CHAPTER 2 | Air Interface Concepts

2.4 Multi-Antenna Operation and MIMO

This section describes the multi-antenna mechanisms adopted by LTE to increase coverage and physical layer capacity. It focuses largely on the air interface as many of the operational details of the system are left to the designers of the eNB.

Adding additional antennas to a radio system gives the possibility of fundamental performance improvements because the radiated signals will take different physical paths. There are three main application categories. First is to make direct use of path diversity in which one radiated path may be subject to fading loss and another may not. Second is to do beamsteering by controlling the phase relationship of the electrical signals radiated at the antennas to physically steer transmitted energy. Third is to put to use the path differences introduced by separating the antennas — i.e., spatial separation — through the use of spatial multiplexing or beamforming, also known as Multiple-Input Multiple-Output (MIMO) techniques.

The section begins with an overview of multi-antenna techniques and terms and an explanation of how spatial multiplexing works. The distinction between diversity and MIMO is also explained. Next comes a description of the signals and the hardware configurations for multi-antenna downlink operation, including the diversity techniques used at the eNB and UE and in Single User MIMO (SU-MIMO). The section continues with the uplink and explains how Multi-User MIMO (MU-MIMO) operates. These sections include basic information about the expected physical layer performance of the links. New terms such as layer, precoding and codeword are introduced. Having described the system operation and how MIMO in particular works, the section concludes with a description of the main features of open and closed loop operation and how diversity, beamsteering and MIMO can be combined.

2.4.1 Overview of Multi-Antenna Techniques

As shown in Figure 2.4-1, there are four ways to make use of the radio channel. For simplicity only those using one or two antennas are shown. The mode of operation changes once there is more than one antenna, and in theory, any number could be used.

The terms that describe the access modes, such as Multiple-Input Single-Output (MISO) and MIMO, use the labels input and output to refer to the channel, not the transmitters or receivers. The channel includes the transmission medium (the air), the antennas, and the cabling and analog circuits connected to the antennas. Thus antennas are vital components in the link. With multi-antenna operation, the physical relationship between the antennas becomes a new variable to deal with, affecting the relationship between the paths the signals take. The relationship between the paths is referred to as correlation.
The significance of the inclusion of analog circuits will become apparent when some of the LTE design challenges and measurements are covered in Chapter 6.

Employing a single antenna at the transmitter and a single antenna at the receiver, Single-Input Single-Output (SISO) is the most basic radio channel access mode. It is the default configuration referred to elsewhere in this book, and it gives the baseline for assessing the performance improvements possible when more antennas are used.

Single-Input Multiple-Output (SIMO) describes receive diversity, a method which isn’t generally dependant on the technology being used. SIMO is suited to low Signal to Noise Ratio (SNR) conditions; for example, due to cell edge operation or fading. There is no improvement in data rates, beyond what comes from improved signal robustness in low SNR conditions.

The colored arrows in the MISO and MIMO cases indicate the use of different user data for each transmitter. Multiple-Input Single-Output (MISO) is a transmit diversity technique and only requires a single receive antenna. It has been used for some time in cellular systems with Alamouti Space Time Block Coding (STBC), where it can offer significant gains in signal robustness under fading channel conditions but, like SIMO, does not improve data rates.

The use of STBC involves the duplication of data onto multiple antennas. The signals for additional antennas are distinguished by a combination of reversing the time allocation and applying a complex conjugation to part of the signal. Space Frequency Block Coding (SFBC) uses the Alamouti principle but copies data onto different frequencies instead of using blocks of time. In LTE, only SFBC is used.

More than one receive antenna can be used with MISO, but it is important to note that the simultaneous use of transmit and receive diversity, MISO plus SIMO, does not equal MIMO. There may be two transmitters and two receivers involved but still only one stream of data.

Figure 2.4-1. Radio channel access modes
To increase spectral capacity, MIMO operation relies on spatial multiplexing in which multiple input data streams are transmitted simultaneously. The terms MIMO and spatial multiplexing are generally synonymous, but some texts also use MIMO to describe MISO with more than one receiver.

### 2.4.2 MIMO Operation

The basics of MIMO operation can be understood by using a static, four port network to represent the channel, as shown in Figure 2.4-2. In this figure, two different signals are transmitted and received. At this point, there is no need to specify the intended destination of the data. It could be intended for one user or several users.

In the ideal case, to use the same frequency and time simultaneously, isolated connections would be established from transmitter 0 to receiver 0 and transmitter 1 to receiver 1. In practice, this is not possible, and there will inevitably be coupling between the signals as soon as they are transmitted. The challenge, therefore, is to reverse the coupling after the signals have been received. As with other radio systems such as IEEE 802.11 and 802.16, LTE uses a “non-blind” technique. Pre-defined orthogonal training signals are transmitted from each antenna. The receiver knows which training signal was used for each antenna and therefore can calculate the channel amplitude and phase responses, $h_{00}$, $h_{10}$ and $h_{11}$, $h_{01}$. Note that a convention of the channel matrix definition is to specify the receiver first; i.e., $h_{R,T}$. In this way the receiver can be informed of the transformation that the signals from each antenna have undergone. Since the unknown data is sent at or around the same time as the known training signals, the receiver can assume that the unknown part of the signal from each antenna has undergone the same transformation as the known part of the signal. In essence, MIMO is using a “trick”: known training signals are mixed with the randomly varying data in such a way that the unknown data can be recovered.
Conceptually, the simplest way to recover the unknown data is to multiply the received signals by the inverse of the channel matrix. In practice this zero forcing technique is vulnerable to noise, and more sophisticated techniques can be used that involve the minimizing of errors during the recovery process.

A key point to note about MIMO is that there must be at least as many receiving antennas as there are transmitted data streams. However, this number of streams should not be confused with the number of transmitting antennas, which may be higher than the number of streams if transmit diversity is mixed with MIMO. The minimum number of receivers is determined by what is mathematically required for the calculation of the channel matrix H. With fewer receivers, the composite received signal from more than one transmitter looks like interference.

This description of MIMO operation intentionally does not consider the source of the data. There is a lot of flexibility in how the two data streams can be used. In LTE, the source data for each stream can have different modulation and coding and does not need be associated with a single user.

It is necessary to consider how to design the training signals to suit the characteristics of the radio channel. In IEEE 802.11n, training signals take the form of a preamble. For more rapidly changing channels, and to suit the frame structure of the signal, LTE interleaves the known signal, called the Reference Signal (RS), throughout the frame in both frequency and time. The RS definition is different for the downlink and uplink. Figure 2.4-3 shows how the individual symbols of the reference signal are allocated to subcarriers for a two-antenna downlink signal. Note how the RS symbols are orthogonal on each antenna in both frequency and time. To see the full range of downlink RS allocations for single, dual and quad antenna configurations, see 36.211 [6] subclause 6.10.

![Figure 2.4-3. Orthogonal structure of downlink reference symbols for dual antenna (adapted from 36.101 [1] Figure 6.10.1.2-1)](image)

The RS allocation for the LTE uplink is very different from the downlink allocation. For data transmission the RS occupies all subcarriers for one symbol of each timeslot. This is explained in more detail in Section 3.2.8. At the time of this writing, uplink SU-MIMO has not been fully specified, although it is known that rather than using orthogonal time and frequency allocations for the RS to identify each antenna, the uplink will use different Zadoff-Chu phase sequences. This use of different codes in the same frequency and time is similar to the approach used for 802.11n.
As with any radio signal, signal recovery depends on the Signal to Noise Ratio (SNR). The Shannon-Hartley capacity theorem predicts the error-free capacity $C$ of a radio channel as:

$$C = B \log_2 (1 + SNR)$$

where

- $C$ = Channel capacity in bits per second
- $B$ = Occupied bandwidth in Hz
- $SNR$ = The linear signal-to-noise ratio

The performance of a MIMO system introduces additional simultaneous paths plus a further dependency, which is the cross-coupling of interfering signals between the different paths from each transmitting antenna to each receiving antenna through the radio channel. The long-form version of the channel capacity theorem can be written as:

$$C = B \left[ \log_2 \left(1+\frac{\sigma}{N}\rho_1^2\right) + \log_2 \left(1+\frac{\sigma}{N}\rho_2^2\right) \right]$$

where

- $\sigma/N$ = signal to noise ratio and $\rho$ = a singular value of the channel matrix, $H$.

It is useful to highlight the potential asymmetry in performance between the streams in a MIMO link. In the ideal, but impractical, case of no cross-coupling, the values of $\rho_i$ will be 1, 1 indicating a doubling of channel capacity. However, in the case of total in-phase coupling, the values of $\rho_i$ will be 2, 0 indicating that the capacity has dropped back to that of a SISO channel. Note that in either case, for a fair comparison, the equivalent SISO transmitter power is shared between each MIMO stream.

The potential increase in instantaneous system capacity can be derived from the ratio of singular values of $H$, also known as the condition number. The condition number can also be used to indicate the increase in SNR needed to recover the MIMO signal, relative to the SISO case.

From the above the following can be concluded:

- For the 2 x 2 case the increase in channel capacity will not exceed twice the SISO case, and achieving this may require a substantial improvement in SNR at the receivers if the values of $\rho_i$ are < 1.
- If the matrix coefficients are known by the transmitters, the asymmetry in stream performance can allow a higher order modulation format on the stronger stream, or the outgoing signals can be modified (precoded) to equalize the performance between the streams. Precoding requires real time feedback from receiver to transmitter, so this is also known as closed loop MIMO. The relative signal phase between transmitters must be stable over the time interval of the feedback process.

The long form capacity equation shows the situation for a snapshot in time of the channel. In practice, the highly variable nature of the channel and the impact of the antenna configurations need to be included. More details on this and the use of channel correlation factors are provided in Section 6.6.
The use of MIMO in non-OFDM systems such as CDMA is possible, as evidenced by its use in UMTS Release 7 for HSDPA, although the processing to recover the same quality of channel information is more difficult. OFDM is particularly well-suited to MIMO operation because the channel is defined by a single vector coefficient for each subcarrier, which makes the required digital processing in the frequency domain much more straightforward than in systems such as CDMA that are defined in the time domain.

### 2.4.3 LTE Terminology for Multiple Antennas

The terms codeword, layer and precoding have been adopted specifically for LTE to refer to signals and their processing. Figure 2.4-4 shows the processing steps to which they refer. The terms are used in the following ways:

- **Codeword**: A codeword represents user data before it is formatted for transmission. One or two codewords, CW0 and CW1, can be used depending on the prevailing channel conditions and use case. In the most common case of SU-MIMO, two codewords are sent to a single UE, but in the case of the less common downlink MU-MIMO, each codeword is sent to only one UE.

- **Layer**: The term layer is synonymous with stream. For spatial multiplexing, at least two layers must be used. Up to four are allowed. The number of layers is denoted by the symbol $\nu$ (pronounced nu). The number of layers is always less than or equal to the number of antennas.

- **Precoding**: Precoding modifies the layer signals before transmission. This may be done for diversity, beamsteering or spatial multiplexing. As noted earlier, the MIMO channel conditions may favor one layer (data stream) over another. If the eNB is given information about the channel — e.g., information sent back from the UE — it can add complex cross-coupling to counteract the imbalance in the channel.

![Figure 2.4-4. Signal processing for transmit diversity and spatial multiplexing (MIMO)](Adapted from 36.211 [6] Figure 6.3-1)

The symbols $d$, $x$ and $y$ are used in the specifications to denote signals before and after layer mapping and after precoding, respectively.