Multiple Antenna Systems in WiMAX

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An Introduction to MIMO, SAS and Diversity
supported by
Airspan's WiMAX Product Line

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WiMAX, championed by the WiMAX Forum to promote conformance and interoperability of the IEEE 802.16 standard, has revolutionised the wireless wide area broadband communications. The latest version of the standard, IEEE 802.16e-2005, extents the earlier specifications in order to address the requirements of mobile WiMAX deployments.

Thanks to its OFDM and SOFDMA based Physical layer, WiMAX is ideally suited to operate in multipath propagation environments. Furthermore, one of the advantages of OFDM/SOFDMA technology is the ease with which multiple-antenna techniques can be utilized to increase throughput, range and improved error rate performance.

The IEEE 802.16 standard supports a number of options for multiple-antenna techniques, including diversity, Smart Antenna Systems (SAS) and Multiple Input Multiple Output (MIMO) systems. In this paper we will mainly focus on the multiple antenna technologies supported by the HiperMAX platform where the transmitter does not have to know the channel conditions, i.e. the diversity and MIMO systems. SAS systems will be briefly mentioned as a future extension.

Please consult the Airspan Web-site (www.airspan.com) for further details about Airspan's WiMAX products and solutions.

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Introduction

According to the theory developed by Shannon, the upper limit of the information that can be transmitted error free across a communications channel comprising of a single RF-chain system is expressed by the following equation:

Channel Capacity = Bandwidth x log2 (1+SNR)

Shannon's formula states that in order to increase channel capacity either the bandwidth or the SNR need to be increased. Until the arrival of multiple-antenna systems these have indeed been the solutions to increase channel capacity.

In the past 10 years considerable research money has been invested in multiple antenna systems in line with the increase in wireless communications, mainly driven by the runaway success of mobile systems. Now these techniques are also being employed in mobile and fixed WiMAX deployments.

When wireless communications systems are deployed in urban or suburban environments, many obstacles may exist between transmit and receive ends. These obstacles give rise to what is known as multi-path propagation because the transmitted signal may take multiple paths to the receiver, some paths longer than others. This in turn, may give rise to destructive interference and make it hard for the receiver to recover a good enough copy of the transmitted signal. Most pre-WiMAX wireless systems are deployed with a view to minimising multipath and its undesirable effects. To minimise or eliminate multipath means that Line of Sight (LOS) needs to be achieved between the transmitter and receiver.

Clearly LOS between the Base Station (BS) and the Subscriber Station (SS) is very hard and costly to achieve especially in dense urban deployments, not least because the SS may be located indoors. By contrast, WiMAX has been conceived to operate in NLOS environments. WiMAX's Orthogonal Frequency Division Multiplexing (OFDM) or Scalable Orthogonal Frequency Division Multiplex Access (SOFDMA) based PHY level is especially suitable for operating in a multipath environment.

Modern multiple-antenna systems can be designed to take advantage of multipath, rather than treat it as something to be avoided, as is the case for traditional single antenna systems. When WiMAX is used in conjunction with multiple-antenna systems it is possible to achieve increased throughput and better error rate performance by taking advantage of the multipath effect.

Multiple-Antenna Systems

There is considerable confusion about the terminology associated with multiple antenna systems. It will be helpful to define the terminology we will use in the rest of this paper.

Multiple antenna techniques can broadly be divided into three:

- Diversity Schemes
- Smart Antenna Systems (SAS) and
- Multiple Input Multiple Output (MIMO) Systems

Definitions

Diversity Schemes

There may be diversity systems with more than one antenna at the BS and at the SS. However, in this paper we will concentrate on simple diversity systems that are defined as having two antennas per channel at the BS and one at the SS. The reason for this is that whilst the BS can carry the additional cost of a second Transmit/Receive chain per channel, cost constraints at the SS may preclude the use of a second Tx/Rx chain there. However, there are products such as Airspan's EasyST, which has multiple antennas feeding a single Tx/Rx chain, which still give significant gains arising from antenna switching. There are transmit diversity and receive diversity schemes examples of which are discussed later.

Smart Antenna Systems

SAS (also called Adaptive Antenna Systems-AAS) utilise sophisticated signal processing techniques in order to construct a model of the channel. The knowledge of the channel is then used in order to direct the signals towards the desired user and away from sources of interference. This is achieved by using techniques such as beamforming towards desired users and null steering towards the interferers.

Multiple Input Multiple Output (MIMO) Systems

MIMO systems are defined as being systems where both the BS and the SS have a minimum of two Tx/Rx chains, per channel, with associated antennas. The 802.16e-2005 WiMAX profiles have defined two MIMO systems known as Matrix A MIMO and Matrix B MIMO. Matrix A MIMO is a rate 1 Space-Time Coding scheme whereas Matrix B MIMO is a rate 2 Spatial Multiplexing scheme. Both systems present different advantages as will be discussed later.

Benefits of Multiple-Antenna Systems

Multiple-Antenna systems provide the following benefits:

Diversity Gain – Achieved by utilising multiple paths between the transmitter and the receiver. Spatial diversity is the simplest form of Downlink (DL) diversity gain achieved by utilising a minimum of two antennas per channel at the BS.

Array Gain – Results from combining two signals coherently. In the DL direction beamforming gain may result in array gain. In the uplink direction Maximum Ratio Combining (MRC) may also provide array gain.

Power Combination – In the case where M antennas are deployed in the downlink, and each antenna is driven by a power amplifier of equivalent rating to the single antenna case, a power combination gain of 10log10(M) is achieved.

Interference Reduction – A feature of the SAS achieved by null steering towards co-channel interferers.

Spatial Multiplexing – Two or more data streams can be resolved by one user or to two or more users, enhancing system capacity and spectral efficiency. For example, spatial multiplexing in the UL direction is implemented using Collaborative Spatial Multiplexing (CSM).

It is possible to use the SAS and MIMO techniques together to achieve even bigger advantages.

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Diversity Schemes

Under this heading we will consider three techniques:

- Space-Time Coding (Alamouti code)
- Antenna Switching
- Maximum Ratio Combining (MRC)

Space-Time Coding (STC)

The 802.16 standard specifies Alamouti scheme as a compliant STC scheme. It is a Space-Time code in that it sends information on two transmit antennas (space) over two consecutive transmissions in time. Therefore it is said to transmit information in space and time.

Please refer to Figure 1. The data stream entering the Modulator is modulated into Symbols S1 and S2. These symbols are then processed by the Space-Time Encoder which then sends S1 followed by –S2* to Antenna 1 and S2 followed by S1* to Antenna 2. Here (*) denotes a complex conjugate of the symbol. Note that the two antennas at the BS will transmit 2 symbols in two time periods. In other words this is a rate 1 code.

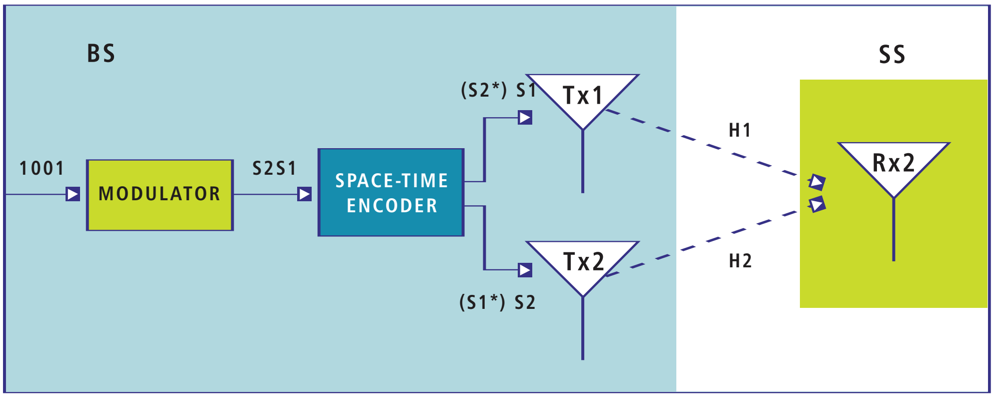

Figure 1 – STC Scheme

The purpose of this scheme is not to increase the system capacity but to improve the error rate performance of the system by transmitting coded information. Since higher order modulation schemes are more susceptible to noise, as the error rate performance of the system improves, it may be possible to use a higher order modulation scheme, which means that each symbol carries more bits of data, which in turn may result in modest increases in system capacity.

The scenario described above can be seen as a special case of MIMO, where Multiple Input Single Output (MISO) technique is used. Indeed this is one of the Matrix A MIMO scenarios.

Airspan's MacroMAX and HiperMAX BS products implement STC/Matrix A MIMO.

Antenna Switching

Antenna Switching is a simple approach for capturing diversity gains. The purpose is not to combine signals from the multiple antennas available but simply to select the single antenna with the best channel gain at any given time. It is applicable to both DL and UL transmission.

Airspan's EasyST product, which is an indoor, self-install SS, utilises this technique in the DL direction. EasyST's built-in antenna comprises of 4 separate 90° antennas. EasyST selects one of the 4 antennas that give the strongest signal at any one time. Furthermore, this approach benefits desktop deployment by not being adversely affected from the SS inadvertently being moved by the user.

Figure 2 – EasyST with 4x90° Antennas built into the vertical cone

Maximum Ratio Combining (MRC)

Maximum Ratio Combining is a processing technique that estimates channel characteristics for multiple antennas and then apply weights to each antenna to maximize signal to noise ratio for the summed signal. MRC achieves diversity and array gain but does not involve active interference mitigation or spatial multiplexing in any way.

Airspan's MacroMAX is an example of a base station implementation of MRC in the uplink direction.

Performance Summary for Diversity Techniques

The characteristics of the Diversity schemes are summarised below:

Scheme	DL/UL	Typical Gain	Implemented at
STC	DL	3-5dB	BS
Antenna Switching	DL	2dB	CPE
MRC	UL	5dB	BS

Table 1 – Summary of Diversity Schemes

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Smart Antenna Systems (SAS)

SAS combine antenna arrays with sophisticated signal processing to enhance SNR for higher throughput and link robustness while simultaneously reducing interference. Beamforming is an example of SAS. When receiving a signal, beamforming can increase the gain in the direction of wanted signals and decrease the gain in the direction of interference and noise. When transmitting a signal, beamforming can increase the gain in the direction the signal is to be sent and direct nulls at users that would otherwise be iterfered with.

SAS typically delivers a +10 to 15 dB link budget improvement relative to a single antenna architecture. In the mobile WiMAX application, its active interference management can push the achievable net spectral efficiency into the 4-5bps/Hz range. SAS alone on the BS side provides operators wnith significant range benefits in the initial stages of network operation, and as their subscriber base grows and the network becomes interference limited, SAS can provide significant capacity benefits, especially when used in combination with spatial multiplexing techniques. SAS interference mitigation benefits start to diminish as subscriber mobility increases.

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Multiple Input Multiple Output (MIMO) Systems

Multiple Tx/Rx chains and antennas in the base stations is now a well-established technique. Technological advances in high scale integration are making multiple Tx/Rx chains and antennas also economically viable for the mobile and stationary subscriber stations. The WiMAX Forum Mobility Task Group (MTG) defined profile specifies two MIMO versions called Matrix A MIMO and Matrix B MIMO. The IEEE 802.16 standard defines other MIMO classes, for example Matrix C MIMO, which may be adopted by the WiMAX Forum in future profiles. In this paper we will concentrate on describing Matrix A MIMO and Matrix B MIMO.

In MIMO systems Multiple Input and Multiple Output are defined in relation to the channel. Two or more Tx antennas input multiple inputs into the channel and two or more Rx antennas extract outputs from the channel.

Matrix A MIMO

Matrix A MIMO implements the rate 1 Space-Time Coding scheme (commonly known as the Alamouti Code). This technique captures diversity gains by sending a single data stream in two parts out of two antennas, interleaved with transformed/conjugated versions of the same information, so that the receiver has higher probability of successfully extracting the desired signal. Matrix A achieves a spatial diversity order of two, but does not set out to achieve combining, interference mitigation, or spatial multiplexing gains.

Matrix A MIMO delivers higher link robustness, reducing fade margin by 5 to 6 dB, with little or no degradation as subscriber mobility increases. The impact on end-user data rate is small; reduced fade margin may allow the use of marginally higher order of modulation, but it is not comparable to the 2x throughput gain achieved by comparable Matrix B MIMO through spatial multiplexing. Matrix A MIMO is useful in networks with light loading and relatively high subscriber mobility.

We will now look at how Matrix A MIMO works in a little more detail.

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Consider a Matrix A MIMO system, consisting of 2 Transmit and 2 Receive antennas as depicted in Figure 3 below.

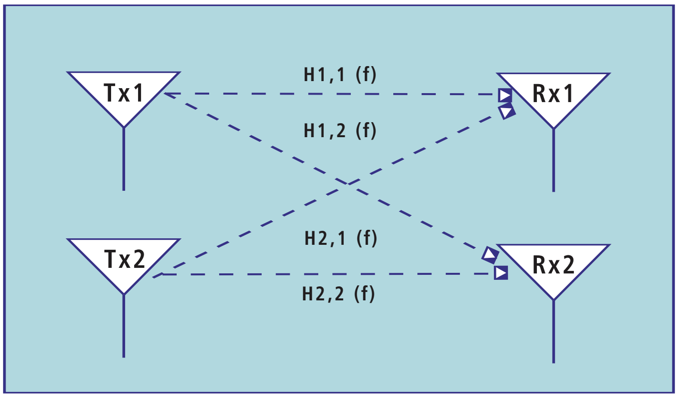


Figure 3 – 2 x 2 Matrix A MIMO Operation

The signal received by one of the antennas at the receiver is a mixture of the signals transmitted from both of the transmit antennas. The receive signals can be expressed by the following simplified equations:

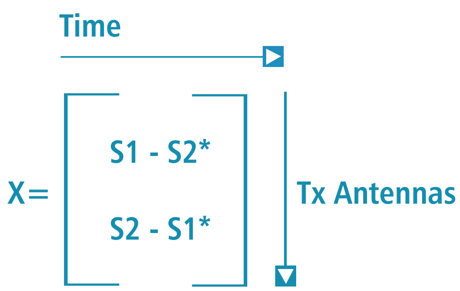
Rx1(f) = (H1,1(f) x Tx1) + (H2,1(f) x Tx2)

Rx2(f) = (H1,2(f) x Tx1) + (H2,2(f) x Tx2)

The receiver sees a combination of the transmissions from the two transmit antennas and needs to recover the actual transmitted signals. MIMO systems achieve this by using coding schemes that define which signal should be transmitted and when in order to make it possible to recover the original signal. These coding schemes are called 'Space-Time' codes because they define a code across both space (antenna separation) and time (symbols).

Matrix A MIMO is a Space-Time Block Code, so called because the code operates over a block of data. Block codes require less processing power to decode than convolutional codes.

The following matrix defines how the code works:



X is the output of the encoder and S1 and S2 are the input symbols into the encoder. '*' denotes a complex conjugate of the symbol. The rows of the matrix represent the transmit antennas and the columns represent time. Each element

of the matrix indicates which symbol is to be transmitted from which antenna and when.

Figure 4 gives a pictorial representation of how this matrix works.

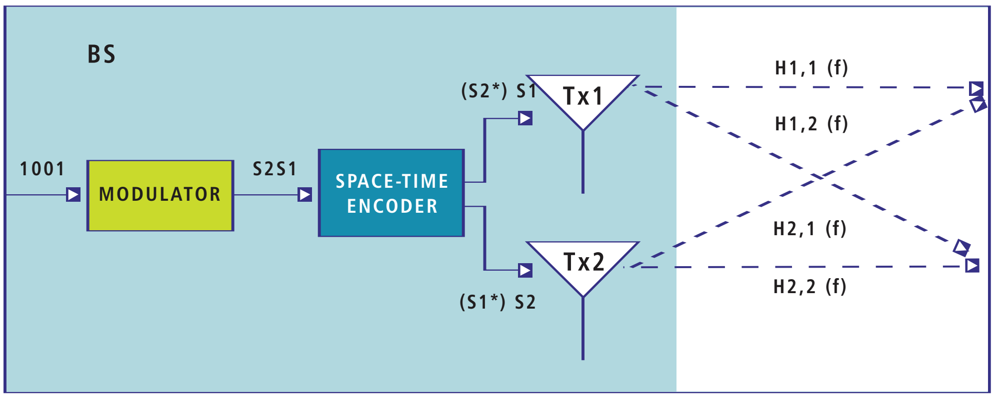


Figure 4 - Matrix A MIMO Tx Module

On the left hand side the binary bits enter a modulator, which converts binary bits into "symbols" according to the modulation scheme. These complex symbols are then fed into the Encoder, which maps the symbols onto the transmit antennas according to the matrix above.

The code works with a pair of symbols at a time and it takes two time periods to transmit the two symbols. Therefore it has the same rate as the data stream that enters the encoder but the error performance of the system is improved due to the coded information transmitted by the system.

In systems with high SNR performance, the improvement in the error rate achieved as a result of using Space-Time codes could be traded for higher capacity by using a higher order modulation than would otherwise be the case, resulting in marginal increases in throughput.

Matrix B MIMO

For channels with a rich multipath environment it is possible to increase the data rate by transmitting separate information streams on each antenna in the DL direction. Using sophisticated receiver technology, the different streams can be separated and decoded. For example, using 2 transmit and 2 receive Tx/Rx chains (and the associated antennas), up to twice the capacity of a single antenna system can be achieved. This is particularly useful in urban deployments where long reach is less important than high data rate at the end user device. In WiMAX, spatial multiplexing on the downlink is made possible using the Matrix B MIMO.

The following matrix defines how the code works:

$$X = \begin{bmatrix} S1 \\ S2 \end{bmatrix} \Big\downarrow \text{Tx Antennas}$$

X is the output of the encoder and S1, S2 are the input symbols into the encoder. The row of the matrix represent the transmit antennas; there is no time element because Matrix B MIMO operates over a single time interval. Each element of the matrix indicates which symbol is to be transmitted from which antenna. In this system 2 symbols are transmitted in a 1-symbol time duration thus providing a two-fold capacity increase.

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Figure 5 depicts the operation of a Matrix B MIMO system.

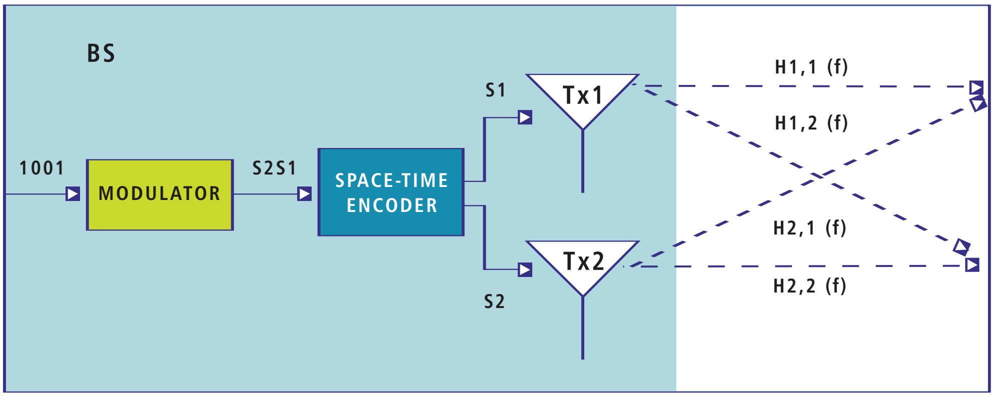

Figure 5 – Matrix B MIMO Tx Module

The theoretical upper band of capacity increases achieved by Matrix B MIMO is roughly proportional to the number of Tx/Rx chains used. A 4x4 system will have up to 4 times the capacity of a single antenna system.

Therefore, the capacity gain delivered by Matrix B MIMO linearly depends on the number of Tx and RX antennas and can be expressed as

X = min (Tx Antennas, Rx Antennas)

However, the number of Tx/Rx chains and antennas that can be used in the mobile subscriber (MS) devices are likely to be the limiting factor for the foreseeable future.

Airspan's HiperMAX base stations and first "Wave 2" mobile device, called the 16eUSB supports both Matrix A and Matrix B downlink MIMO. HiperMAX base stations support 2 or 4 transmit antennas whereas the 16eUSB supports 2 receive antennas. Therefore, Airspan products will initially support 2x2 and 4x2 MIMO implementations.

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Figure 6 depicts the Airspan 16eUSB device, which has been designed to provide instant mobile WiMAX capability to any mobile or desktop PC with a USB 2.0 compatible port.

Figure 6 – Airspan's 16eUSB Mobile WiMAX Device

Adaptive MIMO Systems

Adaptive MIMO or Adaptive MIMO Switching systems enable switching between different MIMO modes in order to maximise spectral efficiency and throughput without compromising coverage or error rate performance. The system parameters such as adaptive coding and modulation techniques are dynamically optimised to keep adapting to the ever-changing wireless channel conditions with the aim of maximising channel resources at all times.

Conclusions

The underlying WiMAX PHY is ideally suited to multipath operations in demanding mobile and fixed WiMAX deployment scenarios. One of the strengths of the WiMAX PHY is the ease with which it supports and cooperates with multiple antenna technologies.

Multiple antenna systems are being implemented in both Airspan's Base Station and Subscriber / Mobile Stations. Increasingly the WiMAX technology will be integrated into portable devices such as laptops and PDAs, in just the same way as Wi-Fi has been, which will then define the technology available at the portable device level, leaving the functional and performance differentiation to take place at the Base Station.

The performance improvements promised by MIMO, and later beamforming in WiMAX deployment scenarios are essential components for the delivery of true broadband services. MIMO equipment is already being deployed in the Wi-Fi market for IEEE802.11n products and has demonstrated massive increases in capacity.

Clearly the environment represented by WiMAX is quite different from that of Wi-Fi and interference management is a key concern for WiMAX. This is where Airspan will combine together the relative merits of the MIMO and beamforming technologies in the same system implementation to deliver the highly desirable dual goals of high system throughput and interference management.