TOPICS IN BROADBAND ACCESS

Broadband Wireless Access with WiMax/8O2.16: Current Performance Benchmarks and Future Potential

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ABSTRACT

The IEEE 802.16 family of standards and its associated industry consortium, WiMax, promise to deliver high data rates over large areas to a large number of users in the near future. This exciting addition to current broadband options such as DSL, cable, and WiFi promises to rapidly provide broadband access to locations in the world's rural and developing areas where broadband is currently unavailable, as well as competing for urban market share. WiMax's competitiveness in the marketplace largely depends on the actual data rates and ranges that are achieved, but this has been difficult to judge due to the large number of possible options and competing marketing claims. This article first provides a tutorial overview of 802.16. Then, based on extensive recent studies, this article presents the realistic attainable throughput and performance of expected WiMax compatible systems based on the 802.16d standard approved in June 2004 (now named 802.16-2004). We also suggest future enhancements to the standard that could at least quadruple the achievable data rate, while also increasing the robustness and coverage, with only moderate complexity increases.

INTRODUCTION

IEEE standard 802.16, the first version of which was completed in October 2001, defines the air interface and medium access control (MAC) protocol for a wireless metropolitan area network (WMAN™), intended for providing high-bandwidth wireless voice and data for residential and enterprise use. This is the first industry-wide standard that can be used for fixed wireless access with substantially higher bandwidth than most cellular networks. The IEEE 802.16 standard, often referred to as WiMax, heralds the entry of broadband wireless access as a major new tool in the effort to link homes and businesses to core telecommunications networks worldwide.

In the near future 802.16 will offer a mobile and quickly deployable alternative to cabled access networks, such as fiber optic links, coaxial systems using cable modems, and digital subscriber line (DSL) links. Because wireless systems have the capacity to address broad geographic areas without the costly infrastructure required to deploy cable links to individual sites, the technology may prove less expensive to deploy and should lead to more ubiquitous broadband access. Wireless broadband systems have been in use for several years, but the development of this new standard marks the maturation of the industry and a new level of competitiveness for non-line of sight (NLOS) wireless broadband services.

Historically, 802.16 activities were initiated at an August 1998 meeting called by the National Wireless Electronics Systems Testbed (N-WEST) of the U.S. National Institute of Standards and Technology. The effort was welcomed in IEEE 802, which led to the formation of the 802.16 Working Group, which has held weeklong meetings at least bimonthly since July 1999. Development of 802.16 and the included WirelessMAN™ air interface, along with associated standards and amendments, is the responsibility of IEEE Working Group 802.16 on Broadband Wireless Access (BWA) Standards [1]. The Working Group's initial interest was in the 10–66 GHz range, but more recent interest is behind the 2–11 GHz amendment project that led to IEEE 802.16a and was completed in January 2001. The new 802.16d upgrade to the 802.16a standard was recently approved in June 2004 (now named 802.16-2004), and primarily introduces some performance enhancement features in the uplink. Equipment based on this standard is expected to be dominant in the first version of products. Currently the standardization of 802.16e is underway, which promises to support mobility up to speeds of 70–80 mi/h and an asymmetrical link structure that will enable the subscriber station to have a handheld form factor for PDAs, phones, or laptops.

In order to rapidly converge on a worldwide standard, a staggering number of options are provided in the various 802.16 standards for

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This large choice of possible bandwidths is being narrowed down to a few possibilities by the WiMax Forum, whose primary task is to ensure interoperability between the implementations of the 802.16d standard by different vendors.

parameters related to the MAC and physical (PHY) layers. In order to ensure that resulting 802.16-based devices are in fact interoperable, an industry consortium called the WiMax Forum was created. The WiMax Forum develops guidelines known as profiles, which specify the frequency band of operation, the PHY to be used, and a number of other parameters. Adherence to a given profile should enable interoperability between vendor products. The WiMax Forum has identified several frequency bands for the initial 802.16d products, notably in both licensed (2.5–2.69 and 3.4–3.6 GHz) and unlicensed spectrum (5.725–5.850 GHz). Due to all the potential options in the standards, as well as the huge ranges of data rates, ranges, and other performance measures that are being quoted as achievable for 802.16, there is presently a significant amount of confusion about what type of performance can really be expected from WiMax-compliant systems in the near future.

This article will distill the important features of WiMax/802.16 systems and give well supported predictions on the performance that can be expected from 802.16d-compliant systems, with a particular focus on the downlink. Since it is probable that many potential customers will want higher performance than we demonstrate as feasible, we also outline suggestions for enhancements to 802.16 that could significantly increase performance while not radically altering the standard.

OVERVIEW OF THE PHYSICAL LAYER

We begin by providing an overview of the IEEE 802.16 PHY and MAC subsystems. This can be considered an update of [2], although we adopt a higher-level approach in order to emphasize the key parameters that will affect the performance of upcoming 802.16 systems. Design of the 2–11 GHz PHY is driven by the need for NLOS operation, which allows inexpensive and flexible consumer deployment and operation. The IEEE 802.l6a/d standard defines three different PHYs that can be used in conjunction with the MAC layer to provide a reliable end-to-end link. These air interface specifications are:

- WirelessMAN-SCa: A single-carrier modulated air interface.
- WirelessMAN-OFDM: A 256-carrier orthogonal-frequency division multiplexing (OFDM) scheme. Multiple access of different subscriber stations (SSs) is time-division multiple access (TDMA)-based.
- WirelessMAN-OFDMA: A 2048-carrier OFDM scheme. Multiple access is provided by assigning a subset of the carriers to an individual receiver,[1] so this version is often referred to as OFD multiple access (OFDMA).

Of these three air interfaces, the two OFDM-based systems are more suitable for non-LOS operation due to the simplicity of the equalization process for multicarrier signals. Of the two OFDM-based air interfaces, 256-carrier WirelessMAN-OFDM seems to be favored by the vendor community for reasons such as lower peak to average ratio, faster fast Fourier transform (FFT) calculation, and less stringent requirements for frequency synchronization compared to 2048-carrier WirelessMAN-OFDMA. All profiles currently defined by the WiMax Forum specify the 256-carrier OFDM PHY. For this reason, the rest of the article will focus primarily on the 256-carrier OFDM air interface. Of these 256 subcarriers, 192 are used for user data, with 56 nulled for a guard band and eight used as permanent pilot symbols. In order to provide robustness to dispersive multipath channels, 8, 16, 32, or 64 additional samples are prepended as the cyclic prefix, depending on the expected channel delay spread.

In order to ensure global implementation, the IEEE 802.16 standard has been defined with a variable channel bandwidth. The channel bandwidth can be an integer multiple of 1.25 MHz, 1.5 MHz, and 1.75 MHz with a maximum of 20 MHz. This large choice of possible bandwidths is being narrowed down to a few possibilities by the WiMax Forum, whose primary task is to ensure interoperability between implementations of the 802.16d standard by different vendors.

ADAPTIVE MODULATION AND CODING

The 802.l6a/d standard defines seven combinations of modulation and coding rate that can be used to achieve various trade-offs of data rate and robustness, depending on channel and interference conditions. These possible combinations, shown in Table 1, follow a similar pattern to the modulation/coding pairs available in the IEEE 802.11 a/g standard for wireless LANs.

One departure from the 802.11 standard is that 802.16 uses an outer Reed-Solomon (RS) block code concatenated with an inner convolutional code. The RS code is fixed and derived from a systematic RS(N = 255, K = 239, T = 8) code using GF(2^8), and thus adds about 10 percent overhead. The inner convolution code has constraint length 7, and its rate varies between 1/2 and 3/4, as shown in Table 1. Naturally, interleaving is also employed to reduce the effect of burst errors. Turbo coding has been left as an optional feature, which can improve the coverage and/or capacity of the system, at the price of increased decoding latency and complexity. Initial versions of WiMax-compliant products are not expected to include turbo coding.

The allowed modulation schemes in the downlink (DL) and uplink (UL) are binary phase shift keying (BPSK,) quaternary PSK (QPSK), 16-quadrature amplitude modulation (QAM), and 64-QAM. A total of eight pilot subcarriers are inserted into each data burst in order to constitute the OFDM symbol, and they are modulated according to their carrier locations within the OFDM symbol. Additionally, known preambles are used in 802.16d to aid the receiver with synchronization and channel estimation. In the DL a "long preamble" of two OFDM symbols is sent at the beginning of each frame. In the UL a "short preamble" of one OFDM symbol is sent by the SS at the beginning of every frame.

SPACE TIME BLOCK CODES

Space-time block codes (STBCs) are an optional feature that can be implemented in the DL to provide increased diversity. A 2 × 1 or 2 × 2 Alamouti STBC [3] may be implemented with-

[1] *In WirelessMAN-OFDMA, multiple access is provided by using a combination of TDMA and OFDMA.*

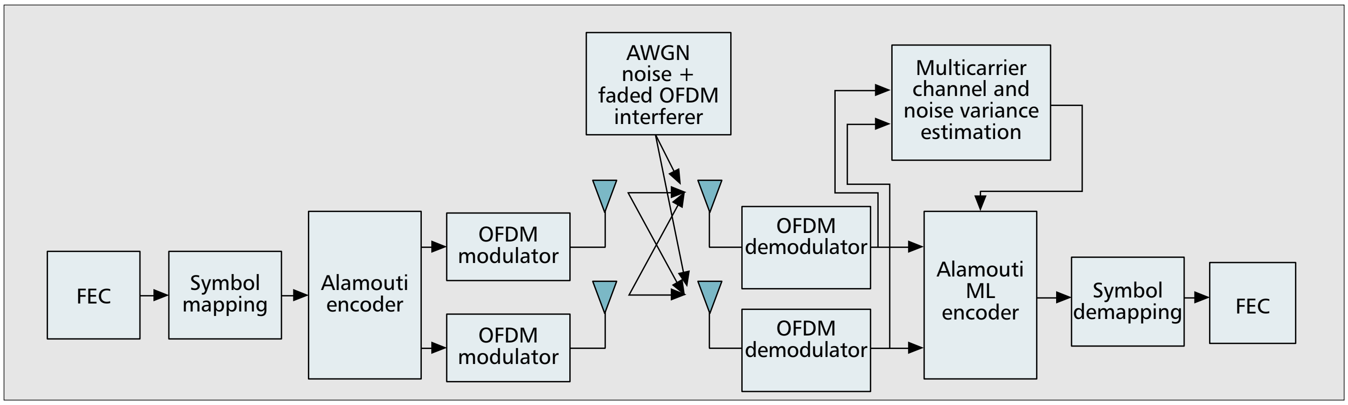

Figure 1. *The 802.16d link simulator.*

out any reduction in the bandwidth (2 × 2 Alamouti codes are rate 1), while providing diversity in time and especially space. The receiver performs maximum likelihood (ML) estimation of the transmitted signal based on the received signal. Since it appears that WiMax will adopt two-antenna transmit diversity using the Alamouti code, our results assume the presence of this performance enhancing optional feature. We also consider multiple antenna receive diversity, which does not require support from the standard and further increases the performance. In general, receive diversity is preferable to transmit diversity since no additional transmit power is required for receive diversity.

ADAPTIVE ANTENNA SYSTEMS

The 802.16 standard provides optional features and a signaling structure that enables the usage of intelligent antenna systems. A separate point-to-multipoint (PMP) frame structure is defined that enables the transmission of DL and UL bursts using directed beams, each intended for one or more SSs. Additional signaling between the base stations (BSs) and SSs has been defined that allows the SS to provide channel quality feedback to the BS. The real and imaginary components of the channel response for each of the directed beams and specific subcarriers are provided to the BS. The BS can specify the resolution in the frequency domain of this feedback. The standard allows the SS to provide channel response for every 4th, 8th, 16th, 32nd, or 64th subcarrier. Some initial WiMax-compliant products will implement adaptive antennas to improve the spectral efficiency of the system.

OVERVIEW OF THE MAC LAYER

The MAC Layer of IEEE 802.16 was designed for PMP broadband wireless access applications.[2] It is designed to meet the requirements of very-high-data-rate applications with a variety of quality of service (QoS) requirements. The signaling and bandwidth allocation algorithms have been designed to accommodate hundreds of terminals per channel. The standard allows each terminal to be shared by multiple end users. The services required by the end users can be varied in their bandwidth and latency requirements, which demands that the MAC layer protocol be flexible and efficient over a vast range of different data traffic models. The system has been designed to include legacy time-division multiplex (TDM) voice and data, Internet Protocol (IP) connectivity, and voice over IP (VoIP).

The MAC layer of IEEE 802.16 is divided into convergence-specific and common part sublayers. Convergence-specific sublayers are used to map the transport-layer-specific traffic to a MAC that is flexible enough to efficiently carry any traffic type. The common part sublayer, as its name suggests, is independent of the transport mechanism, and responsible for fragmentation and segmentation of MAC service data units (SDUx) into MAC protocol data units (PDUs), QoS control, and scheduling and retransmission of MAC PDUs

The bandwidth request and grant mechanism has been designed to be scalable, efficient, and self-correcting. The 802.16 access system does not lose efficiency when presented with multiple connections per terminal, multiple QoS levels per terminal, and a large number of statistically multiplexed users. It takes advantage of a wide variety of request mechanisms, balancing the stability of contentionless access with the efficiency of contention-oriented access. While extensive bandwidth allocation and QoS mechanisms are provided in the standard, the details of scheduling and reservation management are left undefined such that product differentiations may be achieved through different vendor implementations.

TRANSMISSION OF MAC PDUS

The IEEE 802.16 standard has been designed to support frequency-division duplex (FDD) and time-division duplex (TDD). In FDD mode there is additional support for unframed FDD operation, where the transmission does not contain a frame structure and is asynchronous. The MAC at the BS creates a DL frame (subframe for TDD), starting with a preamble that is used for synchronization and channel estimation. A frame control header (FCH) transmitted after the preamble specifies the burst profile for the rest of the frame. This is required since the bursts are transmitted with different modulation and coding schemes. The FCH is followed by one or multiple downlink bursts, each transmitted according to the burst profile and consisting of an integer number of OFDM symbols. The location and profile of the first downlink burst is specified in the downlink frame prefix (DLFP), part of the FCH.

[2] Later amendments to 802.16a and 802.16d also allow for mesh network architecture. We focus on the PMP aspect of the MAC and PHY in this article.

Since the duration of each frame is short (1–2 msec), it is possible to omit adaptive channel tracking for most fixed wireless applications since the channel is unlikely to change significantly during the frame.

Rate ID	Modulation rate	Coding	Information bits/symbol	Information bits/ OFDM symbol	Peak data rate in 5 MHz (Mb/s)
0	BPSK	1/2	0.5	88	1.89
1	QPSK	1/2	1	184	3.95
2	QPSK	3/4	1.5	280	6.00
3	16QAM	1/2	2	376	8.06
4	16QAM	3/4	3	568	12.18
5	64QAM	2/3	4	760	16.30
6	64QAM	3/4	4.5	856	18.36

Table 1. *Modulation and coding schemes for 802.16d.*

The initial channel estimates obtained from the preamble can be used in adaptive tracking of the channel using the embedded pilot in each OFDM symbol. Since the duration of each frame is short (1–2 ms), it is possible to omit adaptive channel tracking for most fixed wireless applications since the channel is unlikely to change significantly during the frame.

Data bursts are transmitted in order of decreasing robustness to allow the SSs to receive reliable data before risking a burst error that could cause loss of synchronization. In the DL, a TDM portion immediately follows the FCH and is used for unsolicited grant service (UGS), useful for constant bit rate applications with strict delay restrictions such as VoIP.

THE PERFORMANCE OF 802.16D

In this section results pertaining to the performance of an 802.16d system in a cellular deployment under different configurations are presented. In order to estimate the system-wide performance of 802.16d, link-level results were first obtained using a baseband simulation written in Matlab™. The link-level simulation provides statistical behavior and performance of each radio link between the BS and the SSs. A schematic representation of the link-level simulator is shown in Fig. 1. At the front end of the transmitter the baseband signal is upsampled four times to model an analog signal and improve the multipath resolution.

Channel coding and transmission of the baseband signal is performed as specified by the IEEE 802.16d standard. At the receiver, realistic channel and noise variance estimation is performed using practical signal processing algorithms, and is used in the log-likelihood ratio (LLR) calculation during soft symbol generation. Soft bit detection adds a certain degree of complexity to the receiver, but its performance benefit over hard detection makes this added complexity worthwhile.

A frequency-selective fading channel defined by the Third Generation Partnership Project (3GPP) multiple-input multiple-output (MIMO) models is used. These models allow the correlation between different transmit and receive antennas to be modeled depending on parameters such as the angle of arrival, antenna separation, orientation of antennas, and angular spread of different multipath components. While it is assumed that BS antennas can be separated by four times the wavelength (57 cm), the physical separation between antenna elements at the space-constrained SS is half the wavelength (7 cm). The delay spread is assumed to be 12 μs, which is reasonable for a chosen cell radius of 3 km. The Doppler spread is 2 Hz, which corresponds to pedestrian speeds at the chosen carrier frequency of 2.1 GHz. The BS transmit power is 50 W.

For a given value of signal-to-noise ratio (SNR) the optimum burst profile is simply the one that maximizes the throughput (i.e., the modulation and coding pair from Table 1 that maximizes the above equation). Throughputs given in this article are actual layer 2 throughputs (including all MAC overhead), and are for a bandwidth of 5 MHz. Average cell-wide throughputs are obtained by numerically averaging over a spatial received signal-to-interference-plus-noise ratio (SINR) profile, which includes all relevant effects such as frequency reuse, BS and SS antenna gain and pattern, number of sectors per BS, inter-BS distance, carrier frequency, and propagation model.

Shown in Fig. 2 is the average DL layer 2 throughput for different combinations of frequency reuse and cell sectorization. The advantage of having multiple receive antennas is evident since it results in a few megabits per second of additional throughput for all configurations. It also shows the expected result that increased sectorization increases throughput, and that if at all possible, 1/1 reuse (frequencies reused every cell) should be employed since the gain from going to 1/3 reuse (frequencies reused every third cell) does not come close to compensating for the associated tripling of consumed bandwidth.

If an outage capacity point of view is taken, the benefits of adding a second receive antenna are more dramatic. Outage capacity refers to the probability that the achievable data rate is below some threshold, with users randomly distributed throughout the cell. This typically occurs because the received SINR is too low, due to interference from neighboring cells and attenuation of the desired BS's signal due to path loss, fading, and shadowing. From Fig. 3 it can be seen that particularly in a 1/1 reuse system (which is likely to be the most practical and give the highest system throughput), an extra receive antenna cuts the probability of outage relative to 1.5 Mb/s by more than half. The merits of dividing cells into nonoverlapping sectors with directional antennas are also more significant in this lower throughput regime, where the goal is to avoid truly bad interference conditions and fades.

FUTURE ENHANCEMENTS TO 802.16

In this section we describe some potential enhancements to 802.16 that are well within reach. Compared to the 802.11 wireless LAN, which operates only in unlicensed spectrum and over much smaller ranges and larger bandwidths, optimizing the capacity of 802.16 is more crucial if it is to prove commercially viable. The proposed advances below, which are summarized in Table 2, should increase the average throughput by approximately a factor of four or more, while also increasing the coverage area and reducing outage probability.

SPATIAL MULTIPLEXING

By encoding the data over both the temporal and spatial domains, STBCs provide spatial diversity and robustness against fading. However, since redundant information is transmitted on each of the antennas, this diversity comes at the expense of peak data rate. Spatial multiplexing (SM), also known as MIMO, is a powerful technique for multiple-antenna systems that, in principle, increases the data rate in proportion to the number of transmit antennas since each transmit antenna carries a unique stream of data symbols. Hence, if the number of transmit antennas is M and the data rate per stream is R, it is straightforward to see that the transmit data rate is MR under spatial multiplexing.

Popular receiver structures for SM include linear receivers, such as zero-forcing (ZF) or minimum mean square error (MMSE), nonlinear receivers such as the optimum maximum likelihood detector (MLD), and spatial interference canceling receivers such as BLAST. One restriction for all these receivers is that the number of receive antennas should be no smaller than the number of transmitted data streams, or the MIMO channel will be ill conditioned and the data cannot be decoded correctly. Linear receivers are easy to implement in a practical system due to their low computational complexity, but are subject to severe noise enhancement in an interference-limited cellular system [4]. MLD and BLAST achieve better performance at the expense of substantially increased complexity, particularly for the MLD.

Although SM achieves theoretically higher transmission rate than STBC schemes, it is at the expense of reduced diversity due to the lack of redundancy across the antennas. This results in poor link-level error performance and may actually reduce the achievable throughput, especially at low SNR. Therefore, in a practical system, it is preferable to find a compromise between diversity and spatial multiplexing.

To address this problem, a simple extension of spatial multiplexing is linear space-time precoding/decoding, in which the number of transmit antennas is larger than the number of data substreams [5, 6]. This redundancy in the trans-

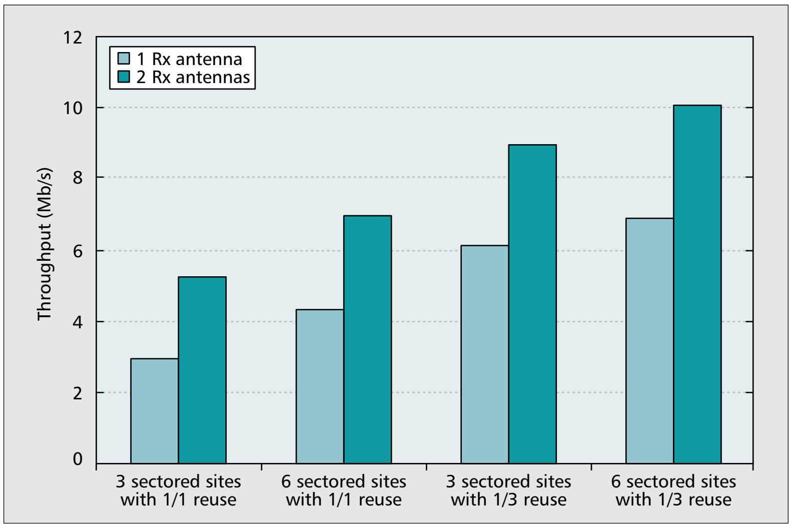

Figure 2. *Average throughput over an entire cell per 5 MHz carrier for 802.16d system under various frequency reuse and sectorization configurations.*

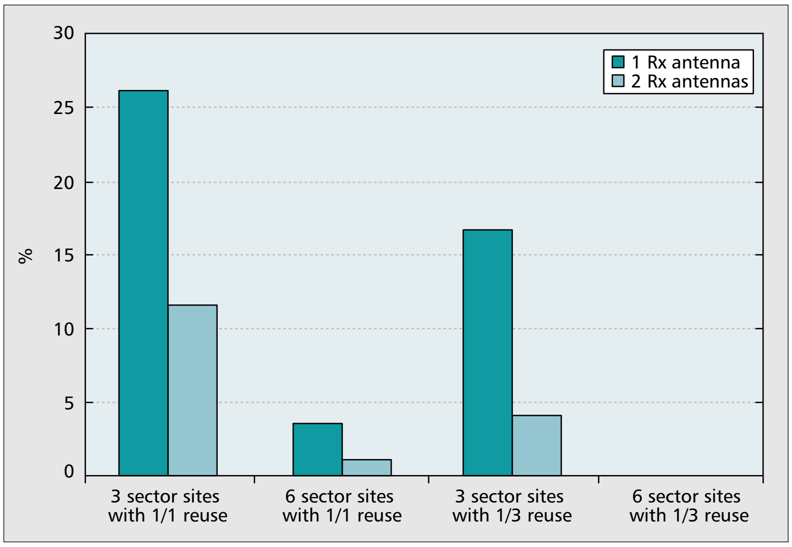

Figure 3. *Percentage of cell area with data rate less than 1.5 Mb/s.*

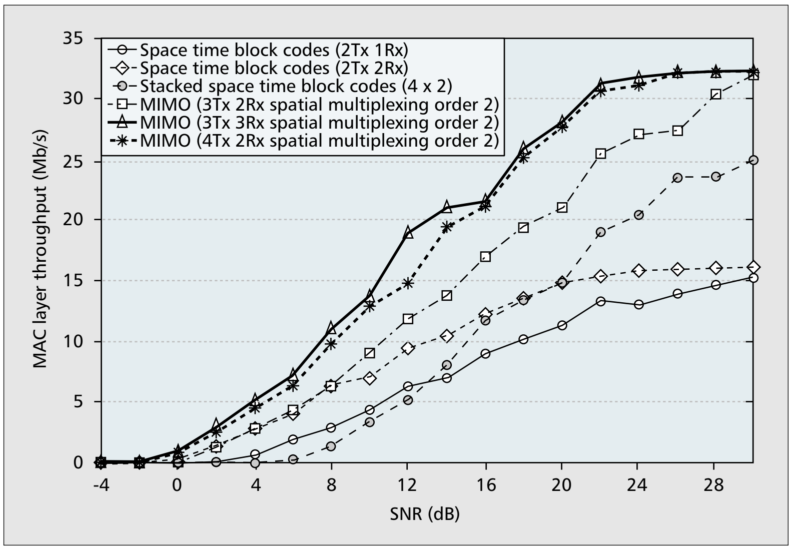

Figure 4. *Maximum throughput of STBC and spatial multiplexing with precoding.*

Technology→ characteristic↓	Spatial multiplexing/ precoding	Hybrid ARQ	Interference cancellation	Adaptive subcarrier/ power allocation
Throughput	Average throughput increases linearly with the multiplexing order (e.g., 100% gain for multiplexing order of 2).	4–5 SNR gain reduction at low to moderate SNR range. More effective for higher mobility (e.g., 802.16e).	Higher throughput and improved robustness, especially on cell boundaries.	As much as 100% throughput increase
Coverage increase	Trade-off between coverage and throughput	Significant	Significant	Minor
Tx antenna	1–2 more antennas than the current standard	No restriction	No restriction	No restriction
Rx antenna	2 or more are needed	No restriction	No restriction	No restriction
Channel feedback	10–50 kb/s (FDD) None (TDD)	Not required	Not required	10–50 kb/s (FDD) None (TDD)
Standards support needed?	Required for feedback, pilot symbols	Required for definition of signaling and puncturing schemes	Not required	Required for rate and subcarrier notification to Rx

Table 2. *A summary of innovative technologies and their effects.*

mit array enables coding across substreams and allows an adaptive transmitter to optimally distribute the data and transmit power over different BS antennas. In precoding, parallel data substreams are multiplied by appropriately designed precoding matrices that are functions of the matrix MIMO channel, and hence require some degree of transmitter channel knowledge. Decoding is implemented by multiplying the received signal vector with the decoding matrices followed by symbol-wise slicing. The transmitter can learn the channel by either feedback in an FDD system or reciprocity in a TDD system. Even in an FDD system, the total amount of feedback required for a low-mobility system is on the order of 10–50 kb/s (depending on the channel and resolution used), which is negligible relative to the gains available by using this combined diversity and spatial multiplexing.

Figure 4 compares achievable throughput of STBC and spatial multiplexing with MMSE precoding, under various antenna configurations. For STBC, which is currently supported by 802.16d, the data rates gradually increase with SNR. For spatial multiplexing with precoding, three antenna configurations are simulated, all with two data substreams.[3] Encouragingly, spatial multiplexing with precoding substantially increases the actual throughput over the STBC scheme, due to the fact that two substreams are multiplexed and transmitted simultaneously. It is interesting to note that although the 3 × 3 system slightly outperforms the 4 × 2 system, it is not by much. This implies that with just two antennas at the SS, the data rate can be reliably doubled in the medium-to-high SNR regime if four antennas are deployed at the BS. In Fig. 5 the system-wide throughput is shown for various MIMO configurations of an enhanced 802.16d system. A 3 × 3 MIMO system has an average throughput of 12 Mb/s, almost three times that of a basic 802.16d system with two Tx and one Rx antennas, thus representing a significant improvement in spectral efficiency. Since the throughput per antenna is higher for the 3 × 3 system than the 2 × 1 system, the additional antenna costs appear to be well justified.

Hybrid ARQ

When data is transmitted in packets (MAC PDUs), an automatic repeat request (ARQ) scheme can be used to guarantee reliable data transmission. A hybrid ARQ (HARQ) scheme, first suggested in [7] and then further enhanced in [8, 9], uses an error control code in conjunction with the retransmission scheme to ensure reliable transmission of data packets. The fundamental difference between a simple ARQ scheme and an HARQ scheme is that in HARQ, subsequent retransmissions are combined with the previous transmission in order to improve reliability.

Currently the 802.16d standard uses a data randomization scheme where the information bits are bit wise scrambled using a pseudo noise (PN) sequence. Since this randomization sequence is expected to change from one transmission to the next, it is not possible to perform codeword combining. In order to use HARQ either the randomization sequence needs to be reset for the retransmissions or data randomization needs to be performed at the MAC layer, thus ensuring that each MAC PDU is transmitted using the same codeword. Our initial investigations have shown that in the low SNR regime (below 4–5 dB), HARQ greatly increases the data rate. This can be interpreted as increasing the range or coverage of the system.

Interference Cancellation

A major problem in 802.16 systems will be delivering reliable high data rates to users who are located on the edge of the cell. This may prove an even bigger problem than in conventional cellular systems since, due to very low mobility, users that are on the edge of the cell are likely to stay there indefinitely. One possibility for addressing this important challenge is to develop a low-complexity interference-canceling receiver for the SS. A similar concept has recently been applied to GSM systems, and has allowed much

[3] 2 × 2 spatial multiplexing performs extremely poorly due to the lack of diversity.

higher throughputs and improved performance on the cell boundaries by canceling just a single interfering user [10, 11]. New research and development will likely be needed to apply existing multicarrier-based interference cancellation research to 802.16 systems in a manner that does not substantially increase the complexity of the price- and power-sensitive SSs.

ADAPTIVE SUBCARRIER/POWER ALLOCATION

Although the 802.16 channel is frequency-selective, presently all subcarriers are constrained to carry the same modulation type. It has been demonstrated extensively in both academia and practice, for DSL systems in particular, that adaptive subcarrier loading and modulation can substantially increase the capacity of a multicarrier system (e.g., [12]). Further gains can be attained in a multi-user OFDM system where different users contend for different subcarriers, since the different users' channels are typically independent. In particular, for an 802.11a-compliant system with four users with independent channels, it was shown in [13] that over a 100 percent gain in average throughput could be attained even with a very low-complexity multi-user loading algorithm that enforced relative fairness factors among the different users' data rates. The principal factor preventing dynamic multi-user OFDM from effecting 802.16 is the requirement for channel knowledge at the transmitter. However, as noted above, some limited feedback is likely to be required to effectively perform spatial multiplexing, which also offers a twofold increase in capacity. If the low-complexity multi-user OFDM scheme can make use of the same feedback, it appears possible that perhaps an additional twofold increase in WiMax capacity could result.

CONCLUSIONS

This article overviews key aspects of the IEEE 802.16 standard, and demonstrates the expected performance for 802.16-based fixed wireless broadband systems. To briefly summarize, for multicell 802.16d systems with universal frequency reuse, the total average downlink throughput can be expected to be between 3 and 7 Mb/s over a 5 MHz bandwidth, with the lower rates corresponding to having a single receive antenna and three-sector cells, and the higher rates for two receive antennas and six-sector cells. A typical cell might be a few kilometers in diameter and have 25 percent of its area unable to achieve a data rate above 1.5 Mb/s for single-antenna users. On the other hand, if two receive antennas and six-sector cells are considered, this drops to about 2 percent. Since the total data rate must be divided among all users in the cell, even these data rates may be too low in many markets to be commercially attractive under reasonable bandwidth allocations.

To improve the performance of the present 802.16 standards, we propose four major areas for future innovation and enhancement; these are summarized in Table 2. In order to increase the data rate by about a factor of four, it is recommended that the complementary emerging technologies of spatial multiplexing and multi-user OFDM be employed to maximize throughput. In order to increase the range and robustness of the system, interference cancellation of dominant interferers is suggested, along with hybrid ARQ. Together, this suite of techniques could substantially increase both the throughput and robustness of future WiMax systems.

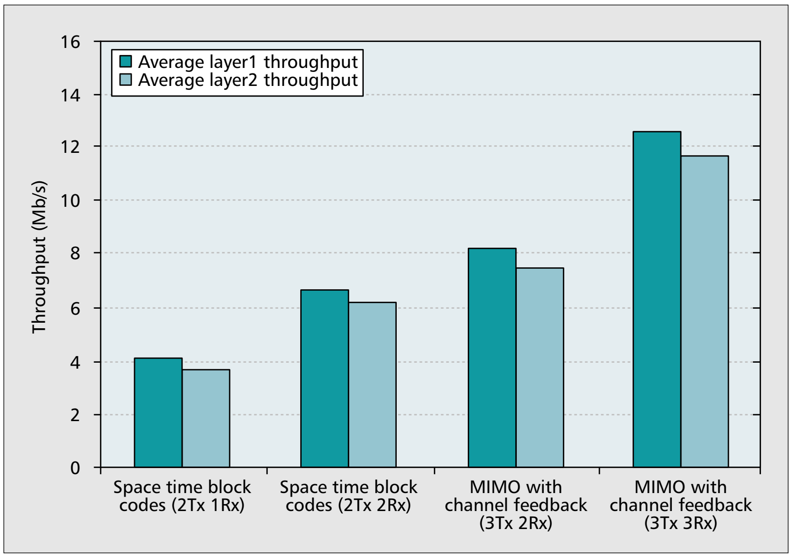

Figure 5. *Average throughput per 5 MHz carrier for an 802.16d system with enhancements.*

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BIOGRAPHIES

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