Study Paper
on
Multiple-Input Multiple-Output (MIMO) Technology

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Multiple-Input Multiple-Output (MIMO) Technology

1. Introduction

Multiple-Input Multiple-Output (MIMO) technology is a wireless technology that uses multiple transmitters and receivers to transfer more data at the same time. MIMO technology takes advantage of a radio-wave phenomenon called multipath where transmitted information bounces off walls, ceilings, and other objects, reaching the receiving antenna multiple times via different angles and at slightly different times.

Figure-1 : MIMO Technology uses multiple radios to transfer more data at the same time

MIMO technology leverages multipath behavior by using multiple, “smart” transmitters and receivers with an added “spatial” dimension to dramatically increase performance and range. MIMO allows multiple antennas to send and receive multiple spatial streams at the same time.

MIMO makes antennas work smarter by enabling them to combine data streams arriving from different paths and at different times to effectively increase receiver signal-capturing power. Smart antennas use spatial diversity technology, which puts surplus antennas to good use. If there are more antennas than spatial streams, the additional antennas can add receiver diversity and increase range.

2. MIMO - Basics

As a result of the use of multiple antennas, MIMO wireless technology is able to considerably increase the capacity of a given channel. By increasing the number of receive and transmit antennas it is possible to linearly increase the throughput of the channel with every pair of antennas added to the system. This makes MIMO wireless technology one of the most important wireless techniques to be employed in recent years. As spectral bandwidth is becoming an ever more valuable commodity for radio communications systems, techniques are needed to use the available bandwidth more effectively. MIMO wireless technology is one of these techniques.

2.1 MIMO - SISO

The simplest form of radio link can be defined in MIMO terms as SISO - Single Input Single Output. This is effectively a standard radio channel - this transmitter operates with one antenna as does the receiver. There is no diversity and no additional processing required.

Figure-2 : SISO - Single Input Single Output

The advantage of a SISO system is its simplicity. SISO requires no processing in terms of the various forms of diversity that may be used. However the SISO channel is limited in its performance as interference and fading will impact the system more than a MIMO system using some form of diversity. The throughput depends upon the channel bandwidth and the signal to noise ratio.

2.2 MIMO - SIMO

The SIMO or Single Input Multiple Output version of MIMO occurs where the transmitter has a single antenna and the receiver has multiple antennas. This is also known as receive diversity. It is often used to enable a receiver system that receives signals from a number of independent sources to combat the effects of fading. It has been used for many years with short wave listening / receiving stations to combat the effects of ionospheric fading and interference.

Figure-3 : SIMO - Single Input Multiple Output

SIMO has the advantage that it is relatively easy to implement although it does have some disadvantages in that the processing is required in the receiver. The use of SIMO may be quite acceptable in many applications, but where the receiver is located in a mobile device such as a cellphone handset, the levels of processing may be limited by size, cost and battery drain.
There are two forms of SIMO that can be used:

- ***Switched diversity SIMO:*** This form of SIMO looks for the strongest signal and switches to that antenna.

- ***Maximum ratio combining SIMO:*** This form of SIMO takes both signals and sums them to give the a combination. In this way, the signals from both antennas contribute to the overall signal.

2.3 MIMO - MISO

Multiple Input Single Output (MISO) is also termed transmit diversity. In this case, the same data is transmitted redundantly from the two transmitter antennas. The receiver is then able to receive the optimum signal which it can then use to receive extract the required data.

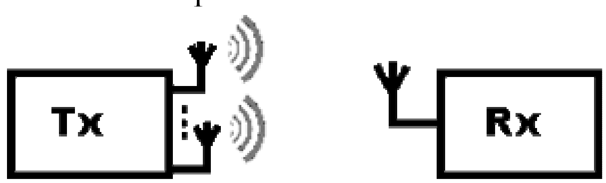


Figure-4 : MISO - Multiple Input Single Output

The advantage of using MISO is that the multiple antennas and the redundancy coding / processing is moved from the receiver to the transmitter. In instances such as cellphone UEs, this can be a significant advantage in terms of space for the antennas and reducing the level of processing required in the receiver for the redundancy coding. This has a positive impact on size, cost and battery life as the lower level of processing requires less battery consumption.

2.4 MIMO

MIMO is effectively a radio antenna technology as it uses multiple antennas at the transmitter and receiver to enable a variety of signal paths to carry the data, choosing separate paths for each antenna to enable multiple signal paths to be used.

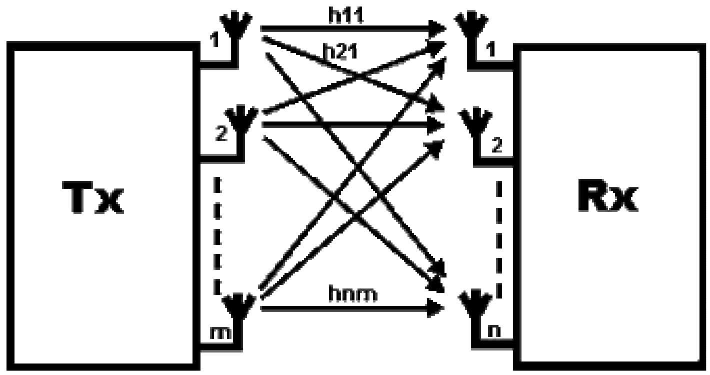


Figure-5 : MIMO - Multiple Input Multiple Output

One of the core ideas behind MIMO wireless systems space-time signal processing in which time is complemented with the spatial dimension inherent in the use of multiple spatially distributed antennas, i.e. the use of multiple antennas located at different points. Accordingly MIMO wireless systems can be viewed as a logical extension to the smart antennas that have been used for many years to improve wireless.

It is found between a transmitter and a receiver, the signal can take many paths. Additionally by moving the antennas even a small distance the paths used will change. The variety of paths available occurs as a result of the number of objects that appear to the side or even in the direct path between the transmitter and receiver. Previously these multiple paths only served to introduce interference. By using MIMO, these additional paths can be used to advantage. They can be used to provide additional robustness to the radio link by improving the signal to noise ratio, or by increasing the link data capacity.

The two main formats for MIMO are given below:

- ***Spatial diversity:*** Spatial diversity used in this narrower sense often refers to transmit and receive diversity. These two methodologies are used to provide improvements in the signal to noise ratio and they are characterised by improving the reliability of the system with respect to the various forms of fading.

- *Spatial multiplexing :* This form of MIMO is used to provide additional data capacity by utilising the different paths to carry additional traffic, i.e. increasing the data throughput capability.

One of the key advantages of MIMO spatial multiplexing is the fact that it is able to provide additional data capacity. MIMO spatial multiplexing achieves this by utilising the multiple paths and effectively using them as additional "channels" to carry data. The maximum amount of data that can be carried by a radio channel is limited by the physical boundaries defined under Shannon's Law.

Multiple-input, multiple-output (MIMO) antenna systems are used in modern wireless standards, including in IEEE 802.11n, 3GPP LTE, and mobile WiMAX systems. The technique supports enhanced data throughput even under conditions of interference, signal fading, and multipath. The demand for higher data rates over longer distances has been one of the primary motivations behind the development of MIMO orthogonal- frequency-division-multiplexing (OFDM) communications systems.

Shannon's law defines the maximum rate at which error free data can be transmitted over a given bandwidth in the presence of noise. It is usually expressed in the form:

$$\textbf{Capacity} = \textbf{BW} \log_2(1 + \textbf{SNR}) \qquad \text{---- Eq. 1}$$

Where C is the channel capacity in bits per second, BW is the bandwidth in Hertz, and SNR is Signal to Noise Ratio.

The above Eq. shows, an increase in a channel's SNR results in marginal gains in channel throughput. As a result, the traditional way to achieve higher data rates is by increasing the signal bandwidth. Unfortunately, increasing the signal bandwidth of a communications channel by increasing the symbol rate of a modulated carrier increases its susceptibility to multipath fading. For wide-bandwidth channels, one partial solution to solving the multipath challenge is to use a series of narrowband overlapping subcarriers. Not only does the use of overlapping OFDM subcarriers improve spectral efficiency, but the lower symbol rates used by narrowband subcarriers reduces the impact of multipath signal products.

MIMO communications channels provide an interesting solution to the multipath challenge by requiring multiple signal paths. In effect, MIMO systems use a combination of multiple antennas and multiple signal paths to gain knowledge of the communications channel. By using the spatial dimension of a communications link, MIMO systems can achieve significantly higher data rates than traditional single-input, single-output (SISO) channels. In a 2 x 2 MIMO system, signals propagate along multiple paths from the transmitter to the receiver antennas.

Using this channel knowledge, a receiver can recover independent streams from each of the transmitter's antennas. A 2 x 2 MIMO system produces two spatial streams to effectively double the maximum data rate of what might be achieved in a traditional 1 x 1 SISO communications channel.

The maximum channel capacity of a MIMO system, the channel capacity can be estimated as a function of N spatial streams. A basic approximation of MIMO channel capacity is a function of spatial streams, bandwidth, and signal-to-noise ratio (SNR) and is shown in the following Eq. :

Capacity = N BW $\log_2$ (1 + SNR) **--- Eq. 2**

Given the equation for MIMO channel capacity, it is possible to investigate the relationship between the number of spatial streams and the throughput of various implementations of SISO and MIMO configurations.

As an example, the IEEE 802.11g specs prescribe that a wireless-local-area-network (WLAN) channel uses a SISO configuration. With this standard, the maximum coded data rate of 54 Mb/s requires use of a 64-QAM modulation scheme and a code rate of 3/4. As a result, the uncoded bit rate is 72 Mb/s (4/3 x 54 Mb/s). With minimum transmitter error vector magnitude (EVM) at -25 dB, an SNR of 25 dB can be estimated as the requirement for a 64-state quadrature-amplitude-modulation (64QAM) scheme. While EVM and SNR are not equivalent in all cases, we can assume that the magnitude error of a symbol will dominate the signal error as the SNR approaches its lower limit.
The maximum data rate of IEEE 802.11g maps closely with the maximum channel capacity dictated by the Shannon- Hartley theorem. According to this theorem, a Gaussian channel with an SNR of 25 dB should produce an uncoded data rate of 94 Mb/s in a 20-MHz channel bandwidth.

By contrast, Eq. 2 would suggest that a MIMO channel with four spatial streams should be capable of four times the capacity of the SISO channel. 20-MHz channel with a signal-to-noise ratio (SNR) of 25 dB and four spatial streams should have an uncoded bit rate of 4 x 94 Mb/s = 376 Mb/s. This estimation maps closely with the expected data rates of the draft IEEE 802.11n physical layer specs. IEEE 802.11n is designed to support MIMO configurations with as many as four spatial streams. At the highest data rate, bursts using a 64QAM modulation scheme with a 5/6 channel code rate produce a data rate of 288.9

Mb/s and an uncoded bit rate of 346.68 Mb/s. At the highest data rate, the IEEE 802.11n channel with four spatial streams produces a data rate that is comparable to the theoretical limit of 376 Mb/s.

It can be observed that the bit rate of a 4 x 4 (four spatial stream) MIMO configuration exceeds that of the Shannon- Hartley limit at all data rates, making MIMO systems attractive for higher data throughput. While MIMO systems provide users with clear benefits at the application level, the design and test of MIMO devices is not without significant challenges.

3. Benefits Of MIMO Technology

(1) Multiple antenna configurations can be used to overcome the detrimental effects of multi-path and fading when trying to achieve high data throughput in limited-bandwidth channels.

Multiple-input, multiple-output (MIMO) antenna systems are used in modern wireless standards, including in IEEE 802.11n, 3GPP LTE, and mobile WiMAX systems. The technique supports enhanced data throughput even under conditions of interference, multi-path and fading. The demand for higher data rates over longer distances has been one of the primary motivations behind the development of MIMO orthogonal- frequency-division-multiplexing (OFDM) communications systems.

(2) Superior Data Rates, Range and Reliability

Systems with multiple antennas at the transmitter and receiver – also referred to as Multiple Input Multiple Output (MIMO) systems – offer superior data rates, range and reliability without requiring additional bandwidth or transmit power. By using several antennas at both the transmitter and receiver, MIMO systems create multiple independent channels for sending multiple data streams.

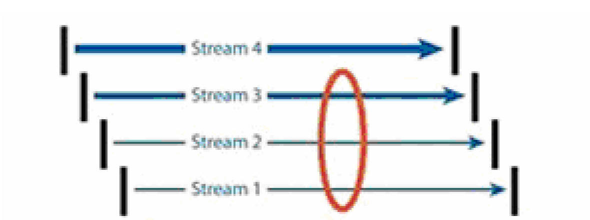


Figure-5 : Stream combining for enhanced reliability

4x4 MIMO system supports up to four independent data streams. These streams can be combined through dynamic digital beamforming and MIMO receiver processing (in the red oval) to increase reliability and range.

The number of independent channels and associated data streams that can be supported over a MIMO channel is equivalent to the minimum number of antennas at the transmitter or receiver. Thus, a 2x2 system can support at most two streams, a 3x3 system can support three streams and a 4x4 system can support four streams. Some of the independent streams can be combined through dynamic digital beamforming and MIMO receiver processing, as shown in the red oval, which results in increased reliability and range.

4. LTE MIMO Concepts

MIMO systems form an essential part of LTE in order to achieve the ambitious requirements for throughput and spectral efficiency. MIMO refers to the use of multiple antennas at transmitter and receiver side.

4.1 Downlink MIMO

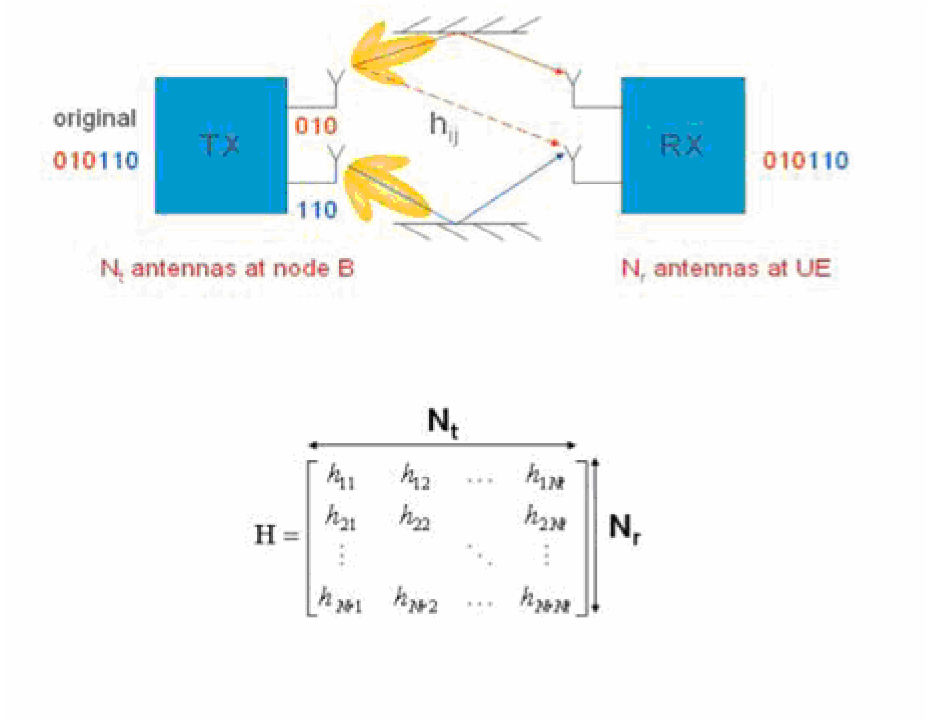
For the LTE downlink, a 2x2 configuration for MIMO is assumed as baseline configuration, i.e. 2 transmit antennas at the base station and 2 receive antennas at the terminal side. Configurations with 4 antennas are also being considered.

Different MIMO modes are envisaged. It has to be differentiated between spatial multiplexing and transmit diversity, and it depends on the channel condition which scheme to select.

4.1.1 Spatial Multiplexing

Spatial multiplexing allows to transmit different streams of data simultaneously on the same downlink resource block(s). These data streams can belong to one single user (single user MIMO / SU-MIMO) or to different users (multi user MIMO / MU-MIMO). While SU-MIMO increases the data rate of one user, MU-MIMO allows to increase the overall capacity. Spatial multiplexing is only possible if the mobile radio channel allows it.

Figure-6 shows the principle of spatial multiplexing, exploiting the spatial dimension of the radio channel which allows to transmit the different data streams simultaneously.



$$H = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1N_t} \\ h_{21} & h_{22} & & h_{2N_t} \\ \vdots & & \ddots & \vdots \\ h_{N_r1} & h_{N_r2} & \cdots & h_{N_rN_t} \end{bmatrix}$$

Figure -6 : Spatial multiplexing

Each transmit antenna transmits a different data stream. Each receive antenna may receive the data streams from all transmit antennas. The channel (for a specific delay) can thus be described by the following channel matrix H: As above figure.

In this general description, Nt is the number of transmit antennas, Nr is the number of receive antennas, resulting in a 2x2 matrix for the baseline LTE scenario. The coefficients hij of this matrix are called channel coefficients from transmit antenna i to receive antenna j, thus describing all possible paths between transmitter and receiver side. The number of data streams that can be transmitted in parallel over the MIMO channel is given by min {Nt, Nr} and is limited by the rank of the matrix H. The transmission quality degrades significantly in case the singular values of matrix H are not sufficiently strong. This can happen in case the 2 antennas are not sufficiently de-correlated, for example in an environment with little scattering or when antennas are too closely spaced. In LTE, up to 2 code words can be mapped onto different so-called layers. The number of layers for transmission is equal to the rank of the matrix H. There is a fixed mapping between code words to layers.

Figure-7 below describes how precoding on transmitter side is used to support spatial multiplexing. This is achieved by applying a precoding matrix W to the signal before transmission.

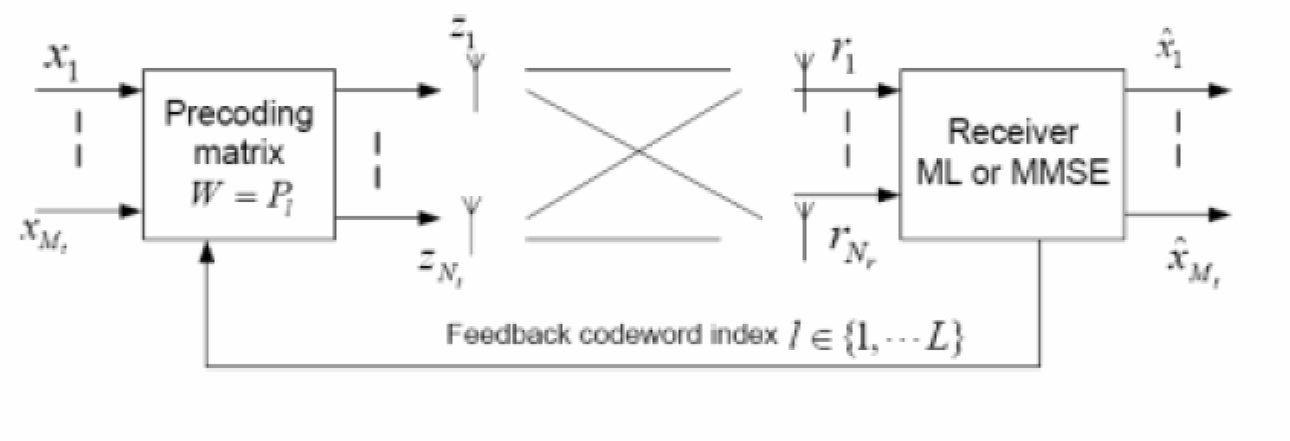


Figure-7 : Pre-coding principle

The optimum pre-coding matrix W is selected from a predefined "codebook" which is known at eNodeB and UE side. Unitary pre-coding is used, i.e. the precoding matrices are unitary: WHW= I. The UE estimates the radio channel and selects the optimum pre-coding matrix. The optimum pre-coding matrix is the one which offers maximum capacity. The UE provides feedback on the uplink control channel regarding the preferred pre-coding matrix (pre-coding vector as a special case). Ideally, this information is made available per resource block or at least group of resource blocks, since the optimum pre-coding matrix varies between resource blocks.

4.1.2 Transmit Diversity

Instead of increasing data rate or capacity, MIMO can be used to exploit diversity. Transmit diversity schemes are already known from WCDMA release 99 and will also form part of LTE as one MIMO mode. In case the channel conditions do not allow spatial multiplexing, a transmit diversity scheme will be used instead, so switching between these two MIMO modes is possible depending on channel conditions. Transmit diversity is used when the selected number of streams (rank) is one.

4.2 Uplink MIMO

Uplink MIMO schemes for LTE will differ from downlink MIMO schemes to take into account terminal complexity issues. For the uplink, MU-MIMO can be used. Multiple user terminals may transmit simultaneously on the same resource block. This is also referred to as spatial domain multiple access (SDMA). The scheme requires only one transmit antenna at UE side which is a big advantage. The UEs sharing the same resource block have to apply mutually orthogonal pilot patterns. To exploit the benefit of two or more transmit antennas but still keep the UE cost low, antenna subset selection can be used. In the beginning, this technique will be used, e.g. a UE will have two transmit antennas but only one transmit chain and amplifier. A switch will then choose the antenna that provides the best channel to the eNodeB.

5. Conclusion

Multiple-input multiple-output, or MIMO, is a radio communications technology or RF technology that is being mentioned and used in many new technologies these days. Wi-Fi, LTE (3G long term evolution) and many other radio, wireless and RF technologies are using the new MIMO wireless technology to provide increased link capacity and spectral efficiency combined with improved link reliability using what were previously seen as interference paths.