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Multiple-Antenna Technology in WiMAX Systems

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ABSTRACT

WiMAX is a wireless technology that provides broadband data at rates over 3 bits/second/Hz. In order to increase the range and reliability of WiMAX systems, the IEEE 802.16-2004 standard supports optional multiple-antenna techniques such as Alamouti Space-Time Coding (STC), Adaptive Antenna Systems (AAS) and Multiple-Input Multiple-Output (MIMO) systems. In this paper, we focus on techniques that do not require channel knowledge at the transmitter, which include both Alamouti STC and MIMO, but not AAS.

In the first half of the paper, we present simple diversity schemes that require only a single RF chain at the receiver. The performance of STC is compared with non-STC performance. Simulations show that STC buys 2-10 dB over a single antenna system, which can double the cell range and quadruple the cell coverage. For STC, multiple Radio Frequency (RF) chains are implemented at the Base Station (BS) to shift cost away from Subscriber Stations (SS), thus enabling market penetration for first-generation, high-performance IEEE 802.16-2004 networks. We then concentrate on other simple standard-compliant diversity schemes that require only a single receive chain at the SS: delay diversity and selection diversity.

The second half of the paper investigates standard-compliant MIMO techniques and proposes new non-standard advanced algorithms for open-loop MIMO. A novel space-frequency bit-interleaver that buys 2-4 dB over a frequency-only interleaver is presented. A 2x2 MIMO can double the throughput at a reduced range. An iterative receiver is introduced to recover range, which buys up to 5 dB with additional baseband complexity.

The intent of this paper is to provide an idea of the benefits of multiple antenna systems over single antenna systems in WiMAX-type deployments.

INTRODUCTION

Wireless broadband promises to bring high-speed data to multitudes of people in various geographical locations where wired transmission is too costly, inconvenient, or unavailable. WiMAX is a technology devoted to making broadband wireless commercially available to the mass market by employing IEEE 802.16 standards-based technology. Other important wireless standards include IEEE 802.11, which is devoted to high-speed Local Area Networks (LANs) and IEEE 802.15, which is devoted to short-range Personal Area Networks (PANs).

WiMAX technology is based on the IEEE 802.16 specification of which IEEE 802.16-2004 and 802.16e amendment are Physical (PHY) layer specifications. The IEEE 802.16-2004 standard is primarily intended for stationary transmission while IEEE 802.16e amendment is intended primarily for both stationary and mobile deployments.

While there are multiple modulations defined in the IEEE 802.16 standards, in this paper, we examine Orthogonal Frequency Division Multiplexing (OFDM) because of OFDM's robustness to multipath propagation and its ease for utilizing multiple antenna techniques [1]. Furthermore, we focus on IEEE 802.16-2004 technology as it has already been ratified.

IEEE 802.16-2004 currently supports several multiple-antenna options including Space-Time Codes (STC), Multiple-Input Multiple-Output (MIMO) antenna systems and Adaptive Antenna Systems (AAS).

There are several advantages to using multiple-antenna technology over single-antenna technology:

- Array Gain: This is the gain achieved by using multiple antennas so that the signal adds coherently.
- Diversity Gain: This is the gain achieved by utilizing multiple paths so that the probability that any one path is bad does not limit performance. Effectively, diversity gain refers to techniques at the transmitter or receiver to achieve multiple "looks" at the fading channel. These schemes improve performance by increasing the stability of the received signal strength in the presence of wireless signal fading. Diversity may be exploited in the spatial (antenna), temporal (time), or spectral (frequency) dimensions.
- Co-channel Interference Rejection (CCIR): This is the rejection of signals by making use of the different channel response of the interferers.

A common scheme that exhibits both array gain and diversity gain is maximal ratio combining: this combines multiple receive paths to maximize Signal to Noise Ratio (SNR). Selection diversity, on the other hand, primarily exhibits diversity gain; the signals are not combined; rather, the signal from the best antenna is chosen.

For AAS, multiple overlapped signals can be transmitted simultaneously using Space Division Multiple Access (SDMA), which is a technique that exploits the spatial dimension to transmit multiple beams that are spatially separated [3]. SDMA makes use of CCIR, diversity gain, and array gain. A good tutorial on AAS can be found in [3].

For MIMO systems, spatial multiplexing is often employed. Spatial multiplexing transmits coded data streams across different spatial domains. Some techniques, such as BLAST [6] do not require feedback, while others, such as vector coding on the modes of the channel [7], do. MIMO techniques can also make use of CCIR, diversity gain, and array gain. A form of transmission codes used in MIMO systems are STC. A good review of techniques for STC and MIMO can be found in [13 and 14].

The higher performance and lower interference capabilities of MIMO and AAS make them attractive over other high-rate techniques for WiMAX systems in costly, licensed bands.

For WiMAX, the simplest MIMO system is actually a Multiple-Input Single-Output (MISO) STC code called the Alamouti code. This requires two antennas at the Base Station (BS). The Alamouti code provides maximal transmit diversity gain for two antennas [2]. Another transmit diversity scheme is cyclic delay diversity. A key advantage of transmit diversity is that it can be implemented at the BS, which can absorb higher costs of multiple antennas and associated RF chains. This shifts cost away from the SS, which enables faster market penetration of 802.16 products.

One of the many advantages of OFDM technology is the ease with which multiple-antenna techniques can be utilized to increase range and throughput (a system description is given below). Using this general system model, we show the primary advantage of OFDM systems over single-carrier systems in multipath propagation environments to explain why OFDM is conceptually less complex in AAS and MIMO systems. We then discuss a fixed point implementation of the Alamouti receiver. The fixed point simulations show several performance enhancements. Several practical aspects of the technology are also discussed. Next, we discuss several other simple diversity options, cyclic delay diversity and selection diversity, to improve system performance. We then describe more advanced schemes that could be used to achieve even higher throughput. We introduce open-loop techniques for multiple-antenna systems, which include standard compliant MIMO equalization, spatial-frequency interleaving, and iterative decoding. Simulation models are discussed that show large performance improvements.

SYSTEM DESCRIPTION

We describe the Physical (PHY) layer of the general communication system. The performance of the PHY layer is strongly correlated to the overall system performance. However, higher-level entities such as Automatic Request (ARQ) for retransmission can also impact system performance.

A wireless environment suffers from multipath propagation. Multipath propagation, also known simply as multipath, is a condition where multiple reflections of the transmitter waveform arrive at the receiver at different times. This is shown in Figure 1, where a and b are the gains of the paths and τ_1 and τ_2 are the delays. The reflected path is actually the sum of multiple reflections from the obstruction, which causes fading. Multipath propagation induces Inter-Symbol Interference (ISI) which is traditionally compensated for by equalizers in single-carrier systems [4].

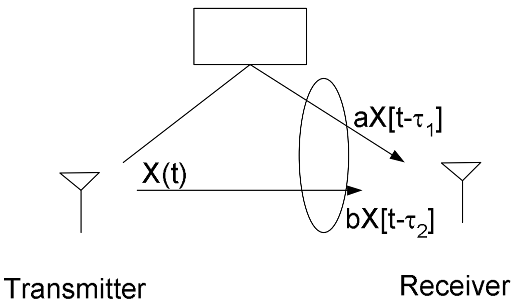

Figure 1: Conventional wireless system

Equalizers are computationally intense compared to the processing required in OFDM systems. Hence, OFDM is preferable in multipath propagation scenarios. A block diagram of OFDM is shown in Figure 2. As long as the CP, or Cyclic Prefix, is longer than the difference in multipath propagation arrival times, or multipath spread, an equalizer is not needed. The CP prepends the output of the Inverse Fast Fourier Transform (IFFT) with the last L samples of the IFFT output, where L is the length of the CP.

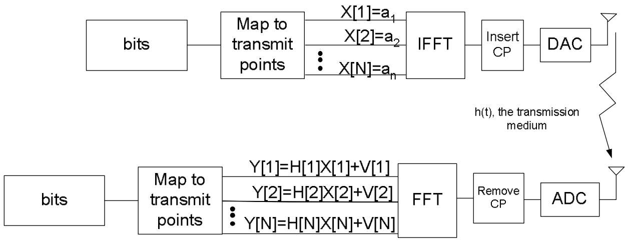

Figure 2: The OFDM system

For terminology, X[k] is the transmitted information symbol on subcarrier k. For subcarrier k, H[k] is the scalar subcarrier response and its value is related to the FFT of the digitized channel response h(t), V[k] is the noise, and Y[k] is the output. The complete set of inputs {X[k]} is called the transmit OFDM symbol, and the set of demodulated signals {Y[k]} is called the receive OFDM symbol. On a subcarrier by subcarrier basis, there is no need for an equalizer.

Consider a MIMO system without noise as shown in Figure 4. In this figure, each ray corresponds to a multipath propagation channel. From the point of view of a subcarrier, each multipath propagation channel collapses to a single scalar tap. For subcarrier k, this can be expressed as shown in Figure 3 below.

$$\begin{bmatrix} Y_1[k] \\ Y_2[k] \\ Y_3[k] \end{bmatrix} = \begin{bmatrix} H_{11}[k] & H_{12}[k] \\ H_{21}[k] & H_{22}[k] \\ H_{31}[k] & H_{32}[k] \end{bmatrix} * \begin{bmatrix} X_1[k] \\ X_2[k] \end{bmatrix}$$

Figure 3: MIMO channel model

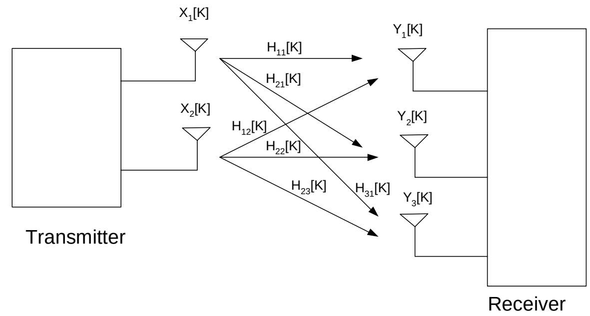

Figure 4: MIMO channel

In Figure 4, $Y_i[k]$ is the kth subcarrier output for receive antenna i, $H_{ij}[k]$ is the kth subcarrier gain from the jth transmit antenna to the ith receive antenna, and $X_j[k]$ is the kth subcarrier input from antenna j.

In the single carrier case, each of the matrix elements would be multipath propagation channel responses. Conceptually, the signal processing is much more complicated; however, such systems can be simplified.

So, without loss of generality, rewriting the above equation, for an OFDM system would be

$$\underline{Y} = H * \underline{X} + \underline{N} \qquad \text{(eq. 1)}$$

where $\underline{Y}$, H, and $\underline{X}$ are the appropriate generalizations of the 2 transmit x 3 receive antenna system and $\underline{N}$ is the noise and interference. For general systems, H is an Mr by Mt matrix representing the number of transmit and receive antennas, respectively.

For an Additive White Gaussian Noise (AWGN) channel, the maximum achievable theoretical data rate of this system is given by the Shannon capacity formula [11]

$$C = \log\det\left(I + {}^{P}\!/\!_{BN_oM_t}\, HH^*\right)$$

where P is the transmit power, N_o is the noise power spectral density, and B is the signal bandwidth. An M_t x M_r MIMO system can provide up to M=min (M_t, M_r) times the spectral efficiency of a 1x1 system. This linear relationship also holds true for outage capacity, which is equal to percentiles of the cumulative distribution function of C.

STC AND OTHER STANDARD-COMPLIANT DIVERSITY SCHEMES

In order to increase the rate and range of the modem, there are several considerations. Generally, the BS can incur more cost and complexity than the SS, so multiple-antenna chains are a good option at the BS, which can then apply receiver diversity techniques. These techniques include switched diversity and maximal ratio combining. To balance the link, the SS needs to have improved performance. Transmission diversity schemes are utilized at the BS that require only one receive antenna at the SS. Two transmit diversity schemes are cyclic delay diversity and Alamouti transmission. We focus on Alamouti transmission.

Alamouti Transmission

The Alamouti transmission scheme is an STC in that it sends information on two transmit antennas and consists of two consecutive transmissions in time. Hence it transmits information in space and time.

In IEEE 802.16-2004 OFDM-256 the Alamouti code is applied to a specific subcarrier index k. For instance, suppose that in the uncoded system $S_1[k]$ and $S_2[k]$ are sent in the first and second OFDM symbol transmissions. The Alamouti encoded symbols send $S_1[k]$ and $S_2[k]$ off the first and second antennas in the first transmission and $-S_2^*[k]$ and $S_1^*[k]$ off the first and second antennas in the next transmission.

The receiver demodulates the received waveform by a few simple operations as follows. Let $Y_1[k]$ and $Y_2[k]$ be the first and second receive OFDM symbols, respectively. Let $C_1[k]$ and $C_2[k]$ be the channel response for the kth subcarrier of the first and second transmit antennas.

$$\begin{aligned} &C_1{}^*[k]Y_1[k]+C_2[k]Y_2{}^*[k]= \\ &(\|C_1[k]\|^2+\|C_2[k]\|^2)\hat{S}_1[k]+ \\ &C_1{}^*[k]V_1[k]+C_2[k]V_2{}^*[k] \end{aligned}$$

(eq. 2)

$$\begin{aligned} &C_2{}^*[k]Y_1[k]-C_1[k]Y_2{}^*[k]= \\ &(\|C_1[k]\|^2+\|C_2[k]\|^2)\hat{S}_2[k]+ \\ &C_2{}^*[k]V_1[k]-C_1[k]V_2{}^*[k] \end{aligned}$$

If the noise $V_1[k]$ and $V_2[k]$ are uncorrelated, then the overall SNR is the maximum achievable and equal to $(\|C_1[k]\|^2+\|C_2[k]\|^2)$(Signal Energy/Noise Energy). Notice that both $C_1[k]$ and $C_2[k]$ need to be in a fade for the overall processed symbol to be in a deep fade. This system has two-fold diversity. For k-fold diversity, the Bit Error Rate (BER) is proportional to $(1/\mathrm{SNR})^k$ in a fading environment.

Alamouti Implementation Details

There are a number of features to IEEE 802.16-2004 OFDM-256 Alamouti transmission that are of interest. The first is that the preamble for Alamouti transmission is transmitted from both antennas with the even subcarriers used for antenna 1 and the odd subcarriers used for subcarrier 2. This means that each set of data needs to be appropriately smoothed, which is done in these simulations. The second is that the pilots have certain degenerate situations: for the first Alamouti transmitted symbol, the pilots destructively add and for the second Alamouti transmitted symbol, the pilots constructively add. Hence, the pilots cannot always be useful. Properly processing the pilot symbols is required. In the simulations, such a technique is used.

We present block diagrams detailing the flow of an Alamouti implementation. This implementation has two parts. The first calculates the parameters that are necessary for data demodulation such as channel estimates. The second part is the actual data demodulation and tracking.

Figure 5 describes the parameter estimation portion. In this part, two channels are estimated, and those channel estimates are used to calculate the Viterbi equalizer coefficients. E_i, is the average energy of the ith transmit path. This is a computationally intensive portion of the Alamouti reception; however, it is a one-time computation per burst, so is feasible.

Alamouti Performance Simulations

For the purposes of simulations, three scenarios are simulated each of which are important to typical system vendors. The first set uses an AWGN channel that is the baseline for performance results. In AWGN, BER is the most important metric. The second set of simulations uses a frequency selective channel normalized so that its average SNR is equal to the instantaneous SNR. These simulations show the performance in frequency selective channels. In fixed wireless scenarios, the receive SNR does not change rapidly, so the average BER during multiple instantiations of the channel is of interest. Finally, in the third set of simulations, the channel is fading. In non-mobile situations, the fading rate is slow, so it is of interest to determine how often the system does not provide good performance. The Packet Error Rate (PER) is a good metric. A fixed-point model of the Alamouti scheme is simulated under the following conditions:

- Full bandwidth IEEE 802.16-2004 OFDM-256
- Stanford University Interim (SUI)-3 model
- 3.5 MHz bandwidth
- Varying SNR
- No timing/frequency offset or drift

All the blocks in Figure 5 are executed. The results are shown in Figures 6 and 7.

The 3 dB theoretical gain, as indicated by Equation 2, is not met at BER=10^{-3}. We expect that at lower BERs, the curves will be closer to expected theoretical gains.

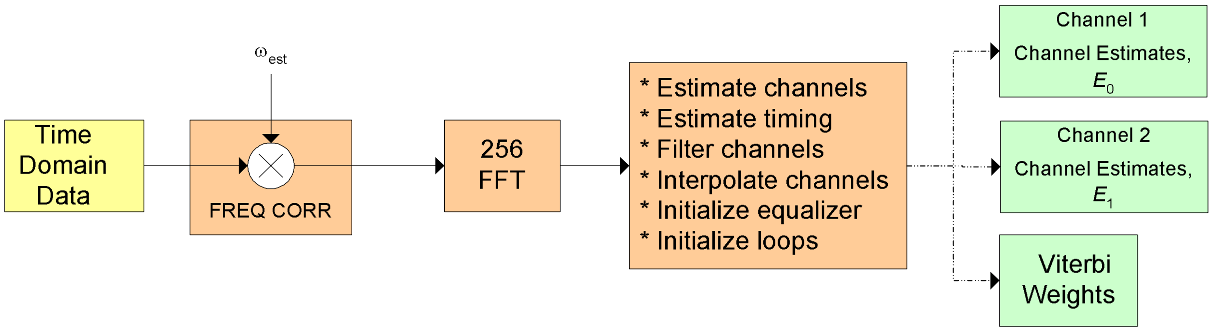

Figure 5: Alamouti parameter estimation

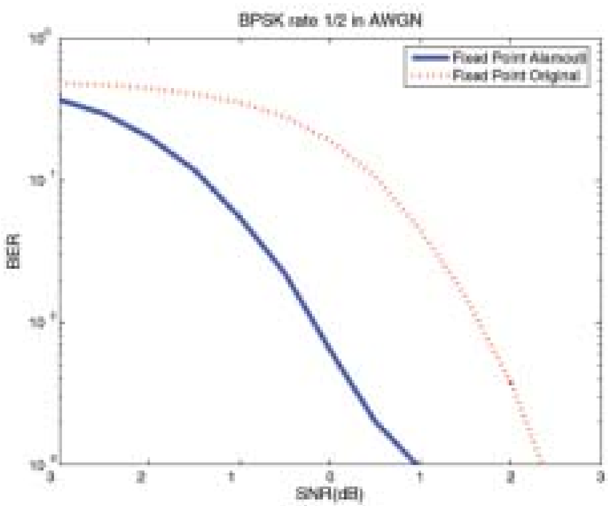

Figure 6: BER vs. SNR(dB) for BPSK rate ½

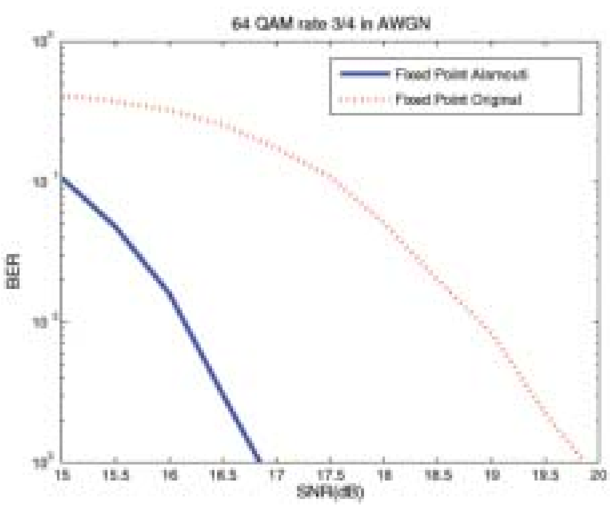

Figure 7: BER vs. SNR (dB) for 64-QAM rate 3/4

To judge the scheme in the presence of frequency selectivity, we simulate a SUI-3 normalized channel.

A normalized channel has the average channel energy normalized to a constant so that instantaneous SNR for the realization is equal to the average SNR. We show the performance results in Figures 8 and 9.

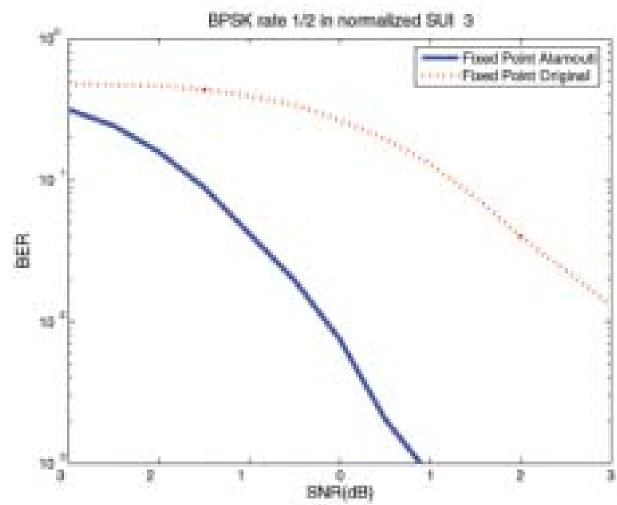

Figure 8: BER vs. SNR (dB) for BPSK rate ½ in SUI-3 channel

In the normalized SUI-3 configurations the gain is more than 3 dB. The main conclusion to draw is that the frequency selectivity can cause deep notches, which the error correction cannot correct; however, the sum channel may not have as deep notches, thereby improving performance beyond the simple 3 dB gain found in AWGN channels.

We now reproduce the results in a fading environment. The main difference between the next simulation and the earlier ones is that SUI-3 fading channels are used.

In fading channels, PER is a better performance metric, since in slowly fading channels, the channel will be in a fade for a long period of time. The results are shown in Figures 10 and 11.

At a 1% PER rate, the gain is quite significant. The PER increase is over 5 dB for the BPSK transmission and over 10 dB for the 64-QAM transmission.

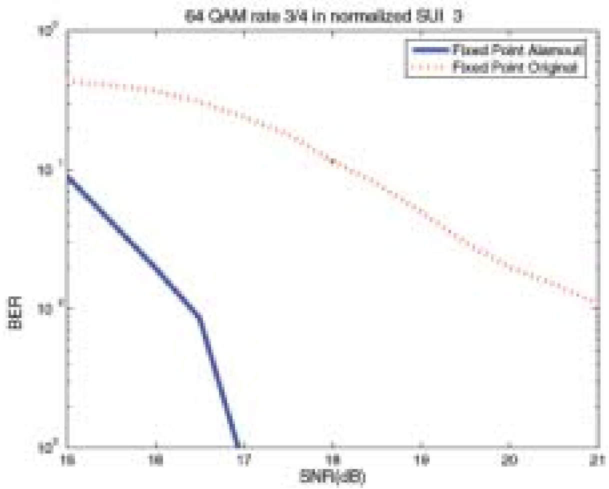

Figure 9: BER vs. SNR (dB) for 64-QAM rate ¾ SUI-3 channel

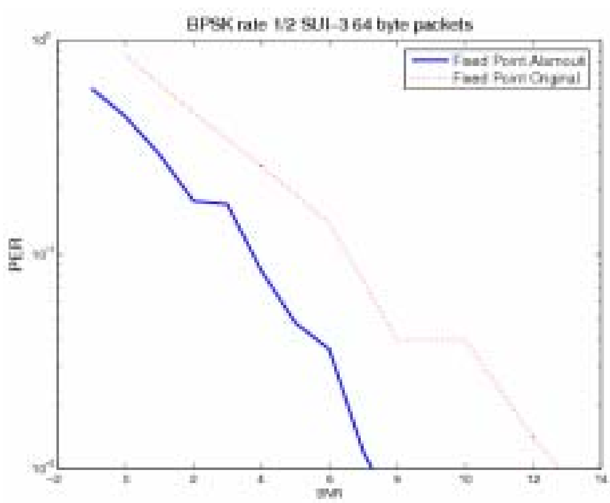

Figure 10: PER vs. SNR (dB) for BPSK rate ½ SUI-3 channels

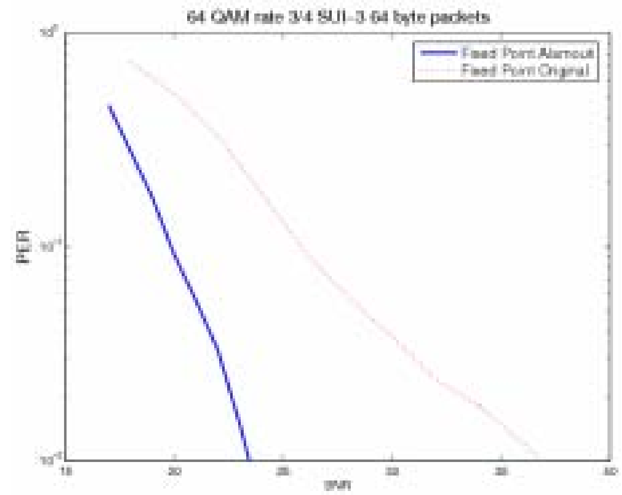

Figure 11: PER vs. SNR (dB) for 64-QAM rate 3/4 SUI-3 channel

OTHER DIVERSITY SCHEMES

In the rest of this section we compare various diversity schemes using floating point models. We primarily depict relative gains since some of the non-ideal modem behavior will not be simulated. We focus on the subscriber side. SS's are typically cost sensitive, hence we focus on single receive chain systems.

The primary forms of diversity we examine are selection diversity and cyclic delay diversity. These are two forms of diversity that do not necessarily have an impact on standards-compliant modems.

Consider the following block diagram:

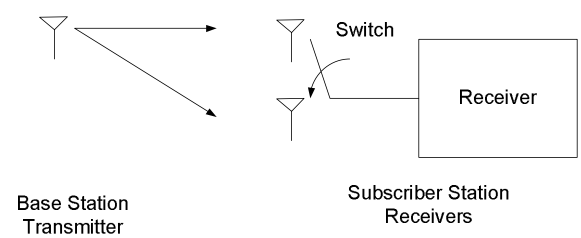

Figure 12: Example of selection diversity

In selection diversity, the receiver chooses the "best" antenna to receive. The additional hardware requirement is simply a switch and an antenna. Many performance metrics can be optimized. For non-multipath propagation channels, the strongest received signal is typically the "best" antenna. For multipath propagation channels, the optimization can be more complicated, for example, the maximum geometric SNR [5]. In the following simulations, the selected antenna was that which had the highest signal power. Selection diversity is a form of receive diversity.

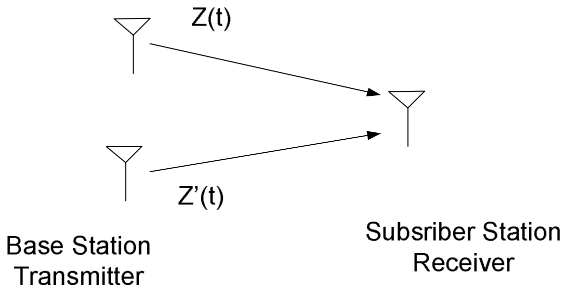

Figure 13: Transmit diversity scheme using cyclic delay diversity

Figure 13 depicts cyclic delay diversity. As shown cyclic delay diversity is a transmission diversity scheme. Details of cyclic delay diversity can be found in [2]. Basically, consider the transmit sequence before appending the CP, x[n]. Then the "delayed version" that is transmitted off the second antenna is $x'[n]=x[((n-m))_{NFFT}]$, where m is the delay, $((.))_a$ represents the modulo operation, and NFFT is the FFT size. Z(t) and Z'(t) are the outputs from the antennas following digital and analog processing.

Simulation Results

In this section we compare these two simple diversity techniques. The setup is the same as in the Alamouti case, where the channel model is a correlated SUI-3 channel including fading as found in IEEE 802.16. We simulate 64 byte packets, which represent the ACK from Ethernet transmission/reception. Figure 14 shows the simulation results.

In typical WiMAX environments, simple schemes such as selection diversity and cyclic delay diversity can give over 4 dB in performance gains. Such simple schemes can increase coverage and throughput. For selection diversity, a switch and another antenna are needed, and for cyclic delay diversity, an additional transmit chain is necessary. As this cost is at the BS, the extra transmit chain is usually acceptable.

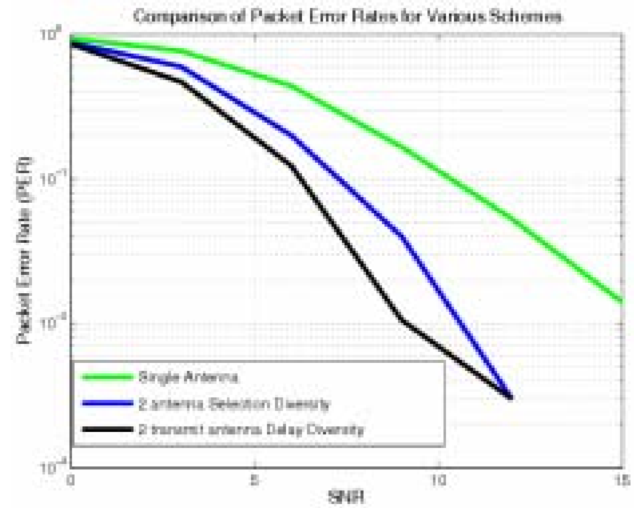

Figure 14: PER as a function of SNR

MULTIPLE-INPUT MULTIPLE-OUTPUT FOR THROUGHPUT AND RANGE

MIMO multiplies the point-to-point spectral efficiency by using multiple antennas and RF chains at both the BS and the SS. MIMO achieves a multiplicative increase in throughput compared to Single Input, Single Output (SISO) architecture by carefully coding the transmitted signal across antennas, OFDM symbols, and frequency tones. This gain is achieved at no cost in bandwidth or transmit power. These simulation results assume ideal channel estimation, channel estimate smoothing, and perfect synchronization.

We concentrate on open-loop systems in this paper. These do not require feedback of channel information to the transmitter. AAS and some MIMO techniques require some amount of channel knowledge at the transmitter. This information can be implicitly estimated using reciprocity in Time Division Duplex (TDD) systems or may be explicitly signaled back to the transmitter in Frequency Division Duplex (FDD) systems. In a slowly changing system such as IEEE 802.16-2004, channel knowledge may remain valid for a long time. In a mobile system like that defined in the IEEE 802.16e amendment, however, the channel may change quickly and require frequent feedback updates. The overhead of channel feedback may become significant for mobile FDD systems. MIMO is an attractive solution for such systems because some methods do not require channel knowledge: it maintains the link by exploiting spatial diversity.

Outage capacity is closely related to PER, which is often used to evaluate performance. In the next sub-section, we present the design and performance of a space-frequency interleaver for mapping coded bits to tones and antennas. With an optimal receiver, this interleaver can provide M times the spectral efficiency of a 1x1 system at a given range depending on the channel conditions.

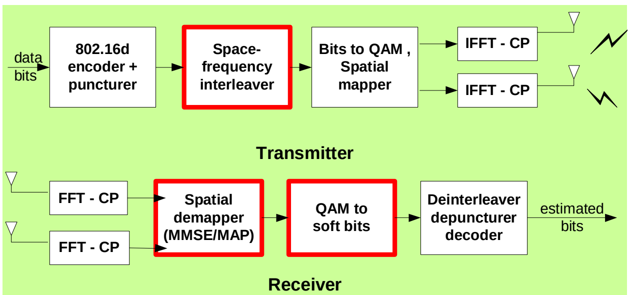

Figure 15: System block diagram for space-frequency interleaving

The simplest MIMO receiver is the zero-forcing receiver that inverts the channel, thus recovering M = min(M_t , M_r) transmitted data streams. However, this inversion can cause noise enhancement. A better receiver is the Minimum Mean Squared Error (MMSE) receiver that performs a weighted inverse so as not to magnify noise in the poor channel modes. In general, the optimal receiver that minimizes the probability of error (and achieves capacity) is the Maximum Likelihood (ML) receiver or the Maximum A Posteriori Probability (MAP) receiver. The transmission source may also have a code incorporated. For instance, the OFDMA section of IEEE 802.16-2004 contains transmission matrices for STC that can be used in conjunction with these reception techniques. The performance of some MIMO receivers is outlined in the following sub-sections.

MIMO Transmitter: Space-Frequency Interleaving

Space-frequency interleaving is a simple way to provide diversity gain to a spatially multiplexed, coded data stream. This method is not currently standard-compliant. The block diagram for the Space-Frequency Interleaver (SFI) transmitter and receiver is illustrated in Figure 15. Information bits are first encoded by a Forward Error Correction (FEC) encoder, which is a concatenation of Reed-Solomon and convolutional encoders in OFDM-256 IEEE 802.16-2004. After puncturing, the binary coded bits are sent to an SFI, which maps bits to antennas and tones so as to exploit full diversity in both space and frequency. The interleaved bits are then mapped to Gray coded QAM data symbols. The receiver uses the MMSE receiver, and it sends the soft bits into the concatenated convolutional and Reed Solomon decoders.

Details of the interleaver design are available in [12]. We provide a short description here. Let q be the number of bits per QAM symbol, assume 192 data tones (256 point FFT with 64 guard tones+pilots) and M transmit antennas. The interleaver consists of three steps: (1) serial-to-parallel multiplexing of incoming q*192*M bits to M antennas, (2) IEEE 802.16-2004 interleaving on each antenna, and (3) forward circular shift of the bits on each antenna by q*cts, where cts = "cyclic tone shift" is a parameter that must be optimized for each data mode and MIMO configuration.

For example, the IEEE 802.16-2004 interleaver output for BPSK modulation is shown in Figure 16 below:

1 2 3 ..	1 3 5 ..	384 362 364 …
13 14 15	25 27 29	2 4 6
25 26 27	49 51 53	26 28 30
37 38 39	73 75 77	50 52 54
:	:	:

Figure 16: IEEE 802.16-2004 bit interleaver BPSK, SF interleaver for 2x2 MIMO on antenna 1 and on antenna 2

In Figure 16 bits are mapped to tones column-by-column. Therefore bits indexed by 1, 13, 25, 37, … are mapped to tones 1, 2, 3, 4, ….etc. Our proposed interleavers are shown in the second two boxes of Figure 16.

Simulation results for this interleaver with BPSK, rate ½, 192 data tones are shown in Figure 17. SUI-3 channel models without spatial correlation are used throughout this section.

Also shown for reference is a simpler interleaver labeled SM, which does not interleave bits across antennas. Instead, it takes contiguous blocks of q*192 bits and maps them to antennas, followed by IEEE 802.16-2004 interleaving on each antenna.

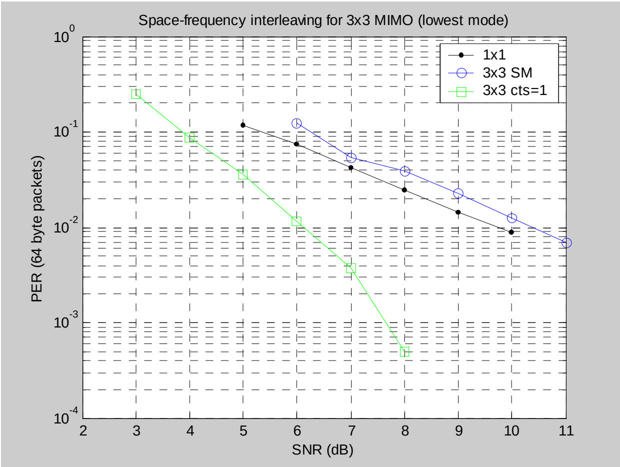

Figure 17: SFI for 3x3 MIMO (lowest mode)

Our interleaver provides gains of 2 to 4 dB over this simple interleaver because it has been designed to extract maximal space-frequency diversity.

At the highest IEEE 802.16-2004 mode with 64-QAM, rate ¾ coding, gains with the interleaver are not as high, but still significant at 1 to 2 dB over SM, as shown in Figure 18.

Figure 18 shows two values of cts: cts=1 and cts=64. Performance of the MMSE receiver is sensitive to the choice of cts, although cts=1 works well for most modes, channel conditions, and MIMO architectures. Performance of the ML receiver is not sensitive to the choice of cts (not shown here).

This suggests that the MMSE receiver induces correlation across space-frequency blocks. The MMSE induces correlation across antennas because of cross-talk, and the channel induces correlation across tones because of limited delay spread. A combination ends up correlating adjacent tones on all antennas. The proposed interleaver places bits on uncorrelated tones and antennas, thereby improving performance with the MMSE receiver.

Figure 18 also shows performance with an SVD receiver, which requires channel feedback to the transmitter in order to diagonalize the channel matrix.

Note in Figures 17 and 18 that the 3x3 architectures fall short of 1x1 by 3 to 5 dB. Therefore these MMSE-MIMO architectures do not maintain range at the higher throughputs.

Advanced receivers are required to improve range at high rates, and they are the subject of the next sub-section.

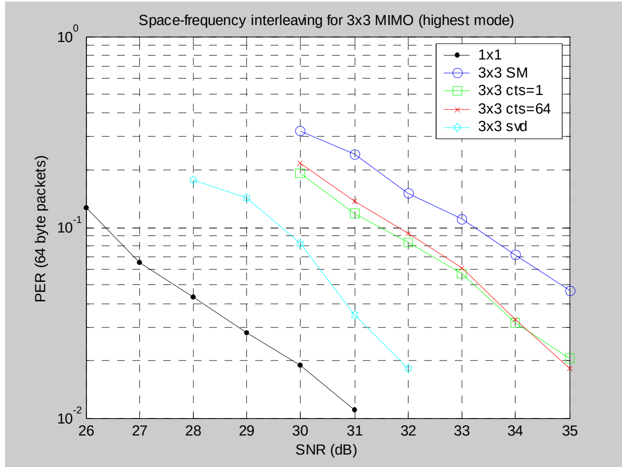

Figure 18: SFI for 3x3 MIMO at highest mode

MIMO Advanced Receivers: Iterative Decoding

A non-iterative receiver similar to that used in the previous sub-section is shown in Figure 19.

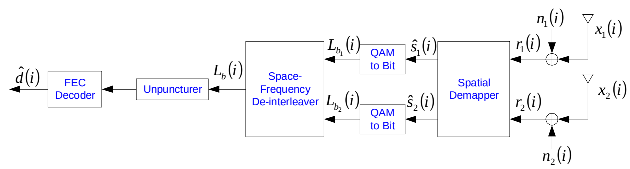

Figure 19: Illustration of non-iterative receiver

The spatial demapper above decouples the data streams mixed by the channel matrix over the air. The MAP demapper has the best performance and the highest complexity, while linear demappers such as MMSE and ZF have low complexity but poor performance compared to MAP. Recently, techniques such as sphere decoding have been proposed to reduce the complexity of MAP receivers.

After the spatial streams are separated, the "QAM to bit" functional block converts the noisy QAM symbols into Log Likelihood Ratios (LLR) for each punctured, coded bit. For the non-iterative receiver, these LLRs are eventually sent to the FEC decoder and bit decisions are made.

For the iterative receiver, there are many more steps before bit decisions are made. Figure 20 shows an iterative receiver based on the turbo principle [8]. The channel matrix H is treated as a rate one linear block code, which is concatenated with the convolutional and Reed-Solomon codes. Iterations are conducted between the spatial demapper and the FEC decoder by passing extrinsic information (i.e., LLRs) back and forth.

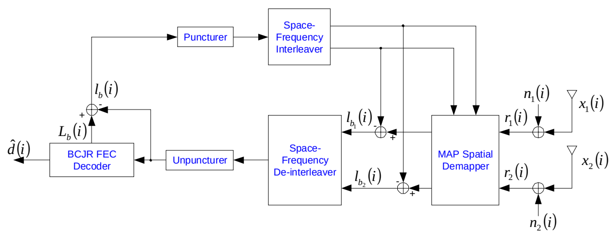

Figure 20: Illustration of an iterative receiver

Performance of this iterative receiver is shown in Figure 21 for 2x2 and 2x3 MIMO architectures. All seven rate modes specified in IEEE 802.16-2004 are used to generate this throughput versus SNR curve. For each architecture, all SIMO subsets such as 1x2 and 1x3 are allowed in the set of possible modulations. For each SNR and each channel realization, all possible combinations of data rate and antenna subsets are run to compute throughput and only the maximum throughput is reported. The maximum throughputs of all channel realizations for that SNR are then averaged and the mean throughput is plotted. The number of iterations for 2x2 MAP curve is 4. The SVD curve includes 2x2 with spatial mode puncturing and 1x2 Maximal Ratio Combining (MRC).

We observe the following:

1. 2x2 MAP buys 3-5 dB gain over 2x2 MMSE at higher throughputs.
2. 2x2 SVD buys 2-3 dB over 2x2 MMSE at higher throughputs.
3. 2x3 MMSE buys 5-7 dB over 2x2 MMSE at higher throughputs.

Therefore we buy the most gain by adding an extra receive chain. This hardware cost can be transferred to baseband complexity by using the MAP [9] and BCJR [10] iterative algorithms instead of MMSE, by taking a 1 dB performance hit. The complexity of the MAP spatial demapper is $O(M^K)$, where M is the size of the QAM symbol and K is the number of data streams. This can be rather large for higher order QAMs. We are looking at methods to reduce the complexity of advanced receivers.

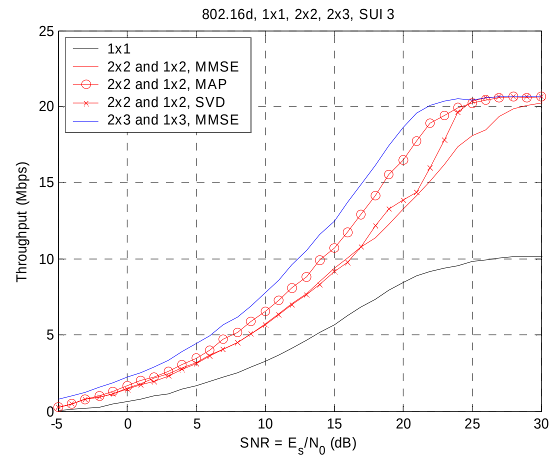

Figure 21: Advanced receivers for 2x2 and 2x3

CONCLUSION

We have shown that multiple-antenna techniques can greatly enhance the performance of wireless transmission systems. Systems are currently trending towards using multiple antennas at the BS and future systems may evolve to multiple antenna systems at the SS. We have demonstrated that Alamouti reception, circular delay diversity, and selection diversity are simple schemes that can increase performance greatly. More advanced MIMO techniques can increase performance well beyond the current limits of data rate and reach.

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