MIMO: Wireless Communications

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Abstract

Multiple input multiple output (MIMO) systems in wireless communications refer to any wireless communication system where at both sides of the communication path more than one antenna is used.

Systems utilizing multiple transmit and multiple receive antennas are commonly known as multiple input multiple output (MIMO) systems. This wireless networking technology greatly improves both the range and the capacity of a wireless communication system. MIMO systems pose new challenges for digital signal processing given that the processing algorithms are becoming more complex with multiple antennas at both ends of the communication channel. Overviews of MIMO systems can be, e.g., found in Refs. 1–3.

MIMO systems constructively explore multi-path propagation using different transmission paths to the receiver. These paths can be exploited to provide redundancy of transmitted data, thus improving the reliability of transmission (diversity gain) or increasing the number of simultaneously transmitted data streams and increasing the data rate of the system (multiplexing gain). The multiple spatial signatures can also be used for combating interference in the system (interferences reduction). A general model of a MIMO system is shown in Fig. 1.

A seminal information theory paper by Foschini and Gans of Lucent Technologies[4] shows that the capacity of these systems can increase linearly with the number of transmit antennas as long as the number of receive antennas is greater than or equal to the number of transmit antennas. As an increase in capacity means capability of faster communication, this unmatched capacity improvement over regular one-antenna systems has fueled a huge interest in MIMO techniques, thus leading to the development of many forms of MIMO systems.

Traditional wireless communication systems with one transmit and one receive antenna are denoted as single input single output (SISO) systems, whereas systems with one transmit and multiple receive antennas are denoted as single input multiple output (SIMO) systems, and systems with multiple transmit and one receive antenna are called multiple input single output (MISO) systems. Conventional smart antenna systems have only a transmit side or only a receive side equipped with multiple antennas, so they fall into one of last two categories. Usually, the base station has the antenna array, as there is enough space and since it is cheaper to install multiple antennas at base stations than to install them in every mobile station. Strictly speaking, only systems with multiple antennas at both ends can be classified as MIMO systems. Although it may sometimes be noted that SIMO and MISO systems are referred as MIMO systems. In the terminology of smart antennas, SIMO and MISO systems are also called antenna arrays.

CAPACITY OF MIMO SYSTEMS

From the mathematical point of view, the MIMO communication is performed through a matrix and not just a vector channel, so it is possible to transmit multiple parallel signal streams simultaneously in the same frequency band and thus increase spectral efficiency. This technique is called spatial multiplexing and is shown in Fig. 2. The data stream is encoded with vector encoder and

Encyclopedia of Wireless and Mobile Communications DOI: 10.1081/E-EWMC-120043484

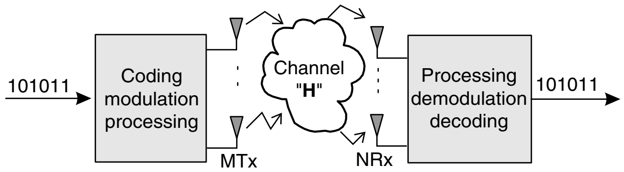

Fig. 1 A general block diagram of a multiple input multiple output wireless communication system.

transmitted concurrently by M transmitters. The MIMO radio channel introduces distortion to the signal. The receiver has N antennas. Each antenna receives the signals from all M transmit antennas, and consequently the received signals exhibit inter-channel interference. The received signals are down converted to the base band and sampled once per symbol interval. The MIMO processing unit estimates the transmitted data streams from the sampled base-band signals. The vector decoder is a parallel-to-serial converter, which combines the parallel input data streams to one output data stream.

In a system with M transmit and N receive antennas, there exist $M*N$ sub-channels between transmitter and receiver. In general, each sub-channel exhibits a selective fading and consequently it is modeled as a linear discrete time finite impulse response (FIR) filter with complex coefficients. In the case of flat fading, the signal in each sub-channel is only attenuated and phase shifted due to different propagation times between each receive and transmit antenna. The sub-channel is reduced to one tap FIR filter, i.e., one complex coefficient. When the channel is constant during the whole time slot, the channel is quasi-static. For capacity investigation, we have assumed that the radio channel is quasi-static and fading flat.

In the aforementioned case, the received signal on the j-th receive antenna can be expressed as:

$$y_j = \sum_{i=1}^{M} h_{ij} x_i + n_j \tag{1}$$

where x_i is the transmitted signal from i-th antenna and y_j is received signal at j-th antenna. Variable n_j denotes samples of circularly symmetric complex Gaussian noise with variance ${\sigma_n}^2$ at j-th receiver. The fading channel is described as a sum of complex paths h_{ij} between receive and transmit antennas. The complex gain coefficient h_{ij} complies with Gaussian distribution. The matrix form of Eq. 1 is:

$$\mathbf{y} = \mathbf{Hx} + \mathbf{n} \tag{2}$$

where $\mathbf{y}$ is the column vector of the received signals, $\mathbf{H}$ is the channel matrix, $\mathbf{x}$ is the column vector of the transmitted signal, and $\mathbf{n}$ is a column vector of the additive white Gaussian noise.

The capacity of the system depends only on the transmitted signal power, noise, and channel characteristics. The channel capacity for flat fading deterministic channel can be expressed as:

$$C = \log_2\left[\det\left(\mathbf{I} + \frac{\rho}{M}\mathbf{HH}^*\right)\right] \tag{3}$$

where $\rho = P/\sigma_n^2$ and P is the cumulative power transmitted by all antennas and σ_n^2 is the noise power at each receive antenna. $\mathbf{H}$ is the matrix describing quasi-static channel response and the superscript * denotes transpose conjugate of channel matrix $\mathbf{H}$.[5]

In the extreme case when we can assume uncorrelated paths, all eigenvalues of the product $\mathbf{HH}^*$ are non-zero and approximately equal. The capacity is then expressed as:

$$C = \sum_{i=1}^{M} \log_2\left(1 + \frac{\lambda_i}{M}\rho\right) \approx A_{\min}\log_2\left(1 + \frac{N}{A_{\min}}\rho\right) \tag{4}$$

where $A_{\min} = \min(M,N)$

The amount of available capacity in idealized MIMO channel increases linearly with $A_{\min}$ without an increase in transmit power. If the channel is time variant, the above expression holds true only for one instance of the channel. Telatar[5] extended the expression for ergodic (mean) capacity in random time-varying Gaussian channel. He found out that ergodic capacity grows linearly with the number of receive antennas for large number of transmit antennas. However, if the number of receive and the transmit antennas are comparable, the benefit of adding a single antenna is much smaller.

An increase of MIMO system capacity can be achieved by multiplexing data streams into parallel sub-channels (pipes) in the same frequency band. The pipes can be viewed as independent radio channels. The column

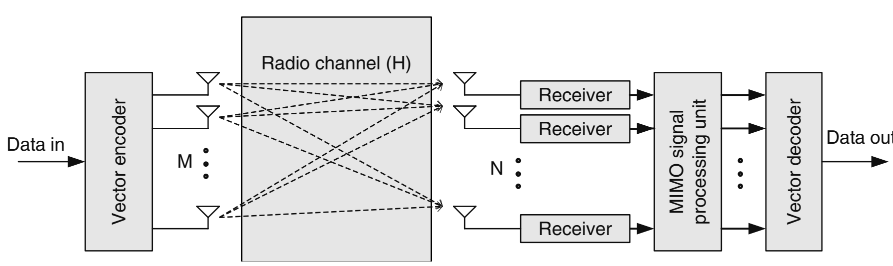

Fig. 2 Block diagram of a MIMO system utilizing spatial multiplexing for capacity maximization.

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vectors of flat fading channel matrix **H** are usually non-orthogonal. However, by singular value decomposition (SVD), the channel matrix can be decomposed into diagonal matrix $\Lambda^{1/2}$ and two unitary matrices **U** and **V**:

$$\mathbf{H} = \underset{M_R \times M_R}{\mathbf{U}} \underset{M_R \times M_T}{\Lambda^{1/2}} \underset{M_T \times M_T}{\mathbf{V}^*} \tag{5}$$

The diagonal entries of $\Lambda^{1/2}$ are in fact the non-negative square roots of the eigenvalues of $\mathbf{HH}^*$. The number of non-zero eigenvalues $\lambda_1, \lambda_2, \ldots, \lambda_K$ of $\mathbf{HH}^*$ is equal to the rank of channel matrix and also to the number of independent sub-channels. The global capacity could be expressed as the sum of the sub-channel capacities. In fact, the singular values of channel matrix determine the gains of the independent parallel channels.

With the knowledge of the gain of the independent channels at the transmitter, we can determine the optimum power distribution at each transmit antenna to achieve maximum capacity. The MIMO channel capacity is determined by water-filling theorem:

$$C = \sum_{i}^{K} \log_2 \left(1 + \lambda_i \frac{P_i}{\sigma_n^2}\right) \tag{6}$$

where P_i is the power allocated to the channel i, calculated by water-filling power allocation.[5]

If the channel matrix at the transmitter is unknown, the uniform power distribution among transmitters is assumed for channel capacity calculation:

$$C = \sum_{i=1}^{K} \log_2 \left(1 + \frac{\lambda_i}{M} \rho\right) \tag{7}$$

When there is no knowledge of the channel state at the transmit side, the capacity is described by Eq. 6, whereas the capacity with perfect channel knowledge at the transmit side can be calculated according to Eq. 7. In the ideal rich scattering (Rayleigh) channel knowledge at the transmit side is beneficial at low SNR, while at high SNR there is no significant difference in the capacities Eqs. 6 and 7. However, the channel knowledge at transmit side can help increase the reliability of practical systems substantially, since we must not forget that the capacity is just theoretical upper bound which can only be achieved with codes of infinite length.

The capacity analysis of different realistic propagation environments has a significant influence on a design of communication systems. It was shown that for low-rank channels or low SNRs, the usage of multiple transmit and receive antennas has much lower gain. In low rank channels capacity grows only logarithmically with the number of receive antennas. In these cases, usage of diversity techniques is recommended.

BENEFITS OF MULTI-ANTENNA SYSTEMS

The most important advantages of multiple antenna systems are array gain, interference reduction, and diversity gain. MIMO systems can exploit not only the transmit and receive multi-antenna benefits simultaneously but they also offer something new compared to the traditional antenna array systems, i.e., multiplexing gain. However, a compromise between diversity and multiplexing has to be made since it is not possible to exploit both maximum diversity gain and maximum multiplexing gain at the same time.[6] Ideally, adaptive systems would adapt the exploitation of multiple antennas to current conditions and thus simultaneously increase both the throughput and the reliability of communication system.

ARRAY GAIN

Array gain indicates improvement of SNR at the receiver compared to traditional systems with one transmit and one receive antenna. The said improvement can be achieved with correct processing of the signals at the transmit or at the receive side, so the transmitted signals are coherently combined at the receiver. To achieve array gain at the transmitter antenna array, the channel state information (CSI) has to be known at the transmit side whereas for the exploitation of antenna array gain at the receiver, the channel has to be known at the receive side. Receive array gain is achieved regardless of the correlation between the antennas.

INTERFERENCE REDUCTION

Interference in the wireless channel appears due to frequency reuse. It decreases the performance of the communication systems. Using multiple antennas, it is possible to separate the signals with different spatial signature and thus decrease inter-channel interference. When traveling through wireless medium, each signal is marked with the path that it has traveled. For the interference reduction, it is necessary to know the CSI.

At the transmit side, the transmitted signal can be directed to the chosen users. With this, the interferences to the other users are decreased, more efficient frequency planning is thus possible, which, in turn, increases the capacity of cellular systems. This technique is also called beamforming and is a very common spatial processing technique. A beamformer can be seen as a spatial filter that separates the desired signal from interfering signals given that all the signals share the same frequency band and originate from different spatial locations. It essentially weighs and sums the signals from different antennas in the antenna array to optimize the quality of the desired signal. In addition to interference rejection and multi-path fading mitigation, a beamformer also increases the antenna gain in the direction of the desired user.

Common beamforming criteria are minimum mean square error (MMSE), maximum signal to interference and noise ratio (MSINR), maximum SNR (MSNR), constant modulus (CMA), and maximum likelihood (ML). Beamforming is typically implemented using adaptive techniques. The adaptive array algorithms are broadly classified as: trained algorithms and blind algorithms. Trained algorithms use a finite set of training symbols to adapt the weights of the array and maximize the signal to interference plus noise ratio (SINR). Blind algorithms do not require training signals to adapt their weights. As a result, these algorithms save bandwidth efficiency since all time slots can be used for transmission of useful data. A comprehensive review of adaptive antenna array systems can be found in Ref. 7.

DIVERSITY GAIN

Diversity in wireless communications is used to combat signal fading. Several techniques exist, but they are all based on the same principle: They transmit the signal through several independently fading paths. More independently fading channels exist, higher is the probability that at least one of them is not in deep fade.

Three types of diversity have been known for quite some time in the wireless communications and have been used widely: time diversity, frequency diversity, and space diversity. For space diversity, there is no need neither for extra bandwidth nor for extra time; however, the price to be paid is an increased complexity of the system since multiple antennas with radio frequency chains and some processing are needed. Antennas must be separated sufficiently; otherwise, the signals are correlated and diversity gain is reduced. The separation of the antennas needed for independent fading is called coherence distance. Coherence distance depends mostly on the departure and arrival angles of the signals. If the multi-path is very rich, meaning that the signals arrive to the receiver from all the directions, then the separation of approximately half of the wavelength is sufficient. If the angles are smaller, then the distance needed for independent fading is larger. Measurements have shown that as regards the base station, the height of the base station and the coherence distance are strongly correlated: higher are the base station antennas, larger is the coherence distance. For the mobile stations in urban environment, separation of more than half of the wavelength is usually sufficient to achieve low correlation and thus high space diversity gain. If several antennas are used just at the receive side, we obtain receive diversity; if several antennas are used just on the transmit side, we obtain transmit diversity.

In MIMO systems, there are several antennas at both ends, which offer the potential of very high diversity gains. Diversity gain is equal to the number of independent channels in the system, which depends on the position of the antennas and the environment. If we have M transmit and N receive antennas, then we have M*N sub-channels and the maximum diversity gain equals M*N. Higher the diversity gain, lower is the probability of erroneous detection of the received signal. The diversity gain indicates how fast the probability of error is decreasing with an increase in the signal strength.

When multiple antennas are used for the reception, the received signals can be weighted and summed together. The phase shift of the received signals has to be taken into account, or the signals from different antennas would not necessarily be added together coherently at the combiner. The output signal would still have large fluctuations because of sometimes constructive and sometimes destructive combining. The method where the weighting coefficients are chosen in such a way that the average quality of the signal (SNR) is maximized called maximum ratio combining or MRC. Using this method, the coefficients are equal to the conjugate complex value of the channel coefficients. This means that all received signals are shifted to the same phase and the signals with higher strengths are getting proportionately more important role at the signal combiner. The SNR at the output of the combiner is equal to the sum of the SNRs on all antennas. Beside the array gain, MRC detection also achieves maximal diversity gain. An advantage of using receive diversity is that it is seamless to the transmitter, so it does not need to be defined in the standards to be used. Most modern communication systems are used with receive diversity if it is thus required.

Besides the receive diversity, it is also possible to use transmit diversity, which became a topic of studies in 1990. The transmit diversity is very suitable for cellular systems, as more space, power, and processing capability is available at the base stations. Systems with transmit diversity differ as regards the knowledge of the CSI at the transmitter. In a case where the CSI is known to the transmitter, the system is dual to the receive diversity, the only difference is that the signal from each antenna is multiplied with the weight prior to the transmission, so that they automatically add together coherently at the receiver. In a case where the CSI is not known at the transmitter, it is a common practice to combine the space diversity with the time diversity. The technique is known as space-time coding (STC) and can achieve maximal diversity gain, but unfortunately, no array gain.

MULTIPLEXING GAIN

To exploit multiplexing gain, one needs to have several antennas at both ends of the communication system. In the MIMO system with rich scattering environment, several communication channels in the same frequency band can be used. As it was shown, the capacity of the spatial multiplexing system can be increased with the minimum number of transmit and receive antennas. Such an increase in spectral efficiency of the system is particularly attractive since there is no need for additional spectrum or for increasing transmit power. However, multiple antennas are needed at both ends to employ spatial multiplexing, while for other multiple antenna benefits just an antenna array at one end is needed. The decoding of spatially multiplexed signals is very demanding, as will be explained later, and spatially multiplexed systems are less reliable given that beside a low signal strength, high correlation between antennas can also cause erroneous detection.

SPACE-TIME CODES

Coding the information across transmit antennas and time slots in a way that the receiver can reliably extract the information and exploit spatial diversity (possibly while providing coding gain) is called STC. Just one receive antenna and no channel knowledge at the transmit side is needed. STC coder generates as many symbols as there are transmit antennas. These symbols are transmitted simultaneously, each one through different antenna. The goal of STC is to code the symbols at the transmitter in such a way that the highest diversity gain is achieved after decoding. Two main categories of STC are *space time trellis codes* (STTCs) and *space time block codes* (STBCs). An in-depth introduction of STC and its applications in wireless communication systems can be found, e.g., in Ref. 8.

STTCs

STTC is an extension of trellis coded modulation (TCM) to multiple transmit antennas. It combines the advantages of transmit diversity and TCM in an ingenious way to obtain reliable, high data rate transmission in wireless channels without feedback from the receiver. STTC was first introduced by Tarokh et al. in 1998.[9] They defined design criteria for STTC over slow flat fading, fast flat fading, and spatially correlated channels assuming high SNRs. They constructed codes that provided a good tradeoff between data rate, diversity advantage, and trellis complexity. STTC can be illustrated in trellis diagram, in which vertexes are defined with diagram of state transitions. Besides maximal diversity gain, coding gain can also be achieved.

STTC decoding can be done with Viterbi algorithm. First, the branch metrics for each vertex in the trellis diagram is calculated, then the Viterbi algorithm finds the path through the trellis diagram for which the cumulative metrics is the smallest. The complexity of this decoding is quite considerable and that is why STBC are more attractive for the implementation.

STBCs

STBCs map a block of input symbols into space and time sequence. The receiver usually uses an ML detection. The greatest benefit of block codes over trellis codes is that the optimal decoding is much simpler. Instead of a joint detection of all the transmitted symbols, the transmitted symbols can be separated with STBC. The class of codes that allow separation is called orthogonal STBC and is particularly important for the implementation. STBC can achieve maximal diversity gain for a given number of transmit and receive antennas; however, they cannot achieve any coding gain. The first STBC with two transmit antennas was discovered by Alamouti,[10] and is now widely known as the Alamouti code. Later it was, with some limitations, generalized to different numbers of transmit antennas.[11]

ALAMOUTI CODE

Alamouti scheme can be compared with MRC scheme for receive diversity exploitation; the main difference is that Alamouti scheme is used when antenna array is at the transmitter (MISO and MIMO), which is particularly important for the downlink from the base stations. With Alamouti scheme, two data symbols are transmitted in two transmission times, so the transmission rate (data throughput) is the same as with traditional systems with one transmit antenna. The diagram of the communication systems with the Alamouti scheme and two receive antennas is presented in Fig. 3. In the first symbol period, symbol one is transmitted from the first transmit antenna and symbol two is transmitted from the second antenna. In the second symbol period, symbol two, multiplied by –1 and complexly conjugated, is transmitted from the first antenna, and the complexly conjugated symbol one is transmitted from the second antenna. Owing to orthogonality, optimal decoding of each transmitted symbol can be done independently, using simple linear decoding. In this way, the maximal diversity gain can be achieved for any number of receive antennas.

As STBC do not give any coding gain, they are usually combined with external forward error correction (FEC) coding, so the quality of transmission increases even further. Given that STBC can give soft output information (exact real value and not just decision on the symbol), it is possible to combine FEC code with advanced iterative decoding, known as turbo coding.

SPATIAL MULTIPLEXING

In spatial multiplexing MIMO systems, independent data streams are transmitted through different antennas which maximize the data throughput of the MIMO systems. This

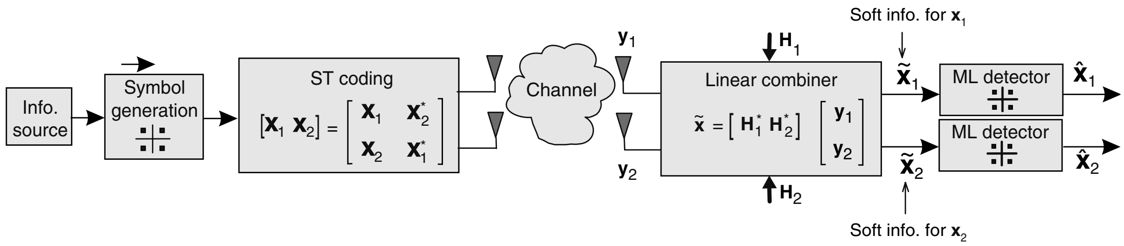

Fig. 3 Space-time coding with Alamouti scheme for two transmit and two receive antennas exploiting maximum diversity gain.

type of communication is often called Vertical Bell laboratories LAyered space-time architecture (V-BLAST).[4] V-BLAST systems divide input data stream into as many independent data streams as there are transmit antennas. Then the signals are modulated and simultaneously sent through all M transmit antennas, as it is shown in Fig. 2.

In the case of spatial multiplexing, the processing at the transmitter is quite simple but the processing at the receiver can be very complex, depending on the complexity of the receiver decoding algorithm. The performance of an MIMO spatial multiplexing system depends highly on the receiver quality, since all N receive antennas receive signals from all M transmit antennas and they have to be separated sufficiently.

ML DECODING

ML decoding of spatially multiplexed sub-streams maximizes the probability of correct detection and therefore optimal decoding is possible. It can be denoted with equation:

$$\mathbf{x}_{\mathrm{ML}} = \arg \min_{\mathbf{x}_j \in \{\mathbf{x}_1, \ldots, \mathbf{x}_K\}} \left\| \mathbf{y} - \mathbf{H}\mathbf{x}_j \right\|^2 \tag{8}$$

The problem of ML decoding is that it usually requires extensive search for all possible combinations of transmitted symbols. The time of computation is exponentionally proportional to the number of transmit antennas and the number of bits coded in each spatially multiplexed substream. As in most cases, this decoding is too complex to be implemented in communication systems, other faster methods of decoding are usually applied. However, ML decoding is important as a measurement of the proximity of other decoding algorithms to the optimum. It is also used in combination with other decoding methods on limited subset of possible solutions.

MATRIX PSEUDO-INVERSION DECODING (PINV)

The most simple, but also the least efficient decoding method is matrix inversion. As matrix inversion exists only for square matrices, pseudo-inversion (PINV) is used. Interference is removed by multiplying the received signal $\mathbf{y}$ with the pseudo inverse of the channel matrix. This method is also called zero forcing (ZF), since the interferences are zeroed by multiplication with the matrix inverse. When the channel matrix is badly conditioned (antennas are correlated), multiplication of the received signal with the matrix inverse significantly increases the noise. A bit better performance is achieved using similar method called ZF-MMSE, where the SNR is taken into account when calculating the matrix inversion to achieve MMSE. Owing to their simplicity, these linear methods are sometimes used as a basis for other detection methods. The diversity gain achieved using this detection method is just $M - N + 1$; however, it is worth noting that this simple linear decoding can give very good results in adaptive MIMO systems when a number of spatially multiplexed sub-streams and the set of used transmit antennas is selected carefully, based on the current channel state.[12,13]

SUCCESSIVE INTERFERENCE CANCELLATION DECODING

Successive interference cancellation (SIC) is an iterative detection method which consists of three steps: zeroing, quantization, and interference cancelation.[14] These steps are iteratively repeated until all transmitted symbols are detected. In each iteration, one symbol is detected with ZF or ZF-MMSE method, then it is quantized (truncated to the nearest possible transmitted values) and the influence of this symbol is subtracted from the received vector $\mathbf{y}$.

This decoding is a good compromise between the complexity (which is much lower than with ML decoding) and efficiency (which is much better than a simple liner ZF decoding). Drawback of iterative cancelation decoding is error propagation. If one symbol is detected erroneously, then it is very likely that all the remaining symbols will also be decoded erroneously. That is why ordered SIC (OSIC) is usually used where the transmitted symbols are decoded in the order of the most likely correct decoding.[14]

SPHERE DECODING

The idea of sphere decoding (SD) is to search for the solution of ML decoding just for those points **Hx**, that are inside defined M dimensional hyper-sphere with defined radium and center in **y**. The size of the radium defines the compromise between computational time and efficiency of decoding. The details of SD are beyond the scope of an encyclopedia, but a good review of SD can be found in Ref. 15. Let us just conclude that SD, if properly implemented, can give results very close to optimal ML decoding with huge complexity reduction.

ADAPTIVE MIMO SYSTEMS

Communication systems can adapt the throughput rate to the current conditions of the channel if channel knowledge is available at the transmit side. This is known as adaptive coding-modulation (ACM) techniques. In MIMO system, ACM can be extended to the selecting mode of operation. It is commonly known that adaptive communication systems are more reliable and robust.

Knowing the channel state at the transmitter is much more difficult than knowing channel state at the receiver, where the channel can be estimated by the training sequence. Feedback information from the receiver to the transmitter is needed, except in the case of reciprocal channel like time division duplex systems, where the same parameters can be used for both sides, but precisely calibrated equipment is needed for that. Several schemes of adaptation were proposed in the literature, one of them has already been mentioned, i.e., beamforming. As the CSI in MIMO systems is quite substantial, it is a good idea to select just from a set of predefined modes of operation. In spatial multiplexing systems, number of spatially multiplexed streams can be selected based on the SNR and correlation between antennas. Transmit antenna selection can be performed to select a set of transmit antennas to be used to meet certain condition.[13,16]

In adaptive MIMO systems, it would be ideal to be able to achieve any tradeoff between the speed and the reliability. Example of such a code, which includes V-BLAST and the orthogonal design STBCs as special cases, was proposed by Hassibi[17] and is called linear dispersion code (LDC). LDC can be used for any number of transmit and receive antennas and can be decoded with V-BLAST like algorithms. The most important property of LDC is that they satisfy an information-theoretic optimality criterion.

APPLICATIONS OF MIMO SYSTEMS

As shown, MIMO systems can significantly increase reliability and/or capacity of communication systems, but many problems are to be faced. Capacities in real environment are much lower than the capacities obtained at the beginning of this chapter, since the antennas are not always uncorrelated, the channel estimation is not always accurate, there can be Doppler shift of frequency and there might be synchronization problems. It is important to determine how many antennas should be used and how large should the distance between them be. The limitations are physical dimensions of the equipment, processing capabilities, and in the case of mobile stations, power consumption. The price of the equipment grows with the number of antennas used since extra amplifiers, filters, and processing power are needed; therefore, it is better to use multiple antennas only at the base station side.

On the other hand, the base stations are located higher than the subscriber stations; therefore, the propagation properties of the channel are less favorable for the exploitations of the MIMO systems. To ensure satisfactory level of independency, they should be separated for approximately ten wavelengths of the signal. For example, at 2 GHz frequency, this distance is approximately 1.5 m. For the subscriber stations, which are usually quite low and in many cases there is no line-of-sight to the base station, the distance of half of the wavelength is usually sufficient.

It is expected that in most of the modern wireless standards, multiple antenna techniques will be enabled, at least as an optional feature.[18] Let us have a closer look at three examples of the standardized MIMO solutions.

WIMAX—IEEE 802.16

The usage of multiple antennas is foreseen in the standard for broadband wireless access (BWA) IEEE 802.16. In the *d* version of the standard, known also as fixed WiMax (802.16-2004), multiple antennas may be used for beamforming (AAS—adaptive antenna system) or for exploiting diversity in downlink for two transit antennas with the described Alamouti scheme (standard regards it as STC).

Newer version of the WiMax standard, also known as mobile WiMax (802.16e) or the *e* version has been ratified in December 2005. Besides beamforming and Alamouti STC schemes, it also provides spatial multiplexing of 2×2 MIMO in the downlink, which has the potential to double the speed of communication.[19] In the uplink, there is also special feature available, called collaborative multiplexing, which provides the ability to use spatial multiplexing in the uplink even with mobile stations with just one antenna. The said operation is performed by collaborative transmission of two mobile stations on the same frequency at the same time. Although these two mobile stations transmit independent data, they are well spatially separated and therefore the base station can decode both of them if at least two receive antennas are available at the base station. This does not increase the data throughput per user, but increases overall data throughput in the sector. Mobile WiMax also supports adaptive switching between these options to maximize the benefit of smart antenna technologies under different channel conditions. This adaptive MIMO switching (AMS) is done between multiple MIMO modes to maximize spectral efficiency with no reduction in coverage area.

WIRELESS LOCAL AREA NETWORK—IEEE 802.11N

MIMO systems have also a great potential in WLANs. IEEE formed a new 802.11 Task Group (TGn) to develop 802.11n standard for WLAN in January 2004. In July 2005, competitors TGnSync and WWiSE agreed to merge their proposals as a draft and sent it to the IEEE in September 2005. It was expected that the standardization process could be completed by the second half of 2006, but unfortunately it seems that ratification of the standard will be delayed. According to the IEEE 802.11 Working Group Project Timelines, the 802.11n standard is not due for final approval until July 2007.

The *n* version of WLAN is supposed to offer great improvement in both capacity and reliability. With more efficient use of orthogonal frequency division multiplexing (OFDM), an increase in the bandwidth from 20 to 40 MHz and the use of spatial multiplexing with up to four simultaneously spatially multiplexed sub-streams data with throughput speeds of over 500 Mbps can theoretically be achieved. Alamouti scheme can be used for the exploitation of transmit diversity and MRC for the receive diversity.

Although 802.11n standard is not approved yet, some manufacturers are already developing and testing equipment. An example is Airgo Networks, where they already produce WLAN devices based on MIMO solutions. Airgo's True MIMO technology is based on drafts of standard IEEE 802.11n, however, question remains whether it will be compatible with the standard.

THE THIRD GENERATION PARTNERSHIP PROJECT

In the third generation partnership project (3GPP) they are intensively engaged to implement MIMO systems in the broadband CDMA systems.[20] The usage of spatial diversity with two antennas was proposed already in R99 version of CDMA system. Multiple antenna systems were divided into those working in open loop (no CSI at the transmit side) and those working in close loop (CSI available at the transmit side). Examples of open loop are yet again the Alamouti scheme (here called space time transmit diversity—STTD) and time switch transmit diversity (TSTD). In the close loop systems, transmit beamforming can be used; it is called transmit adaptive array (TAA). In later versions of the standard, larger numbers of transmit antennas were introduced and they were divided into subgroups, which are hierarchically weighted to exploit transmit diversity and beamforming. Several documents examining the multi-antenna usage on both the base station side and on the terminal (mobile) station side are available on the internet page of 3GPP. There are several STC schemes proposed for one, two or four antennas on both sides.

SUMMARY

In the field of wireless communications, MIMO systems have enabled a huge step forward since they can increase significantly both the coverage and the capacity of cellular systems. The technology is developing very fast and is already present in several standards. Standardization difficulties can appear in supporting the compatibility for previous versions of standards; that is why, it is easier to incorporate MIMO in completely new standards like WiMax. However, no standardization will resolve all issues. They help improve product efficiency but the actual design and manufacturing issues alone will decide on the performance of the final product.

In the future, it is expected that several antennas will be included in many laptop computers or mobile devices. Massive usage of multiple antennas will decrease the prices of such devices, which, in turn, can make the technology available to wider range of users. It is hard to predict which standard or technology will continue the 4G wireless systems, but it will almost certainly incorporate MIMO systems. Those systems will have to include the ability to adapt to the time changing nature of the wireless channel using some form of at least partial feedback to make a fine compromise between rate maximization (spatial multiplexing) and diversity (STC) solutions.

ADDITIONAL READING

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www.ece.utexas.edu/~rheath/research/mimo
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