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Wireless Communication: Trend and Technical Issues for MIMO-OFDM System

Yoon Hyun Kim[1], Bong Youl Cho[2] and Jin Young Kim[3]
[1,3]*Kwangwoon University,*
[2]*Nokia-Siemens Networks,*
Seoul
Korea

1. Introduction

High-performance 4th generation (4G) broadband wireless communication system can be enabled by the use of multiple antennas not only at transmitter but also at receiver ends. A multiple input multiple output (MIMO) system provides multiple independent transmission channels, thus, under certain conditions, leading to a channel capacity that increases linearly with the number of antennas. Orthogonal frequency division multiplexing (OFDM) is known as an effective technique for high data rate wireless mobile communication. By combining these two promising techniques, the MIMO and OFDM techniques, we can significantly increase data rate, which is justified by improving bit error rate (BER) performance. In this section, we briefly describe the concept of MIMO system. Through comparison with CDMA system, its key benefits are discussed.

1.1 Concept of MIMO system

The idea of using multiple receive and multiple transmit antennas has emerged as one of the most significant technical breakthroughs in modern wireless communications. Theoretical studies and initial prototyping of these MIMO systems have shown order of magnitude spectral efficiency improvements in communications. As a result, MIMO is considered a key technology for improving the throughput of future wireless broadband data systems

MIMO is the use of multiple antennas at both the transmitter and receiver to improve communication performance. It is one of several forms of smart antenna technology. MIMO technology has attracted attention in wireless communications, because it offers significant increases in data throughput and link range without requiring additional bandwidth or transmit power. This is achieved by higher spectral efficiency and link reliability or diversity (reduced fading). Because of these properties, MIMO is an important part of modern wireless communication standards such as IEEE 802.11n (Wifi), IEEE 802.16e (WiMAX), 3GPP Long Term Evolution (LTE), 3GPP HSPA+, and 4G systems to come.

Radio communication using MIMO systems enables increased spectral efficiency for a given total transmit power by introducing additional spatial channels which can be made available by using space-time coding. In this section, we survey the environmental factors that affect MIMO performance. These factors include channel complexity, external interference, and channel estimation error. The 'multichannel' term indicates that the

receiver incorporates multiple antennas by using space-time-frequency adaptive processing. Single-input single-output (SISO) is the well-known wireless configuration, single-input multiple-output (SIMO) uses a single transmit antenna and multiple receive antennas, multiple-input single-output (MISO) has multiple transmit antennas and one receive antenna. And multiuser-MIMO (MU-MIMO) refers to a configuration that comprises a base station with multiple transmit/receive antennas interacting with multiple users, each with one or more antennas.

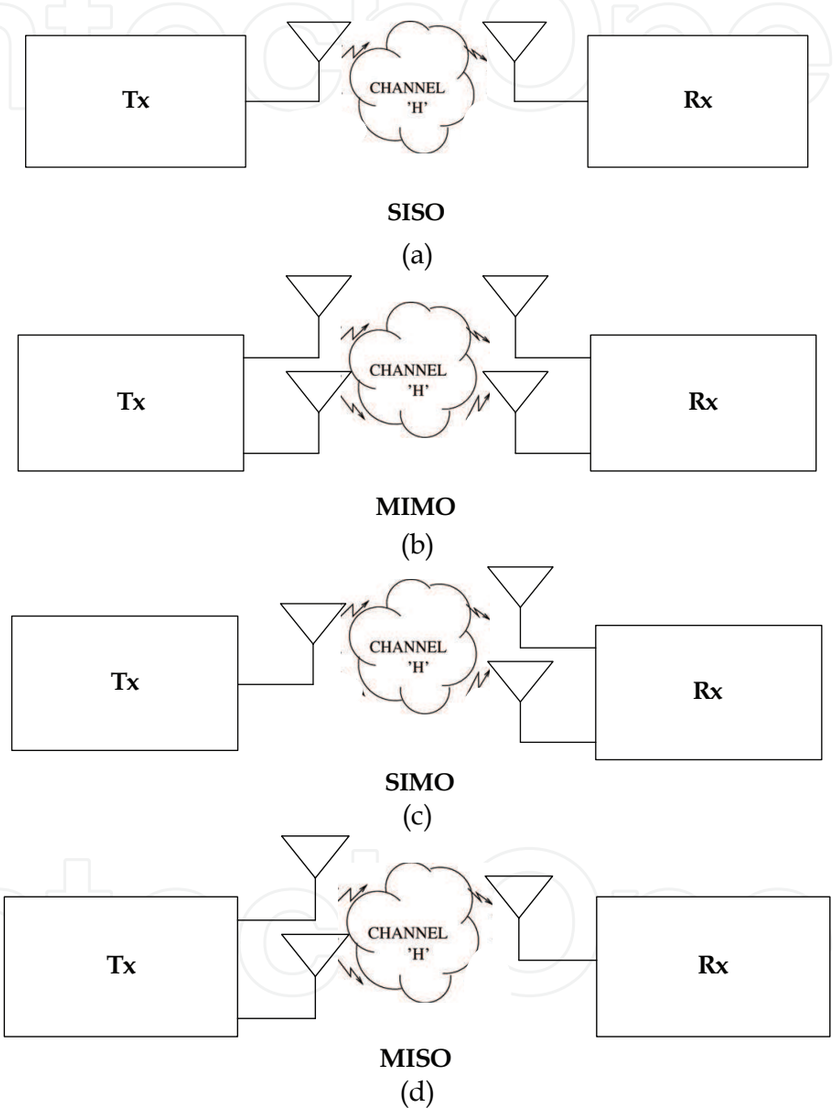


Fig. 1.1. Different antenna system
(a) SISO mode (b) MIMO mode (c) SIMO mode (d) MISO mode

1.2 Key benefits

1.2.1 Array gain

Array gain can be made available through processing at the transmitter and/or the receiver, and results in an increase in average received signal-to-noise ratio (SNR) due to a coherent

combining effect. Transmit-receive array gain requires channel knowledge at the transmitter and receiver, respectively, and depends on the number of transmit and receive antennas. Channel knowledge at the receiver is typically available whereas channel state information at the transmitter is in general more difficult to obtain.
Array gain means a power gain of signals that is achieved by using multiple-antennas at transmitter and/or receiver. It is the average increase in the SNR at the receiver that arises from the coherent combining effect of multiple antennas at the receiver or transmitter or both. If the channel is known to the transmitter with multiple antennas, the transmitter can apply appropriate weight to the transmission, so that there is coherent combining at the receiver. The array gain in this case is called transmitter array gain. Alternately, if we have only one antenna at the transmitter and no knowledge of the channel, then the receiver can suitably weight the incoming signals so that they coherently add up at the output, thereby enhancing the signal. This is called receiver array gain which can be exploited in SIMO case. Essentially, multiple antenna systems require some level of channel knowledge either at the transmitter or receiver or both to achieve this array gain.

1.2.2 Diversity gain

In a wireless channel, signals can experience fadings. When the signal power drops significantly, the channel is said to be in a fade and this gives rise to high BER. Diversity is a powerful technique to mitigate fading in wireless links, so diversity is often used to combat fading. Diversity techniques rely on transmitting the signal over multiple (ideally) independently fading paths over time, frequency, space, or others. Spatial (or antenna) diversity is preferred over time/frequency diversity as it does not incur expenditure in transmission time or bandwidth.
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 plays an important role in combating fading and co-channel interference and avoiding error 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: This type of diversity provides replicas of the original signal in the frequency domain. The signals are transmitted using several frequency channels or the signals are spread over a wide spectrum that is affected by frequency-selective fading. The former method can be found in coded-OFDM systems such as IEEE 802.11agn, WiMAX, and LTE, and the latter method can be found in CDMA systems such as 3GPP WCDMA.
- Multiuser diversity: Multiuser diversity is obtained by opportunistic user scheduling at either the transmitter or the receiver. Opportunistic user scheduling is as follows: the

transmitter selects the best user among candidate receivers according to the qualities of each channel between the transmitter and each receiver. In FDD systems, a receiver typically feedback the channel quality information to the transmitter with the limited level of resolution.

- Space diversity (antenna 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 transmit antennas (transmit diversity) and/or multiple receive antennas (receive 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, MIMO channels and Space–time coding (STC). Space diversity can be further classified as follows.

- Receive diversity: Maximum ratio combining is a frequently applied diversity scheme in receivers to improve signal quality
- Transmit diversity: In this case we introduce controlled redundancies at the transmitter, which can be then exploited by appropriate signal processing techniques at the receiver. There are open loop transmit diversity where transmitter does not require channel information and closed loop transmit diversity where transmitter requires channel information to make this possible. Closed loop transmit diversity is sometimes regarded as a Beamforming. Space-time codes for MIMO exploit both transmit as well as receive diversity schemes, yielding a high quality of reception.
- Polarization diversity: Multiple versions of a signal are transmitted and/or received via antennas with different polarization. A diversity combining technique is applied on the receiver side.
- Cooperative diversity: Achieves antenna diversity gain by using the cooperation of distributed antennas belonging to each node.

1.2.3 Multiplexing gain

Spatial multiplexing gain is achieved when a system is transmitting different streams of data from the same radio resource in separate spatial dimensions. Data is hence sent and received over multiple channels - linked to different pilot signals, over multiple antennas. This results in capacity gain at no additional power or bandwidth.

Spatial multiplexing is transmission techniques in MIMO wireless communication to transmit multiple data signals from each of the multiple transmit antennas. Therefore, the space dimension is reused, or multiplexed, 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 is

$$N_s = \min(N_T, N_R). \tag{1-1}$$

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 practical multiplexing gain can be limited by spatial correlation and the rank property of the channel, which means that some of the parallel streams may have very weak or no channel gains.

1.2.4 Interference reduction

Fig. 1.2 presents a *K*-user MIMO interference channel with *K* transmitter and receiver pairs. The *k*-th transmitter and its corresponding receiver are equipped with M_k and N_k antennas respectively. The *k*-th transmitter generates interference at all $l \neq k$ receivers. Assuming the communication channel to be frequency-flat, the $C^{N_k \times 1}$ received signal y_k at the *k*-th receiver, can be represented as

$$y_k = H_{kk}x_k + \sum_{\substack{l=1 \\ l \neq k}}^{K} H_{kl}x_l + n_k, \tag{1-2}$$

where $H_{kl} \in C^{N_k \times M_l}$ represents the channel matrix between the *l*-th transmitter and *k*-th receiver, x_k is the $C^{M_k \times 1}$ transmit signal vector of the *k*-th transmitter and the $C^{N_k \times 1}$ vector n_k represents AWGN with zero mean and covariance matrix R_{nknk}. Each entry of the channel matrix is a complex random variable drawn form a continuous distribution. It is assumed that each transmitter has complete knowledge of all channel matrices corresponding to its direct link and all the other cross-links in addition to the transmitter power constraints and the receiver noise covariances.

We denote by G_k, the $C^{M_k \times d_k}$ precoding matrix of the *k*-th transmitter. Thus $x_k = G_k s_k$, where s_k is a $d_k \times 1$ vector representing the d_k independent symbol streams for the *k*-th user pair. We assume s_k to have a spatiotemporally white Gaussian distribution with zero

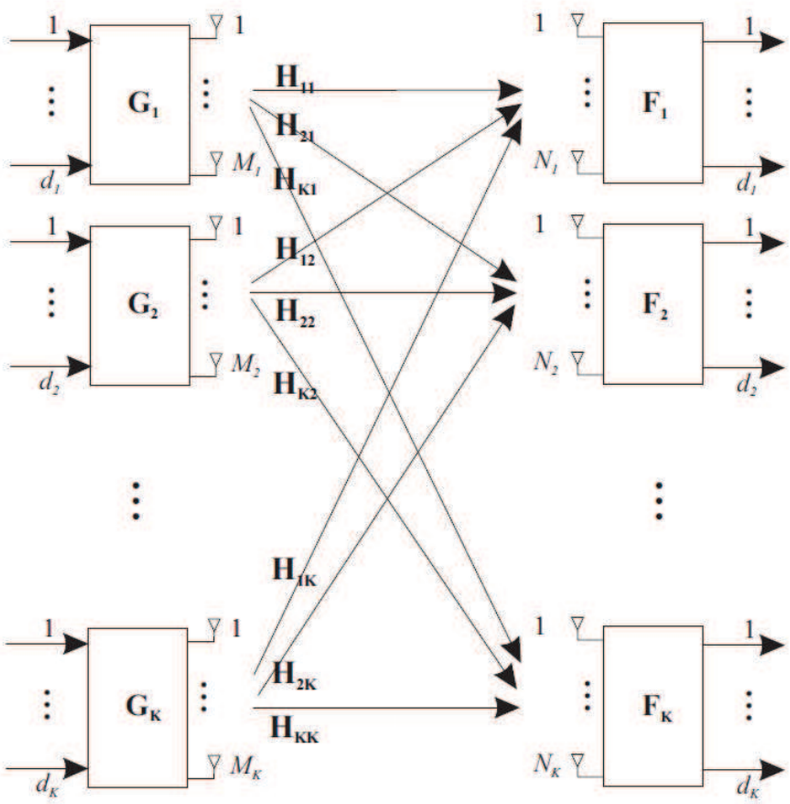


Fig. 1.2. MIMO Interference Channel

mean and unit variance, $s_k \sim \mathrm{N}(0, I_{dk})$. The k-th receiver applies $F_k \in C^{d_k \times N_k}$ to suppress interference and retrieve its d_k desired streams. The output of such a receive filter is then given by

$$r_k = F_k H_{kk} G_k s_k + \sum_{\substack{l=1 \\ l \neq k}}^{K} F_k H_{kl} G_l s_l + F_k n_k \tag{1-3}$$

Note that F_k does not represent the whole receiver but only the reduction from a N_k-dimensional received signal y_k to a d_k-dimensional r_k, to which further receive processing is applied.

Co-channel interference arises due to frequency reuse in MIMO wireless channels. When multiple antennas are used, the differentiation between the spatial signatures of the desired signal and co-channel signals can be exploited to reduce interference. Interference reduction requires knowledge of the desired signal's channel. Exact knowledge of the interferer's channel may not be necessary. Interference reduction can also be implemented at the transmitter, where the goal is to minimize the interference energy sent toward the co-channel users while delivering the signal to the desired user. Interference reduction allows aggressive frequency reuse and thereby increases multicell capacity. We note that in general it is not possible to exploit all the leverages of MIMO technology simultaneously due to conflicting demands on the spatial degrees of or number of antennas. The degree to which these conflicts are resolved depends upon the signalling scheme and transceiver design.

2. MIMO system

In this section, the MIMO channel model is discussed first, which are deterministic, and frequency flat or selective fading channels. This study will be carried out mathematical derivation of the capacity in each MIMO channel. We begin with basic system capacities which compare SISO, SIMO and MIMO, and then we explore to general case that the system has M_T transmit antennas and N_R receive antennas. Finally, fundamental capacity limits for transmission over MIMO channels is discussed

Many kinds of signal encoding schemes that support multiple antenna systems have well been studied [2]. Among them, the primary ones include Bell Labs Layered Space Time (BLAST), space-time trellis codes (STTC), space-time block codes (STBC) and cyclic delay diversity (CDD) and so on. So, the latter part in this chapter, we introduce STBC and STTC signal models for transmitter /receiver structure in MIMO system.

2.1 MIMO channel model

We consider MIMO channels with N_T transmit and N_R receive antennas. The block diagram of such a MIMO channel model is shown in Figure 2.1.

The channel matrix $\mathbf{H}$ is a $N_R \times N_T$ complex matrix with

$$\mathbf{H} = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,N_T} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,N_T} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_R,1} & h_{N_R,2} & \cdots & h_{N_R,N_T} \end{bmatrix}. \tag{2-1}$$

The component of the matrix **H**, $h_{i,j}$ is the coefficient of the each channel from the *j*th transmit antenna to the *i*th receive antenna. We suppose that the power of the received signal for each receive antennas is equal to the sum of transmit power $E_{s.}$ Consequently, we acquire the normalization value of the channel matrix **H**, for a deterministic channel condition as follow,

$$\sum_{j=1}^{N_T} \left| h_{i,j} \right|^2 = N_T, \quad i = 1,\ 2,\ \ldots,\ N_R. \tag{2-2}$$

If the channel coefficients are random, the normalization value will apply to the expected value. The received signal at *i*th receive antenna is given by

$$y(t) = \sum_{j=1}^{N_T} h_{i,j}(t) \cdot s_j(t) + n_i(t), \qquad i = 1,2,\ldots N_R\,, \tag{2-3}$$

where, $s_j(t)$ is the transmit signal at *j*th transmit antenna and $n_i(t)$ is additive white Gaussian noise (AWGN) in the receiver with zero mean and σ^2 variance. In above equation, a transmit signal $s_j(t)$ from each transmit antenna is added to the signal of each receive antenna.

2.1.1 Deterministic channel

To introduce the characteristics of the random channel matrix **H**, first we need to study the deterministic channel model. Coefficient of the deterministic channel model **H** is fixed on H. In other words, the deterministic channel coefficient H is known at the transmitter and receiver.

2.1.2 Flat fading channel

Suppose that the delay spread ($\tau_{\max}$) in the MIMO channel is much smaller than the signal bandwidth (*BW*), i.e., $\tau_{\max} << 1/BW$, the channel is said to be frequency flat fading channel. Frequency flat fading channel has the properties that are known to be exact in non line-of-sight (NLOS) environment with rich scattering and sufficient antenna spacing between transmitter and receiver antennas.

2.1.3 Frequency selective fading channel

Similarly, if the signal bandwidth and MIMO channel delay spread product satisfies $\tau_{\max} >> 0.1/BW$, the MIMO channel is said to be frequency selective. The transfer function of the frequency selective MIMO channel is as follow,

$$\mathbf{H}(f) = \int_0^\infty \mathbf{H}(\tau) \exp(-j2\pi f\tau) d\tau\ . \tag{2-4}$$

2.2 Capacity of each MIMO channel

In this subsection, the capacity of the MIMO channels is introduced. The capacity is defined as the maximum possible transmission rate when the probability of error is almost zero. The capacity of MIMO channel is defined,

$$C = \max_{f(s)} I(\mathbf{s};\mathbf{y})\ , \tag{2-5}$$

where, *f(s)* is the probability distribution function (PDF) of the transmit signal vector **s** and *I(***s**;**y***)* is the mutual information between transmit signal vectors **s** and receive signal vector **y**. The mutual information is given by

$$I(\mathbf{s};\mathbf{y}) = H(\mathbf{y}) - H(\mathbf{y}\,|\,\mathbf{s}), \tag{2-6}$$

where, $H(\mathbf{y})$ is the entropy of the receive signal vector **y**, and $H(\mathbf{y}\,|\,\mathbf{s})$ is the conditional entropy of the receive signal vector **y**. The conditional entropy $H(\mathbf{y}\,|\,\mathbf{s})$ is identical to $H(\mathbf{n})$ because the transmit signal vector **s** and noise vector **n** are independent. So, equation (2-6) is written as

$$I(\mathbf{s};\mathbf{y}) = H(\mathbf{y}) - H(\mathbf{n}). \tag{2-7}$$

For maximize the mutual information, *I(**s**;**y**)*, reduces to maximizing $H(\mathbf{y})$. Consequently, mutual information *I(***s**;**y***)* in equation (2-7) is given by,

$$I(\mathbf{s};\mathbf{y}) = \log_2 \det(\mathbf{I}_{N_R} + \frac{E_S}{N_T N_0}\mathbf{H}\mathbf{R}_{\mathbf{SS}}\mathbf{H}^H) bps/Hz, \tag{2-8}$$

where, $\mathbf{I}_{N_R}$ is an $N_R \times N_R$ identity matrix, E_S is the power across the transmitter irrespective of the number of antennas N_T, $\mathbf{R}_{\mathbf{SS}}$ is the covariance matrix for transmit signal and the superscript H stands for conjugate transposition. From equation (2-8), the general capacity of the MIMO channel is

$$C = \max_{\mathbf{R}_{\mathbf{SS}}, tr(\mathbf{R}_{\mathbf{SS}})=N_T} \log_2 \det(\mathbf{I}_{N_R} + \frac{E_S}{N_T N_0}\mathbf{H}\mathbf{R}_{\mathbf{SS}}\mathbf{H}^H) bps/Hz. \tag{2-9}$$

2.2.1 Capacity of a deterministic MIMO channel

As we mentioned previous, the deterministic channel coefficient H is known at the transmitter and receiver. However, to acquire channel coefficient at the transmitter is very difficult in practical MIMO systems. In the case that the MIMO system do not knows the channel coefficient at the transmitter, generally called an open-loop system, it is a good assumption that the transmitted signals from each transmit antenna has equal power. This condition results in the covariance matrix is identical to the identity matrix, $\mathbf{R}_{\mathbf{SS}} = I_{N_T}$. So, from equation (2-8), equal powered mutual information is given by,

$$I(\mathbf{s};\mathbf{y})_{eq} = \log_2 \det(\mathbf{I}_{N_R} + \frac{E_S}{N_T N_0}\mathbf{H}\mathbf{H}^H) bps/Hz, \tag{2-10}$$

where the subscript "eq" stands for "equal power".

Mutual information in equation (2-10) can be calculated by positive eigenvalues of the channel matrix $\mathbf{H}\mathbf{H}^H$. If r is the rank of the matrix **H** and $\lambda_i, i = 1,2,\ldots r$ are the non-zero eigenvalues of the matrix $\mathbf{H}\mathbf{H}^H$, the mutual information in equation (2-10) is re-written as

$$I(\mathbf{s};\mathbf{y})_{eq} = \sum_{i=1}^{r} \log_2(1 + \frac{E_S}{N_T N_0}\lambda_i)\ bps/Hz. \tag{2-11}$$

2.2.2 Capacity of frequency selective fading MIMO channel

In this subsection, we discuss the capacity of MIMO channel in frequency selective fading condition. The capacity of frequency selective fading channel can be obtained by dividing the whole bandwidth into *N* sub-channel. This results in each sub-channel having *BW/N* bandwidth. If *N* is not sufficient large, each sub-channel is undergone frequency selective fading. So, we can derive the capacity of *i*th sub-channel of frequency selective fading channel is given by

$$I(\mathbf{s};\mathbf{y})_{i,fs} = \log_2 \det(\mathbf{I}_{N_R} + \frac{E_{S,i}}{N_T N_0}\mathbf{H}_i \mathbf{H}_i{}^H) bps / Hz, \tag{2-12}$$

where, subscript '*fs*' stands for 'frequency selective', $E_{S,i}$ is the energy allocated to the *i*th sub-channel and $\mathbf{H}_i$ is the $N_R \times N_T$ sub-channel matrix.

And the ergodic capacity of the frequency selective fading MIMO channel is given by [*H. Jafarkhani*(p.38)] as follow,

$$C_{fs} = \varepsilon\left[I(\mathbf{s};\mathbf{y})_{i,fs} \right]. \tag{2-13}$$

2.3 Transmit signal structure for space time block coding

In this subsection, the basics of the Alamouti STBC with two antennas at the transmitter is briefly introduced. A block diagram of the Alamouti's space time block encoder is shown in Fig. 2.1. The information sources are modulated with an *M*-ary modulation scheme. Then, the encoder takes a group of two modulated symbols. The each group consist of the two modulated symbol s_1 and s_2 in each encoding operation and then it sends to the transmit antennas according to the block code matrix,

$$S = \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix}. \tag{2-14}$$

In above equation (2-14), the first column stands for the first transmission symbol period and the second column stands for the second transmission symbol period. Similarly, the first row corresponds to the symbols which are transmitted from the first antenna and the second row corresponds to the symbols which are transmitted from the second antenna. In detail, the first antenna transmits s_1 and the second antenna transmits s_2 during the first symbol period at the same time. Similarly, for the second period, first antenna transmits $-s_2^*$ and simultaneously, second antenna transmits s_1^*. Note that superscript '*' stands for the complex conjugate of the symbol. By using the Alamouti's space time coding, we can transmit symbol both in space and time. This is "space time block coding".

Symbol groups of the each transmit antenna are given are

$$\begin{aligned} \mathbf{S}_1 &= [s_1, \ -s_2^*] \\ \mathbf{S}_2 &= [s_2, \ \ s_1^*] \end{aligned}, \tag{2-15}$$

where, $\mathbf{S}_1$ is the first symbol group from the first antenna and $\mathbf{S}_2$ is the second symbol group from the second antenna.

In equation (2-15), two group symbols are orthogonal each other. Here, orthogonal means

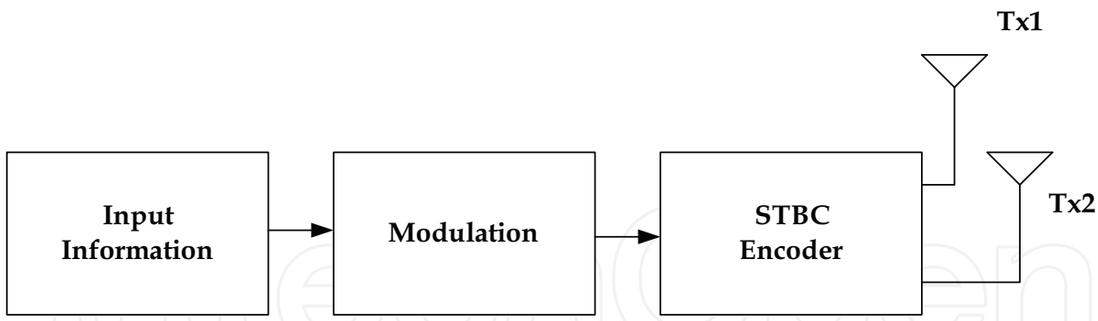


Fig. 2.1. A block diagram of the STBC system

that the inner product of $\mathbf{S}_1$ and $\mathbf{S}_2$ is zero. This orthogonal relationship is given by,

$$\mathbf{S}_1 \cdot \mathbf{S}_2 = s_1 s_2^* - s_2^* s_1 = 0 \,. \tag{2-16}$$

2.4 Receiver structure for space time block coding

If we suppose that the system has one antenna at receiver and two antennas at transmit antenna, the receiver structure is illustrated as Fig. 2.2.

The channel coefficient from transmit antenna 1 and 2 are defined as $h_1(t)$ and $h_2(t)$. As these channel coefficients are generally constant across two consecutive symbol periods, $h_1(t)$ and $h_2(t)$ are given by,

$$\begin{aligned} h_1(t) &= h_1(t+T) = \left|h_1\right| e^{j\theta_1} \\ h_2(t) &= h_2(t+T) = \left|h_2\right| e^{j\theta_2}, \end{aligned} \tag{2-17}$$

where $\left|h_i\right|$ and $\left|\theta_i\right|$ are the amplitude gain and phase shift for the path from each transmit antenna to the receive antenna.

At the receiver, the received signals can be expressed as,

$$\begin{aligned} r_1 &= h_1 s_1 + h_2 s_2 + n_1 \\ r_2 &= -h_1 s_2^* + h_2 s_1^* + n_2, \end{aligned} \tag{2-18}$$

where, n_1 and n_2 are independent complex variables with zero mean and unit variance, representing additive white Gaussian noise (AWGN) samples.

If the channel coefficients h_1 and h_2 can be recovered perfectly at the receiver, the received signal can be combined as follows,

$$\begin{aligned} \tilde{s}_1 &= h_1^* r_1 + h_2 r_2^* = (\alpha_1^2 + \alpha_2^2) s_1 + h_1^* n_1 + h_2 n_2^* \\ \tilde{s}_2 &= h_2^* r_1^* - h_1 r_2^* = (\alpha_1^2 + \alpha_2^2) s_2 - h_1 n_2^* + h_2^* n_1, \end{aligned} \tag{2-19}$$

and these estimated signals are sent to the maximum likelihood detector, which minimizes the following decision metric

$$\left|r_1 - h_1 s_1 - h_2 s_2\right|^2 + \left|r_2 + h_1 s_2^* - h_2 s_1^*\right|^2 . \tag{2-20}$$

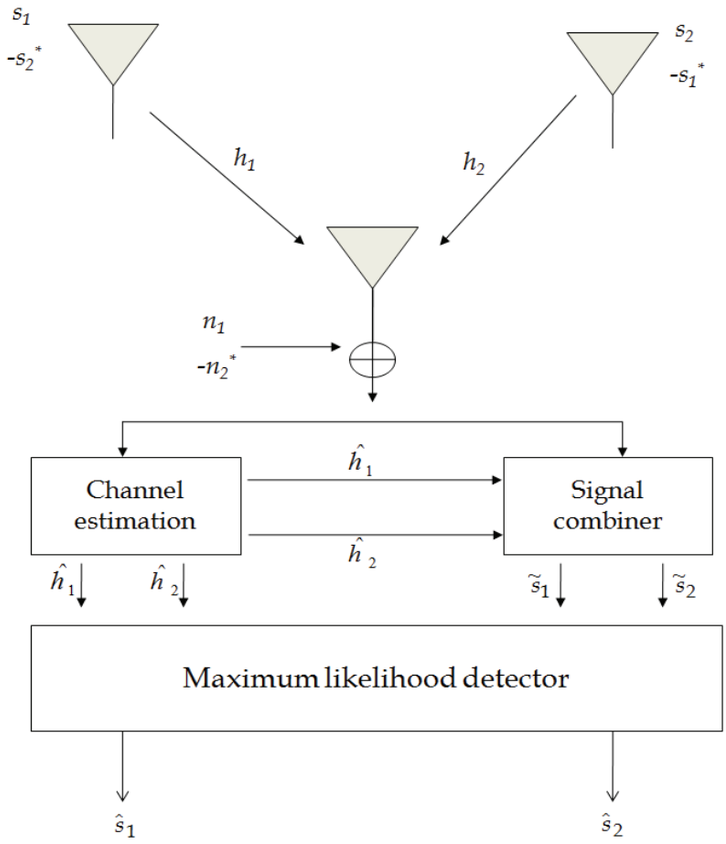


Fig. 2.2. Receiver structure for space time block coding

To expand and delete terms that are orthogonal of the code words, the equation (2-20) is reduced by [*H. Jafarkhani* (p.57)] to,

$$\left|r_1 h_1^* + r_2^* h_2 - s_1\right|^2 + (\alpha_1^2 + \alpha_2^2 - 1)\left|s_1\right|^2, \tag{2-21}$$

And,

$$\left|r_1 h_2^* - r_2^* h_1 - s_2\right|^2 + (\alpha_1^2 + \alpha_2^2 - 1)\left|s_2\right|^2. \tag{2-22}$$

Finally, for PSK signal, maximum likelihood detector calculate signal as follow,

$$d^2(\hat{s}_j, s_i) \le d^2(\hat{s}_j, s_k) \qquad \forall i \ne k, \tag{2-23}$$

where, $d^2(x,y) = (x-y)(x^* - y^*) = \left|x-y\right|^2$.

3. Technology challenges and issues for MIMO-OFDM system

3.1 Data throughput

3.1.1 Adaptive modulation and coding

Adaptive modulation and coding (AMC) is a technical term used in wireless communications to achieve maximum data throughput. AMC denotes the matching of

coding, modulation and other parameters to the conditions on the channel, as the path loss, the interference, the sensitivity of the receiver and available transmitter power margin.
The MIMO-OFDM system typically consists of convolutional encoder, modulation, inverse fast Fourier transform (IFFT), injection of guard interval (GI) and pre-coder. And the multi-user MIMO OFDM system with AMC is depicted in Fig. 3.1.

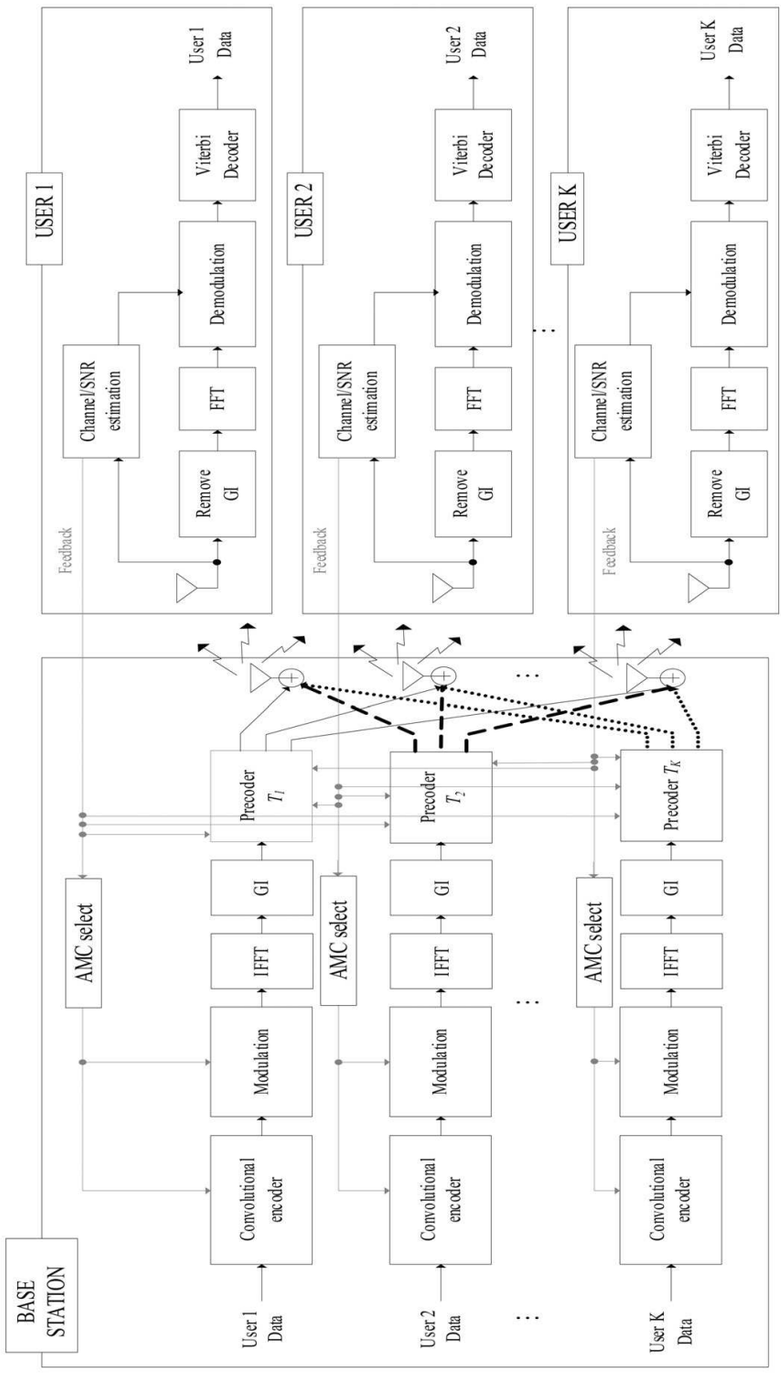


Fig. 3.1. Multi-user MIMO OFDM with AMC

The pre-coded signals are summed at each antenna of a base station. The pre-coding matrix is computed by using channel matrix which is estimated from the feedback from each user and base station.
As an example, the scheme here uses AMC that has 6 modulation and coding scheme (MCS) levels. The coding rate of convolutional encoder and the modulation order are changed per MCS level. MCS level is usually decided by SNR which is estimated and computed at the channel estimator of each user.
In Table 3.1, the coding rate and the modulation order are tabled according to SNR in the multi-user and the single-user system. The AMC of the scheme uses BPSK, QPSK, 16QAM modulation and 2/3, 1/2 coding rate at convolution encoder. The SNR range is defined as the SNR range that the error performance of each user is 10^{-4}.

AMC		SNR[dB] of Single-user (IEEE 802.11n)	SNR[dB] of Multi-user (IEEE 802.11n)
Modulation	Coding rate		
BPSK	1/2	0<SNR≤2.5	0<SNR≤2.5
	3/4	2.5<SNR≤4	2.5<SNR≤4
QPSK	1/2	4<SNR≤6.5	4<SNR≤7
	3/4	6.5<SNR≤19.5	7<SNR≤19.5
16QAM	1/2	19.5<SNR≤37	19.5<SNR≤38
	3/4	37<SNR	38<SNR

Table 3.1. AMC selection according to SNR

The process at the user's side is processed in reverse order of the side of the base station.

3.1.2 CP reduction algorithm

In wireless mobile communication systems, there are Doppler shift and delay spread that introduce significant problem to system performance. Doppler shift introduce the channel fading effect with frequency translation caused by movement of mobile station. Doppler shift will be positive or negative depending on whether the mobile receiver is moving toward or away from the base station. Delay spreads are resulted in multiple versions of the transmitted signals that arrive at the receiving antenna, it causes to displace with respect to one another in time and spatial orientation. The random phase and amplitudes of the different multipath components cause fluctuation in signal strength, thereby inducing small-scale fading, signal distortion, or both. Multipath propagation often lengthens the time required for the baseband portion of the signal to reach the receiver, which can cause signal smearing, which is known as inter-symbol interference (ISI).
To prevent ISI effects, first, OFDM divides the high rate data stream into a number of parallel sub-streams. Next, they are modulated onto different orthogonal sub-carriers, thus it has lower symbol rate, and then a cyclic prefix (CP) is added to the head of each symbol to try to eliminate the effect ofISI.
Although CP insertion highly improves the performance of OFDM systems, fixed CP length introduces overhead to overall system. For example, in 802.11a wireless local area network (WLAN) system where CP length is fixed by proportion 1/5 of data block size, the time and energy for CP are wasted.
To reduce the time and energy wasted, adaptive CPs length using correlation value of receive signals can be used. First, we do not consider the received signals whose power level

of received signal is lower than noise level, and then, search for correlation value between the first arrived signal and the last delayed signal. Finally, CP lengths are controlled by correlation value from the feedback information of receiver. To control the CP length, we assume that channel varies very slowly. So next symbol length applying adaptive CP control is added to some bit for minimization ISI. However, if every symbol's CP length is changed, next symbol's CP length is very short. For this reason, in deep fading channel condition, BER is increased.

Fig. 3.2 shows the OFDM system with adaptive CP length. Data block is fed to serial-to-parallel (S/P) block and is modulated by sub-carriers. The modulated data block is passed by IFFT as follow equation.

$$x_n = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} X_i \exp\left\{\frac{2\pi ik}{N}\right\}, \quad 0 \le i \le N, \tag{3-1}$$

Where, N represents the number of FFT points. CP, which is a proportion of data block size, is added to ahead of the data as shown in equation (3-2).

$$x_n^g = x(n)_N, \; n = -G, \cdots, 0, 1, \cdots, N-1. \tag{3-2}$$

where G represents length of CP. So, equation (3-3) represents signals with CP inserted. The signals that passed by channel can be represented as follow equation.

$$r_n(t) = x_n^g(t) * h_n(t) + n(t), \tag{3-3}$$

where, '$*$', n(t) and $h_n(t)$ are represent convolution sum, AWGN, and impulse response of the Rayleigh fading channel, respectively. Rayleigh fading channel has PDF as follow.

$$p(r) = \begin{cases} \dfrac{r}{\sigma^2} \exp\left(\dfrac{-r^2}{2\sigma^2}\right) & 0 \le r \le \infty \\ 0 & r < 0 \end{cases}. \tag{3-4}$$

where, σ^2 is the time-average power of the received signal.

Transmitted signals are received with reflection, refraction and diffraction. First, we do not consider the received signals whose power level of received signal is lower than noise level, and then, search for correlation value between the first arrived signal and the last delayed signal. Finally, CP lengths are controlled by correlation value from the feedback information of receiver in CP controller of Fig. 3.3.

As shown above Figures, CP length is controlled by correlation value and transmited / received signal are re-calculated as follow.

$$\tilde{x}_n^g = x(n)_N, n = -\tilde{G}, \cdots 0, \cdots, N-1, \tag{3-5}$$

$$r_n(t) = \tilde{x}_n^g(t) * h_n(t) + n(t). \tag{3-6}$$

We obtain the simulation results about data rate and power loss as to mobile speed. Fig. 3.4 shows the gain of data rate when mobile speed is 20km/h. Red line is the conventional OFDM system with fixed CPs length and blue line is the OFDM system with adaptive CPs length.

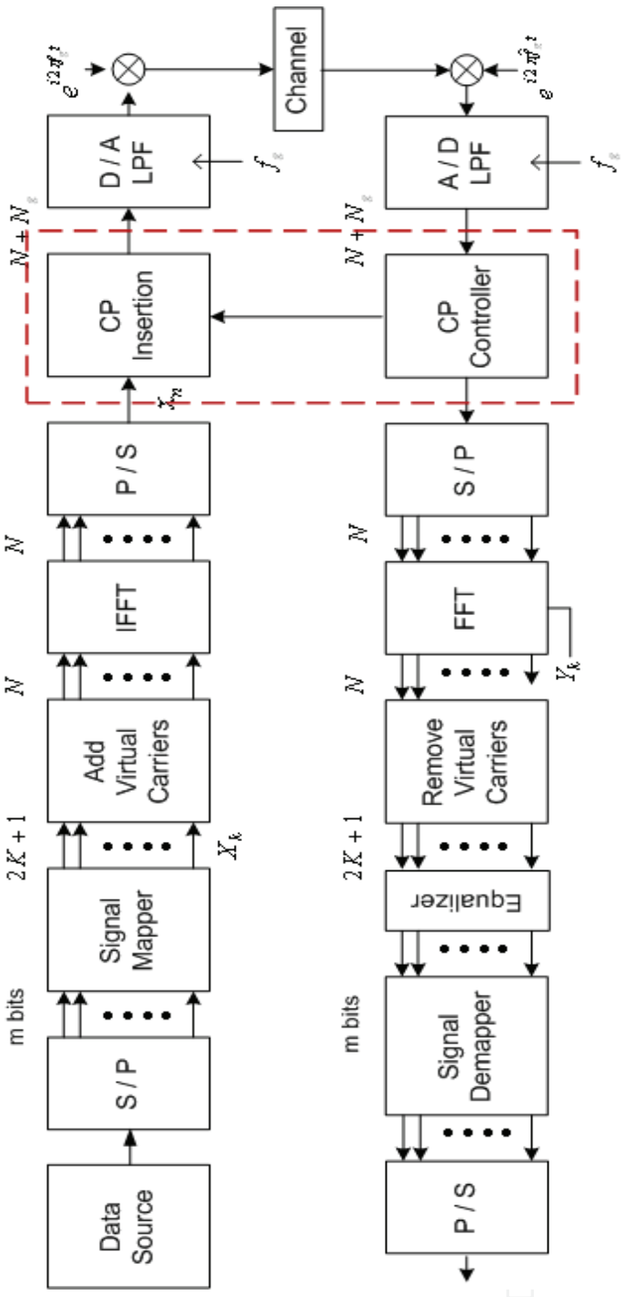


Fig. 3.2. OFDM system with adaptive CP length

In the case of using fixed CPs, there is no gain of data rate. However, the OFDM system using adaptive CP length is able to obtain the gain in data rate about 10Mbps with transmission of 1000 frames.

3.2 Antenna issues

Antenna element numbers and inter-element spacing are key parameters in MIMO system, and especially the latter is really important for the high spectral efficiencies of MIMO to be realized.

Base stations with large numbers of antennas pose environmental concerns. Hence, the antenna element numbers are limited to a modest number, with an inter-element spacing of around 10 λ .

The large spacing is because base stations are usually mounted on elevated positions where the presence of local scatterers to decorrelate the fading cannot be always guaranteed. As an example in four antenna system, four antennas can fit into a linear space of 1.5 m at 10 λ spacing at 2 GHz using dual polarized antennas. For the terminal, (1/2) λ spacing is usually

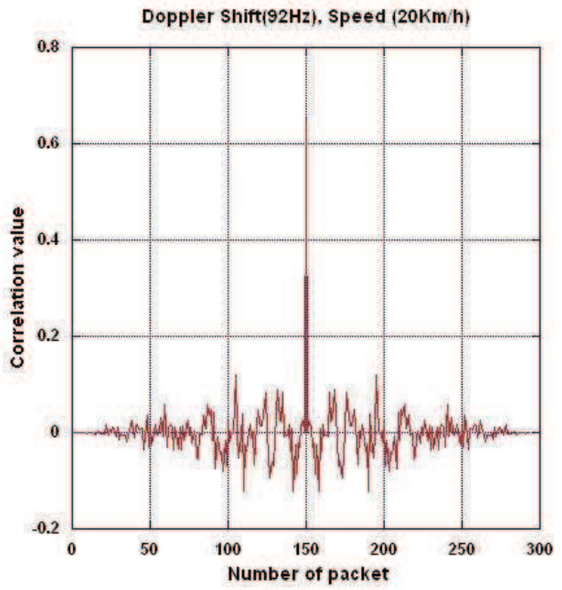


Fig. 3.3. Correlation value of received signals (20km/h)

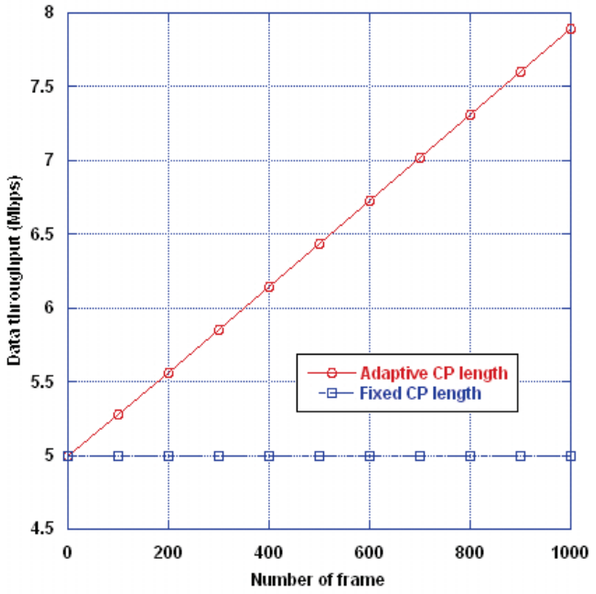


Fig. 3.4. Data rate of proposed scheme (20km/h)

sufficient to ensure a fair amount of uncorrelated fading because the terminal is present amongst local scatterers and quite often there is no direct path. The maximum number of antennas on the terminal is envisaged to be four (or more), though a lower number, say two, is an implementation option. Four dual polarized patch antennas can fit in a linear space of 7.5 cm. These antennas can easily be embedded in casings of lap tops. However, for handsets, even the fitting of two elements may be problematic. This is because, the present trend in handset design is to imbed the antennas inside the case to improve look and appeal. This makes spacing requirements even more critical.

3.3 Precoding schemes for multi-user MIMO system

Precoding scheme linearizes each layer of MIMO and makes beamforming possible. Default precoder can be unitary precoder based on Fourier matrix, and system can utilize specific precoder based on precoder codebook transimitted from mobile station. There are two types of precoder codebook, knockdown precoder and readymade precoder.

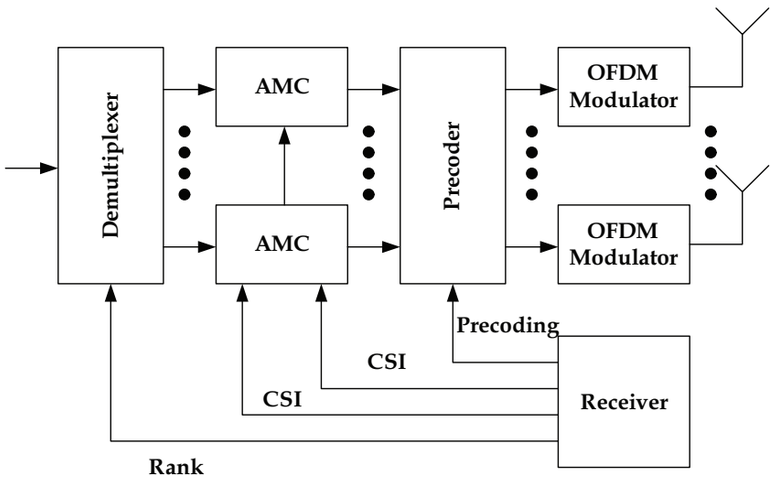


Fig. 3.5. MIMO-OFDM system with a precoder

Knockdown precoder uses the predefined matrix of prime numbers for the formulation of precoder. Then mobile device returns the information about suitable index and column of matrix. And the base station uses the information to select a precoder. This is typically referred to as codebook-based beamforming.

Readymade precoder utilizes the *M* predefined matrices for the precoder. The mobile device feeds the information about the index of the proper matrix back to the base station. Then the base station makes a use of the matrix.

3.4 System complexity

The implementation complexity of the MIMO system represents a substantial increase over existing devices. There are two primary areas of increased complexity associated with the MIMO system: RF and baseband processing. An assessment of FPGA implementation shows that a 2×2 implementation is roughly three times the baseband complexity of current devices. A 4×4 implementation is about eight times the baseband complexity of current devices. Given the continuous increase in transistor density, we anticipate that the baseband processing is not a significant cost driver for next-generation technology.

While additional RF receive and transmit chains are required to support MIMO, some parts of the chains, such as the local oscillator and clock generation circuitry, can be shared. In addition, the transmit power requirement per power amplifier decreases directly in proportion to the number of antennas employed.
Improved support for sleep and idle modes in the MAC will permit highly efficient power utilization for battery-powered devices, achieving charge cycles equivalent to or better than those cell phones achieve today.

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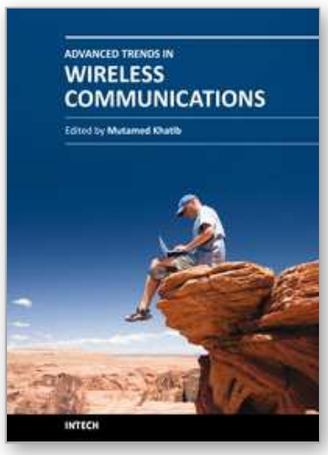
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Physical limitations on wireless communication channels impose huge challenges to reliable communication. Bandwidth limitations, propagation loss, noise and interference make the wireless channel a narrow pipe that does not readily accommodate rapid flow of data. Thus, researches aim to design systems that are suitable to operate in such channels, in order to have high performance quality of service. Also, the mobility of the communication systems requires further investigations to reduce the complexity and the power consumption of the receiver. This book aims to provide highlights of the current research in the field of wireless communications. The subjects discussed are very valuable to communication researchers rather than researchers in the wireless related areas. The book chapters cover a wide range of wireless communication topics.

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University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
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