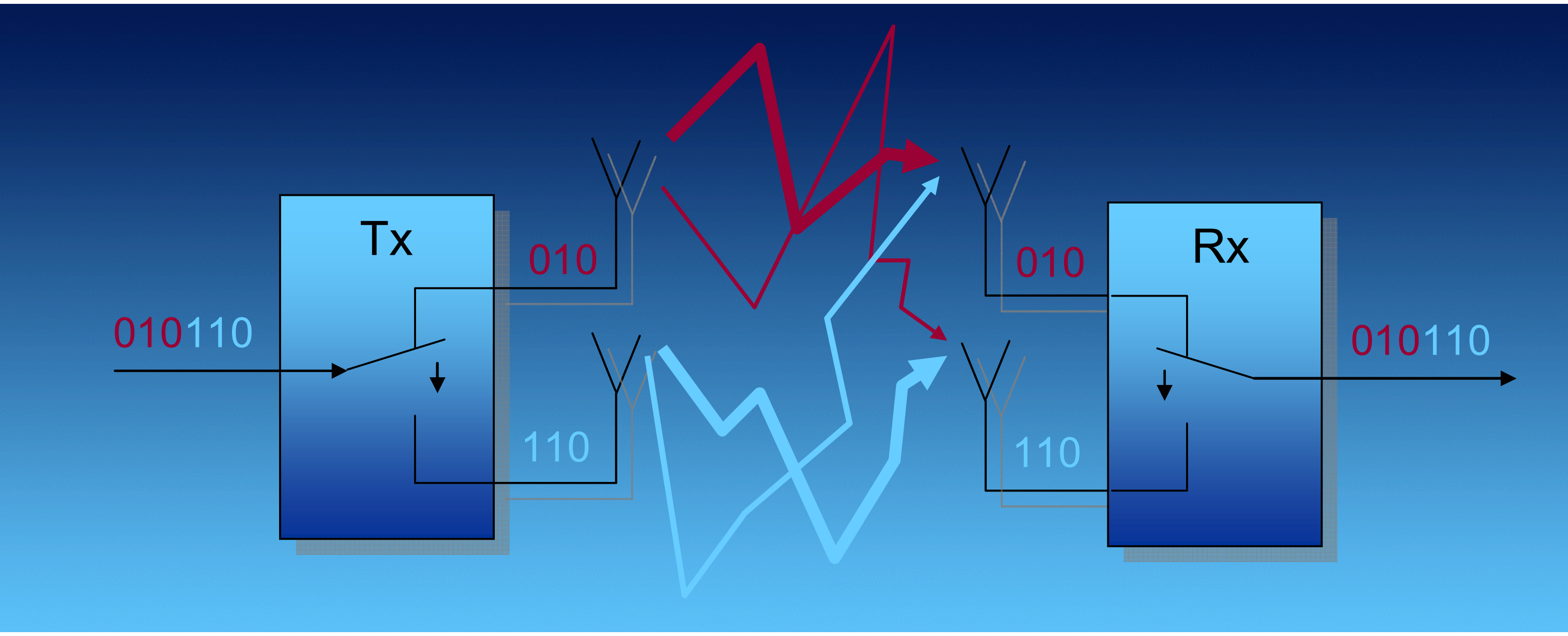


Introduction to MIMO Systems

Application Note 1MA102

The demand for higher network capacity and for higher performance of wireless networks is not breakable. MIMO Systems are able to improve the spectral efficiency significantly, and consequently MIMO will play a key role in many future wireless communication systems. This application note gives an overview of the principles of MIMO Systems and the standardization of these.

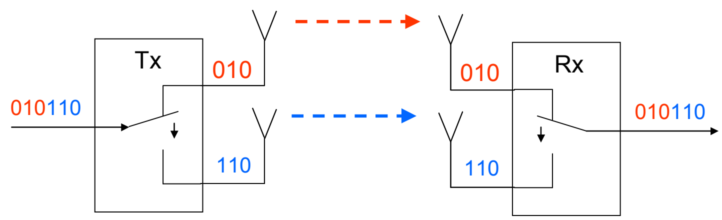
ROHDE & SCHWARZ

Subject to change – S. Schindler, 06/06 – 1MA102_0E

Contents

1 Introduction

In the last few years wireless services have become more and more important. Likewise the demand for higher network capacity and performance has been increased. Several options like higher bandwidth, optimized modulation or even code-multiplex systems offer practically limited potential to increase the spectral efficiency. MIMO (Multiple Input Multiple Output) Systems utilize space-multiplex by using antenna arrays to enhance the efficiency in the used bandwidth.



MIMO systems use multiple inputs and multiple outputs from a single channel. These systems are defined by Spatial Diversity and Spatial Multiplexing. Spatial Diversity is known as Rx- and Tx-Diversity. Signal copies are transferred from another antenna or received at more than one antenna. With Spatial Multiplexing the system is able to carry more than one spatial data stream over one frequency simultaneously.

MIMO was established in IEEE 802.11n, 802.16-2004 and 802.16e as well as in 3GPP. Chapter 7 will discuss the most important features of all the above defined specifications. Further standards which include MIMO are IEEE 802.20 and 802.22.

This application note gives an overview of the principles of MIMO Systems and the standardization of these. It assumes basic knowledge in WCDMA, OFDM and antenna arrays.

2 The MIMO Channel

Non-MIMO Systems are linked over multiple channels by several frequencies. The MIMO channel has multiple links and operates on the same frequency. The challenge of this technology is the separation and the equalization of all the signal paths. The channel model includes the matrix **H** with the direct and the indirect channel components. The direct components (e.g. $h_{11)}$ represent the channel flatness whereas the indirect components (e.g. h_{21}) stand for the channel isolation. The sent signal is represented by *s* and the received signal is *r*. A time-invariant and narrow-band channel is assumed.

$$r = \mathbf{H}s + n$$

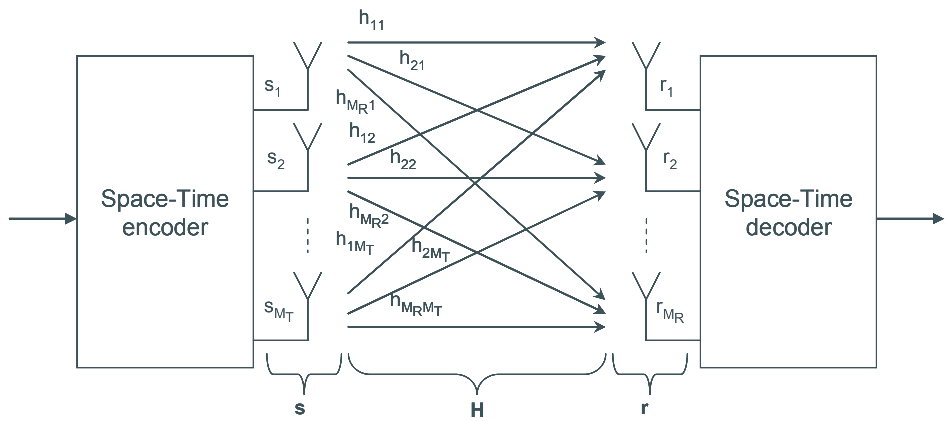


Figure 1 the physical MIMO channel

The knowledge of **H** is essential for decoding and is estimated through a known training-sequence. If the receiver sends the channel approximation to the transmitter it can be used for pre-coding. Pre-coding additionally improves the MIMO performances.

Claude Elwood Shannon developed the following equation for the theoretical channel capacity:

$$C_{SISO} = f_g \log_2\left(1+\frac{S}{N}\right)$$

It includes the transmission bandwidth f_g and the signal-to-noise ratio. Most channel capacity improvements are based on bandwidth extensions or other modulations. The spectral efficiency can not be significantly enhanced by these factors. The Shannon capacity of MIMO Systems additionally depends on the number of antennas. M is the minimum of M_T (number of transmitting antennas) or M_R (number of receiving antennas) and represents the number of spatial streams. For example, a 2x3 system can only support two spatial streams, which is also true for a a 2x4 system.

For MIMO the capacity is given by the following equation:

$$C_{MIMO} = Mf_g \log_2\left(1+\frac{S}{N}\right)$$

The MIMO capacity increases linearly with the number of antennas. Non-symmetric antenna constellations (e.g. 1x2 or 2x1) are referred to as Receive- or Transmit-Diversity (see chapter 4). In these cases the capacity $C_{Tx/Rx}$ grows logarithmically with the number of antennas.

$$C_{Tx/Rx} = f_g \log_2\left(1+M\left(\frac{S}{N}\right)\right)$$

3 Spatial Multiplexing

The transmission of multiple data streams over more than one antenna is called Spatial Multiplexing. There are two types, which have to be taken into account.

The first type is V-BLAST (Vertical Bell Laboratories Layered Space-Time), which transmits spatial un-coded data streams without any consideration in equalizing the signal at the receiver.

The second one is realized by Space-Time Codes. In contrast to V-BLAST, Space-Time Codes deliver orthogonal and thereby independent data streams. The V-BLAST method is not able to separate the streams so that multi-stream interferences (MSI) can appear. That makes the transmission unsteady and forward error coding is not always able to resolve this issue. The detection of a space-time-coded signal is based on a simple linear process and achieves reasonable results.

The advantage of Spatial Multiplexing is a linear capacity gain in relation to the number of transmit antennas.

4 Spatial Diversity

Spatial Multiplexing can provide a higher capacity but no better signal quality. Instead of improving signal quality, Spatial Multiplexing decreases it. Spatial Diversity improves the signal quality and achieves a higher signal-to-noise ratio at the receiver-side. Especially in extensive network areas, Spatial Multiplexing is pushed to its limits. The larger the network environment is, the higher the signal strength has to be.

The principle of diversity relies on the transmission of structured redundancy. This redundancy can be transmitted at any time, from any antenna, over any frequency or at any polarization. However, the latter method has not been considered in MIMO Technologies so far.

Two kinds of Spatial Diversity have to be considered:

- Tx-Diversity, here a signal copy is transmitted from another antenna (e.g. 2x1)
- Rx-Diversity, here the received signal is multiple evaluated (e.g. 2x1)

The first kind is comparable to mono- and stereo signals. The human is able to sense a tone better if it is in the form of a stereo signal. The second type of diversity is similar to two ears, which hear better than just one.

To utilize Tx- Diversity the so called Alamouti Space-Time Code (see figure 3) can be applied. It achieves full diversity and works with one receiving antenna. Rx- Diversity can be used through more receiving antennas than transmitting antennas and a proper combining algorithm. Switched Combining or Maximum Ration Combining are two examples of algorithms. These work independently of the type of diversity if the channel matrix is known.

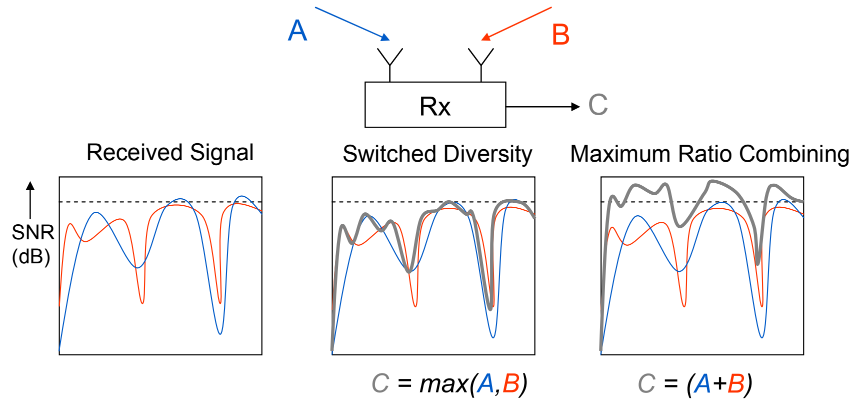


Figure 2 Receiver algorithms for Spatial Diversity, A and B are the same signal

The optimal performance and coverage of a wireless communication system can be reached by Spatial Multiplexing in the near field and Spatial Diversity in the far field.

Space-Time Codes

Space-Time Codes additionally improve the performance and make Spatial Diversity useable. The signal copy is not only transmitted from another antenna but also at another time. This delayed transmission is called Delayed Diversity. Space-Time Codes combine spatial and temporal signal copies like in figure 3. The signals s_1 and s_2 are multiplexed in two data chains. After that a signal replication is added to create the Alamouti Space-Time Block Code.

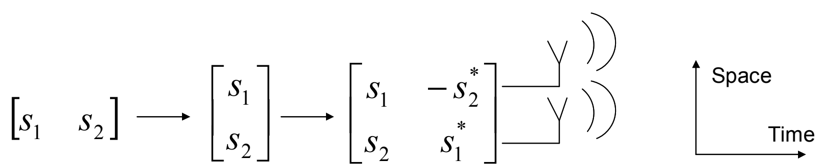


Figure 3 The Alamouti Space-Time Block Code for 2 Tx antennas

Space-Time Codes can be designed in two different ways.

- Space-Time Block Code or STBC (2 transmit antennas = Alamouti Code, see figure 3)
- Space-Time Trellis Code or STTC created by a FSM (Final State Machine)

The first code is the easiest way to achieve Spatial Diversity and is widely used. The second code is more complex and expensive nowadays.

For more than two antennas there are several Pseudo-Alamouti Codes shown in Figure 4.

$$S_{32} = \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \\ s_3 & s_4 \end{bmatrix} \quad S_{42} = \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \\ s_3 & s_4^* \\ s_4 & s_3^* \end{bmatrix} \quad S_{43} = \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \\ s_3 & s_4 \\ s_5 & s_6 \end{bmatrix}$$

Figure 4 Composite Alamouti Code for more than 2 transmit antennas

The index of the Codes above relates firstly to the number of antennas and secondly to the number of spatial data streams. Apart from S_{42} these do no achieve full diversity and four data streams can only be realized by Spatial Multiplexing without any Spatial Diversity.

$$S_{33} = \begin{bmatrix} s_1 & -s_2 & -s_3 & -s_4 & s_1^* & -s_2^* & -s_3^* & -s_4^* \\ s_2 & s_1 & s_4 & -s_3 & s_2^* & s_1^* & s_4^* & -s_3^* \\ s_3 & s_4 & s_1 & -s_2 & s_3^* & s_4^* & s_1^* & -s_2^* \end{bmatrix}$$

Figure 5 Space-Time Block Code for 3 Tx antennas [3]

The code in figure 5 is based on a real Space-Time Block Code design and generates full diversity with full Spatial Multiplexing. The problem with this code is the code rate. The code rate is the rate of used signals and the time needed for transmission. The upper code has a code rate of 1/2.

Vahid Tarokh [3] developed an optimized Space-Time Block Code to increase the code rate to 3/4. This Quasi-Orthogonal STBC (see Figure 6) is efficient but permits some Inter-Symbol-Interferences (ISI). Despite this, the bit error rate (BER) is still within the tolerance range. None of thess codes are able to achieve full code rate like Alamouti.

$$S_{33} = \begin{bmatrix} s_1 & -s_2^* & \frac{s_3^*}{\sqrt{2}} & \frac{s_3^*}{\sqrt{2}} \\ s_2 & s_1^* & \frac{s_3^*}{\sqrt{2}} & -\frac{s_3^*}{\sqrt{2}} \\ \frac{s_3}{\sqrt{2}} & \frac{s_3}{\sqrt{2}} & \frac{\left(-s_1 - s_1^* + s_2 - s_2^*\right)}{2} & \frac{\left(s_1 + s_1^* + s_2 - s_2^*\right)}{2} \end{bmatrix}$$

Figure 6 Optimized Space-Time Block Code for 3 Tx antennas [3]

The number of spatial data streams can not be more than the number of existing antennas. Note that the trade-off between Spatial Diversity and Spatial Multiplexing is important for reliable and powerful MIMO Systems.

In some cases the term Macro Diversity appears. This kind of diversity can be used in MIMO systems but is not associated with these. Macro Diversity is applied in the handover process if the terminal is simultaneously connected to more than one base station. The user terminal receives the same signal from more than one direction and combines all signals to get a higher SNR. [1][2]

5 Antenna Systems

Antenna technologies are the key in increasing the network capacity. It started with sectorized antennas. These antennas illuminate 60 or 120 degrees and operate as one cell. In GSM the capacity can be trebled, by 120 degree antennas. Adaptive antenna arrays intensify spatial multiplexing using narrow beams. Smart Antennas belong to adaptive antenna arrays but differ in its smart DoA (Direction of Arrival) estimation. Independent of any supported feedback and transparent to the user terminal, Smart Antennas can form a user-specific beam. Optional feedback can reduce complexity of the array system. MIMO Systems normally require feedback and are not transparent to the user.

Beamforming is the method used to create the radiation pattern of an antenna array. It can be applied in all antenna array systems as well as MIMO Systems

Smart Antennas are divided into two groups:

- Phased Array Systems (Switched Beamforming) with a finite number of fixed predefined patterns
- Adaptive Array Systems (AAS) (Adaptive Beamforming) with an infinite number of patterns adjusted to the scenario in real time

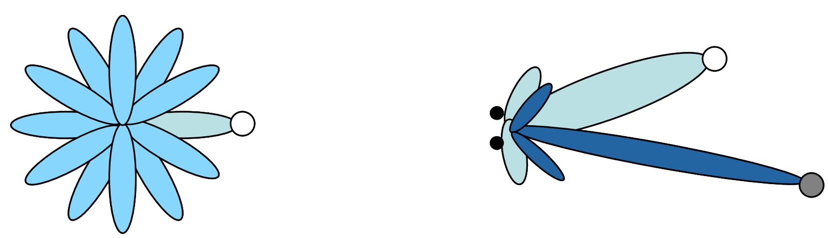


Figure 7 Switched Beamformer and Adaptive Beamformer

Switched Beamformers electrically calculate the DoA and switch on the fixed beam. If the user is moving across these fixed beams, signal jitter can cause interruption. In other words, the user only has the optimal signal strength along the centre of the beam.The Adaptive Beamformer deals with that problem and adjusts the beam in real-time to the moving terminal. The complexity and the cost of such a system is higher than the first type.

6 MIMO and OFDM

MIMO is applicable to all kinds of wireless communication technologies. However, the combination of MIMO and OFDM (Orthogonal Frequency Division Multiplex) has the following advantages.

OFDM is adapted for multi-path propagation in wireless systems. The length of the OFDM-frames is determined by the Guard Interval (GI). This Gurad Interval restricts the maximum path delay and therefore the expansion of the network area. MIMO also uses the multi-path propagation.

OFDM is a wideband system with many narrowband sub-carriers. The mathematical MIMO channel model (see chapter 2) is based on a narrow band non-frequency selective channel. The latter is supported by OFDM as well. Fading effects in wideband systems normally occur only at particular frequencies and interfere with few sub-carriers. The data is spread over all carriers, so that only a small amount of bits get lost, and these can be repaired by a forward error correction (FEC). OFDM provides a robust multi-path system suitable for MIMO. At the same time OFDM provides high spectral efficiency and a degree of freedom in spreading the time dimension of Space-Time Block Codes over several sub-carriers. This results in a stronger system based on the principle described previously.

MIMO Standards

Table 1 gives an overview of all current MIMO standards and their technologies. It is clear to see, that with the exception of 3GPP Release 7, all standards work with OFDM. The advantages of OFDM can obviously be linked to MIMO.

Standard	**Technology**
WLAN 802.11n	OFDM
WiMAX 802.16-2004	OFDM/OFDMA
WiMAX 802.16e	OFDMA
3GPP Release 7	WCDMA
3GPP Release 8 (LTE)	OFDMA
802.20	OFDM
802.22	OFDM

Table 1 MIMO Standards and the corresponding technology

7 Standardization

A review of standardization is important to get an overview as to which of the possible theoretical technologies are actually applied. This chapter will discuss all standards which include MIMO and their main key facts.

WLAN IEEE 802.11n

IEEE is an American organization, which adopted the first WLAN version in 1997. After that, many extensions and new standards followed. Table 2 is an outline of all WLAN standards and it classifies the 802.11n.

WLAN Standard	Definition date	Frequency band	Rate “over the air”	Rate MAC Layer
802.11	1997	2.4 GHz	2 Mbps	2 Mbps
802.11a	1999	5 GHz	54 Mbps	25 Mbps
802.11b	1999	2.4 GHz	11 Mbps	5 Mbps
802.11g	2003	2.4 GHz	54 Mbps	25 Mbps
802.11n	End of 2006	2.4 & 5 GHz	< 600 Mbps	< 200 Mbps

Table 2 IEEE WLAN Standards

Apart from MIMO, this 802.11n WLAN Standard has several new features, which provide a higher level of performance. The first feature is a bandwidth extension from 20 MHz to 40 MHz and 4 more data carriers in the 20 MHz mode. This results in difficulties in the 2.4 GHz band, with only 3 non-overlapping 20 MHz-channels. Within the 5 GHz band there are 12 non-overlapping channels and consequently a higher degree of freedom. The next point is the modified FEC (Forward Error Correction) code rate to 5/6, which means up to 10 percent higher rates in contrast to the legacy code rate of 3/4. It can be adapted by 76 MCS (Modulation and Coding Schemes). To optimize the MAC-Layer efficiency, Packet Bursting and Frame Aggregation are introduced. This unsocial approach to reduce the frame over-head leads to some incompatibilities with regard to the old 802.11 gear.

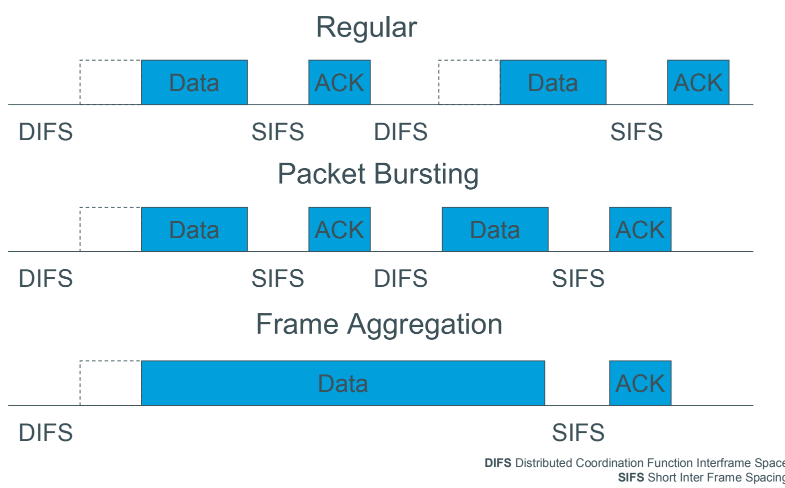


Figure 8 Methods to optimize frame over-head

Furthermore the OFDM frame structure is modified. In 802.11n the Guard Interval (GI) is reduced from 800 ns to 400 ns. Consequently, the maximum coverage is reduced but the transfer rate speeds up to approximately 10 percent.

The WLAN standard provides up to four spatial data streams and thus up to a fourfold bit rate. It should be noted that up to three streams can be transmitted by applying Space-Time Codes. Four data steams are supported by Spatial Multiplexing (see chapter 3). The codes are similar to figure 3 and figure 4. [4]

WiMAX IEEE 802.16-2004

WiMAX was created to deliver Broadband Wireless Access (BWA) in metropolitan areas. The working group of IEEE finalized the WiMAX standard of fixed access on the 1st October 2004. It includes all prior standards. Table 3 shows the history of all standards.

WMAN Standard	Definition date	Frequency band	Comments
802.16	2002	10-66 GHz	
802.16a	2003	2-11GHz	
802.16b	2003	5-6 GHz	WirelessHUMAN
802.16c	2003	10-66 GHz	WirelessMAN SC
802.16d	2003	2-11 GHz	
802.16-2004	2004	2-66 GHz	Sum of all above
802.16e	2005	2-11 GHz	Mobile extension

Table 3 IEEE WiMAX Standards

The standard for wireless fixed connections is called 802.16-2004 and is seen as an alternative approach to a wired DSL service. That standard is specified for 2 to 66 GHz whereby the licensed frequencies around 2.5 GHz and 3.5 GHz and the unlicensed frequencies around 5.2 GHz and 5.8 GHz are actually used.

802.16-2004 includes five sub-standards (named Air Interface) as follows:

- WirelessMAN SC (Single Carrier, without NLOS component)
- WirelessMAN SCa (Single Carrier, with NLOS component)
- WirelessMAN OFDM
- WirelessMAN OFDMA
- WirelessHUMAN (Wireless High-speed Unlicensed MAN)

The Air Interface WirelessMAN OFDM includes Transmit Diversity but no MIMO functionality. MIMO is established in WirelessMAN OFDMA with up to four antennas. Whereas just one and two data streams use Space-Time Codes, adapted from the Alamouti Code, four streams are realized by spatial un-coded Spatial Multiplexing.

The bandwidth within fixed WiMAX can vary between 1.75 to 10 MHz in the OFDM Air Interface and from 1.25 to 28 MHz in the OFDMA Air Interface. In Single Carrier operation WiMAX 802.16-2004 defines 256QAM, otherwise 64QAM is used. The FEC code rate of 7/8 is supported as well and provides an additional gain of 5 percent relating to 5/6 in WLAN 802.11n. Virtual Antenna is a new WiMAX feature, which enables MIMO in the uplink. The principle does not require terminals with more than one antenna. Spatial Multiplexing is achieved by two users sending one spatial stream each along the same frequency. [8]

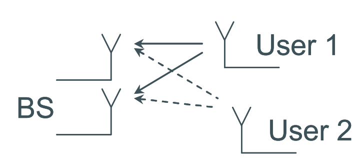


Figure 9 Principle of Virtual Antennas

WiMAX IEEE 802.16e

WiMAX 802.16e is the latest development, which makes mobile WiMAX access possible. In December 2005 three Air Interfaces were determined.

- WirelessMAN SCa
- WirelessMAN OFDM
- WirelessMAN OFDMA

Only the OFDMA Air Interface offers MIMO functionality. One and two spatial streams operate with Space-Time Codes whereas three and four streams are transmitted spatial un-coded. The Space-Time Codes are based on Alamouti and for more than two antennas on compositions of it. The bandwidth is similar to the fixed standard and has a range of 1.25 MHz to 28 MHz. The code rate and the modulation are limited by 5/6 and 64QAM. 802.16e is able to hand over the user connection and offers macro diversity in combination with that. The maximum radial speed currently lies at approximately 60 km/h.

WiBRO is the Korean WiMAX pendant of 802.16e. WiBRO cover just one Air Interface:

- WirelessMAN OFDMA

Other characteristics are the restriction to the TDD mode and to the bandwidth of 10 MHz. The frequency range is limited at 11 GHz. [9]

3GPP Release 7

In UTRA (UMTS Terrestrial Radio Access) Release 7 was established, which will be functionally frozen in 2006. It is based on WCDMA and provides the typical bandwidth of 5 MHz. Alamouti Space-Time Codes will be used in antenna constellation of 2x1 or 4x2. The release 7 includes a TDD (Time Division Duplex) mode and a FDD (Frequency Division Duplex) ,ode. [5]

In the TDD mode the PARC (Per Antenna Rate Control) proposal will be used, which is similar to MCS (Modulation and Coding Scheme) in WLAN. It is able to adapt the modulation and the coding rate to the quality of the channel. There are four coding schemes consisting of QPSK and 16QAM as well as a FEC code rate of 1/2 and 3/4. In total PARC is able to provide four data streams. [6]

The latter mode uses the D-TxAA (Double Transmit Antenna Array) proposal which is based on the STTD (Space-Time Transmit Diversity) principle defined in Release 99. It can be seen as a twofold Transmit Diversity chain. Each chain can be rate-controlled similar to PARC depending on the channel feedback. Additionally D-TxAA provides a weighting considering the CQI. [7]

3GPP Release 8 (LTE)

This release is also known as “Long Term Evolution” and relate to E-UTRA (Evolved UTRA). The standardization process has only released high-level principles, such as the agreement to use OFDMA in the downlink and SC-FDMA (Single Carrier FDMA) in the uplink. The single carrier transmission has the advantage of a small Crest-Factor, whereby cheaper terminal amplifiers can be used.

The bandwidths shall lie between 1.25 MHz and 20 MHz with 16QAM being applied. The MIMO antenna constellations will be initially 2x2 and later 4x4. Space-Time Codes will be used. [10]

IEEE 802.20 and IEEE 802.22

These standards are still under definition. MIMO and some high-level principles have been decided and only a few details have been published so far.

8 Conclusion

Space-Time Codes are an important part of MIMO Systems. These allow profitable usage. The Alamouti Code is currently the most deployed Space-Time Code. Other Codes will be available if higher computing performance becomes available.

MIMO is worthwhile with up to 4 spatial streams, which means a minimum of 4 antennas at Tx- or Rx-side.

Beamforming can be applied and leads to an additional improvement of the performance of MIMO systems. It is usually an optional feature for the standards.

The multiple antenna technology is especially applied for OFDM Systems and is part of many standards. MIMO will become an increasing key technology over the next years for increasing the channel capacity.

	Antenna constellation	Space-Time Code	Spatial Streams
IEEE 802.11n	2x2 later 4x4	Alamouti	3 with Alamouti, max. 4
IEEE 802.16-2004	2x1 later 4x4	Alamouti	2 with Alamouti, max. 4
IEEE 802.16e	2x1 later 4x4	Alamouti	2 with Alamouti, max. 4
3GPP Release 7	2x1 later 4x2	Alamouti	2 with Alamouti, max. 4
3GPP Release 8 (LTE)	2x2 later 4x4	n/a	n/a

9 Abbreviations

3GPP	3rd Generation Partnership Project
AAS	Adaptive Antenna Systems
DoA	Direction of Arrival
E-UTRA	Evolved UMTS Terrestrial Radio Access
FEC	Forward Error Correction
FDD	Frequency Division Duplex
FSM	Final State Machine
GI	Guard Interval
IEEE	Institute of Electrical and Electronics Engineers
ISI	Inter Symbol Inference
MAC	Medium Access Layer
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
MSI	Multi-stream interferences
NLOS	Non Line of Sight
OFDM	Orthogonal Frequency Division Multiplex
OFDMA	Orthogonal Frequency Division Multiple Access
SC	Single Carrier
SNR	Signal to Noise Ratio
STBC	Space-Time Block Code
STTC	Space-Time Trellis Code
TDD	Time Division Duplex
UTRA	UMTS Terrestrial Radio Access
V-BLAST	Vertical Bell Laboratories Layered Space-Time
WCDMA	Wideband Code Division Multiple Access
WMAN	Wireless Metropolitan Area Network
WiBRO	Wireless Broadband
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network

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[10] 3GPP TR 25.814 V1.2.2: “Physical Layer Aspects for Evolved UTRA (Release 7)”, (March 2006)

11 Additional Information

This application note is updated from time to time. Please visit the website **1MA102** in order to download new versions.

Please send any comments or suggestions about this application note to **TM-Applications@rsd.rohde-schwarz.com**.

12 Ordering information

Please note, that suitable instruments for various tests on MIMO systems are available from Rohde & Schwarz.

For additional information about signal generators, signal and spectrum analyzers, vector network analyzers and other measurement equipment, see the Rohde & Schwarz website **www.rohde-schwarz.com**.

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