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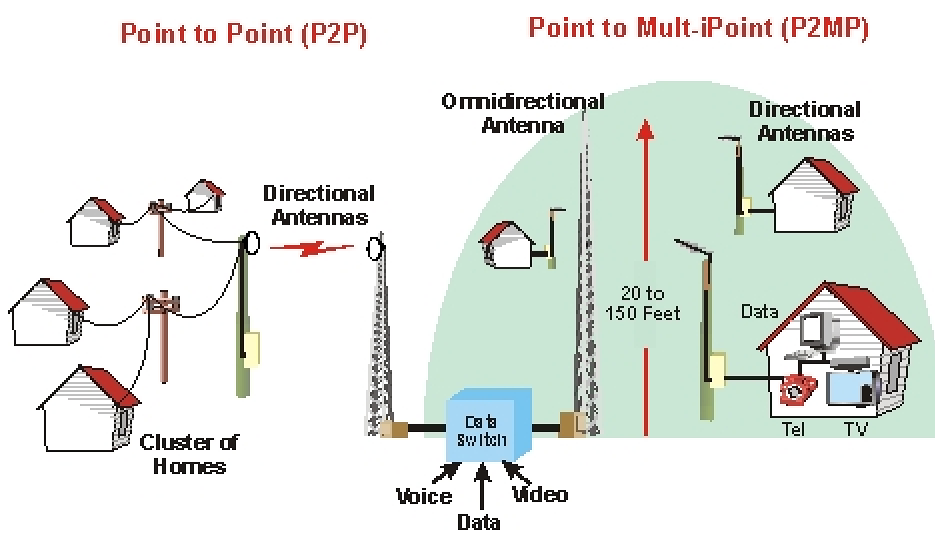

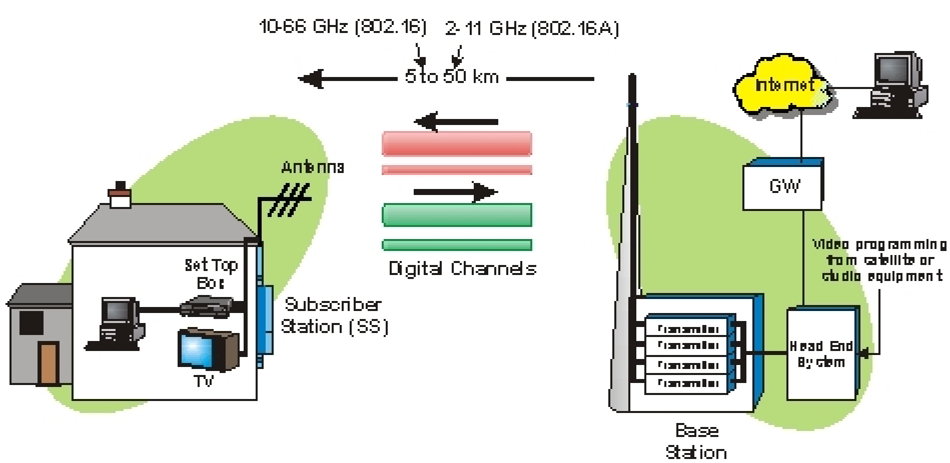

WiMax/802.16 Overview for the 2006 Digital Communications Conference

Abstract

This abstract is an overview of the upcoming IEEE 802.16 specifications submitted to the ARRL Digital Communications Conference for 2006.The IEEE 802.16 family of standards, and its associated industry consortium WiMax, promises 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 Wi-Fi 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 paper first provides a tutorial overview of 802.16. Then, based on extensive recent studies, this paper 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). I also suggested 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.

1 Introduction

The IEEE Standard 802.16, the first version of which was completed in October of 2001, defines the air interface and medium access control (MAC) protocol for a wireless metropolitan area network (WirelessMAN™), 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 in deploying 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 Test bed (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].

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The Working Group's initial interest was the 10–66 GHz range, but more recent inertia 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 mph 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 parameters related to the MAC and physical (PHY) layers. In order to make sure 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 paper 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 what we demonstrate as feasible, we also outline suggestions for enhancements to 802.16 that could significantly increase the performance while not radically altering the standard.

2 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 802.16a/d standard defines 3 different PHYs that can be used in conjunction with the MAC layer to provide a reliable end-to-end link.

The 3 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 (SS's) 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 receiver1, and so this version is often referred to as OFDMA (OFD multiple access).

Of these three air interfaces, the two OFDM-based systems are more suitable for non-LOS of operation due to the simplicity of the equalization process for multicarrier signals. Of the two OFDM based air interfaces, the 256 carrier WirelessMAN-OFDM seems to be favored by the vendor community for reasons such as lower peak to average ratio, faster FFT calculation, and less stringent requirements for frequency synchronization compared to the 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 paper will focus primarily on the 256 carrier OFDM air interface. Of these 256 subcarriers, 192 are used for user data, with 56 being 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 a global implementation, the IEEE 802.16 standard has been defined with a variable channel bandwidth. The channel bandwidth can be an integer multiple of 1.25MHz, 1.5MHz, and 1.75MHz 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 the implementations of the 802.16d standard by different vendors.

2.1 Adaptive Modulation and Coding

The 802.16a/d standard defines seven combinations of modulation and coding rate that can be used to achieve various tradeoffs of data rate and robustness, depending on the channel and interference conditions. These possible combinations, shown in Table 1, follow a similar pattern to the modulation/coding pairs available in the IEEE 802.11a/g standard for wireless LANs.

One departure from the 802.11 standard is that 802.16 uses an outer Reed-Solomon 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 so adds about 10% overhead. The inner convolution code has constraint length 7 and its rate varies between ½ and ¾ as shown in 1 In WirelessMAN-OFDMA multiple access is provided by using a combination of TDMA and OFDMA.

Table 1. Naturally, interleaving is also employed to reduce the effect of burst errors. Turbocoding 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 BPSK,QPSK, 16QAM, and 64QAM. A total of 8 pilot sub-carriers 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 downlink, a “long preamble” of two OFDM symbols is sent at the beginning of each frame. In the uplink a “short preamble” of one OFDM symbol is sent by the SS at the beginning of every frame.

2.2 Space Time Block Codes

Space time block codes are an optional feature that can be implemented in the DL to provide increased diversity. A 2x1 or a 2x2 Alamouti space time block code [3] may be implemented without any reduction in the bandwidth (2x2 Alamouti codes are rate 1), while providing diversity in time and especially space. The receiver performs maximum

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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.

2.3 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 subscriber stations (SS). Additional signaling between the base stations (BS) and SS 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 sub-carrier. Some initial WiMax-compliant products will implement adaptive antennas to improve the spectral efficiency of the system.

3 Overview of the MAC Layer

The MAC Layer of IEEE 802.16 was designed for point-to-multipoint (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 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, this demands the MAC layer protocol to 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 the Convergence Specific sub-Layer and the Common Part sub-Layer. The Convergence Specific sub-layers 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 sub-Layer, as the name suggests, is independent of the transport mechanism and is responsible for fragmentation and segmentation of MAC-Service Data Units (SDUs) into MACProtocol 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 contention-less 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.

[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 paper.

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3.1 Transmission of MAC PDUs

The IEEE 802.16 standard has been designed to support frequency division duplex (FDD) and time division duplex (TDD). In the 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 (sub-frame 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), a part of the FCH.The initial channel estimates as 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 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.

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 downlink, 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.

4 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 Figure 1. At the front end of the transmitter the baseband signal is upsampled 4 times to model an analog signal and to 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 (3G) Partnership Project (3GPP) 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 the antennas, and angular spread of the different multipath components. While it is assumed that base station antennas can be separated by four times the wavelength (57 cm), the physical separation between antenna elements at the spaceconstrained SS is ½ the wavelength (7 cm). The delay spread is assumed to be 12 µsec, 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 base station transmit power is 50 Watts.

For a given value of SNR the optimum burst profile is simply the one that maximizes the throughput, i.e. it is the modulation and coding pair from Table 1 that maximizes the above equation. Throughputs given in this paper are actual layer 2 throughput (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 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 the propagation model.

Shown in Figure 2 is the average downlink 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 Mbps 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) doesn't 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 due to attenuation of the desired base station's signal due to path loss, fading, and shadowing. From Figure 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 Mbps by more than half. The merits of dividing cells into non-overlapping sectors with directional antennas are also more significant in this lower throughput regime, where the goal is to avoid the truly bad interference conditions and fades.

5 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 the outage probability.

5.1 Spatial Multiplexing

By encoding the data over both the temporal and spatial domains, space-time block codes 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 Multi-input Multi-output (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 the linear receiver, for example zero-forcing (ZF) or minimum mean square error (MMSE), and non-linear 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, otherwise 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 space-time block code (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 transmit 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 a symbol-wise slicing. The transmitter can learn the channel either by 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 kbps (depending on the channel and resolution used), which is negligible relative to the gains available by going to 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 substreams3. 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 3x3 system slightly outperforms the 4x2 system, it is not by that 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 base station. In Figure 5 the system wide throughput is shown for various MIMO configuration of an enhanced 802.16d system. A 3x3 MIMO system has an average throughput of 12 Mbps, almost 3 times 3 2x2 spatial multiplexing performs extremely poorly due to the lack of diversity that of a basic 802.16d system with 2 Tx and 1 Rx antennas, thus representing a significant improvement in the spectral efficiency. Since the throughput per antenna is higher for the 3x3 system than the 2x1 system, the additional antenna costs appear to be well justified.

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5.2 Hybrid ARQ

When data is transmitted in packets (MAC-PDU), an ARQ (automatic repeat request) 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 the reliable transmission of data packets. The fundamental difference between a simple ARQ scheme and a HARQ scheme is that in HARQ, the subsequent retransmissions are combined with the previous transmission in order to improve the reliability.

Currently the 802.16d standard uses a data randomization scheme where the information bits are bit wise scrambled using a PN sequence. Since this randomization sequence is expected to change from one transmission to the next it is not possible to perform a 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.

5.3 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 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.

5.4 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 multiuser 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% gain in average throughput could be attained even with a very low-complexity multiuser loading algorithm that enforced relative fairness factors amongst the different users' data rates.The principal factor preventing dynamic multiuser OFDM from effecting 802.16 is therequirement for channel knowledge at the transmitter. However, as noted above, some limited feedback will likely be required to effectively perform spatial multiplexing, which also offers a two-fold increase in capacity. If the low-complexity multiuser OFDM scheme can make use of the same feedback, it appears possible that perhaps an additional two-fold increase in WiMax capacity could result.

6 Conclusions

This paper has overviewed key aspects of the IEEE 802.16 standard, and demonstrated 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 Mbps over a 5 MHz bandwidth, with the lower rates corresponding to having a single receive antenna and 3-sector cells, and the higher rates for two receive antennas and 6-sector cells. A typical cell might be a few kilometers in diameter and have 25% of its area unable to achieve a data rate above 1.5 Mbps for singleantenna users. On the other hand, if 2 receive antennas and 6-sector cells are considered, this drops to about 2%. Since the total data rate must be divided amongst all the 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 have proposed four major areas for future innovation and enhancement, and these are summarized in Table 2. In order to increase the data rate by about a factor of 4, it is recommended that the complementary emerging technologies of spatial multiplexing and multiuser OFDM be employed to maximize the 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.

7 References

802.16 IEEE Forums

[1] Wireless MAN working group, http://WirelessMAN.org/

[2] C. Eklund, R. B. Marks, K. L. Stanwood, and S. Wang, "IEEE Standard 802.16: A Technical Overview of the WirelessMAN™ Air Interface for Broadband Wireless Access", *IEEE Communications Magazine*, pp. 98-107, June 2002.

[3] S.M. Alamouti, "A simple transmit diversity technique for wireless communications", *IEEE Journal on Sel. Areas in Communications*, vol. 16, no. 8, pp. 1451 – 1458, Oct. 1998.

[4] S. Catreux, P. F. Driessen, and L. J. Greenstein, "Attainable throughput of an interference-limited multiple-input multipleoutput (MIMO) cellular system," *IEEE Trans. Commun.*, vol. 49, no. 8, pp. 1307-1311, Aug. 2001.

[5] A. Scaglione, P. Stoica, S. Barbarossa, G. Giannakis, and H. Sampath, "Optimal designs for space-time linear precoders and decoders," *IEEE Trans. Sig. Proc.*, vol. 50, no. 5, pp. 1051-1064, May 2002.

[6] H. Sampath, P. Stoica, and A. Paulraj, "Generalized linear precoder and decoder design for MIMO channel using the weighted MMSE criterion," *IEEE Trans. Commun.*, vol. 49, no. 12, pp. 2198-2206, Dec. 2001. [7] J. M. Wozencraft and M. Horstein, "Coding for two-way channels", Research Laboratory of Electronics, MIT, MA, Technical Report 383, 1961.

[8] D. M. Mandelbaum, "An adaptive-feedback coding scheme using incremental redundancy," *IEEE Transactions on Information Theory*, vol. 20, no. 3, pp. 388-389, 1974.

[9] S. Lin and P. S. Yu, "A hybrid ARQ scheme with parity retransmission for error control of satellite channels," *IEEE Transactions on Communications*, vol. 30, no. 7, pp 1701 – 1719, July 1982 [10] A. Mostafa, R. Kobylinksi, I. Kostanic, and M. Austin, "Single antenna interference cancellation (SAIC) for GSM networks," in Proc., *IEEE Veh. Technology Conf*., Oct. 2003.

[11] C. Y. Wong, R. S. Cheng, K. B. Letaief, and R. D. Murch, "Multicarrier OFDM with Adaptive Subcarrier, Bit, and Power Allocation," IEEE Journal on Selected Areas in Communications, vol. 17, no. 10, Oct. 1999. [12] Z. Shen, J. G. Andrews, and B. L. Evans, "Optimal Power Allocation for Multiuser OFDM", *IEEE Globecom*, San Francisco, CA, pp. 337 - 341, Dec. 2003.

8 Biographical Information

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Appendix A: Tables

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Rate ID	Modulation	Coding Rate	Information Bits/Symbol	Information Bits / OFDM Symbol	Peak Data Rate in 5MHz (Mbps)
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

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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	Tradeoff 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 kbps (FDD) None (TDD)	Not required	Not required	10-50kbps (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: Summary of Innovative Technologies and their effects

Appendix B Figures

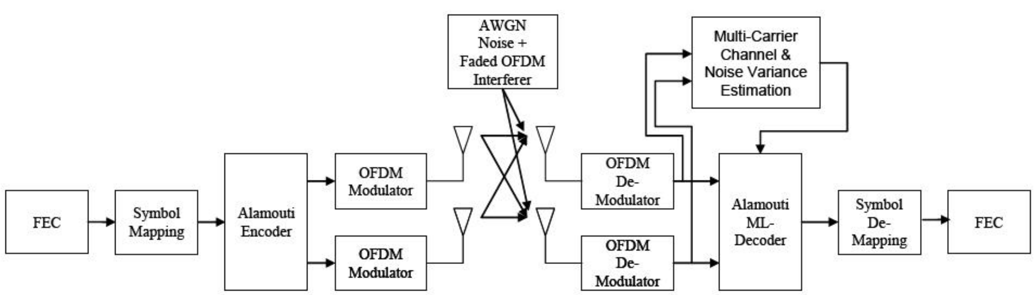

Figure 1 802.16d Link Simulator

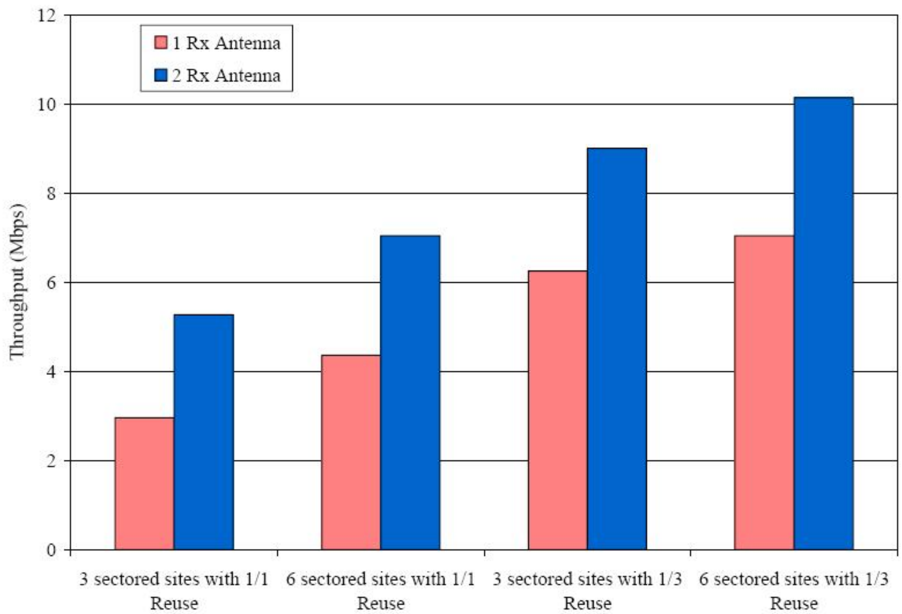

Figure 2 Average throughput over an entire cell per 5 MHz carrier for 802.16d system under various frequency reuse and sectorization configurations

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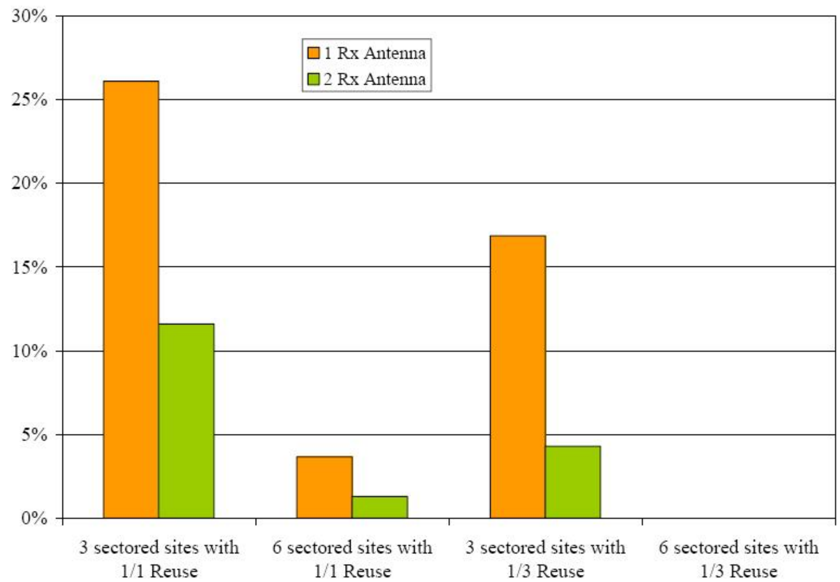

Figure 3 Percentage of cell area with data rate less than 1.5 Mbps

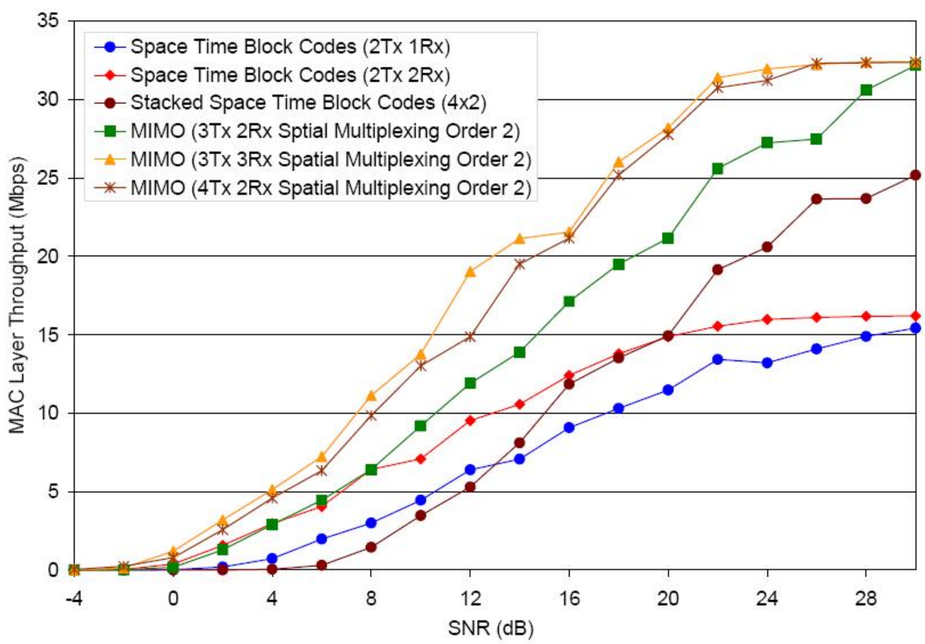

Figure 4: Maximum throughput of STBC and Spatial Multiplexing with Precoding

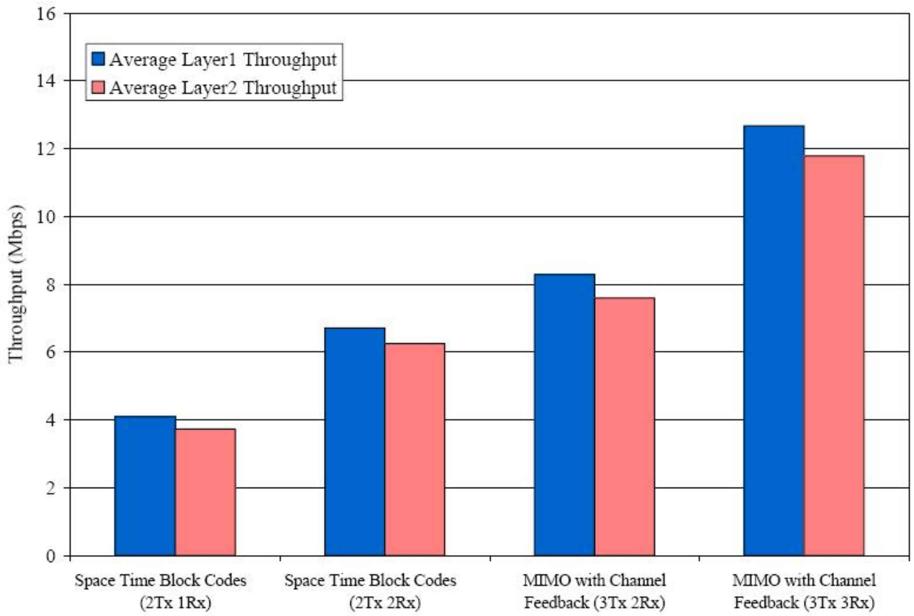

Figure 5 Average throughput per 5 MHz carrier for 802.16d system with enhancements