FUNCTIONS OF MIMO

MIMO can be sub-divided into three main categories, precoding, spatial multiplexing or SM, and diversity coding.

Precoding is multi-stream beamforming, in the narrowest definition. In more general terms, it is considered to be all spatial processing that occurs at the transmitter. In (single-stream) beamforming, the same signal is emitted from each of the transmit antennas with appropriate phase and gain weighting such that the signal power is maximized at the receiver input. The benefits of beamforming are to increase the received signal gain - by making signals emitted from different antennas add up constructively - and to reduce the multipath fading effect. In line-of-sight propagation, beamforming results in a well-defined directional pattern. However, conventional beams are not a good analogy in cellular networks, which are mainly characterized bymultipath propagation. When the receiver has multiple antennas, the transmit beamforming cannot simultaneously maximize the signal level at all of the receive antennas, and precoding with multiple streams is often beneficial. Note that precoding requires knowledge of channel state information (CSI) at the transmitter and the receiver.

$$\underbrace{\mathbf{Y}}_{n_R \times T} = \underbrace{\mathbf{H}}_{n_R \times n_T} \underbrace{\mathbf{X}}_{n_T \times T} + \underbrace{\mathbf{N}}_{n_R \times T} = \underbrace{\mathbf{H}}_{n_R \times n_T} \underbrace{\mathbf{V}}_{n_T \times Q} \underbrace{\mathbf{P}}_{Q \times Q} \underbrace{\mathbf{S}}_{Q \times T} + \underbrace{\mathbf{N}}_{n_R \times T}$$

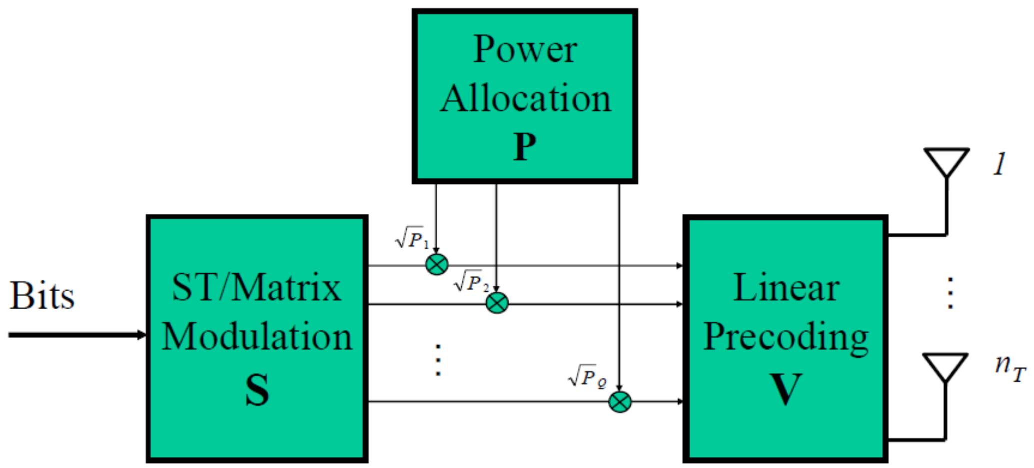
Spatial multiplexing requires MIMO antenna configuration. In spatial multiplexing, a high-rate signal is split into multiple lower-rate streams and each stream is transmitted from a different transmit antenna in the same frequency channel. If these signals arrive at the receiver antenna array with sufficiently different spatial signatures and the receiver has accurate CSI, it can separate these streams into (almost) parallel channels. Spatial multiplexing is a very powerful technique for increasing channel capacity at higher signal-to-noise ratios (SNR). The maximum number of spatial streams is limited by the lesser of the number of antennas at the transmitter or receiver. Spatial multiplexing can be used without CSI at the transmitter, but can be combined with precoding if CSI is available. Spatial multiplexing can also be used for simultaneous transmission to multiple receivers, known as space-division multiple access or multi-user MIMO, in which case CSI is required at the transmitter. The scheduling of receivers with different spatial signatures allows good separability.

Diversity coding techniques are used when there is no channel knowledge at the transmitter. In diversity methods, a single stream (unlike multiple streams in spatial multiplexing) is transmitted, but the signal is coded using techniques called space-time coding. The signal is emitted from each of the transmit antennas with full or near orthogonal coding. Diversity coding exploits the independent fading in the multiple antenna links to enhance signal diversity. Because there is no channel knowledge, there is no beamforming or array gain from diversity coding. Diversity coding can be combined with spatial multiplexing when some channel knowledge is available at the transmitter.

APPLICATIONS OF MIMO

Spatial multiplexing techniques make the receivers very complex, and therefore they are typically combined with Orthogonal frequency-division multiplexing (OFDM) or with Orthogonal Frequency Division Multiple Access (OFDMA) modulation, where the problems created by a multi-path channel are handled efficiently. The IEEE 802.16e standard incorporates MIMO-OFDMA. The IEEE 802.11n standard, released in October 2009, recommends MIMO-OFDM.

MIMO is also planned to be used in Mobile radio telephone standards such as recent 3GPP and 3GPP2. In 3GPP, High-Speed Packet Access plus (HSPA+) and Long Term Evolution (LTE)standards take MIMO into account. Moreover, to fully support cellular environments, MIMO research consortia including IST-MASCOT propose to develop advanced MIMO techniques, e.g.,multi-user MIMO (MU-MIMO).



MIMO technology can be used in non-wireless communications systems. One example is the home networking standard ITU-T G.9963, which defines a powerline communications system that uses MIMO techniques to transmit multiple signals over multiple AC wires (phase, neutral and ground).

Spatial multiplexing (often abbreviated **SM** or **SMX**)

It is a transmission technique in MIMO wireless communication to transmit independent and separately encoded data signals, so-called *streams*, from each of the multiple transmit antennas. Therefore, the space dimension is reused, ormultiplexed, more than one time.

If the transmitter is equipped with N_t antennas and the receiver has N_r antennas, the maximum spatial multiplexing order (the number of streams) is,

$$N_s = \min(N_t, N_r)$$

if a linear receiver is used. This means that N_s streams can be transmitted in parallel, ideally leading to an N_s increase of the spectral efficiency (the number of bits per second and per Hz that can be transmitted over the wireless channel). The practical multiplexing gain can be limited by spatial correlation, which means that some of the parallel streams may have very weak channel gains

$$\mathbf{S}_{VBLAST} = \begin{bmatrix} s_1 & s_5 & s_9 & s_{13} \\ s_2 & s_6 & s_{10} & s_{14} \\ s_3 & s_7 & s_{11} & s_{15} \\ s_4 & s_8 & s_{12} & s_{16} \end{bmatrix}$$

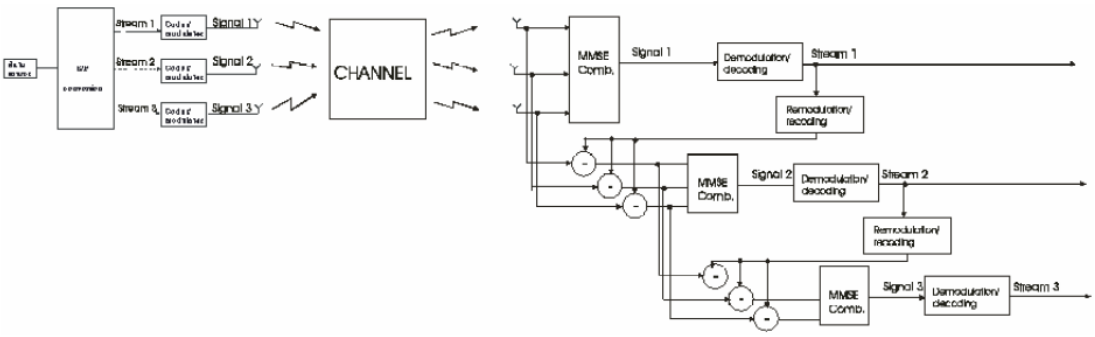
Precoding is a generalization of beamforming to support multi-stream (or multi-layer) transmission in multi-antenna wireless communications. In conventional single-stream beamforming, the same signal is emitted from each of the transmit antennas with appropriate weighting (phase and gain) such that the signal power is maximized at the receiver output. When the receiver has multiple antennas, single-stream beamforming cannot simultaneously maximize the signal level at all of the receive antennas.[1] In order to maximize the throughput in multiple receive antenna systems, multi-stream transmission is generally required.

In point-to-point systems, precoding means that multiple data streams are emitted from the transmit antennas with independent and appropriate weightings such that the link throughput is maximized at the receiver output. In multi-user MIMO, the data streams are intended for different users (known as SDMA) and some measure of the total throughput (e.g., the sum performance or max-min fairness) is maximized. In point-to-point systems, some of the benefits of precoding can be realized without requiring channel state information at the transmitter, while such information is essential to handle the inter-user interference in multi-user systems. Precoding in the downlink of cellular networks, known as network MIMO or coordinated multipoint (CoMP), is a generalized form of multi-user MIMO that can be analyzed by the same mathematical techniques

Precoding

Precoding is a technique which exploits transmit diversity by weighting information stream, i.e. the transmitter send the coded information to the receiver in order to the pre-knowledge of the channel. The receiver is a simple detector, such as a matched filter, and does not have to know the channel side information. This technique will reduce the corrupted effect of the communication channel.

For example you are sending the information s and it will pass through the channel, h, and add Gaussian noise, n. The received signal at the receiver front-end will be $r = sh + n$;The receiver will have to know the information about h and n. It will suppress the effect of n by increasing SNR, but what about h? It needs information about the channel, h, and this will increase the complexity. The receiver (mobile units) has to be simple for many reasons like cost or size of mobile unit. So, the transmitter (the base station) will do the hard work and predict the channel.



Precoding for Point-to-Point MIMO Systems

In point-to-point multiple-input multiple-output (MIMO) systems, a transmitter equipped with multiple antennas communicates with a receiver that has multiple antennas. Most classic precoding results assume narrowband, slowly fading channels, meaning that the channel for a certain period of time can be described by a single channel matrix which does not change faster. In practice, such channels can be achieved, for example, through OFDM. The precoding strategy that maximizes the throughput, called channel capacity, depends on the channel state information available in the system.

Statistical channel state information

If the receiver knows the channel matrix and the transmitter has statistical information, eigenbeamforming is known to achieve the MIMO channel capacity. In this approach, the transmitter emits multiple streams in eigendirections of the channel covariance matrix.

Full channel state information

If the channel matrix is completely known, singular value decomposition (SVD) precoding is known to achieve the MIMO channel capacity. In this approach, the channel matrix is diagonalized by taking an SVD and removing the two unitary matrices through pre- and post-multiplication at the transmitter and receiver, respectively. Then, one data stream per singular value can be transmitted (with appropriate power loading) without creating any interference whatsoever.

Precoding for Multi-user MIMO Systems

In multi-user MIMO, a multi-antenna transmitter communicates simultaneously with multiple receivers (each having one or multiple antennas). This is known as space-division multiple access (SDMA). From an implementation perspective, precoding algorithms for SDMA systems can be sub-divided into linear and nonlinear precoding types. The capacity achieving algorithms are nonlinear, but linear precoding approaches usually achieve reasonable performance with much lower complexity. Linear precoding strategies include maximum ratio transmission (MRT), zero-forcing (ZF) precoding, and transmit Wiener precoding. There are also precoding strategies tailored for low-rate feedback of channel state information, for example random beamforming. Nonlinear precoding is designed based on the concept of dirty paper coding (DPC), which shows that any known interference at the transmitter can be subtracted without the penalty of radio resources if the optimal precoding scheme can be applied on the transmit signal.

While performance maximization has a clear interpretation in point-to-point MIMO, a multi-user system cannot simultaneously maximize the performance for all users. This can be viewed as a multi-objective optimization problem where each objective corresponds to maximization of the capacity of one of the users. The usual way to simplify this problem is to select a system utility function; for example, the weighted sum capacity where the weights correspond to the system's subjective user priorities. Furthermore, there might be more users than data streams, requiring a scheduling algorithm to decide which users to serve at a given time instant.

Linear precoding with full channel state information

This suboptimal approach cannot achieve the weighted sum rate, but it can still maximize the weighted sum performance (or some other metric of achievable rates under linear precoding). The optimal linear precoding does not have any closed-form expression, but it takes the form of a weighted MMSE precoding for single-antenna receivers. The precoding weights for a given user are selected to maximize a ratio between the signal gain at this user and the interference generated at other users (with some weights) plus noise. Thus, precoding can be interpreted as finding the optimal balance between achieving strong signal gain and limiting inter-user interference.

Finding the optimal weighted MMSE precoding is difficult, leading to approximate approaches where the weights are selected heuristically. A common approach is to concentrate on either the numerator or the denominator of the mentioned ratio; that is, maximum ratio transmission (MRT) and zero-forcing (ZF) precoding. MRT only maximizes the signal gain at the intended user. MRT is close-to-optimal in noise-limited systems, where the inter-user interference is negligible compared to the noise. ZF precoding aims at nulling the inter-user interference, at the expense of losing some signal gain. ZF precoding can achieve performance close to the sum capacity when the number of users is large or the system is interference-limited (i.e., the noise is weak compared to the interference). A balance between MRT and ZF is obtained by the so-called regularized zero-forcing (also known as signal-to-leakage-and-interference ratio (SLNR) beamforming and transmit Wiener filtering. All of these heuristic approaches can also be applied to receivers that have multiple antennas.

Also for multiuser MIMO system setup, another approach has been used to reformulate the weighted sum rate optimization problem to a weighted sum MSE problem with additional optimization MSE weights for each symbol in. However, still this work is not able to solve this problem optimally (i.e., its solution is suboptimal). On the other hand, duality approach also considered in and to get sub-optimal solution for weighted sum rate optimization.

Note that the optimal linear precoding can be computed using monotonic optimization algorithms, but the computational complexity scales exponentially fast with the number of users. These algorithms are therefore only useful for benchmarking in small systems.

Linear precoding with limited channel state information

In practice, the channel state information is limited at the transmitter due to estimation errors and quantization. Inaccurate channel knowledge may result in significant loss of system throughput, as the interference between the multiplexed streams cannot be completely controlled. In closed-loop systems, the feedback capabilities decide which precoding strategies that are feasible. Each receiver can either feedback a quantized version of its complete channel knowledge or focus on certain critical performance indicators (e.g., the channel gain).

If the complete channel knowledge is fed back with good accuracy, then one can use strategies designed for having full channel knowledge with minor performance degradation. Zero-forcing precoding may even achieve the full multiplexing gain, but only provided that the accuracy of the channel feedback increases linearly with signal-to-noise ratio (in dB). Quantization and feedback of channel state information is based on vector quantization, and codebooks based on Grassmannian line packing have shown good performance.

Other precoding strategies have been developed for the case with very low channel feedback rates. Random beamforming or opportunistic beamforming was proposed as a simple way of achieving good performance that scales like the sum capacity when the number of receivers is large. In this suboptimal strategy, a set of beamforming directions are selected randomly and users feed back a few bits to tell the transmitter which beam gives the best performance and what rate they can support using it. When the number of users is large, it is likely that each random beamforming weight will provide good performance for some user.

In spatially correlated environments, the long-term channel statistics can be combined with low-rate feedback to perform multi-user precoding. As spatially correlated statistics contain much directional information, it is only necessary for users to feed back their current channel gain to achieve reasonable channel knowledge. As the beamforming weights are selected from the statistics, and not randomly, this approach outperforms random beamforming under strong spatial correlation.

Beamforming or **spatial filtering** is a signal processing technique used in sensor arrays for directional signal transmission or reception.This is achieved by combining elements in a phased array in such a way that signals at particular angles experience constructive interference while others experience destructive interference. Beamforming can be used at both the transmitting and receiving ends in order to achieve spatial selectivity. The improvement compared with omnidirectional reception/transmission is known as the receive/transmit gain (or loss).

Beamforming can be used for radio or sound waves. It has found numerous applications in radar, sonar, seismology, wireless communications, radio astronomy, acoustics, and biomedicine. Adaptive beamforming is used to detect and estimate the signal-of-interest at the output of a sensor array by means of optimal (e.g., least-squares) spatial filtering and interference rejection.

Beamforming techniques

To change the directionality of the array when transmitting, a beamformer controls the phase and relative amplitude of the signal at each transmitter, in order to create a pattern of constructive and destructive interference in the wavefront. When receiving, information from different sensors is combined in a way where the expected pattern of radiation is preferentially observed.

For example in sonar, to send a sharp pulse of underwater sound towards a ship in the distance, simply transmitting that sharp pulse from everysonar projector in an array simultaneously fails because the ship will first hear the pulse from the speaker that happens to be nearest the ship, then later pulses from speakers that happen to be the further from the ship. The beamforming technique involves sending the pulse from each projector at slightly different times (the projector closest to the ship last), so that every pulse hits the ship at exactly the same time, producing the effect of a single strong pulse from a single powerful projector. The same thing can be carried out in air using loudspeakers, or in radar/radio using antennas.

In passive sonar, and in reception in active sonar, the beamforming technique involves combining delayed signals from each hydrophone at slightly different times (the hydrophone closest to the target will be combined after the longest delay), so that every signal reaches the output at exactly the same time, making one loud signal, as if the signal came from a single, very sensitive hydrophone. Receive beamforming can also be used with microphones or radar antennas.

With narrow-band systems the time delay is equivalent to a "phase shift", so in this case the array of antennas, each one shifted a slightly different amount, is called a phased array. A narrow band system, typical of radars, is one where the bandwidth is only a small fraction of the centre frequency. With wide band systems this approximation no longer holds, which is typical in sonars.

In the receive beamformer the signal from each antenna may be amplified by a different "weight." Different weighting patterns (e.g., Dolph-Chebyshev) can be used to achieve the desired sensitivity patterns. A main lobe is produced together with nulls and sidelobes. As well as controlling the main lobe width (the beam) and the sidelobe levels, the position of a null can be controlled. This is useful to ignore noise or jammers in one particular direction, while listening for events in other directions. A similar result can be obtained on transmission.

For the full mathematics on directing beams using amplitude and phase shifts, see the mathematical section in phased array.

Beamforming techniques can be broadly divided into two categories:

- conventional (fixed or switched beam) beamformers
- adaptive beamformers or phased array
- Desired signal maximization mode
- Interference signal minimization or cancellation mode

Conventional beamformers use a fixed set of weightings and time-delays (or phasings) to combine the signals from the sensors in the array, primarily using only information about the location of the sensors in space and the wave directions of interest. In contrast, adaptive beamforming techniques generally combine this information with properties of the signals actually received by the array, typically to improve rejection of unwanted signals from other directions. This process may be carried out in either the time or the frequency domain.

As the name indicates, an adaptive beamformer is able to automatically adapt its response to different situations. Some criterion has to be set up to allow the adaption to proceed such as minimising the total noise output. Because of the variation of noise with frequency, in wide band systems it may be desirable to carry out the process in the frequency domain.

Beamforming can be computationally intensive. Sonar phased array has a data rate low enough that it can be processed in real-time in software, which is flexible enough to transmit and/or receive in several directions at once. In contrast, radar phased array has a data rate so high that it usually requires dedicated hardware processing, which is hard-wired to transmit and/or receive in only one direction at a time. However, newer field programmable gate arrays are fast enough to handle radar data in real-time, and can be quickly re-programmed like software, blurring the hardware/software distinction.

Diversity scheme

In telecommunications, a **diversity scheme** refers to a method for improving the reliability of a message signal by using two or more communication channels with different characteristics. Diversity is mainly used in radio communication and is a common technique for combatting fading and co-channel interference and avoidingerror bursts. It is based on the fact that individual channels experience different levels of fading and interference. Multiple versions of the same signal may be transmitted and/or received and combined in the receiver. Alternatively, a redundant forward error correction code may be added and different parts of the message transmitted over different channels. Diversity techniques may exploit the multipath propagation, resulting in a diversity gain, often measured in decibels.

The following classes of diversity schemes can be identified:

- **Time diversity**: Multiple versions of the same signal are transmitted at different time instants. Alternatively, a redundant forward error correction code is added and the message is spread in time by means of bit-interleaving before it is transmitted. Thus, error bursts are avoided, which simplifies the error correction.

- **Frequency diversity**: The signal is transmitted using several frequency channels or spread over a wide spectrum that is affected by frequency-selective fading. Middle-late 20th century microwave radio relay lines often used several regular wideband radio channels, and one protection channel for automatic use by any faded channel. Later examples include:
  - OFDM modulation in combination with subcarrier interleaving and forward error correction
  - Spread spectrum, for example frequency hopping or DS-CDMA.

- **Space diversity**: The signal is transmitted over several different propagation paths. In the case of wired transmission, this can be achieved by transmitting via multiple wires. In the case of wireless transmission, it can be achieved by antenna diversity using multiple transmitter antennas (transmit diversity) and/or multiple receiving antennas (reception diversity). In the latter case, a diversity combining technique is applied before further signal processing takes place. If the antennas are far apart, for example at different cellular base station sites or WLAN access points, this is called macrodiversity or site diversity. If the antennas are at a distance in the order of one wavelength, this is called microdiversity. A special case is phased antenna arrays, which also can be used for beamforming, MIMOchannels and space–time coding (STC).

- **Polarization diversity**: Multiple versions of a signal are transmitted and received via antennas with different polarization. A diversity combining technique is applied on the receiver side.

- **Multiuser diversity**: Multiuser diversity is obtained by opportunistic user scheduling at either the transmitter or the receiver. Opportunistic user scheduling is as follows: at any given time, the transmitter selects the best user among candidate receivers according to the qualities of each channel between the transmitter and each receiver. A receiver must feed back the channel quality information to the transmitter using limited levels of resolution, in order for the transmitter to implement Multiuser diversity.

- **Cooperative diversity**: Achieves antenna diversity gain by using the cooperation of distributed antennas belonging to each node.

Channel state information

In wireless communications, **channel state information** (**CSI**) refers to known channel properties of a communication link. This information describes how a signal propagates from the transmitter to the receiver and represents the combined effect of, for example, scattering, fading, and power decay with distance. The CSI makes it possible to adapt transmissions to current channel conditions, which is crucial for achieving reliable communication with high data rates in multiantenna systems.

CSI needs to be estimated at the receiver and usually quantized and fed back to the transmitter (although reverse-link estimation is possible in TDD systems). Therefore, the transmitter and receiver can have different CSI. The CSI at the transmitter and the CSI at the receiver are sometimes referred to as CSIT and CSIR, respectively.

Different kinds of channel state information

There are basically two levels of CSI, namely instantaneous CSI and statistical CSI.

Instantaneous CSI (or short-term CSI) means that the current channel conditions are known, which can be viewed as knowing the impulse response of a digital filter. This gives an opportunity to adapt the transmitted signal to the impulse response and thereby optimize the received signal for spatial multiplexing or to achieve low bit error rates.

Statistical CSI (or long-term CSI) means that a statistical characterization of the channel is known. This description can include, for example, the type of fading distribution, the average channel gain, the line-of-sight component, and the spatial correlation. As with instantaneous CSI, this information can be used for transmission optimization.

The CSI acquisition is practically limited by how fast the channel conditions are changing. In fast fading systems where channel conditions vary rapidly under the transmission of a single information symbol, only statistical CSI is reasonable. On the other hand, in slow fading systems instantaneous CSI can be estimated with reasonable accuracy and used for transmission adaptation for some time before being outdated.

In practical systems, the available CSI often lies in between these two levels; instantaneous CSI with some estimation/quantization error is combined with statistical information.