Introduction to MIMO Systems

CHAPTER 1

1.1 Introduction

In this chapter, we will give introduction to MIMO (pronounced "My-Moe", J. G. Andrews et al., 2007) systems. First we will summarize some of the background in wireless communications which are required for better understanding of MIMO systems.

We will start with three diversity, viz. frequency, time and space diversity to combat detrimental effects of wireless fading channels.

Then we will discuss about the fading channel characteristics. We will define two important terms, viz. coherence bandwidth and coherence time. Then we will define what are frequency-flat and selective fading and slow and fast fading.

Then we will discuss about multi-antenna systems like Multiple-Input Multiple-Output (MIMO), Multiple-Input Single-Output (MISO) and Single-Input Multiple-Output (SIMO) systems. In SIMO systems, we will briefly discuss about the receiver diversity techniques like Equal-Gain Combining (EGC), Selection Combining (SC) and Maximal Ratio Combining (MRC).

In MIMO transmit diversity schemes we will define Open Loop, Close Loop and Blind MIMO systems.

MIMO systems have rate and diversity gain over Single-Input Single-Output (SISO) systems. We will define rate and diversity gain and discuss concisely about the diversity multiplexing trade-offs.

Finally we will mention some of the applications of MIMO systems.

1.2 Diversity in wireless communications

Wireless communications, which allow movement while communicating, is a very attractive feature for the mobile users. But it is a challenge to the wireless engineers because of channel fading due to random signal attenuation and phase distortions from the Multipath Components (MPCs). There are three diversity techniques (S. Haykin et al., 2005) to mitigate fading, viz.

(a) *Frequency diversity*: In frequency diversity techniques, we will send information bearing signals by carriers whose frequency gap is greater than coherence bandwidth of the channel; for instance, frequency hopped spread spectrum system.

(b) *Time diversity*: In time diversity techniques, we will send information bearing signals in different time slots which is greater than coherence time of the channel: for example, channel coding with interleaving and

(c) *Space diversity*: In space diversity techniques, we employ multiple antennas, which are placed amply far away, at the transmitter and receiver. Space diversity was left aside for many years in the literature due to the problem of spatial interference. We will explore this diversity in this book.

1.3 Wireless fading channel characteristics

The characteristics of wireless communication channels between the transmitter and receiver decide the performance of the wireless systems. Let us try to understand some terminologies of fading channel first. The time and frequency variations of the channel are quantified in terms of channel coherence time (D. Tse et al., 2005) and coherence bandwidth.

The *coherence bandwidth,* (B_c), is the frequency range, (Δf), over which the channel frequency response, $h(f)$, is flat and is inversely proportional to delay spread of the channel (R. Janaswamy, 2001 and A. K. Jagannatham, 2016). Assume a signal, $x(t)$, is sent over a channel with impulse response, $h(t)$, then the output of the wireless channel, $y(t)$, can be obtained as the convolution of $x(t)$ and $h(t)$ for a linear time invariant system. In the frequency domain, the convolution of $x(t)$ and $h(t)$ is transformed to multiplication of $X(f)$ and $h(f)$. If the bandwidth, B_s, of the signal is less than the coherence bandwidth, B_c, of the channel, then the output will be undistorted. On the contrary, if the bandwidth, B_s, of the signal is greater than the coherence bandwidth, B_c, of the channel, then the output will be distorted.

The motion of users in wireless communications gives rise to Doppler shift which in turn converts the wireless channel coefficient into time-varying and introduces time-selectivity in wireless channels. The *coherence time,* (T_c), is approximate duration of the time for which the wireless channel can be assumed constant, and is inversely proportional to the maximum Doppler frequency shift or spread, (B_d). Let us summarize.

(a) When coherence bandwidth is greater than signal bandwidth, then all frequency components of the signal will experience the similar kind of fading (*frequency-flat fading*).

(b) If coherence bandwidth is smaller than signal bandwidth, then all frequency components will not experience same fading (*frequency-selective fading*).

(c) When coherence time is greater than symbol time duration, it means channel variation is slower than the signal variation (*slow fading*).

(d) If coherence time is smaller than symbol time duration, it means channel variation is faster than the signal variation (*fast fading*).

Review question 1.1 *What is the coherence bandwidth of channel?*

Review question 1.2 *What is coherence time of channel?*

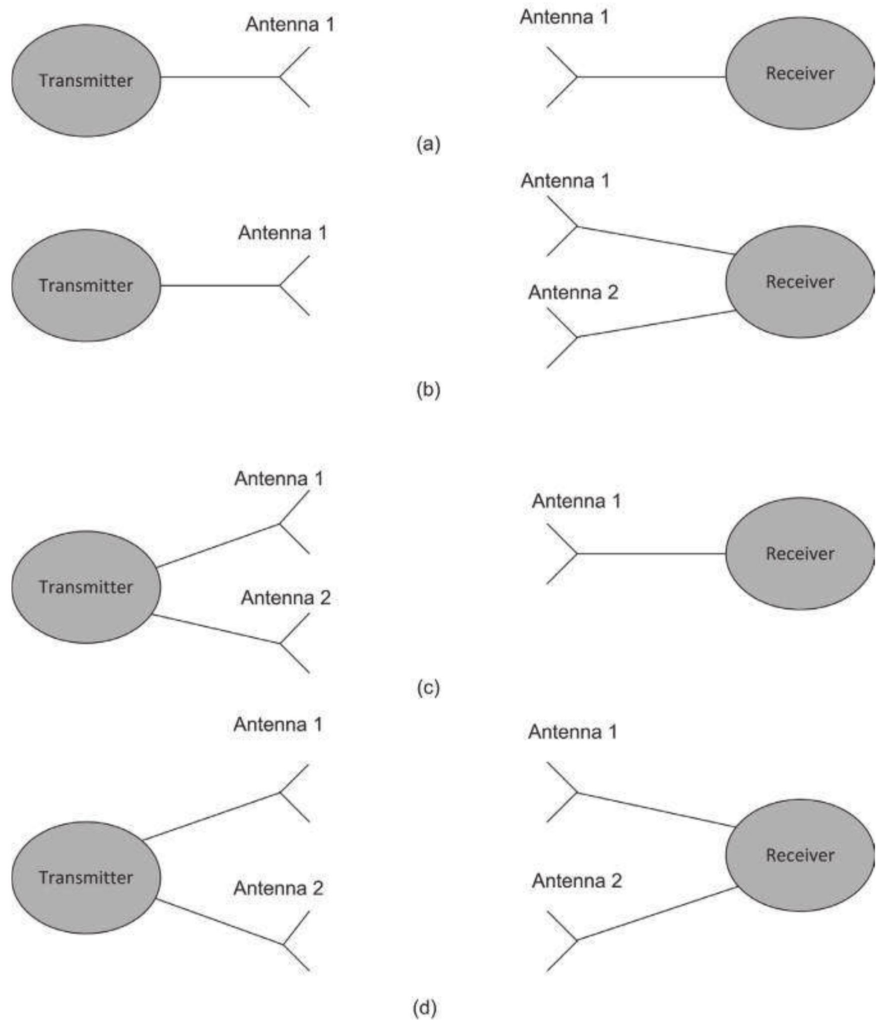

Fig. 1.1 (a) 1×1 SISO (b) 1×2 SIMO (c) 2×1 MISO and (d) 2×2 MIMO systems

1.4 What are MIMO systems?

Space diversity employing multiple antennas at the transmitter and receiver, also popularly known as Multiple-Input Multiple-Output (MIMO)/multi-antenna systems, are capacity boosters for wireless channels without penalty in bandwidth and power. The capacity of the channel increases linearly with the minimum of N_R or N_T for a $N_R \times N_T$ MIMO system in a rich Rayleigh scattering environment. N_T and N_R are number of transmitting and receiving antennas, respectively.

A particular case for $N_T = N_R = 1$ is referred to as *Single-Input, Single-Output (SISO) system,* which is the single link communication as depicted in Fig. 1.1 (a). Low-Density Parity-Check Code (LDPC) and Turbo codes with iterative decoding algorithms are the capacity booster for SISO systems.

Another particular case is for $N_T = 1$ and $N_R \geq 2$; such a system is referred to as *Single-Input, Multiple-Output (SIMO) system* (receive diversity). A 1×2 SIMO system is shown in Fig. 1.1 (b). Receiver diversity techniques like Equal Gain Combining (EGC), Selection Combining (SC) and Maximal Ratio Combining (MRC) can be employed at the receiver to combat multipath fading phenomenon. For SIMO systems, there are N_R channel links. SC selects the signal branch with the highest signal-to-noise ratio (SNR) among the N_R channel links. Each channel link will have different channel gain coefficients, path delays and phases. EGC co-phases signal on each branch and then combine them with equal weight. MRC outputs the weighted sum of all the branches. Weights are chosen as the complex conjugate of the channel gain coefficients. Branches with high SNR should be weighted more than with branches with low SNR. MRC is optimal in terms of SNR but complex to implement from the other two combining schemes (A. Molisch, 2005 and A. Goldsmith, 2005). We will discuss MRC briefly when we study Alamouti space-time codes.

Another particular case is for $N_T \geq 2$ and $N_R = 1$; such a system is referred to as *Multiple-Input, Single-Output (MISO) system* (transmit diversity). A 2×1 MISO system is depicted in Fig. 1.2 (c). Mobile station (MS) is generally small and receive diversity is not cost-impressive. Instead transmit diversity at the base station (BS) is a better choice.

But in 5G wireless communications, both receive and transmit diversities are envisaged. A *MIMO* system employing N_T transmitting antennas and N_R receiving antennas has both transmit and receive diversities (J. G. Proakis et al., 2007). A 2×2 MIMO system is also shown in Fig. 1.1 (d).

Review question 1.3 *What is the main advantage of MIMO system?*

Review question 1.4 *What is Equal gain combining?*

Review question 1.5 *What is Maximum ratio combining?*

Review question 1.6 *What is Selection combining?*

1.5 Which are the three cases of MIMO transmit diversity schemes?

Let us consider three types of transmit diversity (C. Yuen et al., 2007):

(a) *Closed loop MIMO system*: In closed loop MIMO system, feedback of channel gain and phase from the receiver is given to the transmitter. Hence Channel State Information (CSI) is available at both the transmitter and receiver. CSI could be of two types (T. Brown et al., 2012): instantaneous channel and statistical average of the channel (distribution of the channel).

(b) *Open loop MIMO system*: In open loop MIMO system, the receiver estimates the channel using the feed forward pilot signals but no feedback given to the transmitter. Hence CSI is available at the receiver and not at the transmitter. It is usually difficult to obtain the instantaneous CSI at the transmitter, but it is fairly possible to obtain CSI at the receiver by sending a training sequence or separate pilot signals.

(c) *Blind MIMO system*: In blind MIMO system, no channel state information is available at both the transmitter and receiver.

Pilot signals are sent orthogonal to the message signal either in frequency or time. For N_T transmit antenna an optimal pilot signal set comprises N_T mutually orthogonal signals with equal power, each assigned for a transmitting antenna (H. Huang et al., 2012). For slow fading, channel stability enables the receiver to acquire the CSI required for coherent detection of the transmitted code-word. In fast fading case, the channel coefficients vary fast and reliable channel estimation may not possible. In order to acquire CSI properly, we require more pilot signals resources than that of the slow varying channel. Hence, CSI is not available, and the receiver should operate in a non-coherent mode.

Review question 1.7 *What are non-coherent and coherent systems?*

1.6 Why MIMO systems?

In SISO system, data rate can be increased by either increasing the transmission bandwidth and power (a direct implication of Shannon's channel capacity formula, $C = BW \log_2 (1 + SNR)$, T. M. Cover et al. 1999). But frequency spectrum is a valuable resource and sometimes restricted for use, increasing transmission bandwidth is not acceptable solution for increasing data rate. Similarly, increasing transmission power is also not a proper solution for increasing data rate since we need highly expensive radio frequency (RF) amplifier. It will also reduce battery life time of mobile unit. Besides, there is the problem of higher interference with higher power. It may be considered unlawful by transmission regulations (H. Huang et al., 2012). MIMO increases the spectral efficiency without increasing the transmission power and bandwidth. Note that if the bandwidth is fixed, data rate and spectral efficiency could be used interchangeably. Basically two fundamental gains are achieved from MIMO systems (E. Biglieri et al., 2004):

(a) *Rate gain:* For parallel MIMO channels, there is at the most minimum $\{N_R, N_T\}$ rate gain from that of a SISO system. It is also known as multiplexing gain. In spatial multiplexing MIMO systems different data are sent through the parallel channels with the help of a serial to parallel converter as shown in Fig. 1.2 (a). It is a highly simplified model for easier understanding. It gives higher transmission rate.

(b) *Diversity gain:* The maximum number of independent paths travelled by each signals can be at the most $N_R \times N_T$. It is highly possible that not all the paths are highly faded. In this case, same data is sent through all the multiple antennas at the transmitter. If some of the paths are completely down, some paths will still be working. The receiver tries to make an efficient use of this to decode the data accurately. It gives higher link reliability.

For instance, the maximum data rate of a 3×3 MIMO system and diversity gains for a 2×2 MIMO system depicted in Fig. 1.2 (b) and (c) are 3 and 4, respectively. For 3×3 MIMO system of Fig. 1.2 (a) and (b), we may be sending bits in three parallel streams. Hence the data rate will be tripled. For 2×2 MIMO system of Fig. 1.2 (c), we may be sending same data stream over the four independent paths. So the data rate is the same with that of a SISO system. In this case, if any of the links/paths is down, the other link may be working. The receiver can decode the data stream correctly (with less probability of error) using the working link/path. This is possible because of the diversity gain. Assumption made is that the rank of the 3×3 MIMO channel is 3 and all the paths are independent for the 2×2 MIMO system. Other gains may be array gain and interference reduction gain which we will not discuss here.

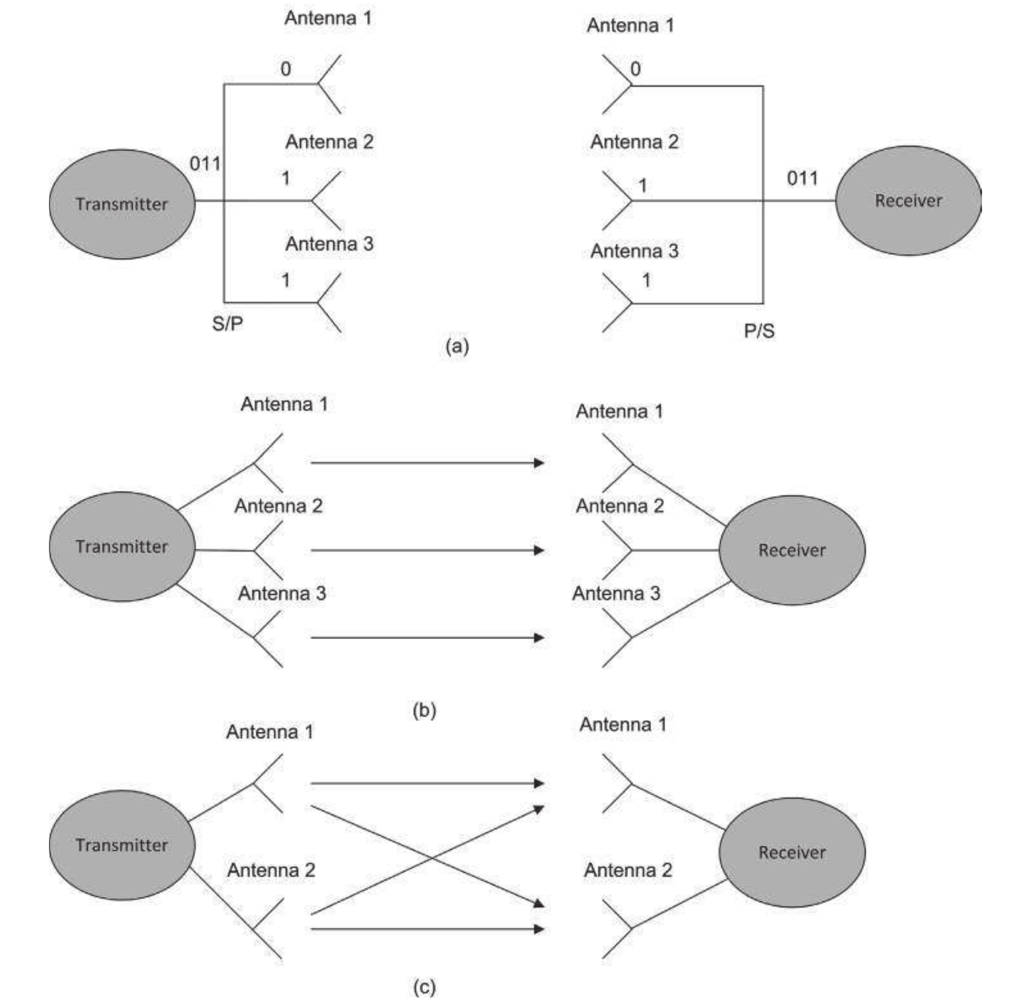

Fig. 1.2 (a) Spatial MUX 3×3 MIMO system (simplified case) (b) Rate gain of a 3×3 MIMO system, and (c) Diversity gain of a 2×2 MIMO system {S/P: Serial to parallel conversion; P/S: Parallel to serial conversion}

In fact there is trade-off, popularly known as *diversity-multiplexing trade-off,* between these two fundamental gains (diversity and rate gains). It is called *diversity-multiplexing trade-off* because if we increase diversity gain, rate gain automatically reduces and vice versa. MIMO system must be designed considering this trade-off. A simple characterization of this trade-off is given for block fading channel in the limit of asymptotically high SNR.

The rate gain is associated with the data rate of transmission. What is the exact relationship (mathematically)? Note that a transmission scheme is said to achieve *multiplexing gain r* if the data rate (bps) per unit Hertz, R (SNR) which is a function of SNR satisfy

$$r = \lim_{SNR \to \infty} \frac{R(SNR)}{\log_2(SNR)} \tag{1.1}$$

Hence the multiplexing gain is given by slope of the data rate for fixed frame error rate plotted as function of the SNR on a linear-log scale. The diversity gain is associated with the probability of error in detection. What is the exact relationship (mathematically)? A transmission scheme is said to achieve *diversity gain, d,* if the probability of error, P_e (*SNR*), as functions of SNR satisfies

$$d = -\lim_{SNR \to \infty} \frac{\log_2\{P_e(SNR)\}}{\log_2(SNR)} \tag{1.2}$$

Hence diversity gain is given by the negative of slope of frame error rate for a fixed transmission rate plotted as a function of SNR on a log–log scale. For a given *r*, the *optimal diversity gain, d_{opt}* (*r*), is the supreme diversity gain that can be accomplished by any MIMO system. It is shown (L. Zheng et al., 2003) that if the fading block length, $T \geq N_T + N_R - 1$, then, the optimal diversity gain can be calculated as

$$d_{opt} = (N_T - r)(N_R - r), 0 \leq r \leq \min(N_T, N_R) \tag{1.3}$$

The maximum value of rate gain *r* is always the minimum of (N_T, N_R) since we can have that many parallel data streams only. Note that if one employ entire transmit and receive antennas for enhancing diversity then one may achieve full diversity gain $N_T N_R$ (r = 0, it means we are not using any antenna for rate gain). Instead one may also employ a few antennas to augment data rate sacrificing the diversity gain.

For instance, we may consider the following case study for diversity-multiplexing trade-off.

Example 1.1

Assume that the multiplexing gain, (*r*), and diversity gain, (*d*), satisfy the diversity-multiplexing trade-off $d_{opt} = (N_T - r)(N_R - r)$ for SNR→∞. Assume $N_T = N_R = 7$ MIMO system with an SNR of 10 dB, one needs a spectral efficiency of R = 16 bps per Hertz. Find the supreme diversity gain such MIMO system can achieve.

Solution

Note that Shannon's channel capacity in bits/sec/Hz for a SISO link is $\log_2(1 + SNR)$. For high SNR case, it is approximately $\log_2(SNR)$. Our spatial multiplexing MIMO system here is equivalent to *r* parallel SISO channels (*r* parallel Gaussian channels) and its capacity is $r \log_2(SNR)$. With SNR = 10 dB, to get R = 16 bps, we require $r \log_2(SNR) = R$ which implies that $r \log_2(10^{1.0}) = 16$. Hence, r = 4.8165. Therefore five antennas may be used for multiplexing and remaining (7-2) two antennas may be used for diversity. The maximum diversity gain can be calculated as, $d_{opt} = (N_T - r)(N_R - r)$ = (7 – 5) (7 – 5) = 4. This means we are sending data over five parallel data streams only and we are utilizing four paths/links for decreasing the probability of error in detection.

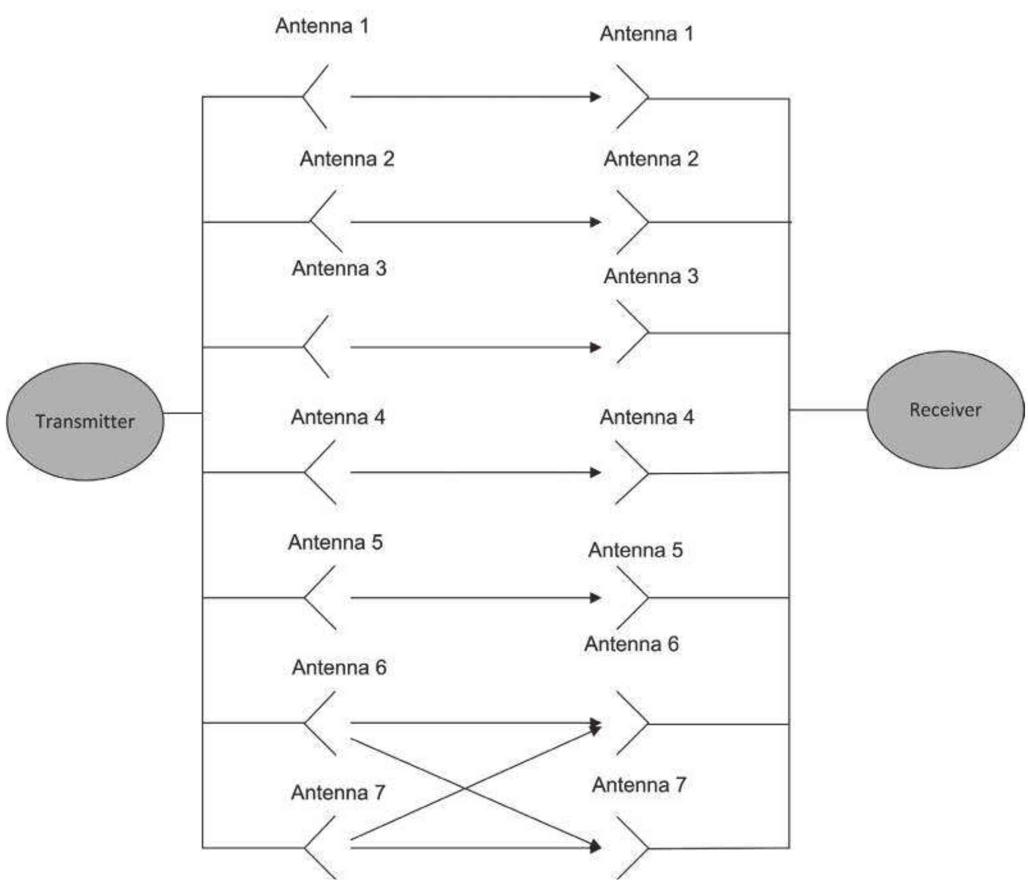

Fig. 1.3 Illustration of diversity-multiplexing trade-off of Example 1.1

Table 1.1
Diversity-multiplexing trade-offs for a 7×7 MIMO system

Serial No.	*Rate gain (r)*	*Diversity gain (d)*
1.	2	25
2.	3	16
3.	4	9
4.	5	4
5.	6	1

Similarly, there are other possible MIMO system designs as shown in Table 1.1.

1.7 Applications of MIMO systems

MIMO has been accepted in numerous wireless standards such as IEEE 802.11n (K.-L. Du et al., 2010 and N. Costa et al., 2010). Note that IEEE 802.11 standard is for wireless local area network (WLAN) applications, IEEE 802.15 standard is for wireless personal area networks (WPAN) and IEEE 802.16 standard is for wireless metropolitan area networks (WMAN). MIMO–OFDM may be employed for next generation WLANs. OFDM stands for Orthogonal Frequency Division Multiplexing. OFDM splits the information stream into N parallel sub-streams which are then transmitted by modulating onto N distinct orthogonal sub-carriers. Basically, it converts a high data stream into a number of low-rate sub-streams that are transmitted over parallel, narrowband channels that can be easily equalized.

MIMO is also envisaged for use in Fifth generation (5G) cellular downlink and uplink. MIMO–OFDM is used in wideband code division multiple access (WCDMA), CDMA 2000 (3 G mobile technology standards), IEEE 802.11n, IEEE 802.16m and 4G Long-term evolution (LTE). Spectral efficiency of 2–3 bits/sec/Hz is available in present cellular and WLAN systems. Bell Labs layered space time (BLAST) coding can achieve spectral efficiency of 42 bits/sec/Hz (B. Vucetic et al., 2003). MIMO-based Wi-Fi and Wireless Interoperability of Microwave Access (WiMAX) (IEEE 802.16 standard) systems are available in the market whereas MIMO-based High speed packet access (HSPA+) and Long term evolution (LTE) are in offing (A. Sibille et al., 2010). Nowadays, single user MIMO (base station to single subscriber and vice versa) is expanding into multiuser MIMO (base station to multiple users), network MIMO (multi-base station to single user), large-scale MIMO (with hundreds or thousands of transmitting and receiving antennas) and MIMO based cooperative communication and cognitive radios.

Review question 1.8 *What are the two gains achieved from MIMO systems?*

Review question 1.9 *What is diversity-multiplexing trade-off?*

Review question 1.10 *List some applications of MIMO systems.*

1.8 Summary

Figure 1.4 shows the chapter in a nutshell. In this chapter, we have discussed about wireless fading channels and diversity techniques. In fading channels, we have defined frequency-flat, frequency-selective, fast and slow fading channels. We have discussed briefly time, frequency and space diversity. We have defined SISO, SIMO, MISO and MIMO systems. In receiver diversity, we have mentioned about SC, EGC and MRC schemes. In transmit diversity, we have defined close loop, open loop and blind MIMO systems. We have also studied about rate and diversity in MIMO systems and their trade-off. Finally, we have mentioned some applications of MIMO systems.

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More Information

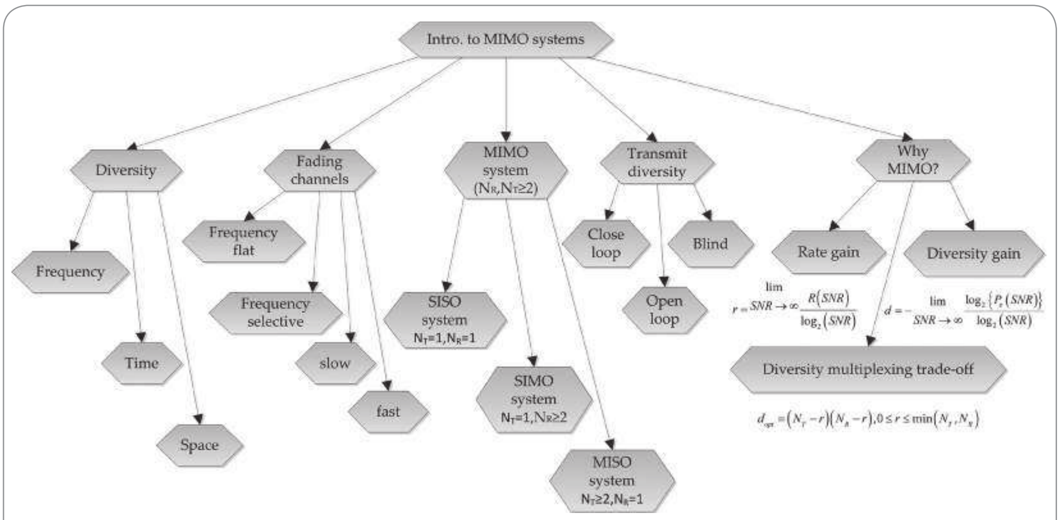

Fig. 1.4 Chapter 1 in a nutshell

Exercises

Exercise 1.1

Explain the two gains we can achieve from MIMO systems taking example for 4×4 MIMO system. Assume rich Rayleigh scattering environment.

Exercise 1.2

Define diversity and rate gain of a MIMO system.

Exercise 1.3

What are close loop, open loop and blind MIMO systems?

Exercise 1.4

Which diversity was left aside for many years? Why?

Exercise 1.5

What are frequency-flat, frequency-selective, fast and slow fading channels?