Multiple Antenna Techniques

- In LTE, BS and mobile could both use multiple antennas for radio transmission and reception
- In LTE, three main multiple antenna techniques
  - Diversity processing
    - The transmitter, the receiver or both use multiple antennas to
      - Increase the received **signal power**
      - Reduce the amount of **fading**
    - Diversity processing has been used since the early days of mobile communications

- Spatial multiplexing
  - The transmitter and receiver both use multiple antennas to
    - Increase the **data rate**
  - Spatial multiplexing is a relatively new technique that has only recently been introduced into mobile communications
- Beamforming
  - Uses multiple antennas at the BS to
    - Increase the **coverage** of the cell

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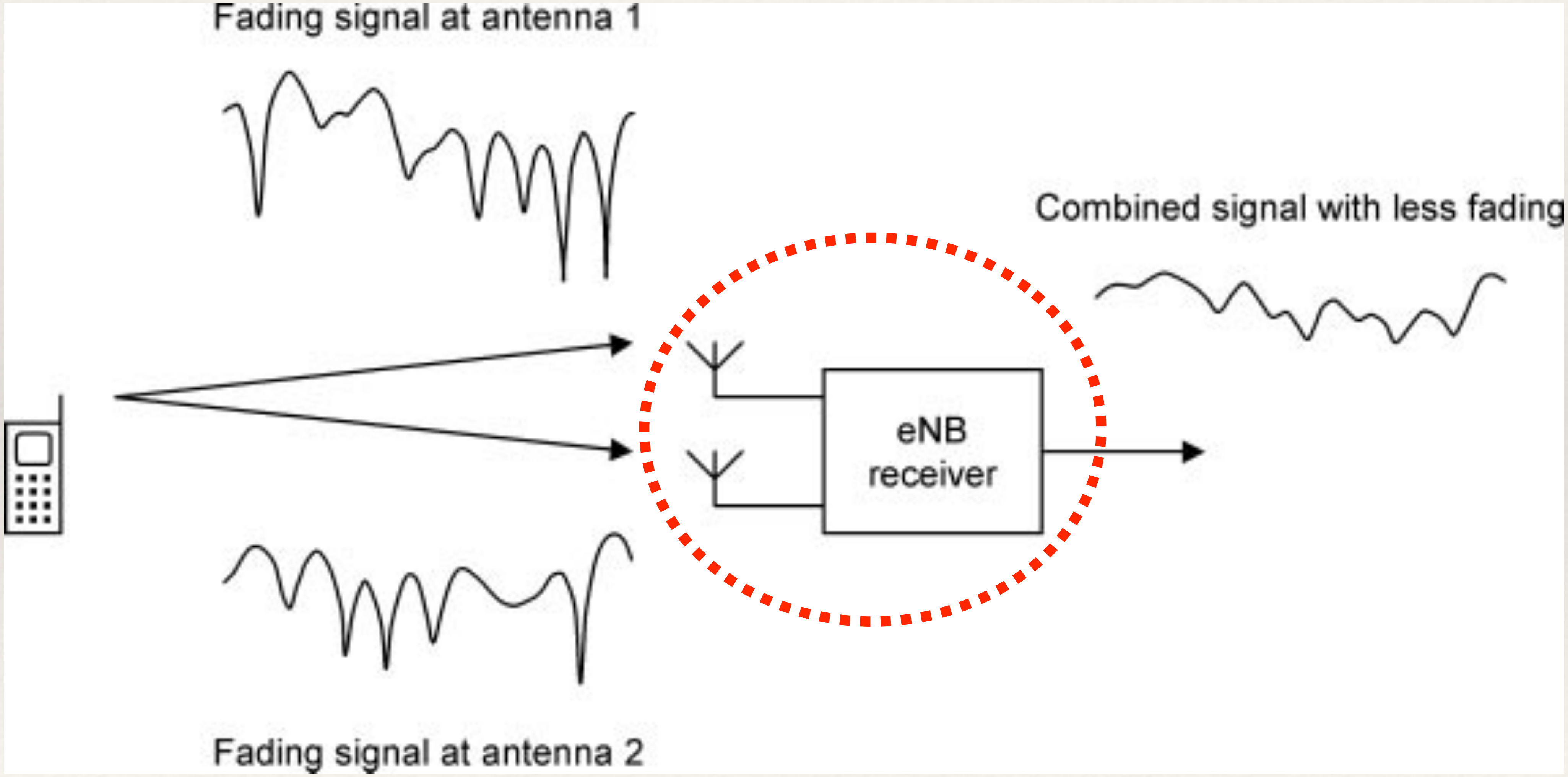
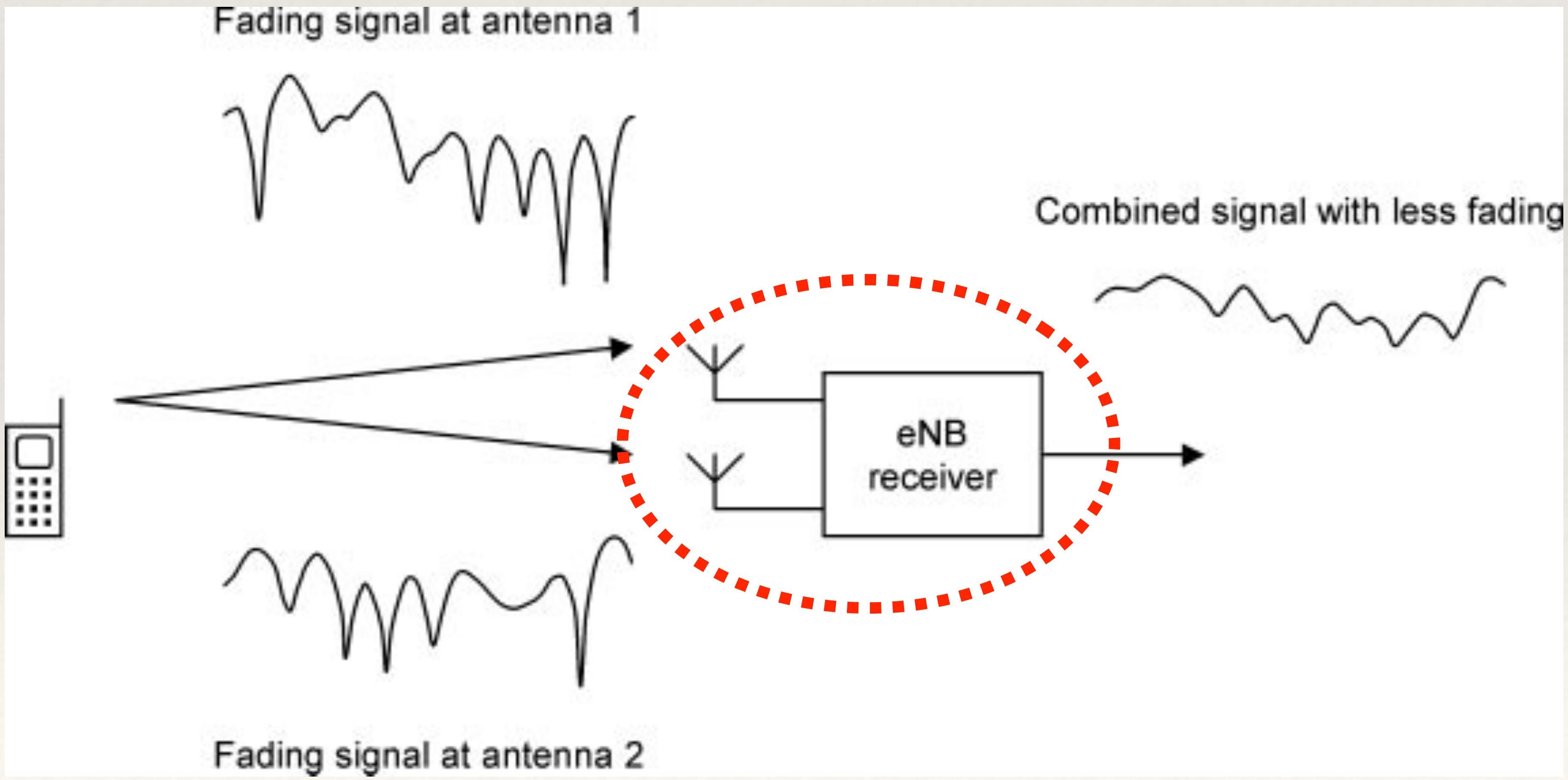
5.1.1 Receive Diversity

- Receive diversity is most often used in the uplink



Reduction in fading by the use of a **diversity receiver**

- BS uses two antennas to pick up two copies of the received signal
- The signals reach the receive antennas with different phase shifts, but these can be removed by antenna-specific channel estimation
- BS can then add the signals together in phase



- The signals are both made up from several <u>smaller rays</u>, so they are both <u>subject to fading</u>
  - If the two individual signals undergo <u>fades</u> at the <u>same time</u>, then the <u>power</u> of the <u>combined signal</u> will be <u>low</u>
  - If the antennas are <u>far enough apart</u> (a few wavelengths of the carrier frequency), then the two sets of <u>fading geometries</u> will be very <u>different</u>, so the signals will be far more likely to undergo fades at <u>completely different times</u>

- BSs
    - Usually have more than one receive antenna
- Mobile
    - In LTE, the mobile's test specifications assume that the mobile is using two receive antennas, so LTE systems are expected to use receive diversity on the downlink as well as the uplink
    - A mobile's antennas are closer together than a BS's, which reduces the benefit of receive diversity, but the situation can often be improved using antennas that measure two independent polarizations [極化] of the incoming signal

5.1 Diversity Processing

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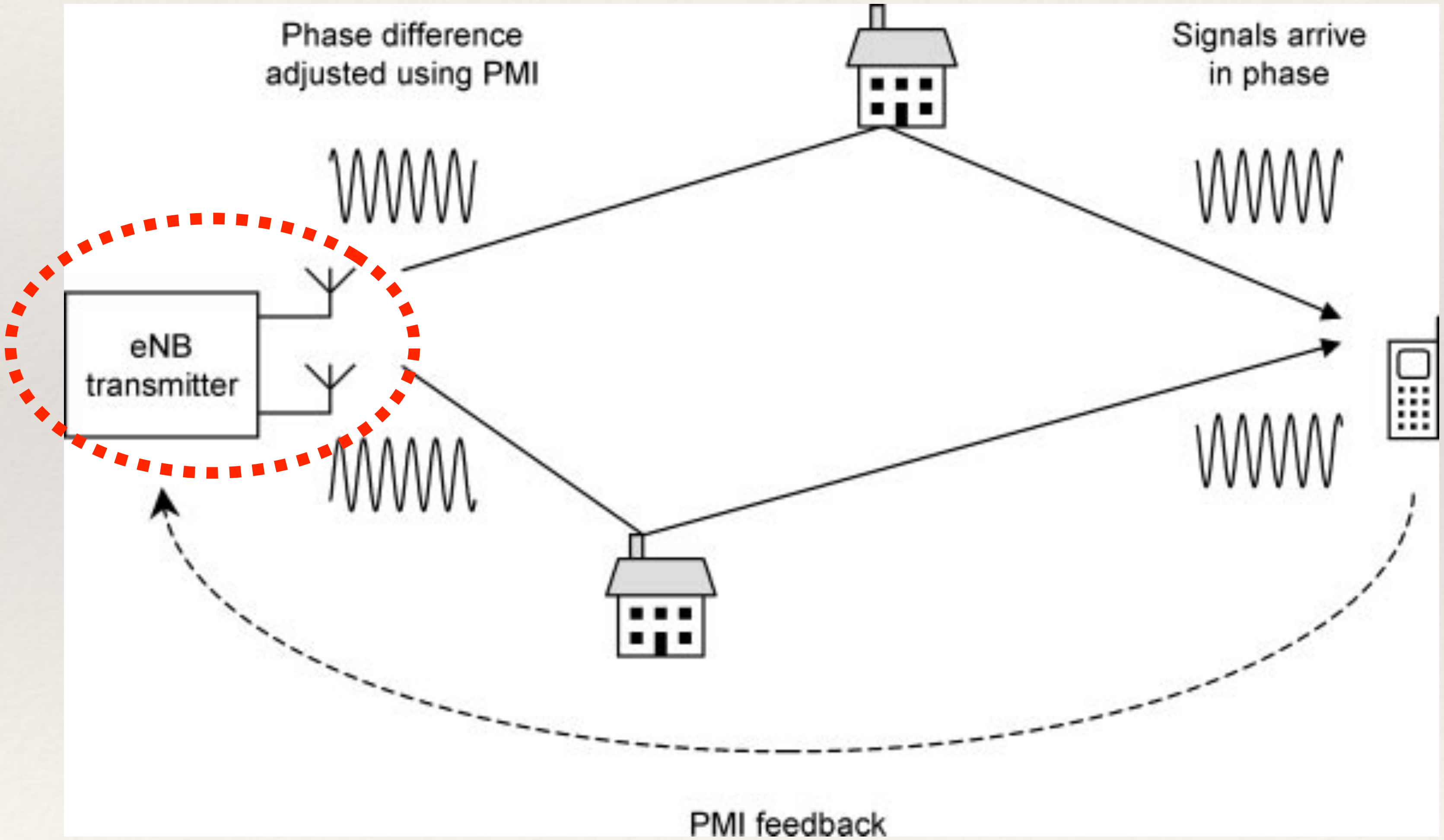
5.1.2 Closed Loop Transmit Diversity

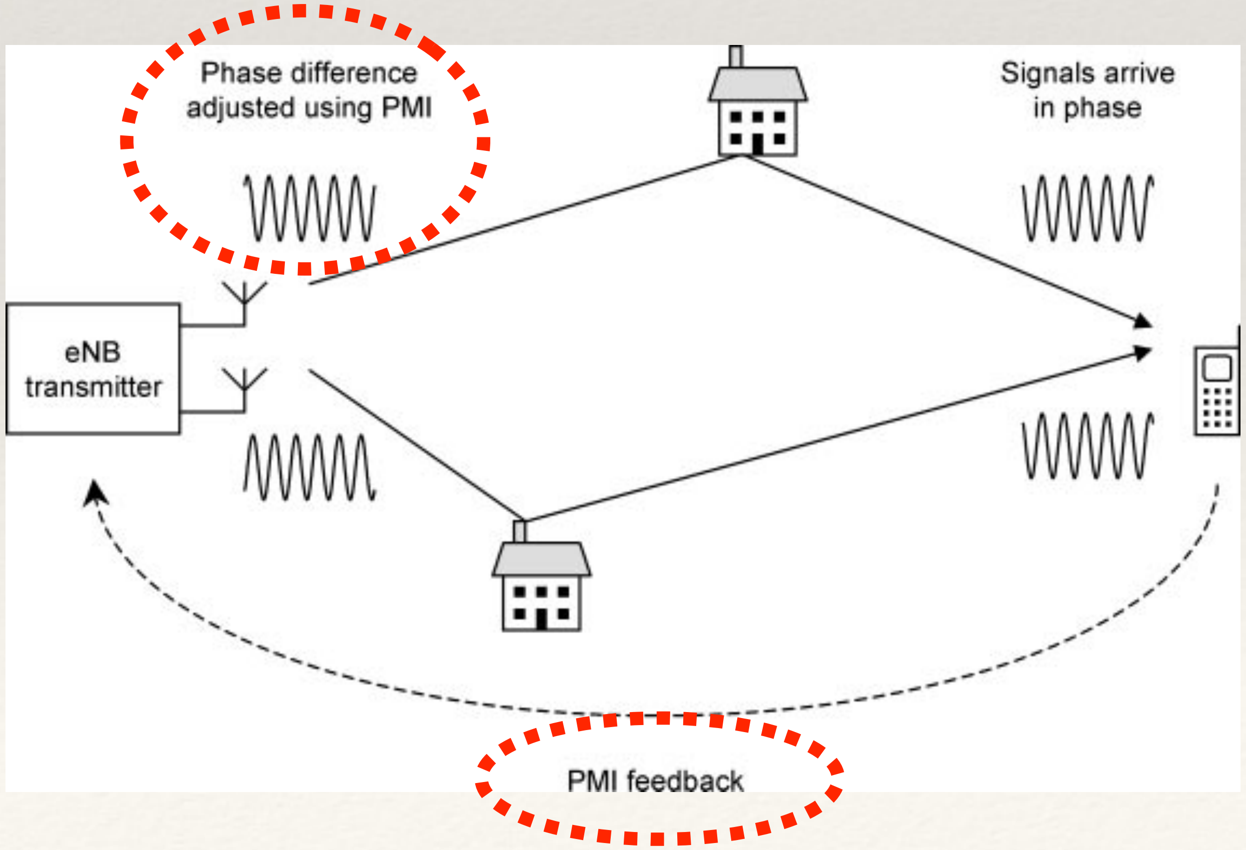
- Transmit diversity reduces the amount of fading by using two or more antennas at the transmitter
- It is superficially similar to receive diversity, but with a **crucial problem**
  - The signals add together at the single receive antenna, which brings a risk of destructive interference

- Two ways to solve the problem
  - Closed loop transmit diversity
  - Open loop transmit diversity
- Closed loop transmit diversity

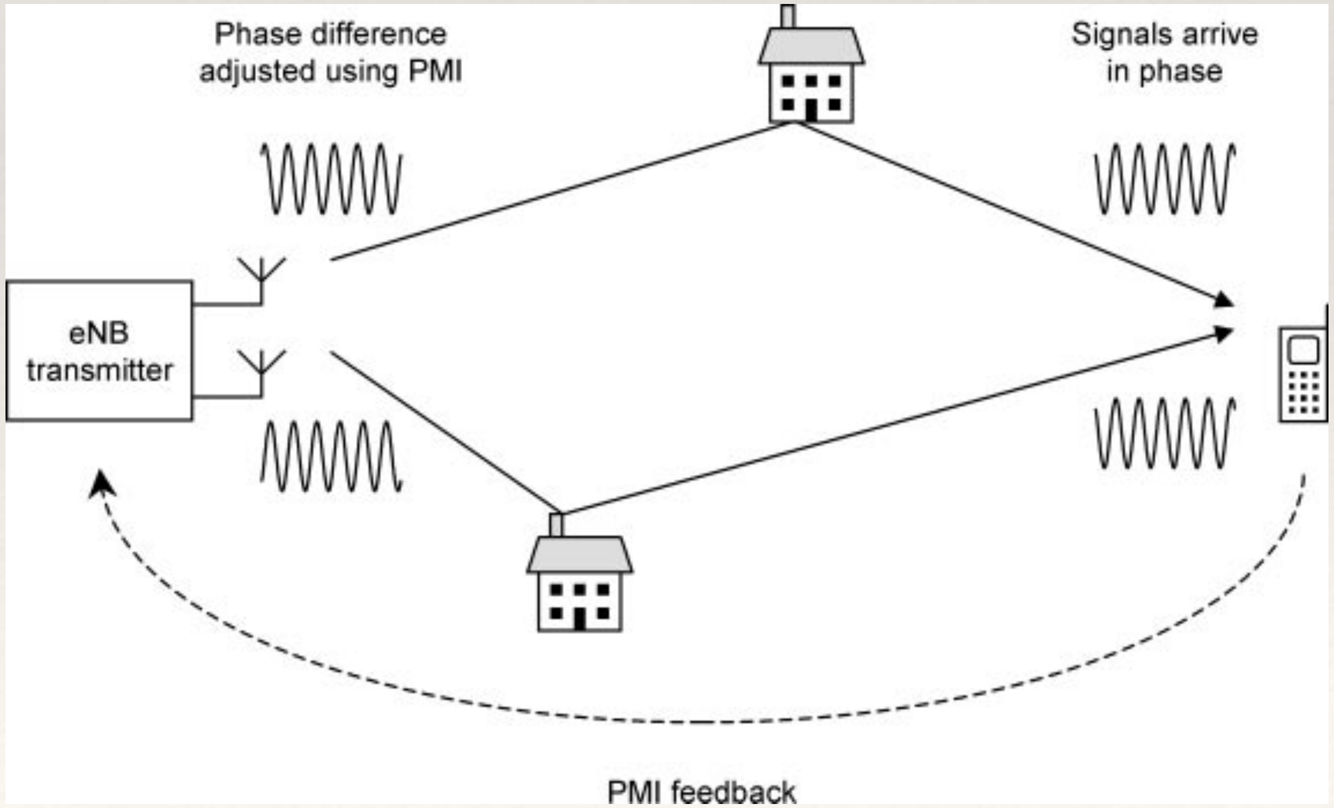


Operation of **closed loop** transmit diversity

- The transmitter sends two copies of the signal in the expected way, but it also applies a phase shift to one or both signals before transmission
  - By doing this, it can ensure that the two signals reach the receiver in phase, without any risk of destructive interference
  - The phase shift is determined by a precoding matrix indicator (PMI), which is calculated by the receiver and fed back to the transmitter



- A simple PMI might indicate two options
  - Transmit both signals without any phase shifts
  - Transmit the second with a phase shift of 180°
  - If the first option leads to destructive interference, then the second will automatically work
- The amplitude of the combined signal is only low in the unlikely event that the two received signals undergo fades at the same time



- The phase shifts introduced by the radio channel depend on the wavelength of the carrier signal and hence on its frequency
  - This implies that the best choice of PMI is a function of frequency as well
    - This is easily handled in an OFDMA system, as the receiver can feed back different PMI values for different sets of sub-carriers
  - The best choice of PMI also depends on the position of the mobile, so a fast moving mobile will have a PMI that frequently changes
    - Unfortunately the feedback loop introduces time delays into the system, so in the case of fast moving mobiles, the PMI may be out of date by the time it is used
    - For this reason, **closed loop transmit diversity** is **only suitable** for mobiles that are moving **sufficiently slowly**
    - For **fast moving mobiles**, it is better to use the **open loop** technique

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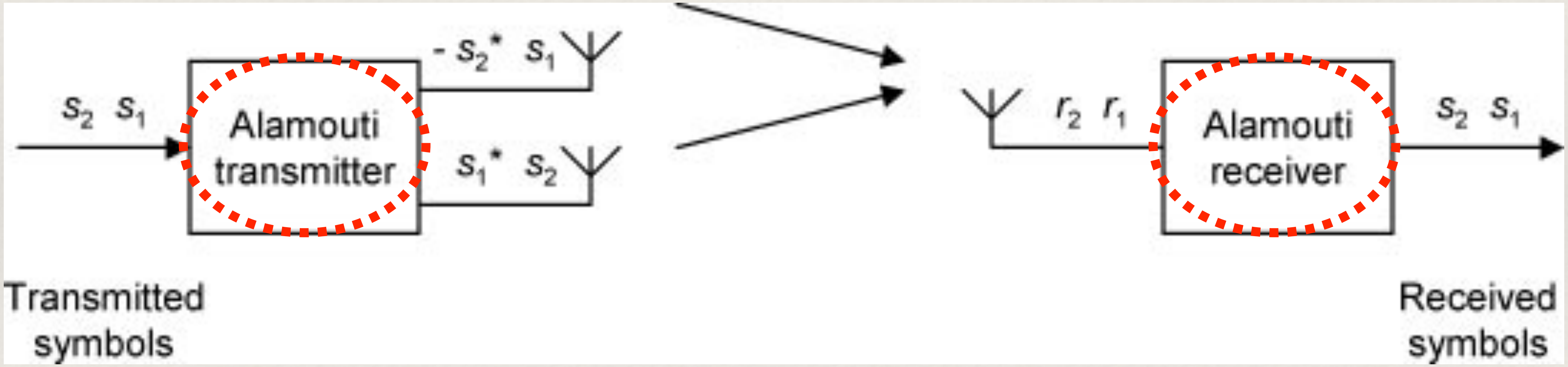
5.1.3 Open Loop Transmit Diversity

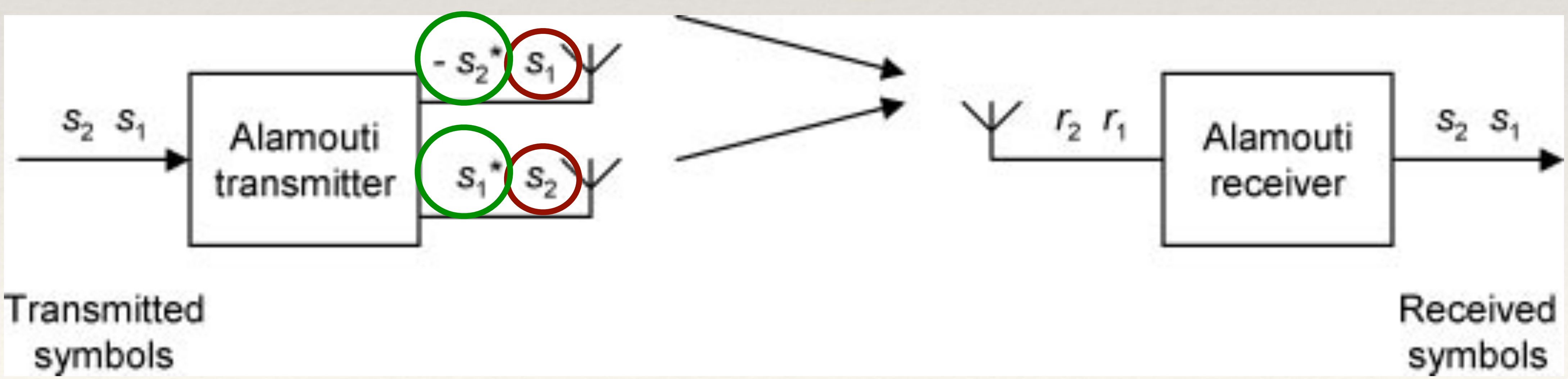
- An implementation of open loop transmit diversity that is known as Alamouti's technique



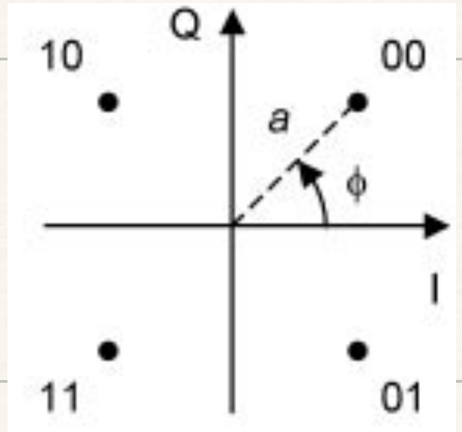
Operation of Alamouti's technique for **open loop** transmit diversity

- The transmitter uses two antennas to send two symbols, denoted s_1 and s_2, in two successive time steps
  - In the first step, the transmitter sends s_1 from the first antenna and s_2 from the second
  - In the second step, it sends $-s_2^*$ from the first antenna and s_1^* from the second

  (The symbol $*$ indicates that the transmitter should change the sign of the quadrature component, in a process known as complex conjugation)



Note: QPSK



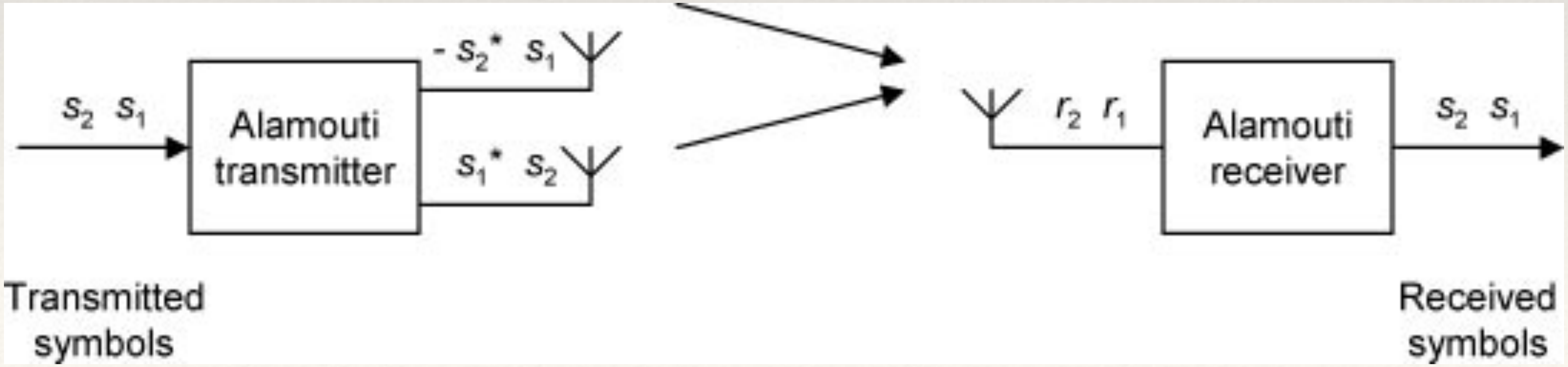
- In the Quadrature Phase Shift Keying (QPSK), it is more convenient to represent each symbol using two numbers, which are known as the **in-phase (I)** and **quadrature (Q) components**
- These are computed as follows

$$I = a \cos \phi$$

$$Q = a \sin \phi$$

  - where a is the amplitude of the transmitted wave and ϕ is its phase
- Mathematicians will recognize the in-phase and quadrature components as the real and imaginary parts of a complex number

- The receiver can now make two successive measurements of the received signal, which correspond to two different combinations of s_1 and s_2
  - It can then solve the resulting equations, so as to recover the two transmitted symbols
- There are only two requirements
  - The fading patterns must stay roughly the same between the first time step and the second
  - The two signals must not undergo fades at the same time
  - Both requirements are usually met



- We can combine open and closed loop transmit diversity with the receive diversity techniques, giving a system that carries out diversity processing using multiple antennas at both the transmitter and the receiver

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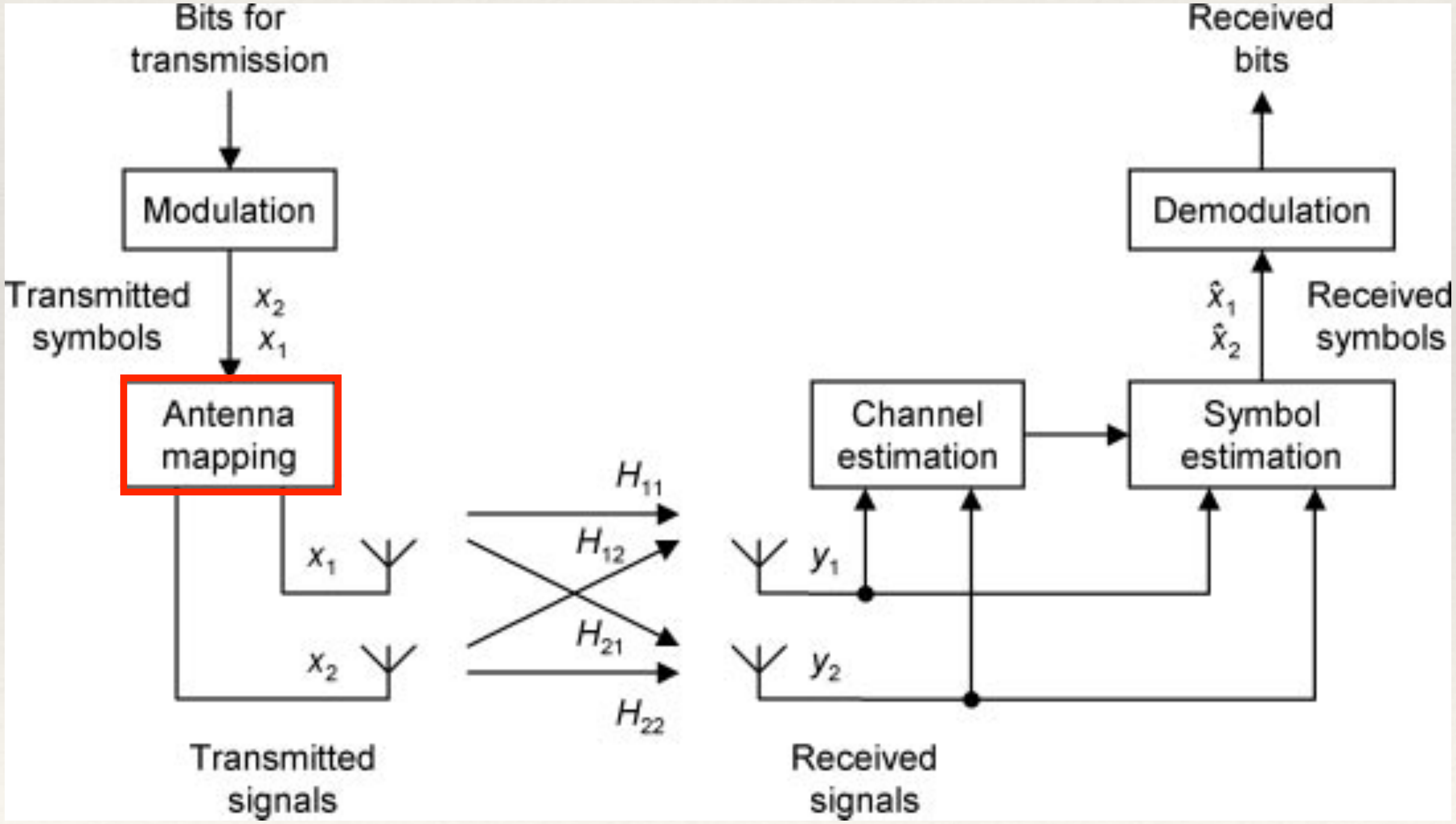
5.2.1 Principles of Operation

- If the transmitter and receiver both have multiple antennas, then we can set up multiple parallel data streams between them, so as to **increase the data rate**
- In a system with N_T transmit and N_R receive antennas, often known as an $N_T \times N_R$ spatial multiplexing system, the peak data rate is proportional to $\min(N_T, N_R)$

- A basic spatial multiplexing system, in which the transmitter and receiver both have two antennas
  - In the transmitter, the antenna mapper takes symbols from the modulator two at a time, and sends one symbol to each antenna
  - The antennas transmit the two symbols simultaneously, so as to double the transmitted data rate



Basic principles of a 2x2 spatial multiplexing system

- The symbols travel to the receive antennas by way of four separate radio paths, so the received signals can be written as follows

$$y_1 = H_{11} x_1 + H_{12} x_2 + n_1$$

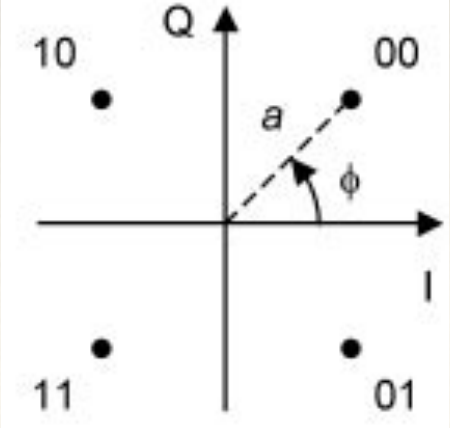
$$y_2 = H_{21} x_1 + H_{22} x_2 + n_2$$

  - x_1 and x_2 are the signals sent from the two transmit antennas
  - y_1 and y_2 are the signals that arrive at the two receive antennas
  - n_1 and n_2 represent the received noise and interference
  - H_{ij} expresses the way in which the transmitted symbols are attenuated and phase-shifted, as they travel to receive antenna *i* from transmit antenna *j*

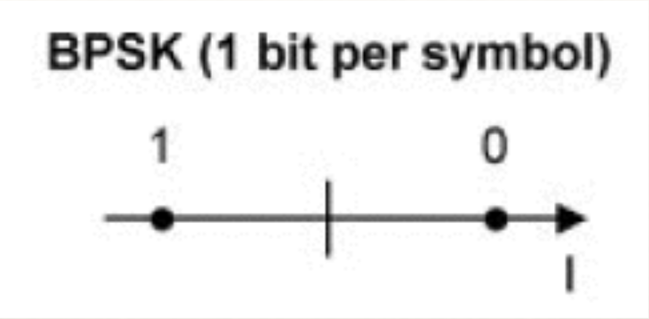
- In general, all the terms in the equation above are complex
  - In the transmitted and received symbols x_j and y_j and the noise terms n_i, the real and imaginary parts are the amplitudes of the in-phase and quadrature components
  - In each of the channel elements H_{ij}
    - The magnitude represents the attenuation of the radio signal
    - The phase represents the phase shift

$$I = a \cos \phi$$

$$Q = a \sin \phi$$



- We will simplify the examples by using real numbers alone
  - We assume that the transmitter is modulating the bits using binary phase shift keying
    - The in-phase components are +1 and −1
    - The quadrature components are zero



  - We will also assume that the radio channel can attenuate or invert the signal, but does not introduce any other phase shifts

- Consistent with these assumptions, let us consider the following example

$$H_{11} = 0.8 \quad H_{12} = 0.6 \quad x_1 = +1 \quad n_1 = +0.02$$

$$H_{21} = 0.2 \quad H_{22} = 0.4 \quad x_2 = -1 \quad n_2 = -0.02$$

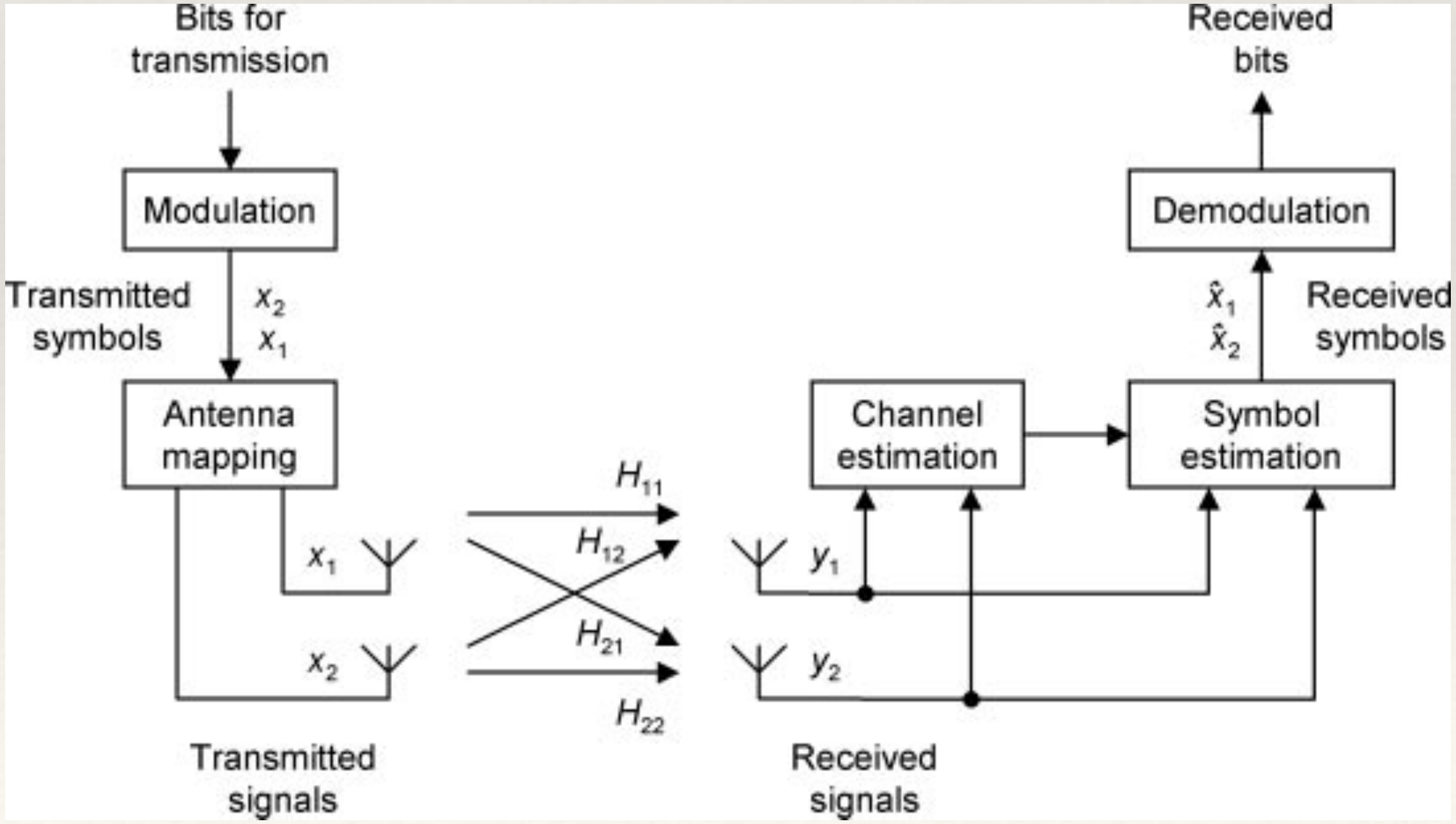
- Substituting these numbers into the previous equation shows that the received signals are as follows

$$y_1 = +0.22$$

$$y_2 = -0.22$$

- The receiver's first task is to estimate the four channel elements H_{ij}
  - The **transmitter** broadcasts reference symbols with one extra feature
    - When one antenna transmits a reference symbol, the other antenna keeps quiet and sends nothing at all

- The **receiver** can then estimate the channel elements H_{11} and H_{21}, by measuring the two received signals at the times when transmit antenna 1 is sending a reference symbol
- It can then wait until transmit antenna 2 sends a reference symbol, before estimating the channel elements H_{12} and H_{22}



$$\begin{aligned} y_1 &= H_{11}x_1 + H_{12}x_2 + n_1 \\ y_2 &= H_{21}x_1 + H_{22}x_2 + n_2 \end{aligned} \tag{5.1}$$

- The receiver now has enough information to estimate the transmitted symbols x_1 and x_2
  - The simplest way is a zero-forcing detector, which operates as follows
    - If we ignore the noise and interference, then the equation (5.1) is a pair of simultaneous equations for two unknown quantities, x_1 and x_2

$$\hat{x}_1 = \frac{\hat{H}_{22}y_1 - \hat{H}_{12}y_2}{\hat{H}_{11}\hat{H}_{22} - \hat{H}_{21}\hat{H}_{12}}$$

$$\hat{x}_2 = \frac{\hat{H}_{11}y_2 - \hat{H}_{21}y_1}{\hat{H}_{11}\hat{H}_{22} - \hat{H}_{21}\hat{H}_{12}}$$

$$\hat{x}_1 = \frac{\hat{H}_{22} y_1 - \hat{H}_{12} y_2}{\hat{H}_{11}\hat{H}_{22} - \hat{H}_{21}\hat{H}_{12}}$$

$$\hat{x}_2 = \frac{\hat{H}_{11} y_2 - \hat{H}_{21} y_1}{\hat{H}_{11}\hat{H}_{22} - \hat{H}_{21}\hat{H}_{12}}$$

- $\hat{H}_{ij}$ is the receiver's estimate of the channel element H_{ij} (This quantity may be different from H_{ij}, because of noise and other errors in the channel estimation process)
- $\hat{x}_1$ and $\hat{x}_2$ are the receiver's estimates of the transmitted symbols x_1 and x_2

$$H_{11} = 0.8 \quad H_{12} = 0.6 \quad x_1 = +1 \quad n_1 = +0.02$$
$$H_{21} = 0.2 \quad H_{22} = 0.4 \quad x_2 = -1 \quad n_2 = -0.02 \tag{5.2}$$

$$y_1 = +0.22$$
$$y_2 = -0.22 \tag{5.3}$$

- Substituting the numbers from Equations (5.2) and (5.3) gives the following result

$$\hat{x}_1 = +1.1$$

$$\hat{x}_2 = -1.1$$

  - This is consistent with transmitted symbols of +1 and–1

- We have therefore <u>transferred two symbols</u> at the same time using the <u>same sub-carriers</u>, and have <u>doubled the data rate</u>

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5.2.2 Open Loop Spatial Multiplexing

- There is a problem with the technique described above
  - Let us change one of the channel elements, H_{11}, to give the following example

$$H_{11} = 0.3 \quad H_{12} = 0.6$$

$$H_{21} = 0.2 \quad H_{22} = 0.4$$

$$\hat{x}_1 = \frac{\hat{H}_{22} y_1 - \hat{H}_{12} y_2}{\hat{H}_{11}\hat{H}_{22} - \hat{H}_{21}\hat{H}_{12}}$$
$$\hat{x}_2 = \frac{\hat{H}_{11} y_2 - \hat{H}_{21} y_1}{\hat{H}_{11}\hat{H}_{22} - \hat{H}_{21}\hat{H}_{12}} \quad (5.4)$$

- If we try to estimate the transmitted symbols using Equation (5.4), we find that $H_{11}H_{22} - H_{21}H_{12}$ is zero
  - We therefore end up dividing by <u>zero</u>, which is nonsense
  - So, for this choice of channel elements, the technique has <u>failed</u>

$$y_1 = H_{11}x_1 + H_{12}x_2 + n_1$$
$$y_2 = H_{21}x_1 + H_{22}x_2 + n_2 \quad (5.1)$$

- We can see what has gone <u>wrong</u> by substituting the channel elements into Equation (5.1), and writing the received signals as follows

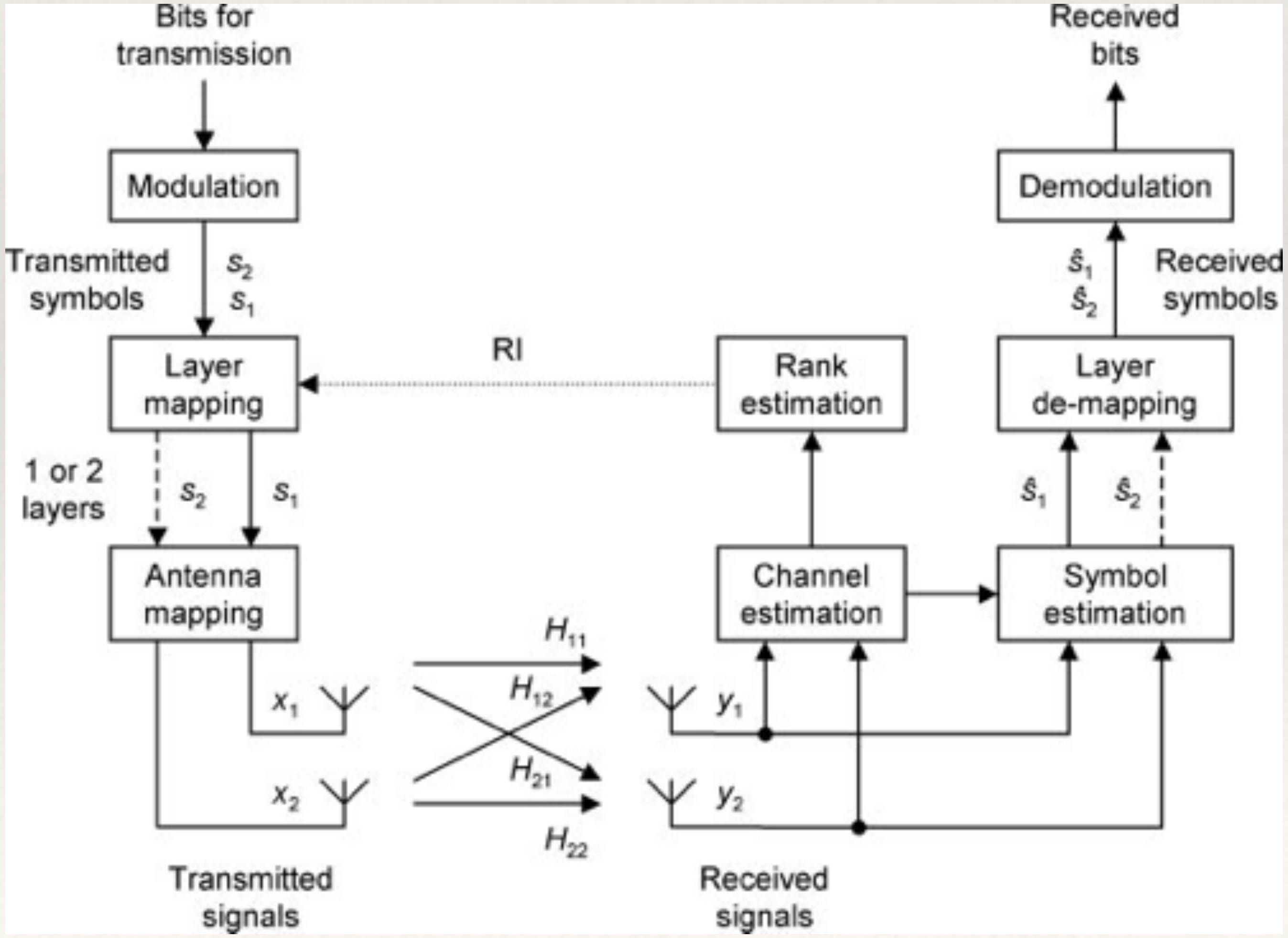
$$y_1 = 0.3(x_1 + 2x_2) + n_1$$

$$y_2 = 0.2(x_1 + 2x_2) + n_2$$

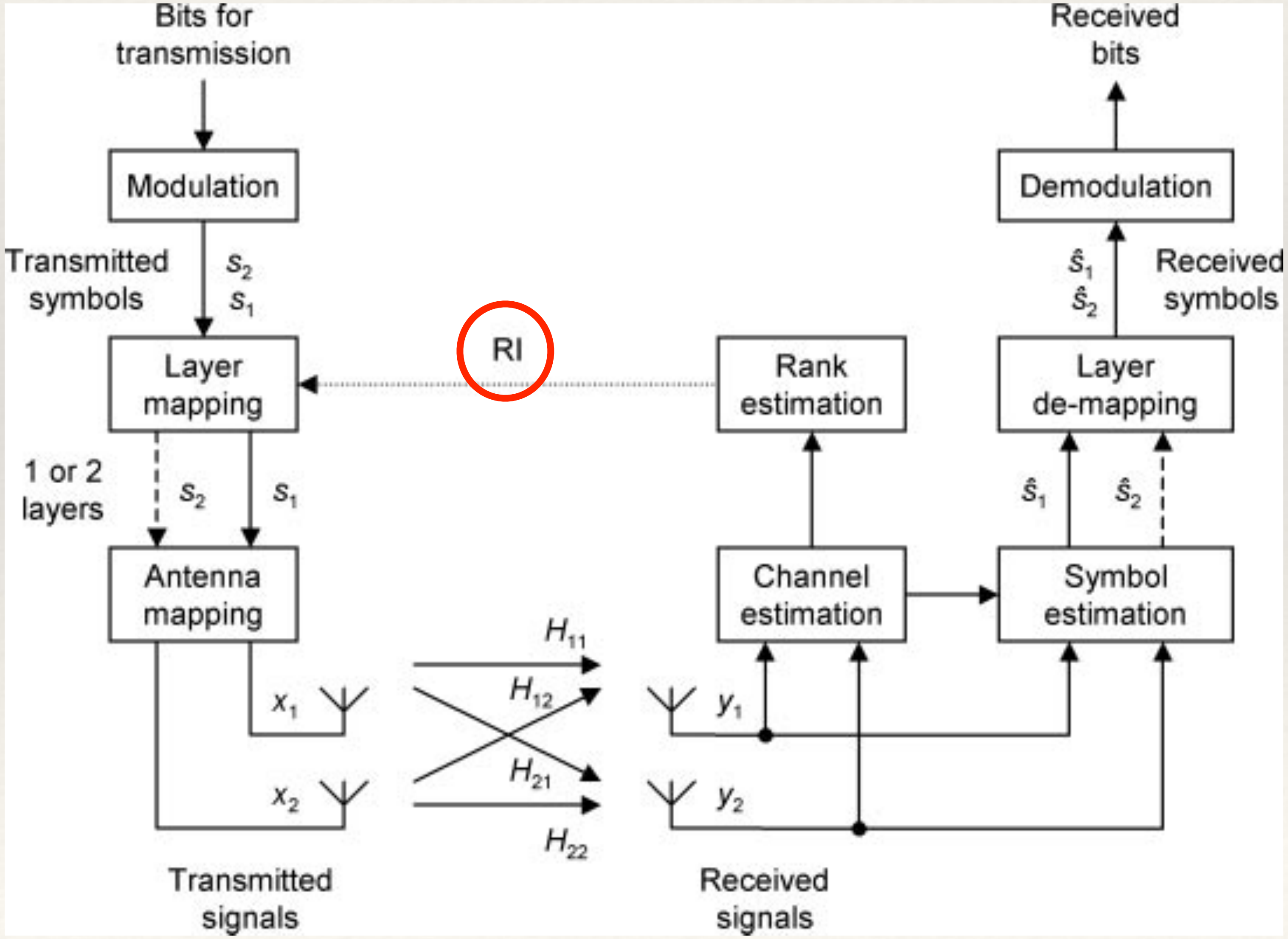
$$y_1 = 0.3(x_1 + 2x_2) + n_1$$
$$y_2 = 0.2(x_1 + 2x_2) + n_2 \quad (5.7)$$

- By measuring the received signals y_1 and y_2, we were expecting to measure two different pieces of information, from which we could recover the transmitted data
  - This time, we have measured the same piece of information, namely $x_1 + 2x_2$, twice
  - As a result, we do not have enough information to recover x_1 and x_2 independently
- Furthermore, this is not just an isolated special case
  - If $H_{11}H_{22} - H_{21}H_{12}$ is small but non-zero, then our estimates of x_1 and x_2 turn out to be badly corrupted by noise and are completely unusable

- The solution comes from the knowledge that we can still send one symbol at a time, by the use of diversity processing
- We therefore require an adaptive system
  - Use spatial multiplexing to send two symbols at a time if the channel elements are well behaved
  - Can fall back to diversity processing otherwise



- Here, the receiver measures the channel elements and works out a rank indication (RI), which indicates the number of symbols that it can successfully receive
- It then feeds the rank indication back to the transmitter

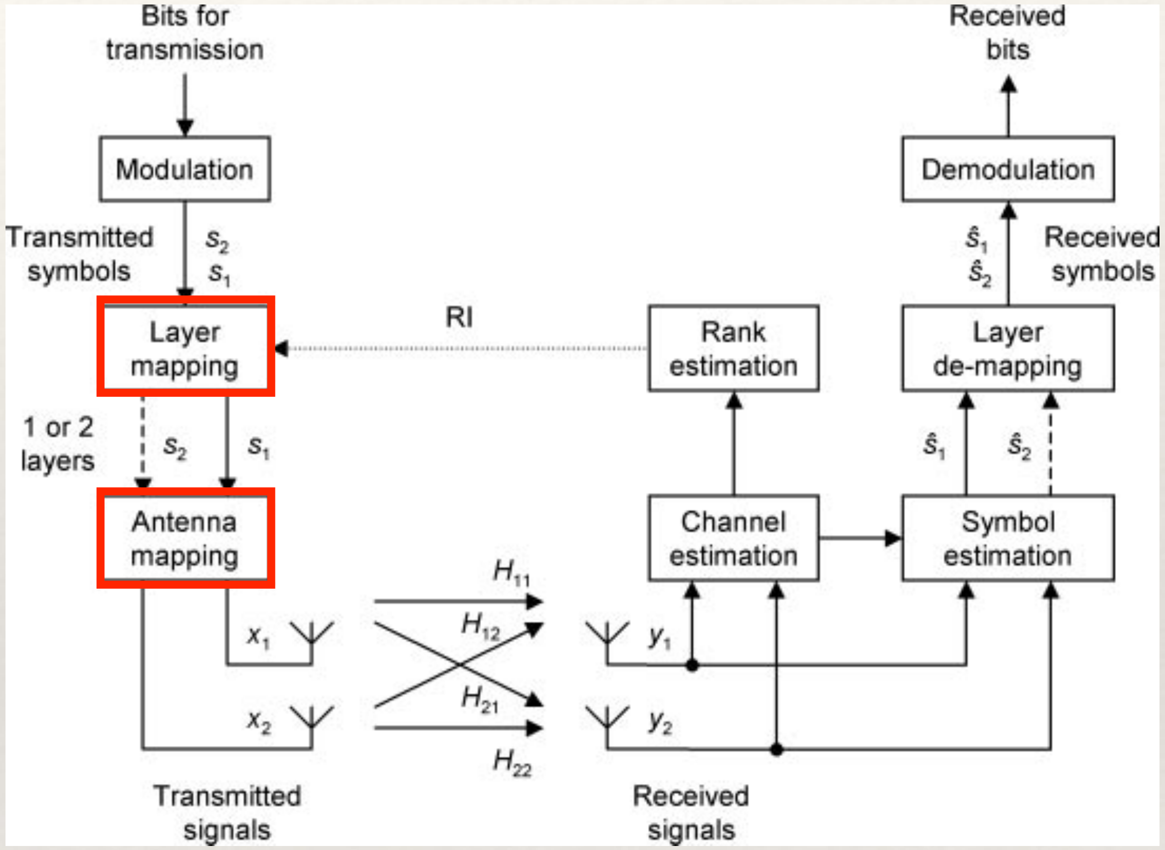


- If the rank indication is two
  - The transmitter's layer mapper grabs two symbols, s_1 and s_2, from the transmit buffer, so as to create two independent data streams that are known as layers
  - The antenna mapper then sends one symbol to each antenna, by a straightforward mapping operation

$$x_1 = s_1$$

$$x_2 = s_2$$

  - The receiver measures the incoming signals and recovers the transmitted symbols as before



$$y_1 = 0.3(x_1 + 2x_2) + n_1$$
$$y_2 = 0.2(x_1 + 2x_2) + n_2 \quad (5.7)$$

- If the rank indication is one
  - The layer mapper only grabs one symbol, s_1
  - The antenna mapper sends to both transmit antennas as follows

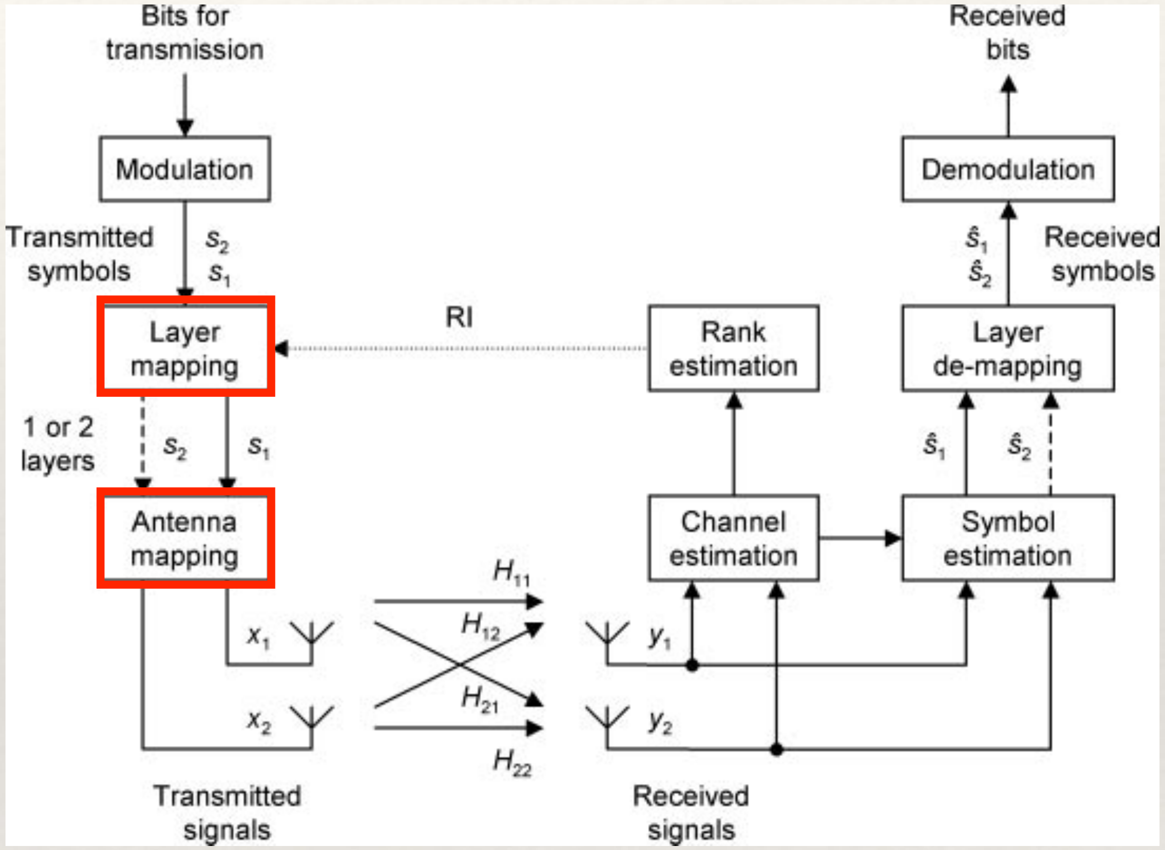
$$x_1 = s_1$$

$$x_2 = s_1$$

  - Under these assumptions, Equation (5.7) becomes the following

$$y_1 = 0.9s_1 + n_1$$

$$y_2 = 0.6s_1 + n_2$$



- The receiver now has two measurements of the transmitted symbol s_1, and can combine these in a diversity receiver so as to recover the transmitted data
- This technique is implemented in LTE and is known as open loop spatial multiplexing

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5.2.3 Closed Loop Spatial Multiplexing

- There is one remaining problem
- Let us change two more of the channel elements, so that

$$H_{11} = 0.3 \quad H_{12} = -0.3$$

$$H_{21} = 0.2 \quad H_{22} = -0.2$$

- These channel elements are badly behaved, in that $H_{11}H_{22} - H_{21}H_{12}$ is zero
- But if we try to handle the situation in the manner described above, by sending the same symbol from both transmit antennas, then the received signals are as follows

$$y_1 = 0.3s_1 - 0.3s_1 + n_1$$

$$y_2 = 0.2s_1 - 0.2s_1 + n_2$$

- So the <u>transmitted</u> signals cancel out at both <u>receive</u> antennas and we are left with measurements of the <u>incoming noise</u> and <u>interference</u>
- We therefore have <u>insufficient information</u> even to <u>recover s_1</u>
- To see the way out, consider what happens if we send <u>one symbol at a time</u> as before, but <u>invert the signal</u> that is sent from the <u>second</u> antenna

$$x_1 = s_1$$

$$x_2 = -s_1$$

- The received signal can now be written as follows

$$y_1 = 0.3s_1 + 0.3s_1 + n_1$$

$$y_2 = 0.2s_1 + 0.2s_1 + n_2$$

- This time, we can recover the transmitted symbol s_1
- So we now require two levels of adaptation
  - If the rank indication is two, then the transmitter sends two symbols at a time using the antenna mapping of Equation (5.8)

$$x_1 = s_1 \qquad x_2 = s_2 \qquad (5.8)$$

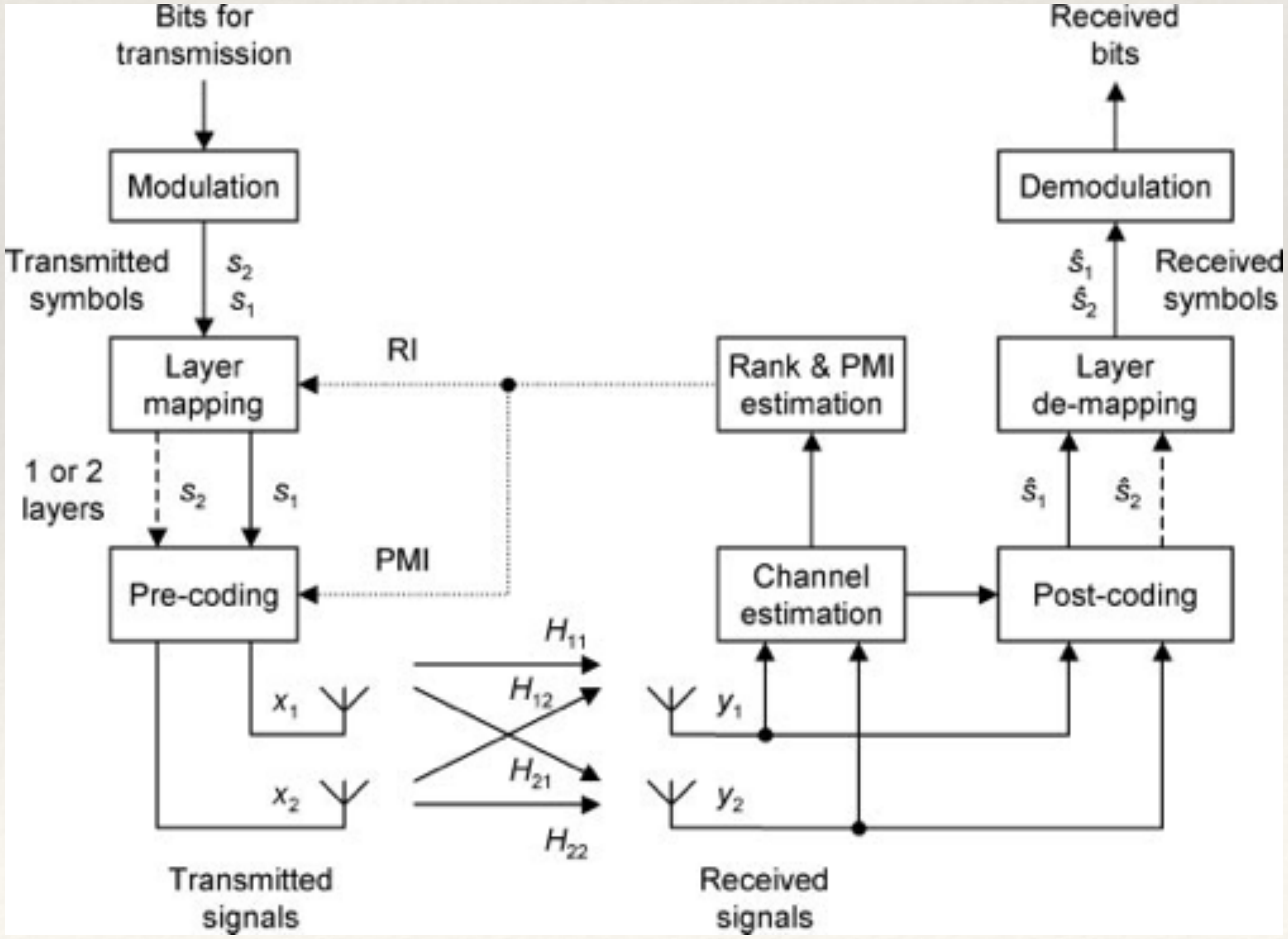
  - If the rank indication is one, then the transmitter falls back to diversity processing and sends one symbol at a time

- In doing so, it chooses an antenna mapping such as Equation (5.9) or (5/13), which depends on the exact nature of the channel elements and which guarantees a strong signal at the receiver

$$x_1 = s_1 \quad x_2 = s_1 \qquad (5.9)$$

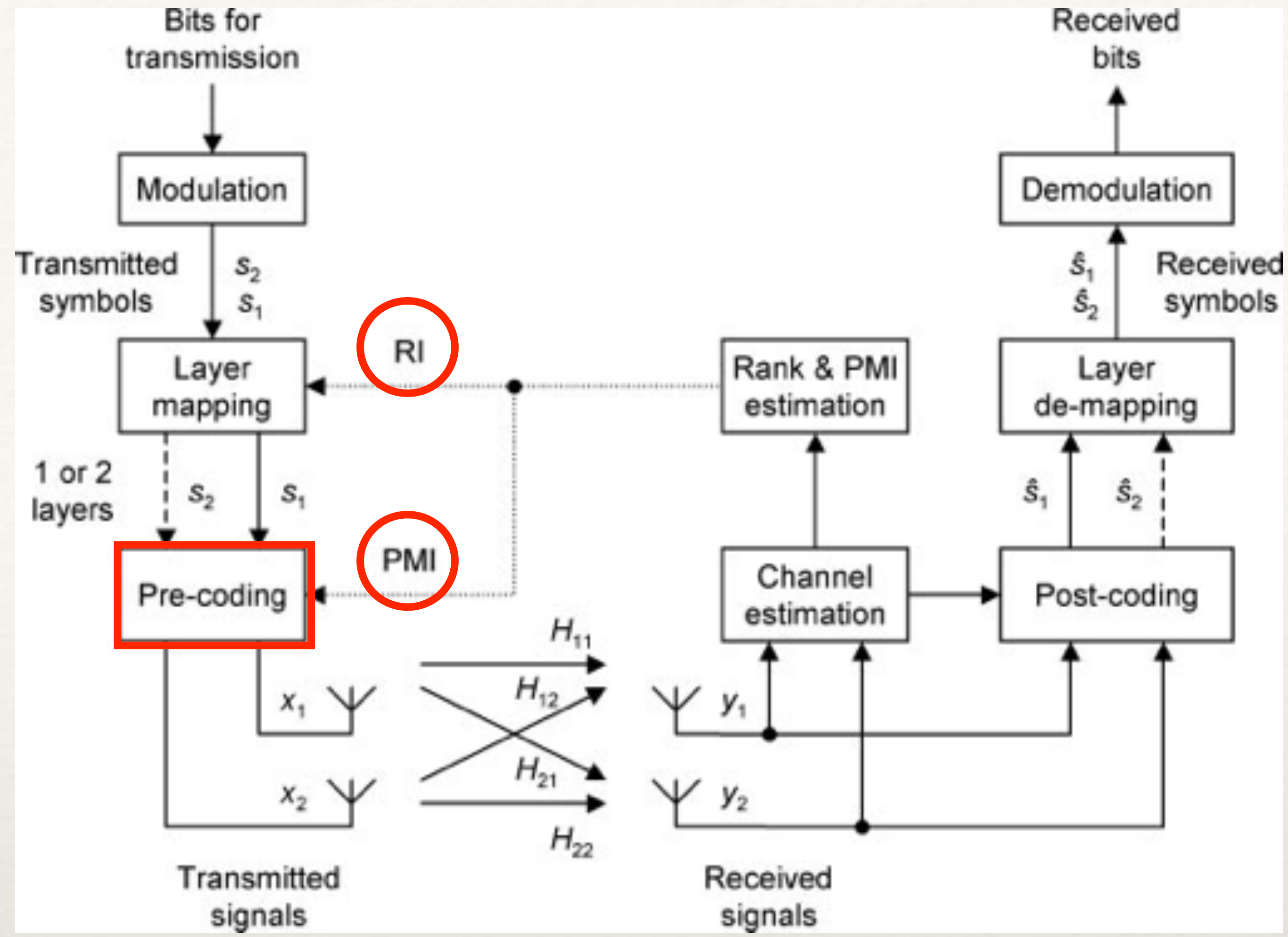
$$x_1 = s_1 \quad x_2 = -s_1 \qquad (5.13)$$

- Such a system is shown s follows:



Operation of a 2x2 **closed loop** spatial multiplexing system

- The receiver measures the channel elements as before and uses them to feed back two quantities
    - Rank Indication (RI)
    - Precoding Matrix Indicator (PMI)
- PMI
    - Controls a **precoding** step in the transmitter
    - It implements an adaptive antenna mapping using (for example) Equations (5.8), (5.9) and (5.13), to ensure that the signals reach the receiver without cancellation (In fact the PMI has exactly the same role that we saw earlier when discussing closed loop transmit diversity, which is why its name is the same)

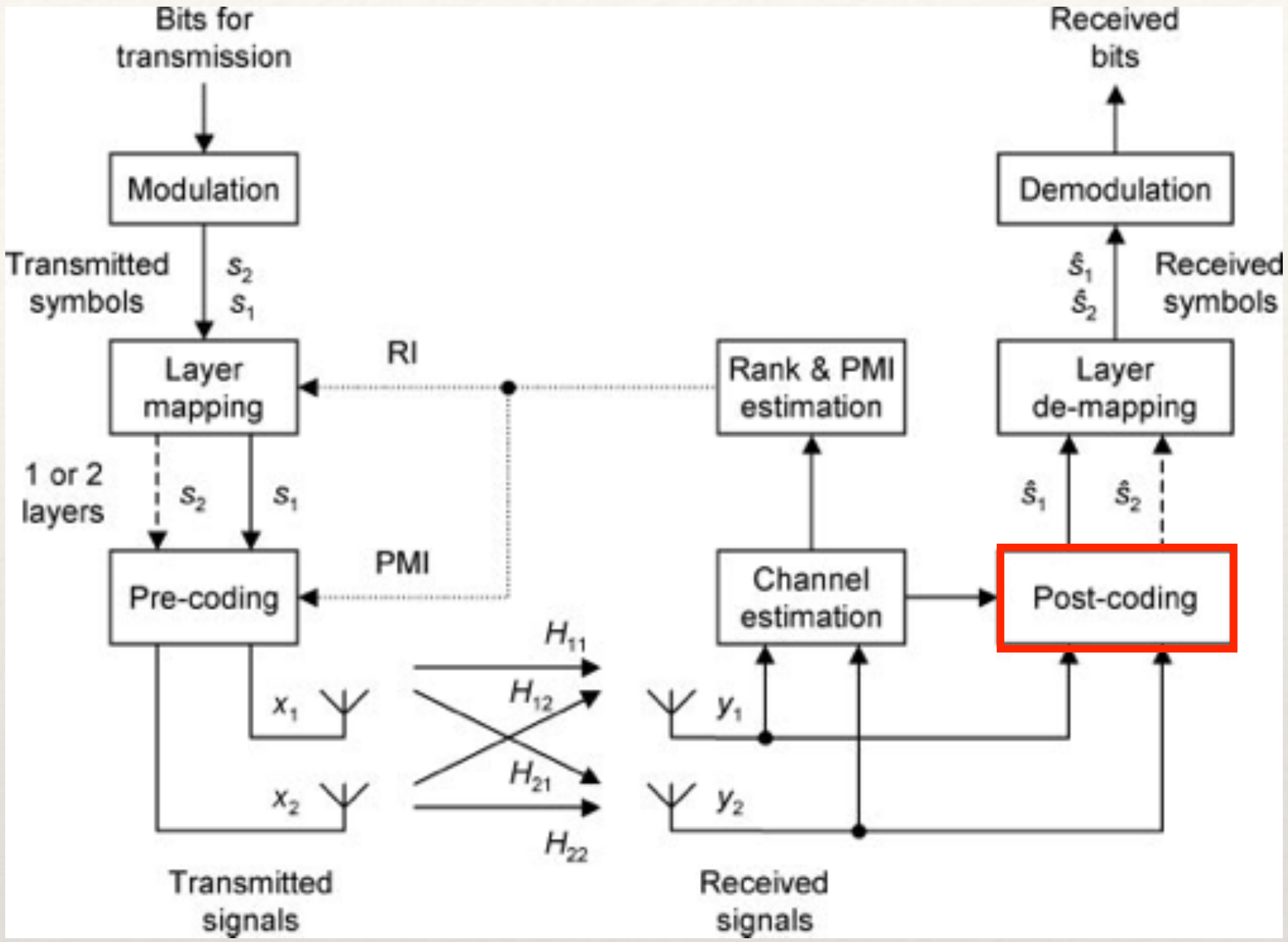


$$x_1 = s_1 \\ x_2 = s_2 \tag{5.8}$$

$$x_1 = s_1 \\ x_2 = s_1 \tag{5.9}$$

$$x_1 = s_1 \\ x_2 = -s_1 \tag{5.13}$$

- In the receiver, the **post-coding** step reverses the effect of precoding and also includes the soft decision estimation step from earlier
- This technique is also implemented in LTE, and is known as **closed loop spatial multiplexing**
- In this expression, the term ‘closed loop’ refers specifically to the loop that is created by feeding back the PMI



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5.2.5 Implementation Issues

- Spatial multiplexing is implemented in the downlink of LTE Release 8, using a maximum of four transmit antennas on the BS and four receive antennas on the mobile
- There are similar implementation issues to diversity processing
  - Firstly, the antennas at the BS and mobile should be reasonably far apart, ideally a few wavelengths of the carrier frequency, or should handle different polarizations
  - If the antennas are too close together, then the channel elements H_{ij} will be very similar
  - This can easily take us into the situation where spatial multiplexing was unusable and we had to fall back to diversity processing

- A similar situation can easily arise in the case of line-of-sight transmission and reception. This leads us to an unexpected conclusion
  - Spatial multiplexing actually works best in conditions with no direct line-of-sight and significant multipath, because, in these conditions, the channel elements H_{ij} are uncorrelated with each other
- In line-of-sight conditions, we often have to fall back to diversity processing

- As in the case of closed loop transmit diversity, the PMI depends on the carrier frequency and the position of the mobile
- For fast moving mobiles, delays in the feedback loop can make the PMI unreliable by the time the transmitter comes to use it, so open loop spatial multiplexing is often preferred

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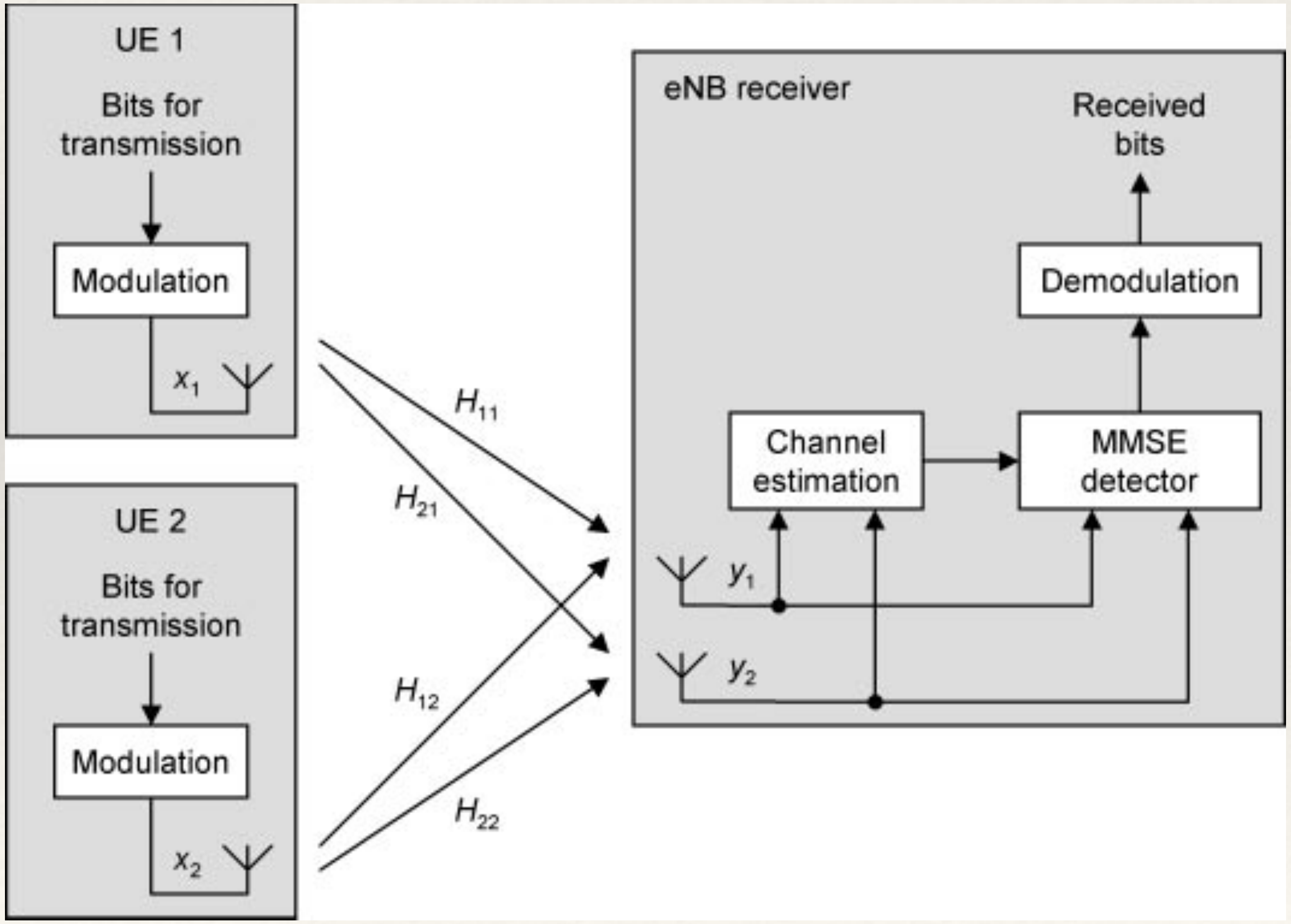
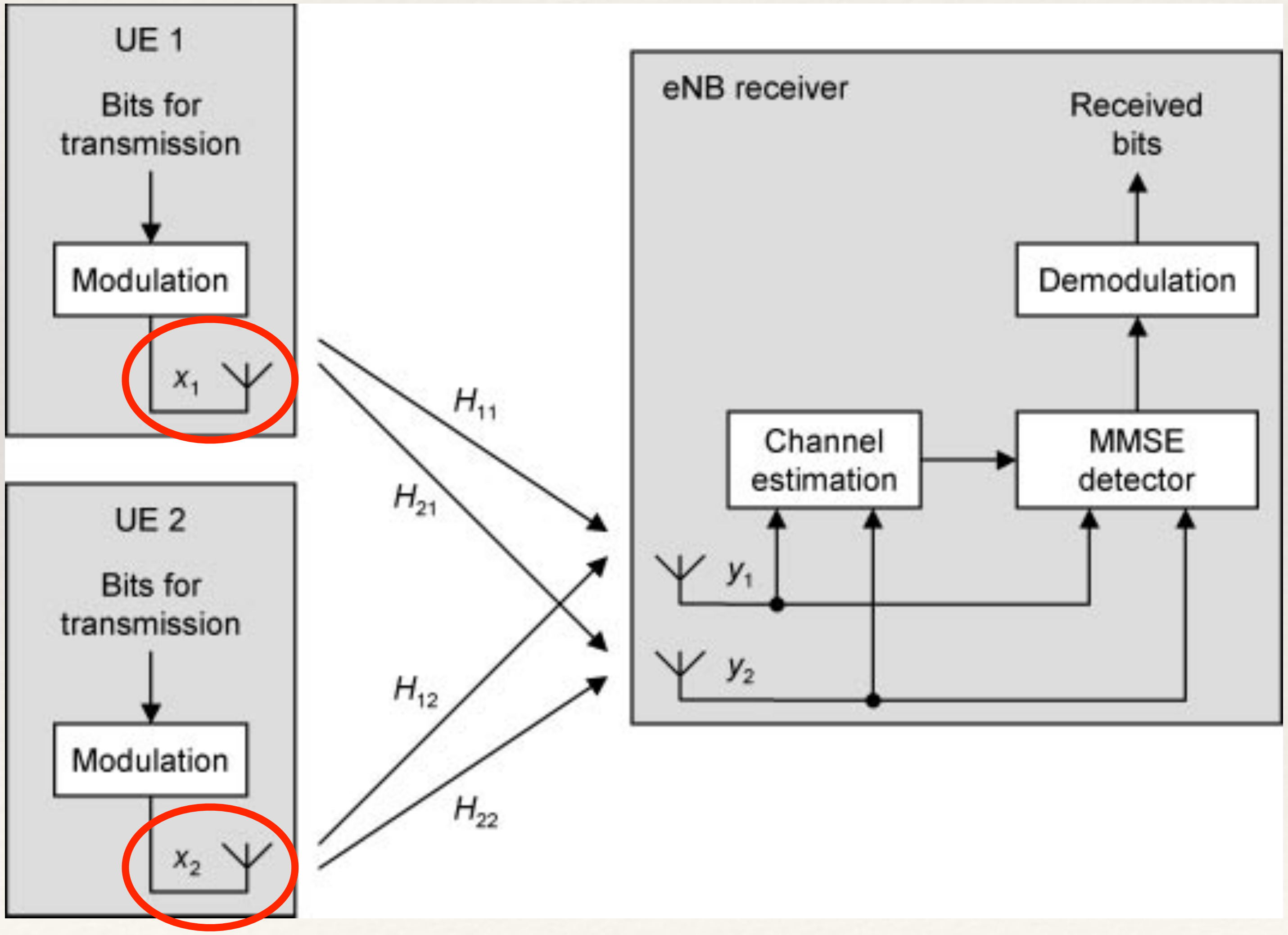
5.2.6 Multiple User MIMO

- Two transmit and two receive antennas are sharing the same transmission times and frequencies, in the same way as before



Uplink multiple user MIMO

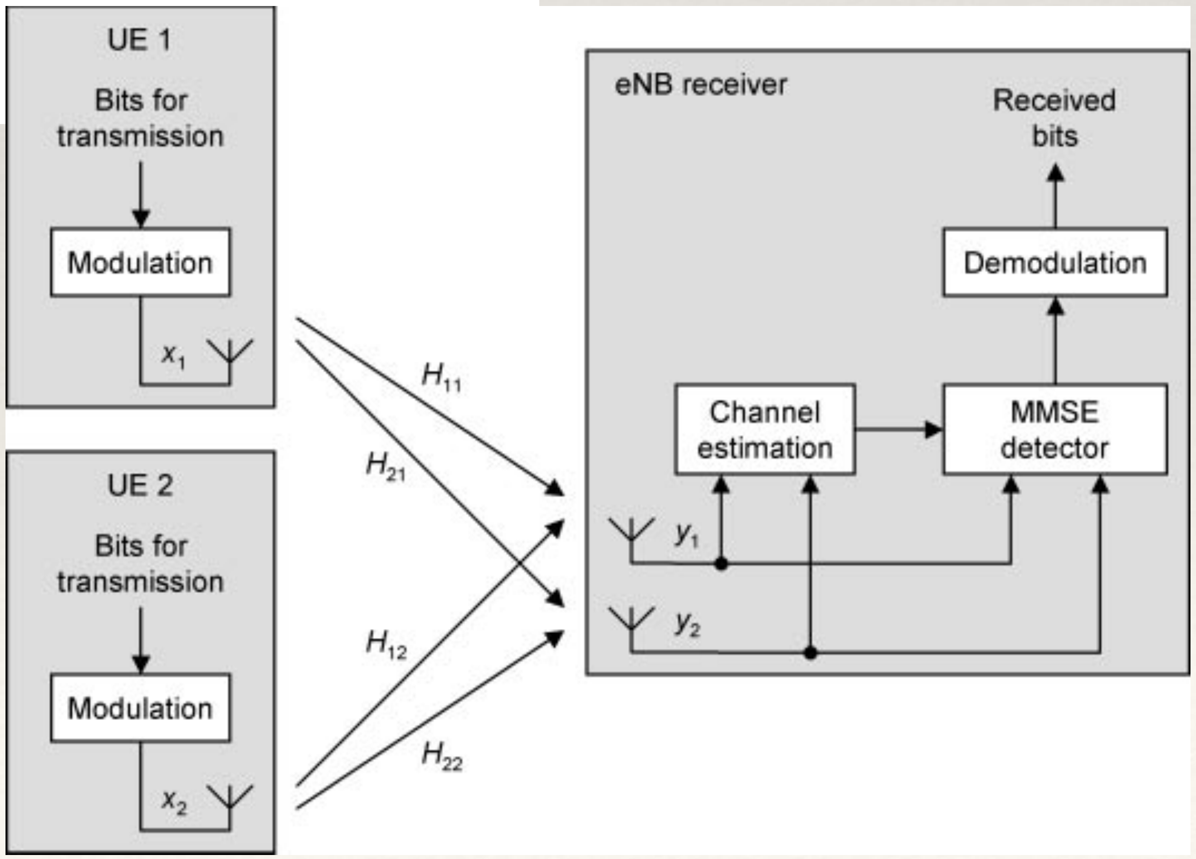
- The mobile antennas are on <u>two different mobiles</u> instead of one
- This technique is known as <u>multiple user MIMO</u> (MU-MIMO), in contrast with the earlier spatial multiplexing techniques, which are sometimes known as single user MIMO (SU-MIMO)



- This figure specifically shows the implementation of multiple user MIMO on the uplink, which is the more common situation
- The mobiles transmit at the same time and on the same carrier frequency, but without using any precoding and without even knowing that they are part of a spatial multiplexing system
- The BS receives their transmissions and separates them using (for example) the minimum mean square error detector

If $\hat{Y}$ is a vector of n predictions, and Y is the vector of the true values, then the (estimated) MSE of the predictor is:

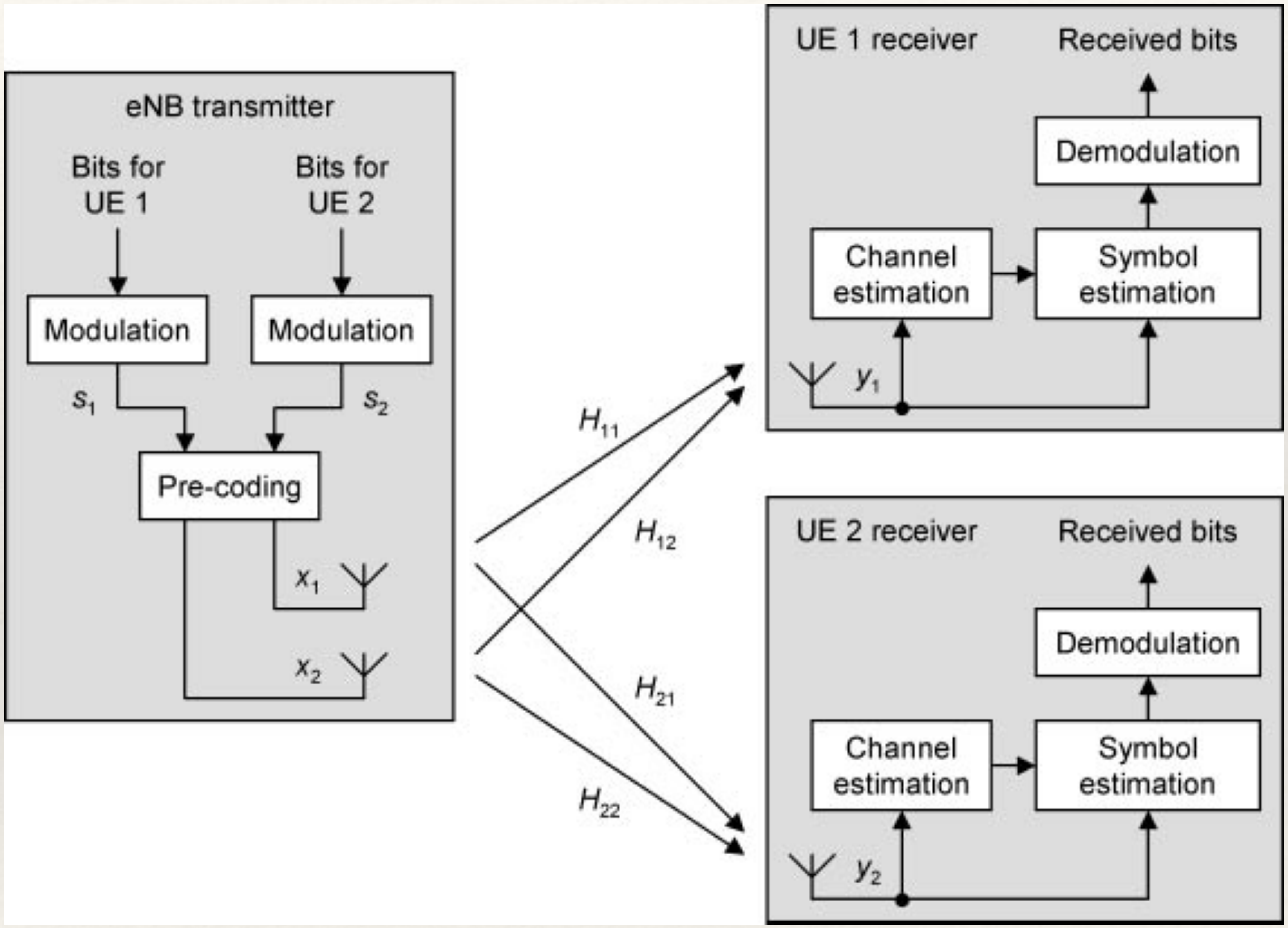
$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}(\hat{Y}_i - Y_i)^2.$$



- This technique only works if the channel matrix is well behaved, but we can usually guarantee this for two reasons
  - Firstly, the mobiles are likely to be far apart, so their ray paths are likely to be very different
  - Secondly, the BS can freely choose the mobiles that are taking part, so it can freely choose mobiles that lead to a well-behaved channel matrix

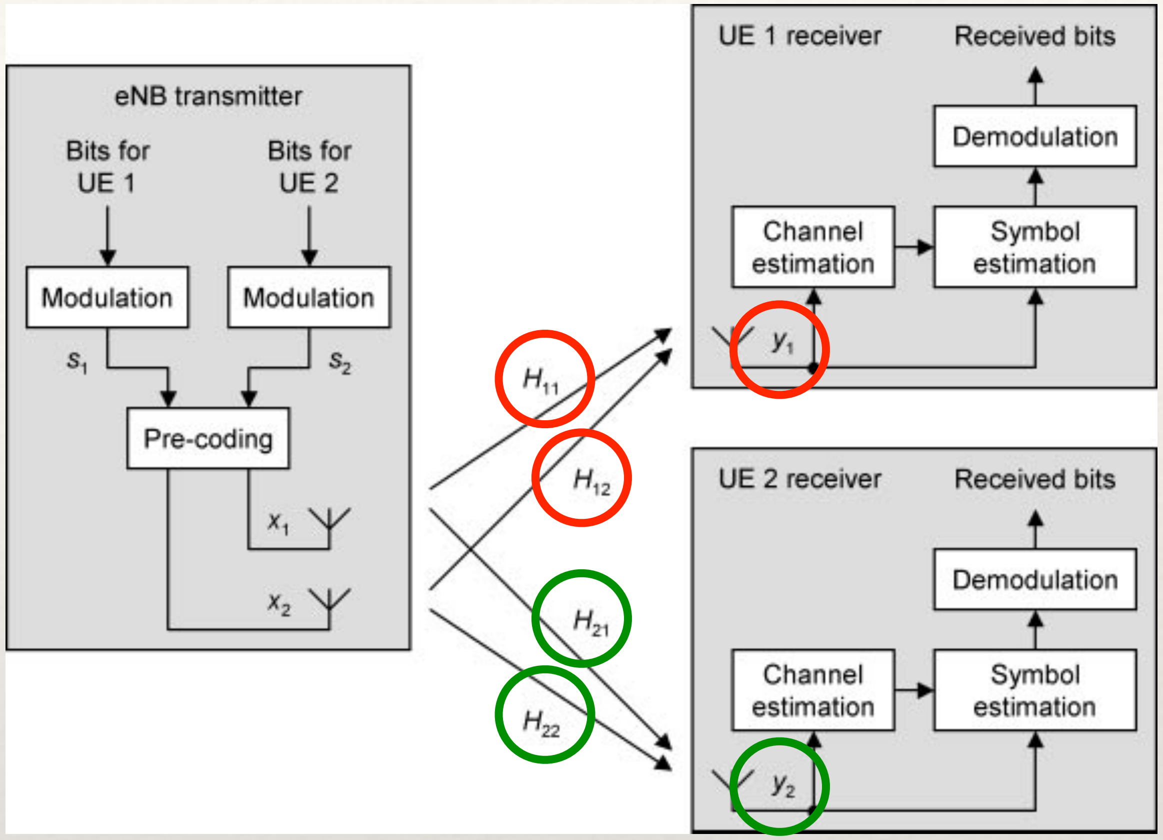
- Uplink multiple user MIMO does not increase the peak data rate of an individual mobile, but it is still beneficial because of the increase in cell throughput
- It can also be implemented using inexpensive mobiles that just have one power amplifier and one transmit antenna, not two
- For these reasons, multiple user MIMO is the standard technique in the uplink of LTE Release 8: single user MIMO is not introduced into the uplink until Release 10

- We can also apply multiple user MIMO to the downlink, as shown in the following figure:

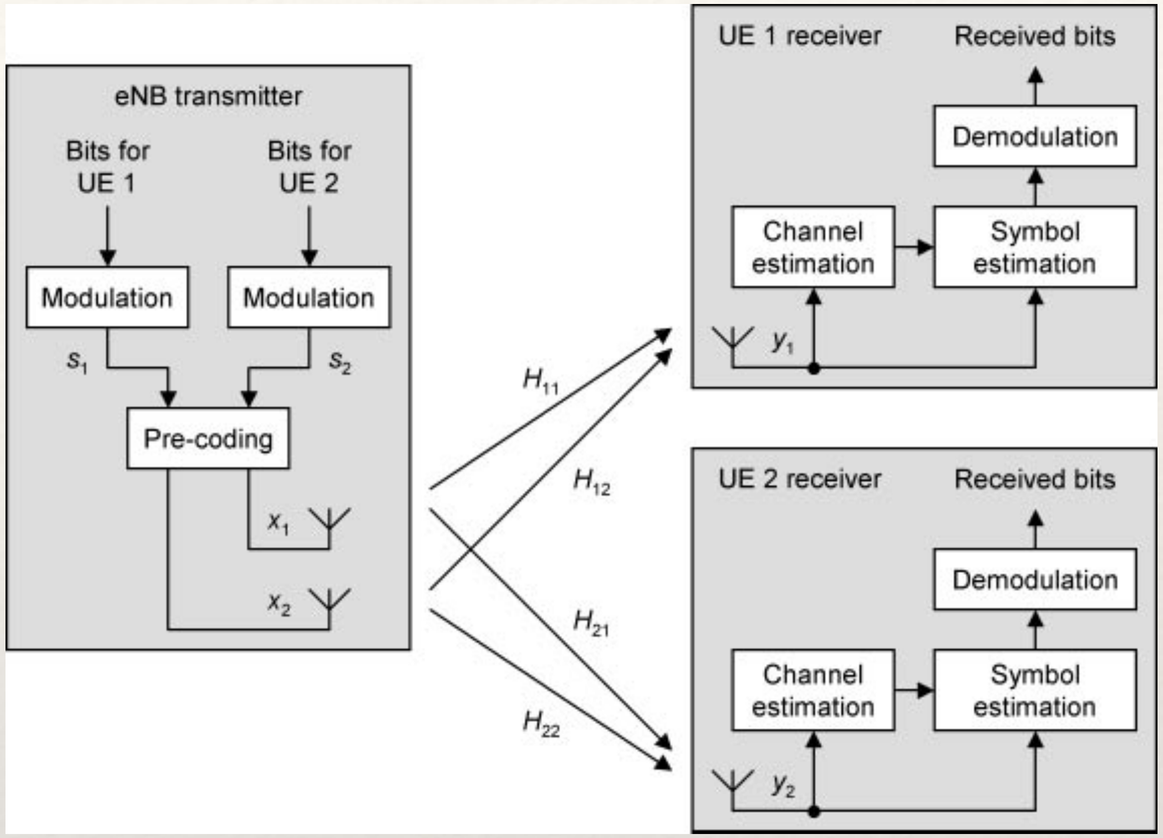


Downlink multiple user MIMO

- This time, there is a problem
- Mobile 1 can measure its received signal y_1 and the channel elements H_{11} and H_{12}, in the same way as before
  - However, it has no knowledge of the other received signal y_2, or of the other channel elements H_{21} and H_{22}
- The opposite situation applies for mobile 2



- Neither mobile has complete knowledge of the channel elements or of the received signals, which invalidates the techniques we have been using
- The solution is to implement downlink multiple user MIMO by adapting another multiple antenna technique, known as beamforming



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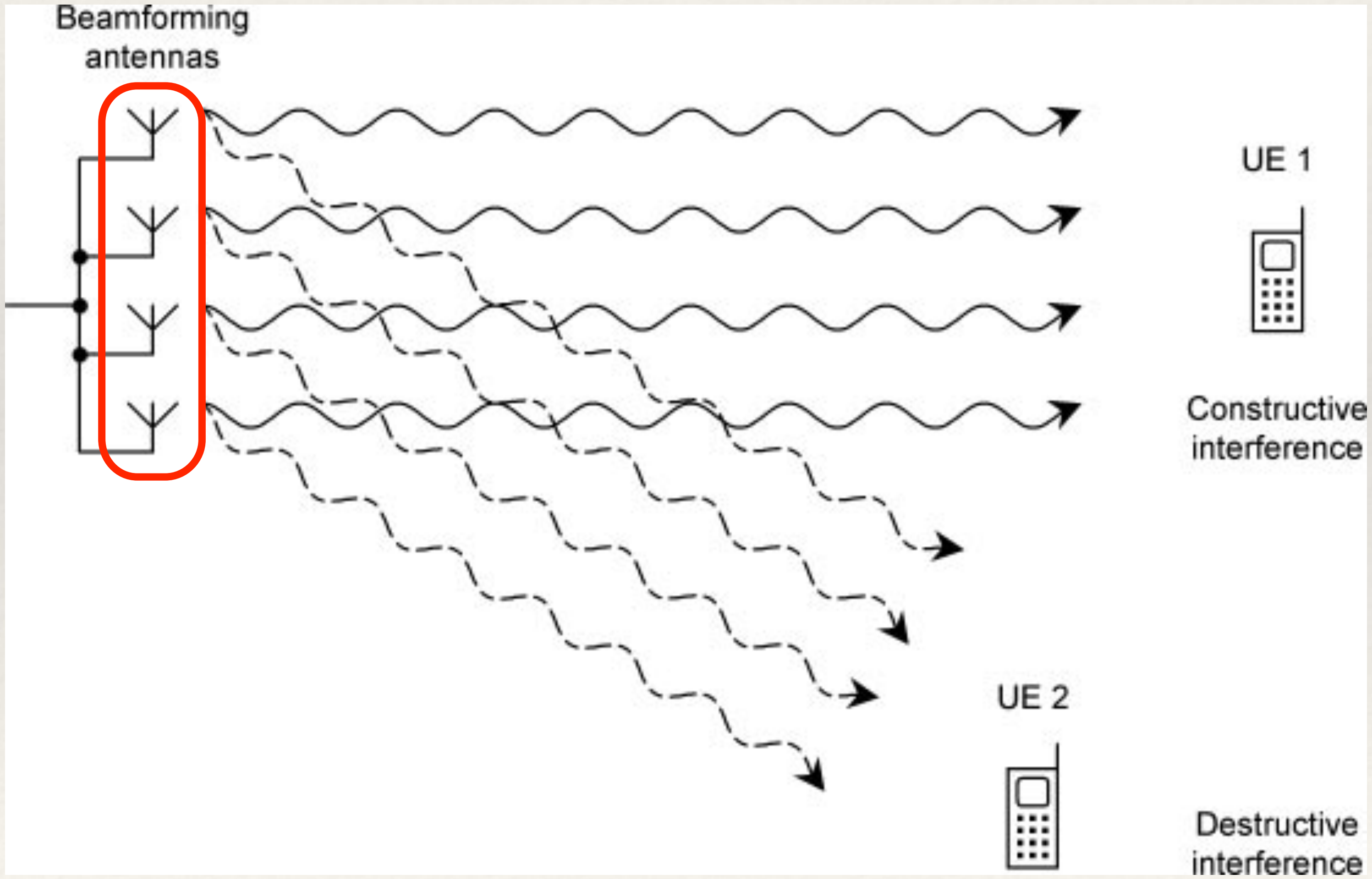
- 5.3.3 Dual Layer Beamforming
- 5.3.4 Downlink Multiple User MIMO Revisited

5.3.1 Principles of Operation

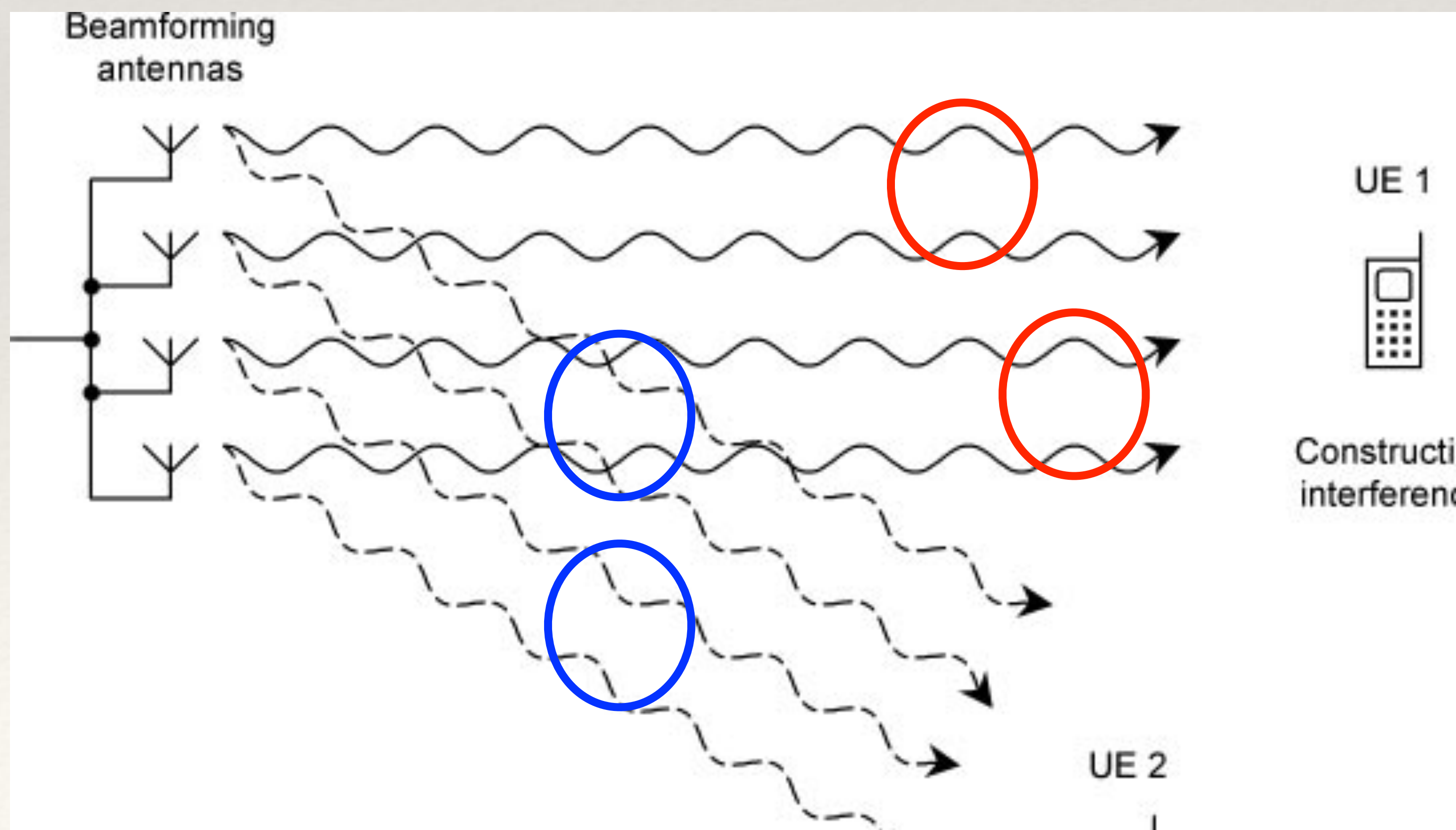
- In beamforming, a BS uses multiple antennas in a completely different way, to **increase its coverage**



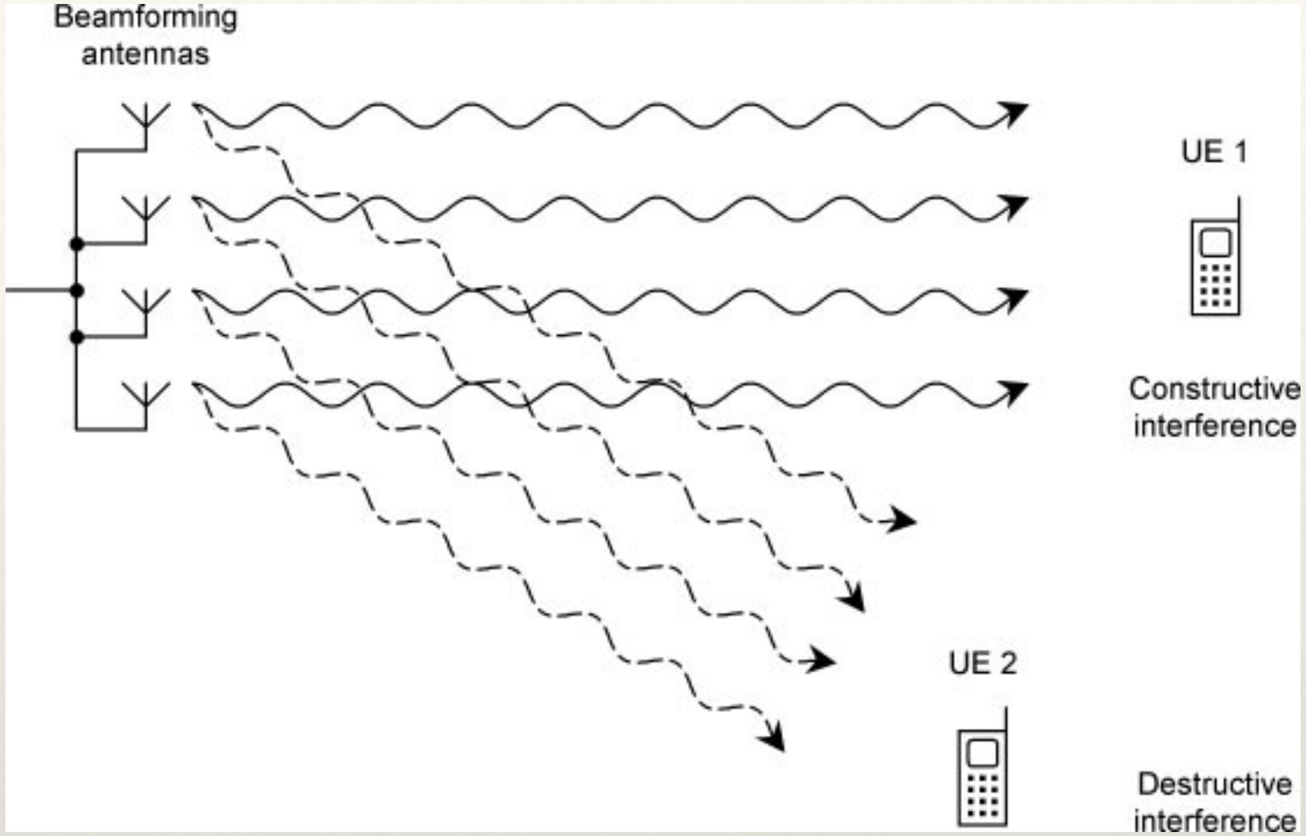
Basic principles of beamforming

- UE 1
  - Long way from the BS, on a line of sight that is at right angles to the antenna array
  - The signals from each antenna reach UE 1 in phase, so they interfere constructively, and the received signal power is high
- UE 2
  - At an oblique [斜的] angle, and receives signals from alternate antennas that are 180○ out of phase
  - These signals interfere destructively, so the received signal power is low
- We have therefore created a synthetic antenna beam, which has a main beam pointing towards UE 1 and a null pointing towards UE 2

Beam steering using a set of phase shifts

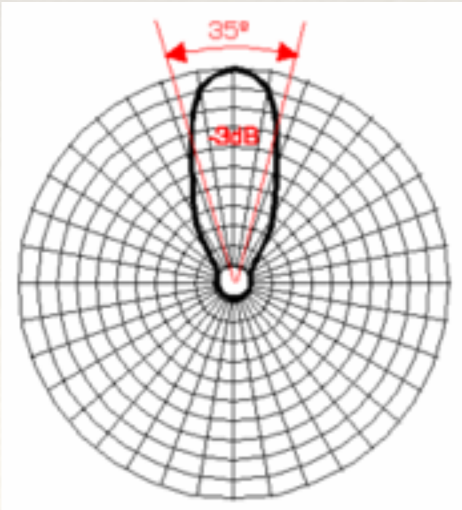


- The beamwidth is narrower than one from a single antenna, so the transmitted power is focussed towards mobile 1

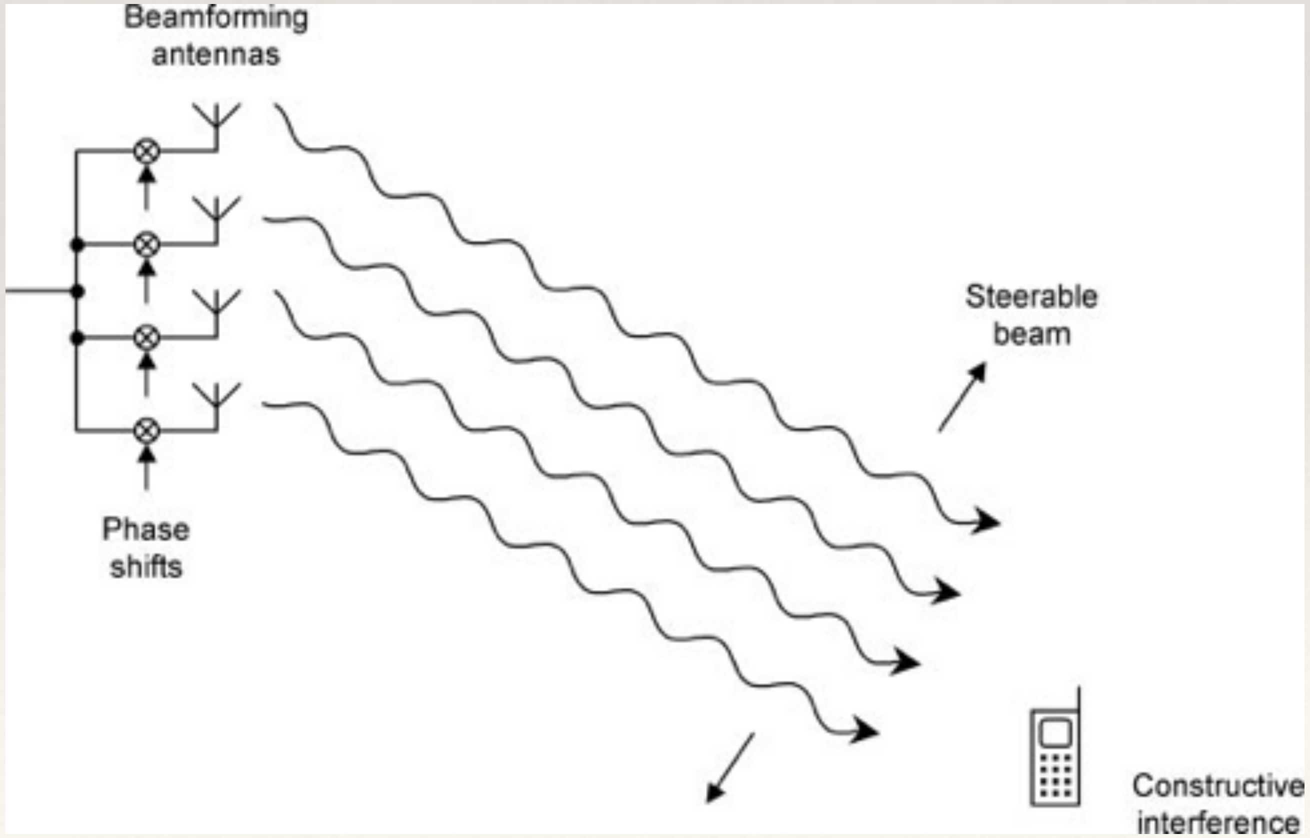


Beamwidth: In a radio antenna pattern, the half power beam width is the **angle** between the half-power (-3 dB) points of the main lobe [波瓣], when referenced to the peak effective radiated power of the main lobe

$$10 \log_{10}(1/2) = -3\text{dB}$$



- By applying a phase ramp [斜坡] to the transmitted signals, we can change the direction at which constructive interference arises, so we can direct the beam towards any direction we choose
- More generally, we can adjust the amplitudes and phases of the transmitted signals, by applying a suitable set of antenna weights



- We can use the same technique to construct a synthetic reception beam for the uplink
- By applying a suitable set of antenna weights at the BS receiver, we can ensure that the received signals add together in phase and interfere constructively
- In OFDMA, we can process different sub-carriers using different sets of antenna weights, so as to create synthetic antenna beams that point in different directions
- We can therefore use beamforming to communicate with several different mobiles at once using different sub-carriers, even if those mobiles are in completely different locations

- Beamforming works best if the antennas are close together, with a separation comparable with the wavelength of the radio waves
    - This ensures that the signals sent or received by those antennas are highly correlated
    - This is a different situation from diversity processing or spatial multiplexing, which work best if the antennas are far apart, with uncorrelated signals
- A BS is therefore likely to use two sets of antennas
    - A closely spaced set for beamforming
    - A widely spaced set for diversity and spatial multiplexing

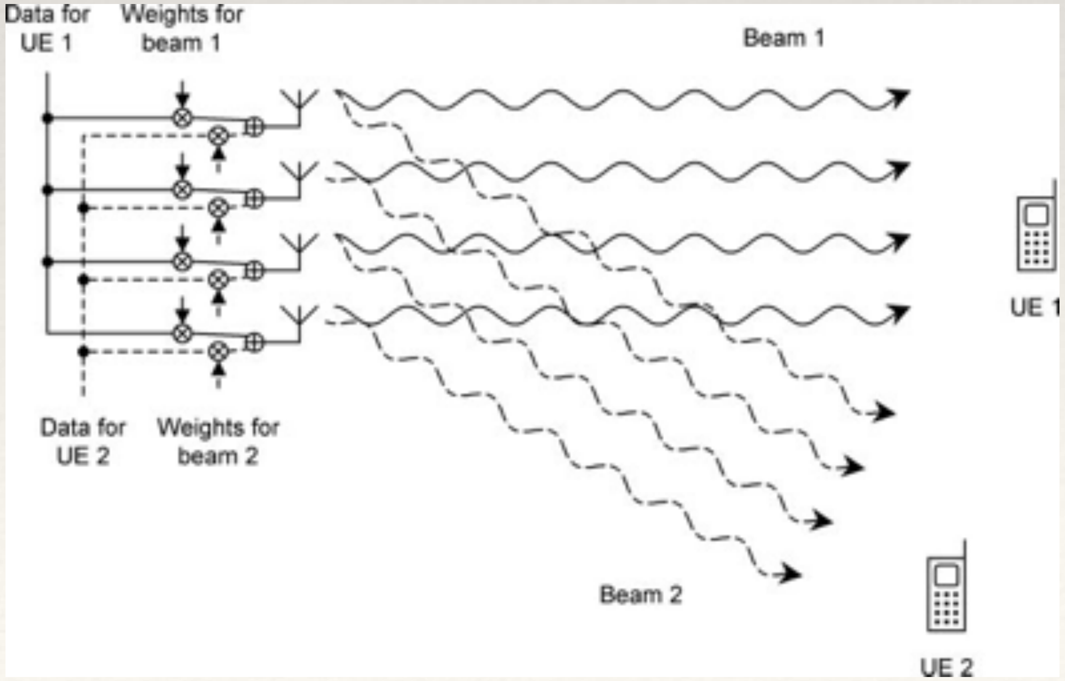
5.3.2 Beam Steering

- How to calculate the antenna weights and steer [引導] the beam?
- For the reception beams on the uplink, there are two main techniques
  - Using the **reference signal** technique
    - The BS adjusts the antenna weights so as to reconstruct the mobile's reference symbols with the correct signal phase and the greatest possible signal to interference plus noise ratio (SINR)
  - An alternative is the **direction of arrival technique**
    - The BS measures the signals that are received by each antenna and estimates the direction of the target mobile
  - From this quantity, it can estimate the antenna weights that are needed for satisfactory reception

- For the transmission beams on the downlink, how to calculate the antenna weights and steer the beam depends on the BS's mode of operation
  - In TDD mode
    - The uplink and the downlink use the same carrier frequency, so the BS can use the same antenna weights on the downlink that it calculated for the uplink
  - In FDD mode
    - The carrier frequencies are different, so the downlink antenna weights are different and are harder to estimate
  - For this reason, beamforming is more common in systems that are using TDD rather than FDD

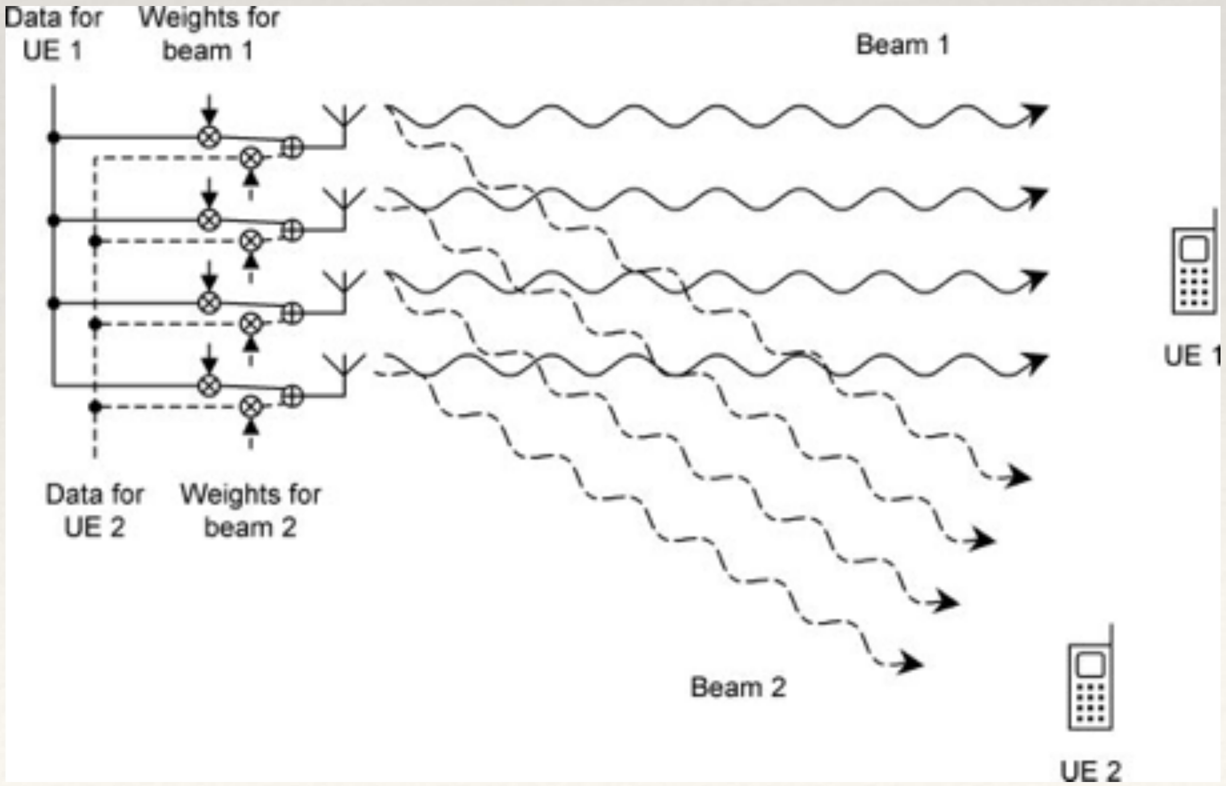
5.3.3 Dual Layer Beamforming

- In this technique, the BS sends two different data streams into its antenna array, instead of just one
- It then processes the data using two different sets of antenna weights and adds the results together before transmission
- In doing so, it has created two separate antenna beams, which share the same sub-carriers but carry two different sets of information



Dual layer beamforming using two parallel sets of antenna weights

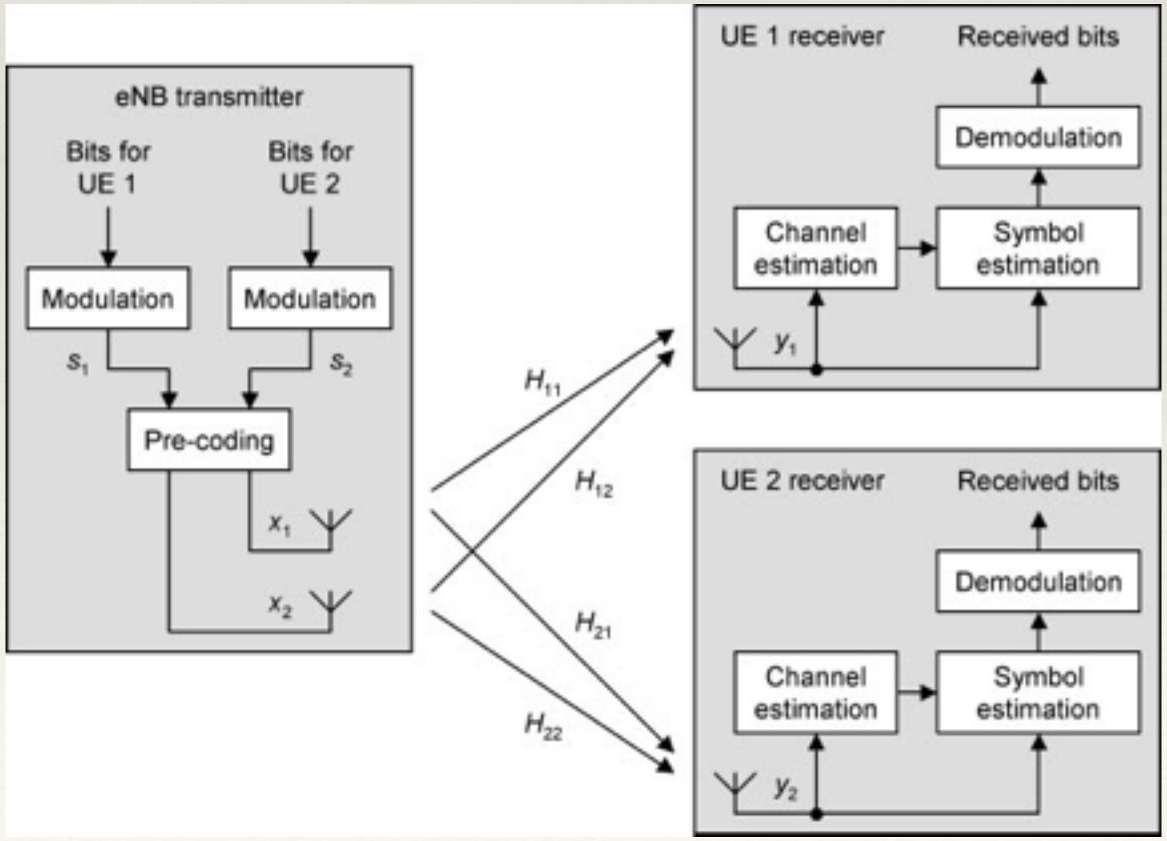
- The BS can then adjust the antenna weights so as to steer the beams to two different mobiles, so that the first mobile receives constructive interference from beam 1 and destructive interference from beam 2 and vice-versa
  - By doing this, the BS can double the capacity of the cell
- Alternatively, the BS can steer the beams to two different antennas on a single mobile, so as to double that mobile's instantaneous data rate



- In ideal conditions, the maximum number of independent data streams is equal to the number of antennas in the array
- LTE first supports the technique in Release 9 of the 3GPP specifications
  - In that release, the maximum number of data streams is limited to two, leading to the name of dual layer beamforming

5.3.4 Downlink Multiple User MIMO Revisited

- Referring back to Figure 5.9, the only reliable solution is to precode the transmitted symbols s_1 and s_2, so that s_1 is subject to constructive interference at UE 1 and destructive interference at UE 2, with the opposite situation applying for s_2
- This implies that downlink MU-MIMO is best treated as a variety of beamforming, using BS antennas that are close together rather than far apart



- The difference between **downlink multiple user MIMO** and **dual layer beamforming** lies in the calculation of the antenna weights
  - In multiple user MIMO
    - Each mobile feeds back a precoding matrix from which the BS determines the antenna weights that it requires
  - There is no such feedback in **dual layer beamforming**
    - Instead, the BS calculates the downlink antenna weights from its measurements of the mobile's uplink transmissions

- LTE first supports this implementation of downlink multiple user MIMO in Release 10 of the 3GPP specifications
- There is, however, limited support for downlink multiple user MIMO in Release 8
  - The Release 8 implementation uses the same algorithms that single user MIMO does, so the performance of downlink multiple user MIMO in Release 8 is comparatively poor