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RF Transceiver Design for MIMO Wireless Communications

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Preface

The multiple-input multiple-output (MIMO) technique provides higher bit rates and better reliability in wireless systems. The efficient design of RF transceivers has a vital impact on the implementation of this technique. This first book is completely devoted to RF transceiver design for MIMO communications. The book covers the most recent research in practical design and applications and can be an important resource for graduate students, wireless designers, and practical engineers.

The book opens with an introduction to MIMO wireless communications, where the main advantages of using MIMO technique are described. This is followed by a discussion on the implementation techniques for MIMO modulators. After describing the fundamental concepts for RF transceivers and power amplifiers, the design and analysis methods for the RF section of MIMO transmitters and receivers are presented. Furthermore, the RF impairments in MIMO and OFDM systems, including nonlinearity, phase noise, I/Q imbalance and DC offset, are discussed; and, their compensation methods are presented. Finally, the design techniques for single RF front-end MIMO systems are described.

Audience

The book can be used by graduate students, researchers and design engineers in microwave and wireless design areas. It is assumed that the reader has a fundamental knowledge of communication circuit design and communication systems theory. The book may be used as a textbook for a graduate course on wireless transceiver design techniques.

Acknowledgments

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Finally, we would like to profoundly thank our spouses for their understanding and patience throughout the many evenings and weekends taken to prepare this book, as well as our parents for their encouragement and valuable support in our early professional years as graduate students and young researchers.

Contents

Chapter 1
Introduction

Multiple input multiple output (MIMO) wireless systems provide many advantages by using more than a single antenna. As such, it is considered in the current and future wireless standards. However, radio frequency (RF) transceiver design for MIMO wireless communications is a challenging task. This subject has been attracting research attention in both academia and industry. This chapter provides a general overview of MIMO systems and transceiver implementation.

1.1 Multiantenna Wireless Communications

Wireless communication systems are realized by using a transmitter, receiver and wireless channel. The classic implementation of these systems is usually a transmitter and its single antenna on the transmitting side and a receiver and its single antenna on the receiving side. The concept of using multiple antennas at receiver was introduced in the early 1960s [1]. The basic idea is the provision of multiple copies from a transmitted signal on the receiving side and their combination to obtain a signal with better performance. This technique is called the space diversity technique. To realize the receiver diversity technique, multiple antennas are employed on the receiver side. The antennas' output signals are then combined by applying different weighting coefficients, according to different diversity techniques.

Figure 1.1 shows the general diagram of the receiver diversity method. The receiver diversity may be realized using three different methods, selection combining, equal gain combining, and maximal ratio combining. In the selection combining method, the receiver selects the strongest signals among the antennas' outputs. This signal is processed in the single receiver. Maximal ratio combining is realized by weighting both the gain and phase of the received signals to maximize the signal-to-noise ratio (SNR) at the output of the receiver.

On the other hand, in the equal gain combining method, only the phases of the channel using weighting coefficients are cancelled. The maximum ratio combiner diversity technique provides the best performance to mitigate the wireless channel impact, while the selection diversity offers the simplest implementation technique among the different diversity methods [1].

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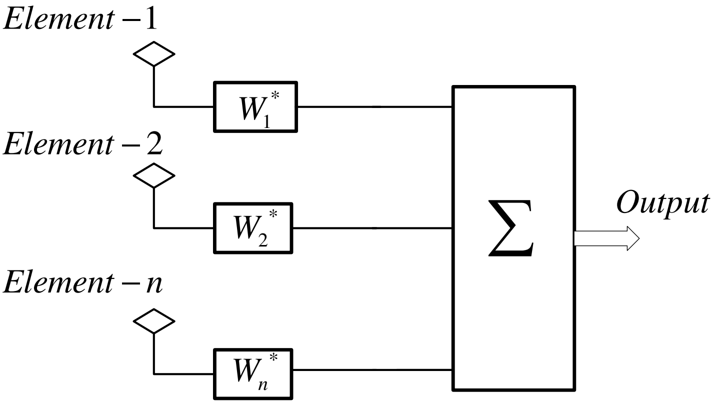

Fig. 1.1 Diagram of the receiver diversity technique

The receiver diversity technique is a special implementation for the use of multiple antennas. The multiple antenna technique can be used in both the transmitter and the receiver. This technique is generally known as a multiple input, multiple output (MIMO) system. The various realization techniques for MIMO systems are shown in Figure 1.2. A system that uses a single antenna on both the transmitting and receiving sides is called a single input single output (SISO) system.

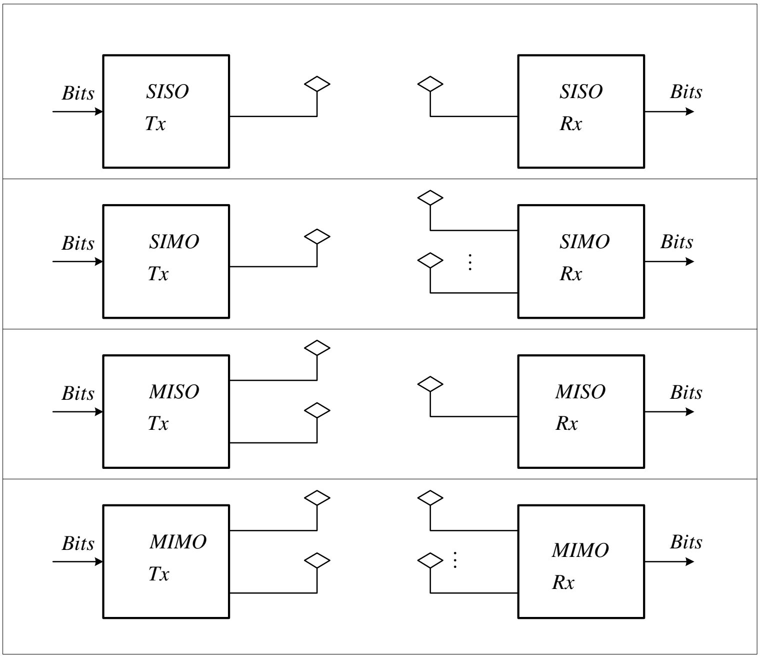

Fig. 1.2 Block diagram of multiple antennas systems

On the other hand, a system that employs a single antenna in the transmitter and multiple antennas in the receiver is called a single input multiple output (SIMO) system. Indeed, this system realizes the receiver diversity scenario. The idea of exploring the transmitter diversity was introduced in 1990s [2]. By using a similar notation, a system that uses multiple antennas at the transmitter and a single antenna in the receiver is called a multiple input single output (MISO) system. Likewise, the system that employs multiple antennas in the transmitter and multiple antennas in the receiver edges is the MIMO system.

A MIMO system with M_T transmitter antennas and M_R receiver antennas is shown in Figure 1.3. The input data is transmitted through M_T antennas after processing on the transmitter side. The processing includes channel coding, modulation, space-time encoding, spatial mapping, and RF up-conversion.

Each antenna transmits a signal through a wireless channel. Accordingly, all M_T simultaneous radiators operate as a transmitter.

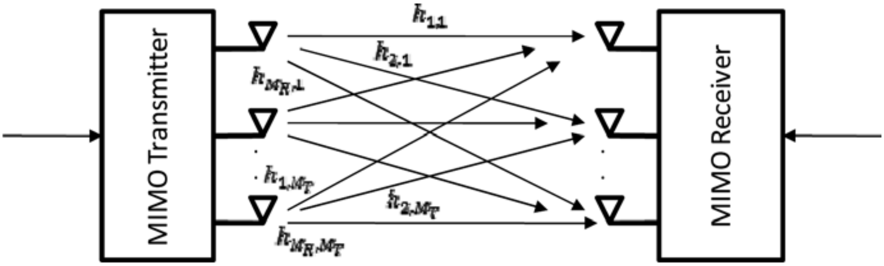

Fig. 1.3 General block diagram of MIMO systems

1.2 MIMO Wireless Transceivers

The art of designing modern wireless transceivers has seen extensive progress during the last two decades. The design of these transceivers generally must follow three main factors. They should be high performance, low cost, and able to handle the complex objectives of advanced wireless communication systems. A general block diagram of a wireless transceiver using multiple antennas in both the transmitter and the receiver is shown in Figure 1.4.

In recent transceivers, a great amount of signal processing is achieved in the baseband using digital signal processors (DSPs), application specific integrated circuits (ASICs), and field-programmable gate arrays (FPGAs). A signal at the output of the baseband section is up-converted to RF frequency using a heterodyne technique or a direct conversion method. A frequency synthesizer provides the carrier signal for up-conversion. The power amplifiers play a crucial role in providing the performance of the system. The RF front-end delivers the signal to the transmitter antennas. After passing through a wireless channel on the receiver side, the signals of the multiple antennas must be down-converted. This process includes RF signal processing using low noise amplifiers (LNAs), frequency synthesizing, and down conversion. Signals must then be delivered to the receiver baseband.

The excessive signal processing is performed in the receiver to detect the signals. Likewise, on the transmitter side, digital signal processing is carried by receiver digital circuits.

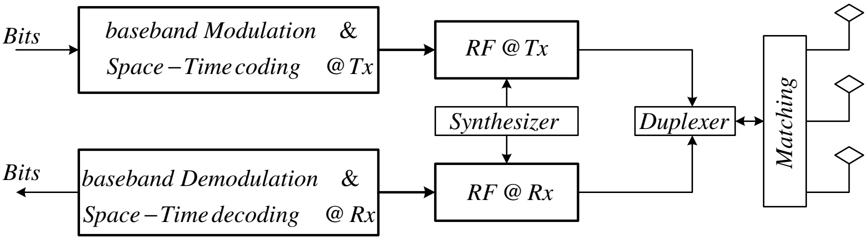

Fig. 1.4 Block diagram for MIMO wireless transceivers

1.3 MIMO Techniques in Commercial Wireless Systems

In a fading environment, the performance of a wireless link can be greatly improved by using multiple antennas on both the transmitting and receiving sides. These benefits include increased reliability as well as high data rates. A MIMO wireless communication system can be designed to take advantage of reliability improvement or increasing the data rate. The first improvement is called a diversity order improvement, and the latter is called spatial multiplexing. However, it has been shown that both types of gains can be simultaneously obtained using a fundamental tradeoff between them [4-5]. The application of the MIMO technique in wireless communications is aimed for both spatial multiplexing and diversity improvement.

Most wireless standards have been reconsidered regarding the usage of MIMO systems. In the case of wireless networking standards (IEEE 802.11x), the IEEE 802.11n amendment introduces MIMO in the physical layer of the network to improve the network throughput over previous standards. This increases the maximum data rate from 54 Mbps for the IEEE 802.11a/g standards to 600 Mbps for the IEEE 802.11n standard, using a 40 MHz bandwidth with MIMO capability. The MIMO technique is used in IEEE 802.11n wireless local area network (LAN) to provide spatial multiplexing.

The increased throughput comes from a mixture of changes to the way data packets are sent, along with the use of sophisticated radio techniques that demand high performance from the RF hardware. Multiple RF channels may be implemented with integrated transceivers and the same local oscillator (LO) with a separate front-end module. Figure 1.5 shows the main components for the IEEE 802.11n wireless LAN [3].

In addition, the World Interoperability for Microwave Access (WiMAX) standard also supports MIMO for both fixed and mobile WiMAX (IEEE 802.16e and IEEE 802.16m). Its MIMO feature is intended for high-speed applications, and it covers both space-time and spatial multiplexing codes [10]. The functional block diagram of a WiMAX IEEE802.16e from NXP Semiconductors (Philips) is shown in Figure 1.6 [11]. By using two antennas, this system provides a better performance for a wireless system.

The MIMO technique is also considered in the 3G (third generation) Long Term Evolution (LTE) standard, in order to increase the data rate to up to 277 Mbps in the downlink for a single user in an ideal radio link condition using a 4x4 MIMO system with a 20 MHz bandwidth [6]. Figure 1.7 shows a simplified block diagram of a LTE transceiver using two-channel reception [9].

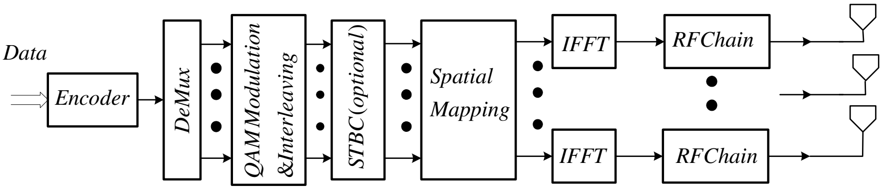

Fig. 1.5 Simplified block diagram of WLAN IEEE802.11n using MIMO

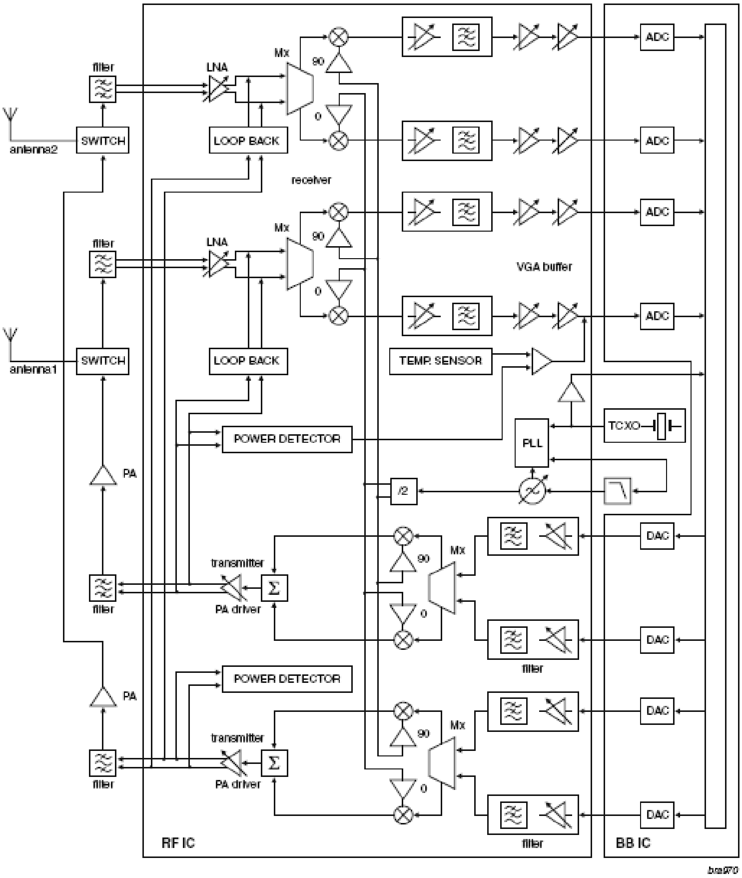

Fig. 1.6 Block diagram of WiMAX RF transceiver IEEE802.16e using MIMO from NXP [11]

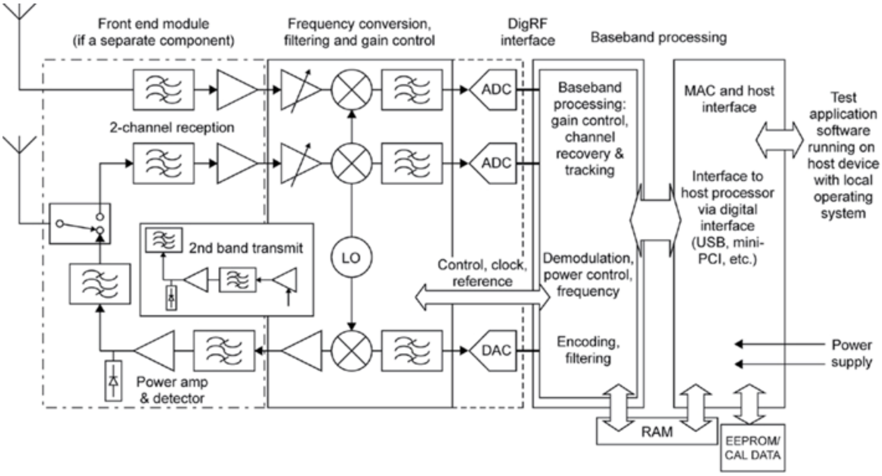

Fig. 1.7 Simplified transceiver block diagram of LTE [9]

1.4 Organization of the Book and Future Challenges

The book addresses some of the key design techniques for RF transceivers of MIMO wireless systems. Chapter 2 presents the fundamentals for understanding the multiple-antenna theory and advantages. This begins by presenting the MIMO system model, and MIMO channel models are the briefly discussed. This is followed by an examination of the MIMO capacity concept. The diversity gain and spatial multiplexing concepts are also introduced.

Chapter 3 deals with digital modulation techniques and orthogonal frequency-division multiplexing (OFDM) systems. After introducing the power efficiency and bandwidth efficiency concepts in digital modulation, the impact of fading channels on these modulators are discussed. The MIMO-OFDM technique and its implementation process are also discussed in this chapter. Chapter 4 provides a comprehensive overview of the fundamental concepts in wireless transceivers design. Chapter 5 covers the different subjects on RF power amplifiers and linearization techniques. The various power amplifier design techniques, including linear, high-efficiency and broadband techniques, are described. This is followed by a discussion on power amplifier linearization techniques. RF transceiver design for MIMO wireless communications is an active research area where more suitable architecture of MIMO transceiver is still an ongoing research topic [12-14].

Chapter 6 deals with transmitter design issues in MIMO wireless transceivers. The various transmitter architectures, such as heterodyne and direct conversion, are investigated. This is followed by the introduction of the transmitter design technique for MIMO applications. Chapter 7 presents the receiver design procedure for wireless MIMO communications. This chapter includes the commercial receiver design techniques for MIMO wireless communications. RF impairments in MIMO systems and their compensation techniques have been attracting the research attention in both academia and industry [15-18].

Chapter 8 discusses RF impairments and compensation techniques for OFDM wireless transceivers. The impairments include phase noise and power amplifier nonlinearities. The impacts of the impairments are also examined in this chapter, and the compensation techniques are presented. Chapter 9 discusses RF impairments and compensation techniques for MIMO wireless transceivers. The impairments include phase noise, DC offset, I/Q imbalance, and nonlinearities. The last chapter addresses the different alternatives in designing single RF front-end MIMO transceivers. The cost and complexity of the RF transceiver of a MIMO system increases linearly with an increasing number of antennas. The simple RF front-end design for MIMO systems is actively researched in both academia and industry [18-24].

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Chapter 2
MIMO Wireless Communications

The multiple input multiple output (MIMO) technique provides the higher bit rate and the better reliability in wireless systems. These advantages are achieved by designing appropriate apace-time codes that provide diversity improvement, spatial multiplexing gain, or a trade-off between diversity order and spatial multiplexing. This chapter provides an overoview on MIMO wireless system concept and its performance. Moreover, the MIMO channel models are discussed.

2.1 MIMO System

A multiple input multiple out (MIMO) system with M_T transmitting antennas and M_R receiving antennas is shown in Figure 2.1. The input data are transmitted through M_T antennas after processing on the transmitter side. The processing includes channel coding, modulation, space-time encoding, spatial mapping, and radio frequency (RF) up-conversion. Each antenna transmits a signal through a wireless channel. Accordingly, the M_T antennas simultaneously operate as an entire transmitter. The radiated signals are represented by a column vector ($\mathbf{x}$) that has $M_T \times 1$ dimensions. These signals, after passing through the wireless channel, are received by M_R receiving antennas.

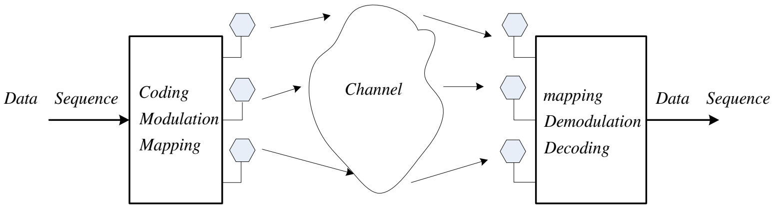

Fig. 2.1 Block diagram of a MIMO system

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2.2 MIMO Channel

The impulse response of a linear time-varying communication system between a transmitter and a receiver is used to describe the effects of a linear transmission channel.

2.2.1 SISO Channel Model

In the first step, a narrowband system using a single antenna at both the transmitter and the receiver is assumed (single input single out – SISO). The symbol period is assumed to be *T*. Moreover, the digital signal in discrete time may be represented by the complex time series $\{x_k\}$.

In this case, the transmitted signal is represented by:

$$x(t) = \sum_{m=-\infty}^{\infty} \sqrt{E_s}\, x_m \delta(t - mT) \tag{2.1}$$

where E_s is the transmitted symbol energy, assuming that the average energy constellation is normalized to unity. In a linear time-invariant (LTI) system, a function *h(t)* as the time-invariant impulse response of the channel can be considered [1]. If the signal $x(t)$ is transmitted, the received signal $r(t)$ is given by

$$r(t) = h(t) * x(t) + n(t) \tag{2.2}$$

where * denotes the convolution product, and *n(t)* is the additive noise of the system. Therefore, the input-output relation is represented as:

$$r(t) = \sum_{m=-\infty}^{\infty} \sqrt{E_s}\, x_m h(t - mT) + n(t) \tag{2.3}$$

One obtains the discrete representation of the received signal by sampling the received signal at the rate of *T*, (*r(kT)*) as:

$$\begin{gathered} r(kT) = \sum_{m=-\infty}^{\infty} \sqrt{E_s}\, x_m h[(k - m)T] + n(kT) \\ r[k] = \sum_{m=-\infty}^{\infty} \sqrt{E_s}\, x_m h[k - m] + n[k] \end{gathered} \tag{2.4}$$

As may be seen, a time-invariant channel can be represented as an LTI system and its sampled representation *h[k]*. The extension of this representation to a time-varying channel is completely straightforward [2], [4]. Moreover, there are different methods to extract the channel impulse response both in narrowband and broadband transmissions [3]. The channel impulse response generally depends on attenuation of the path loss term, shadowing, and multipath fading.

2.2.2 MIMO Channel Modeling

In MIMO systems, both the transmitter and receiver have several antennas. A MIMO system with M_T transmitting antennas and M_R receiving antennas is shown in Figure 2.2. In this system, the channel between each transmitting-receiving antenna pair can be modeled as a SISO channel. Accordingly, the channel matrix (**H**) for a MIMO system with M_T transmitting antennas and M_R receiving antennas may be obtained. By arranging all inputs and outputs in vectors, $\mathbf{x}[k]=[x_{1,k},...,x_{M_T,k}]^T$ and $\mathbf{r}[k]=[r_{1,k},...,r_{M_R,k}]^T$, the input-output relationship at any given time instant (k) is obtained as:

$$\mathbf{r}[k]=\sqrt{E_s}\,\mathbf{H}[k]\mathbf{x}[k]+\mathbf{n}[k] \tag{2.5}$$

where $\mathbf{H}[k]$ is defined as the $M_R \times M_T$ MIMO channel matrix in sampling time kT, and $\mathbf{n}[k]=[n_{1,k},...,n_{M_R,k}]^T$ is the sampled noise vector, containing the noise contribution at each receive antenna, such that the noise is white in both time and spatial dimensions as:

$$E\{\mathbf{n}[k]\mathbf{n}[m]\}=\sigma_n^2\mathbf{I}_{M_R}\delta[k-m] \tag{2.6}$$

where σ_n^2 is the Gaussian noise variance and $\mathbf{I}_{M_R}$ is the identity matrix. By normalizing the transmit symbol energy to unity, the received signal is shown to be:

$$\mathbf{r}=\mathbf{H}\mathbf{x}+\mathbf{n} \tag{2.7}$$

where $\mathbf{r}$ is the received column vector signal with dimensions of $M_R \times 1$ composed of the received signal, r_j; $\mathbf{n}$ is an $M_R \times 1$ column vector composed of the noise components, n_j; and, $\mathbf{H}$ is the $M_R \times M_T$ channel matrix with jith component being the channel coefficient, $h_{j,i}$. Accordingly, a MIMO system can be represented using the following matrix equation:

$$\begin{bmatrix} r_1 \\ \vdots \\ r_{M_R} \end{bmatrix} = \begin{bmatrix} h_{1,1} & \cdots & h_{1,M_T} \\ \vdots & \ddots & \vdots \\ h_{M_R,1} & \cdots & h_{M_R,M_T} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_{M_T} \end{bmatrix} + \begin{bmatrix} n_1 \\ \vdots \\ n_{M_R} \end{bmatrix} \tag{2.8}$$

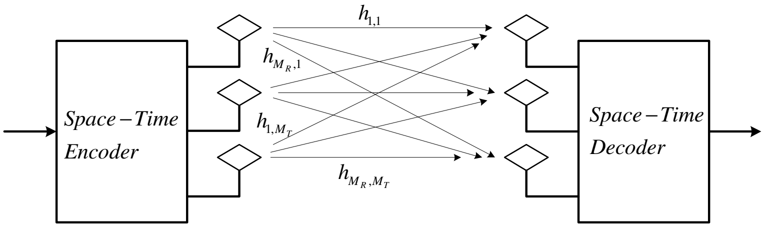

Fig. 2.2 MIMO channel

■ ***Example 2.1:*** *Independent and Identically distributed Rayleigh MIMO Channel*

If each individual channel coefficients is a zero-mean complex, circularly symmetric Gaussian variable or, equivalently, a complex variable whose amplitude and phase are Rayleigh and uniformly distributed, respectively, it is called a wide-sense stationary uncorrelated scattering homogeneous (WSSUSH) Rayleigh fading channel [4]. When the antenna spacing on both sides of the link is large enough, the various channel correlations become very small and can be assumed to be equal to zero [2]. The typical antenna spacing for negligible correlation is about $\lambda / 2$, where λ is the wavelength. Furthermore, if all individual channels coefficients are characterized by the same average power, the channel matrix is represented as $\mathbf{H}_w$. This is a random fading matrix with unit variance and circularly symmetric complex Gaussian entries. This channel, which uses the independent and identically distributed (i.i.d.) assumption, is represented by as $CN(0,1)$.

2.3 MIMO Capacity

The channel capacity is a fundamental limit on the rate of error-free messages that can be transmitted through a communication channel. In this section, the capacity of SISO and MIMO channels under fading are discussed.

2.3.1 SISO Capacity

The channel capacity for SISO communication systems over additive white Gaussian noise (AWGN) channels has been extracted by Shannon as:

$$C = B \log_2 (1 + \frac{S}{N}) \tag{2.9}$$

where C is the channel capacity in bit per second, B is the channel bandwidth in Hz, S is the transmitted power, and N is the noise power in the channel bandwidth.

Defining $\gamma \triangleq S/N$, the channel capacity for fading channels can be obtained as [5], [6]:

$$C = \int_0^\infty B \log_2(1+\gamma) p_\gamma(\gamma) d\gamma \tag{2.10}$$

where $p_\gamma(\gamma)$ is the probability density function of fading channel.

2.3.2 MIMO Capacity

MIMO systems with multiple antennas on both the transmitting and receiving sides have been considered. The capacity of MIMO systems can be expressed in bits per second per hertz (bps/Hz) as [4], [7]:

$$\begin{aligned} &C = \max\{\log_2 \det(I_{M_R} + \frac{\gamma}{M_T} H R_{ss} H^H)\} \\ &T_r(R_{ss}) = M_T \end{aligned} \tag{2.11}$$

where I_{M_R} is the identity matrix, H is the channel matrix with H^H being its transpose conjugate, $R_{ss} = E\{ss^H\}$ is covariance matrix of the transmit signal, γ gives the average signal-to-noise ratio (SNR) per receiver branch, and $T_r(.)$ represents the trace of a matrix. As can be seen, the channel capacity may be reached by choosing the optimal covariance structure for the transmitted signals. If the channel is unknown on the transmitter side, the transmitted signal can be considered spatially white, e.g., $R_{ss} = I_{M_T}$. Accordingly, the MIMO channel capacity for a sample deterministic realization is given by:

$$C = \log_2 \det(I_{M_R} + \frac{\gamma}{M_T} HH^H) \tag{2.12}$$

If the eigendecomposition of HH^H is represented as $Q\Lambda Q^H$, where Q is an $M_R \times M_R$ matrix satisfying $QQ^H = Q^H Q = I_{M_R}$ and $\Lambda = diag\{\lambda_1, \lambda_2, ..., \lambda_{M_R}\}$ with $\lambda_i \geq 0$, equation (2.12) can be written as:

$$C = \log_2 \det(I_{M_R} + \frac{\gamma}{M_T} Q\Lambda Q^H) \tag{2.13}$$

By using the identity of $\det(I_m + AB) = \det(I_n + BA)$ for A_{mn}, B_{nm} and using $QQ^H = Q^H Q = I_{M_R}$, the capacity relation may be written as:

$$C = \log_2 \det(I_{M_R} + \frac{\gamma}{M_T}\Lambda) \tag{2.14}$$

This relation equivalently may be represented as:

$$C = \sum_{i=1}^{r} \log_2 (1 + \frac{\gamma}{M_T}\lambda_i) \tag{2.15}$$

where r is the rank of channel and $\lambda_i \geq 0$ are the eigenvalues of HH^H [4].

Equation (2.12) can be also used to obtain the MIMO capacity in the fading channel. Extending equation (2.10) for an MIMO channel, the capacity of the MIMO channel under fading can be represented by:

$$C = E\{\log_2 \det(I_{M_R} + \frac{\gamma}{M_T} HH^H)\} \tag{2.16}$$

where the average is over the distribution of the elements of H.

In order to provide a clear idea about MIMO capacity, the asymptotic MIMO capacity should be examined. Assuming the spatially white Guassian channel ($CN(0,1)$) and using the law of large numbers considering large $M \, (M_T = M_R = M)$ [14], [7] yields:

$$\frac{1}{M} H_W H_W^H \to I_M \qquad M \to \infty \tag{2.17}$$

where H_W is the spatially white Gaussian channel. Accordingly, the capacity can be written as:

$$C = M \log_2 (1 + \gamma) \tag{2.18}$$

This interesting result shows that the capacity increases linearly with an increasing number of antennas.

The capacity of a single input multiple out (SIMO) system, which is also known as the receiver diversity, can be expressed as [7]:

$$C_{SIMO} = \log_2 (1 + \gamma M_R) \tag{2.19}$$

As can be seen, only the logarithmic improvement in capacity with increasing M_R is achievable in the SIMO system. For a random channel, this relation is valid for both the known channel state information (CSI) at the transmitter and the unknown CSI. This is due to the implementation of a single transmitting antenna. The capacity of the multiple input single output (MISO) channel when no CSI is provided at transmitter is obtained as:

$$C_{SIMO} = \log_2(1+\gamma) \tag{2.20}$$

The capacity of the MISO system with a known CSI at transmitter is expressed as:

$$C_{MISO} = \log_2(1+\gamma M_T) \tag{2.21}$$

■ ***Example 2.2:*** *Capacity Estimation for 2X2 MIMO System*

The capacity of a 2X2 MIMO system is presented in this example [25]. As shown in Figure 2.3, a MIMO system with polarized matched transmitting and receiving antennas is assumed. The antennas gains are 0 dBm.

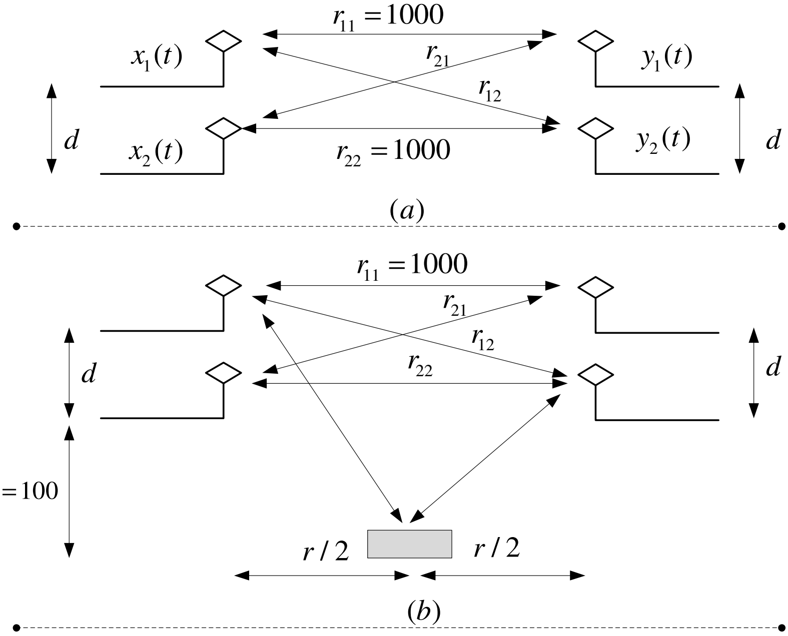

Fig. 2.3 Capacity estimation for 2X2 MIMO channel: a) without scattering b) with single scattering [25]

The communications system operates at 1.9 GHz with a 200 KHz bandwidth and a transmitting power of 1 mW. The noise temperature is 300 K. The capacity is calculated in the following cases:

Case I: *SISO Capacity*

The received power due to the propagation path loss is a function of frequency operation and is obtained as:

$$P_r = P_t G_t G_r \left(\frac{16\pi^2 d^n}{\lambda^2}\right)$$

where P_r, P_t are the receiving and transmitting powers; G_r, G_t are the receiving and transmitting antenna gains; d is the distance between the transmitter and the receiver; n is the path loss exponent, which is usually between 2 and 6; and, λ is the free space path length. In this example, it is assumed that n = 2. Using the above relations and equation (2.20):

$$\begin{aligned}
&P_r = 1.58\times10^{-13} W(-98dBm) \\
&N_o = kT_e B = 8.28\times10^{-16} W(-120.8dBm) \\
&\gamma = 22.8dBm \\
&C_{1\times1} = \log_2(1+\gamma) = 7.6 \qquad bps / Hz
\end{aligned}$$

Case II: *MIMO Capacity without Scattering*

As illustrated in Figure 2.3(a), by calculating **H** and using equation (2.15):

$$\mathbf{H} = \begin{pmatrix} e^{-jkr_{11}} & e^{-jkr_{12}} \\ e^{-jkr_{21}} & e^{-jk_{11}r_{22}} \end{pmatrix}$$

where $k = \omega\sqrt{\mu_0\varepsilon_0}$.

The capacity is obtained as:

$$if \qquad d = .5 \rightarrow \lambda_1 = 2.0, \lambda_2 = 0 \rightarrow C_{2\times2} = \sum_{i=1}^{2}\log_2\left(1+\frac{\gamma}{2}\lambda_i\right) = 7.6 \quad bps / Hz$$

$$if \qquad d = 10 \rightarrow \lambda_1 = 1.41, \lambda_2 = .6 \rightarrow C_{2\times2} = \sum_{i=1}^{2}\log_2\left(1+\frac{\gamma}{2}\lambda_i\right) = 12.95 \quad bps / Hz$$

***Case III:** MIMO Capacity with Single Scattering*

Similarly, as shown in Figure 2.3(b), by calculating **H** and using equation (2.15), the capacity is obtained as:

$$if \qquad d=.5 \rightarrow \lambda_1 = 2.14, \lambda_2 = .2 \rightarrow C_{2\times 2} = \sum_{i=1}^{2} \log_2(1+\frac{\gamma}{2}\lambda_i) = 12.01 \quad bps/Hz$$

***Case IV:** MIMO Capacity in a Rich Scattering Environment*

By using equation (2.18) and assuming a scenario of rich scattering, the capacity is obtained as *15.2 bps/Hz.*

2.4 MIMO Design Advantages

MIMO systems can be designed either to provide maximal diversity to increase transmission reliability or to achieve maximal multiplexing gain to support high data rates [8]. Equation (2.15) shows that the channel capacity of a MIMO system can be much higher than that of a SISO system. This performance of a MIMO system is quantified with spatial multiplexing gain. On the other hand, if the signal copies are transmitted from multiple antennas or received at more than one antenna, the multiple antenna systems can provide a gain that can improve reliability of a wireless link. This gain is called diversity gain.

Furthermore, MIMO systems can be used to simultaneously provide both diversity and multiplexing gain. However, there is a fundamental tradeoff between them, either in large SNR values [9] or finite SNR values [11].

2.4.1 Space-Time Codes for Diversity

In this design, the signal copies are transmitted from multiple antennas or received at more than one antenna in space-time multi-antenna systems. The average symbol error probability of a MIMO communications system for maximum likelihood (ML) detection is has an upper boundary in high SNR values as [4]:

$$p_e \le \overline{N_e}(\frac{\gamma d_{\min}}{4M})^{-M} \tag{2.22}$$

where $\overline{N_e}$ is the number of nearest neighbors in a scalar constellation, $d_{\min}$ is the minimum distance of separation of the scalar constellation, and $M=min\{M_R,M_T\}$.

As can be seen in Figure 2.4, increasing the number of antennas increases the slope of the bit error rate (BER) curves and improves the reliability of wireless communications. Two general techniques to generate the space-time codes for diversity are space-time block codes and space-time trellis codes [4], [7]. Although the space-time trellis codes were introduced earlier [12], the space-time block codes have been the preferred coding techniques in practice, due to the ease of their implementation.

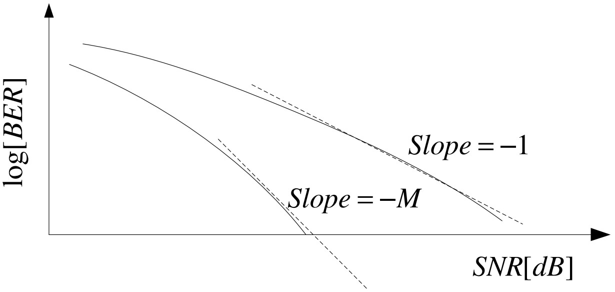

Fig. 2.4 Space-time diversity gain in MIMO systems

■ ***Example 2.3:*** *Alamouti Space-Time Coding*

The Alamouti code is an orthogonal space-time block code (O-STBC). It is implemented by using two antennas at the transmitter and an arbitrary number of the antennas at the receiver [10]. The code words for multiple antennas are written as:

$$\mathrm{X} = \frac{1}{\sqrt{2}} \begin{pmatrix} \chi_1 & -\chi_2^* \\ \chi_2 & \chi_1^* \end{pmatrix} \tag{2.23}$$

The Alamouti transmitter is shown in Figure 2.5. The Alamouti code has a spatial multiplexing rate equal to one, as two symbols are transmitted over two symbol durations. The performance of the Alamouti code is presented in Figure 2.6.

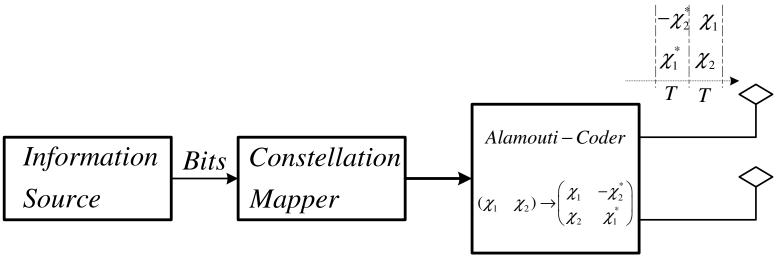

Fig. 2.5 The Alamouti space-time coding