleans, LA, June 2000.

[13] V. Erceg, et al, "A Model for the Multipath Delay Profile of Fixed Wireless Channels," IEEE Journal on Selected Areas in Communications (JSAC), Vol. 17, No. 3, March 1999, pp. 399-410.