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Introduction

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People in the modern day are on the move, either just within a home or office building or traveling from place to place. In previous years, having to go to a fixed location in order to make a telephone call was an inconvenience. Nowadays this inconvenience is minimised because the facility of a mobile phone allows someone to carry out this mundane task almost whenever or whenever they please.

As mobile communications have grown exponentially in recent years and, in parallel, the World Wide Web and its applications have spread widely, the possibility to have access to Internet, entertainment and multimedia communications wirelessly has accelerated a similar trend: people want to avoid further inconveniences of having to go to a fixed location and establish the necessary communication link to get access to the Internet. Moreover, it is desirable to avoid having to install the corresponding cables into a building or home and to avoid incurring the related costs.

Speech communication for mobile telephones was at the time a tremendous task to achieve wirelessly, and internet and multimedia applications which by nature demand a significantly higher volume of data to be transmitted both ways through the communication link pose today an equally, if not more, challenging problem.

Multiple input multiple output (MIMO) systems have emerged as an enabling technology to achieve the design goals of contemporary communication systems and has given rise to a proliferation of research activity worldwide. The technology itself has hit the public domain and it is possible for someone today to buy a state of the art wireless access point and modem with MIMO written on the box. If the wireless communications industry will be producing more and more products with this technology then there is a need for engineers to have a comprehensive guide to learning the concept. Therefore, MIMO has

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become a widespread research topic and is a major component on the teaching agenda in many universities delivering courses on modern-day mobile communication systems.

As an aid to the telecommunications engineer of the future, this book aims to approach the subject in a way that is both intuitive and technical. The goal is to show how MIMO systems have emerged from conventional systems, and what special technical features enable MIMO systems to transmit data through a radio environment more rapidly. To the extent possible, visual means will be used to develop understanding and intuition.

This chapter will explain where MIMO came from, what it is for and how it is used. The purpose is to help the reader establish on an abstract level the right frame of mind to read the remainder of the book. The final section of this chapter will explain the structure of the book and how it will take the reader through the different stages of learning about the subject. The same structure characterises the rest of the book: every chapter contains a summary at the end, which will provide bullet points of the fundamental facts that the reader should grasp in order to progress through the book effectively.

1.1 From SISO to MISO/ SIMO to MIMO

1.1.1 Single Input Single Output SISO

SISO stands for Single Input Single Output and has conventionally been the structure used in communications systems: in general, an ‘input’ is the signal transmitted from a single antenna, whereas an output is the signal received on a single antenna. Indeed, conventional wisdom tells us that cellular phones have one single antenna (e.g. visible antenna extending on one end of the phone, or patch antenna embedded on its back) and communicate with a single antenna at the base station. In any radio environment there is going to be more than one user and all the users need to have access to the cellular services at the same time. The signals to the users are then separated in time (time division multiple access, TDMA), in frequency (frequency division multiple access, FDMA), or code (code division multiple access, CDMA). In TDMA systems, all users use the same set of frequencies to communicate, but not simultaneously. For example, two users can use the same frequency but they will have allocated time slots as illustrated in Figure 1.1. In this case, the communication link switches alternately between the two users so that

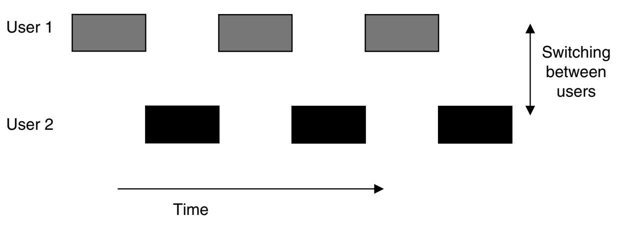

Figure 1.1 Illustration of a simple time slot allocation scheme for two users.

they can take turns to use the spectrum for equal time periods. Therefore each user's link will effectively get switched on and off for equal time periods. During the period that each user is receiving data, the data are conveyed in digital form in packets which are then re-assembled at the receiver.

In FDMA systems, all users have access to the system at the same time, but they use different parts of the spectrum to communicate. As long as the users use different frequencies, their signals do not interfere with each other.

In CDMA systems, all users use the same spectrum at the same time, but their signals are separated in the code domain, that is, each user's signal uses a code that is specific to this user and orthogonal to other users.

1.1.2 Single Input Multiple Output, SIMO, and Multiple Input Single Output, MISO

In any of the above cases, the link between the transmit and the receive antenna is impaired by the features of the radio environment. As the user moves, the signal strength varies over the small and large scale, and at times, the quality of the link is too low to deliver data successfully. This leads to unacceptable error rates or radio link failure. In order to combat this problem, a technique known as 'diversity' has been developed. Diversity relies on the use of multiple copies of the same signal, which the receiver can combine or select from. The idea behind it is that, even if one copy of the signal is of poor quality, it is unlikely that all the copies will be so, and therefore this redundancy allows the communication quality to be maintained.

There are different flavours of diversity techniques, and they can be employed either in the downlink or in the uplink.

Depending on how the multiple copies are generated, one can distinguish different types of diversity domains. For example, one can generate multiple copies of the same signal by transmitting it multiple times, which gives rise to time diversity, or one can generate multiple copies of the same signal at different parts of the spectrum, which gives rise to frequency diversity. Moreover, one can exploit the space domain, for example when the same signal is transmitted from several base station antennas and received at a single mobile terminal (this is known as large-scale or site diversity), or a receiver has several spatially separated antennas each of which receives a different copy of the signal (this is known as small-scale diversity).

Depending on the end of the communication link which employs multiple antennas, one can distinguish between transmit diversity techniques, where multiple copies of the signal are transmitted from several antennas and their superposition is received at a single receive antenna, and receive diversity techniques, where the signal is transmitted from a single antenna and multiple copies of the signal are received at several antennas. These combinations gave rise to Multiple Input Single Output techniques (multiple transmitters, a single receiver), and Single Output Multiple Input techniques (single transmitter, multiple receivers).

Another way to classify diversity techniques is according to the way the multiple copies of the signals are exploited. In this respect, one can distinguish, in ascending order of performance, selection diversity, wherein the 'best' copy of the signal is selected; equal gain combining, wherein the multiple copies of the signal are added; and maximum ratio combining, wherein the multiple copies of the signal are weighted by appropriately selected scaling factors such that the quality of the resulting signal is optimised.

As an example, let us consider the scenario in Figure 1.4 and imagine that there is one transmitting mobile M_1 and one receiving base station that has two antennas. The signal transmitted from the mobile station is denoted as x and the signals received at the two base station antennas are indicated as y_1 and y_2. The relationship between them is

$$\begin{aligned} y_1 &= h_1 x + n_1 \\ y_2 &= h_2 x + n_2 \end{aligned} \tag{1.1}$$

where h_1, h_2 are the channel coefficients between the mobile station and the two receive antennas respectively, and n_1, n_2 are the noise signals at the two receive antennas, which for simplicity will be assumed to be independent and of the same statistics. The base station can combine the signals from its two receive antennas to improve the quality of the signal.

Selection diversity would select the best of the two signals, that is, the one with the largest channel coefficient, and therefore the output of a selection diversity receiver would be

$$y_{\text{sel}} = \max(|h_{11}|, |h_{12}|)x_1 + n_i \tag{1.2}$$

where the index i is the one of the maximum channel coefficient.

Equal gain combining would simply add the two signals, after aligning their phases so that they add coherently. Therefore the base station apply the phase weights, u_1 and u_2, to output y_{equal}:

$$\begin{aligned} y_{\text{equal}} = u_1 y_1 + u_2 y_2 &= (u_1 h_{11} + u_2 h_{12})x + (u_1 n_1 + u_2 n_2) \\ &= (|h_{11}| + |h_{12}|)x + (u_1 n_1 + u_2 n_2) \end{aligned} \tag{1.3}$$

If the antenna elements are within close proximity to each other, and one assumes that the magnitudes of the channel coefficients $|h_{11}|$ and $|h_{12}|$ are the same, only their phase is different, thus the equation simplifies to $y_{\text{equal}} = 2|h_1|x$. Therefore the signal received is twice that of the signal that would be received if there had been only one single antenna at the receiver. Therefore due to using an array antenna, there is a signal gain, which is known as an array gain or beamforming gain.

Maximum ratio combining would not simply add the two signals, after aligning their phases so that they add coherently, but it would scale them suitably so that stronger signals have more weight. We denote the scaling weights as u_1 and u_2 and it can be mathematically shown that, in the case of equal average noise power, the optimal weights are proportional

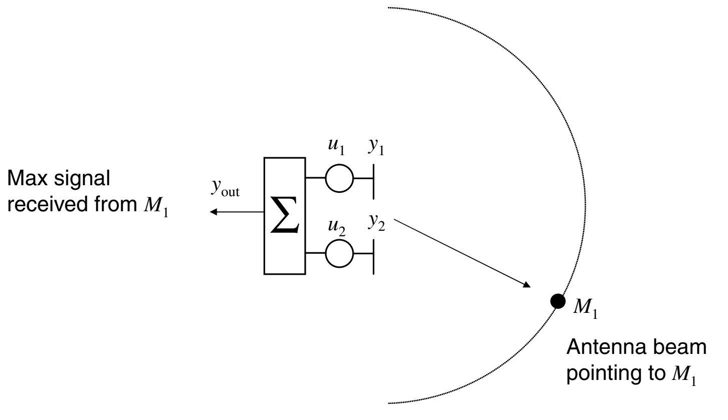

Figure 1.2 Simple illustration of beamforming gain.

to the channel coefficients $u_1 = h_1^*$ and $u_2 = h_2^*$.[1] Therefore the base station apply the scaling weights, to output y_{mrc} :

$$\begin{aligned} y_{\mathrm{mrc}} &= u_1 y_1 + u_2 y_2 = (u_1 h_1 + u_2 h_{12})x + (u_1 n_1 + u_2 n_2) \\ &= (|h_{11}|^2 + |h_{12}|^2)x + (h_1^* n_1 + h_2^* n_2) \end{aligned} \tag{1.4}$$

In general, the application of gains to the signals transmitted or received from multiple antennas is called beamforming. The easiest way to understand it in this context is shown in Figure 1.2, where the phase weights are optimised so as to receive the maximum signal from mobile station at a specific location. If the position of the mobile was moved to any point on the dotted semi-circle such that it was the same distance away from the array antenna, only at a different angle, the output signal received would certainly decrease because the phase factors would not correspond to the actual phases of the channel coefficients, and the signals to be added would no longer be phase-aligned. At some point, the phases might be so misaligned that the signals to be added would have opposite phases and would cancel each other. Since there is therefore only one angle at which the array antenna will receive the maximum signal from the mobile station, it is effectively forming a *beam* in a single direction, which is determined by the phase weights, u_1 and u_2.

The example shown is a case of a single input and multiple output (SIMO) system since there is one antenna at the input (i.e. the transmitter) and more than one antenna combined at the output (i.e. receiver). Given that a SIMO channel is reciprocal, we can make the array antenna the transmitter and the single mobile antenna the receiver. The beamforming gain is still valid if the phase weights are still optimised, which means we now have a

[1] In the case of unequal noise powers, the optimal gains are proportional to signal to noise ratio on each branch, which simplifies to the expression shown for equal noise powers.

multiple input single output (MISO) system as it is the receiver that now has only one antenna.

In the general case, the application of weights at multiple antennas, for example at the transmitter, allows the transmitter to point the energy in specific directions. Moreover, appropriate choice of weights can allow the transmitter to null the energy transmitted in others. The principle of beamforming can be used to enhance the system performance to one user, or to accommodate more that one user.

In the examples shown earlier, the benefit of diversity has been attributed to the difference in the channel coefficient using the multiple antennas. Although separating the antennas in space is an obvious way to achieve this, even co-located antennas can perceive different channel coefficients as long as they have different patterns, which would be referred to as pattern diversity. Moreover, antennas can also perceive two differently oriented electromagnetic field radiations, known as polarisations, which allow for polarisation diversity. Finally, it is possible to achieve circuit-based decoupling of antennas that are located close to each other and this is exactly the enabling factor for the use of multiple antennas on small terminals where spatial separation is not possible.

As a summary, diversity techniques have several benefits: the link quality is more stable, the average performance is improved, and we in general refer to these benefits as diversity gain. However, such techniques come at a price, namely they require more system resources. This is perhaps easier to understand on the basis of time diversity techniques, where more system time is required to transmit the same data. That extra time expenditure could have been used to transmit new data, thereby improving the system efficiency. The cost associated with the use of multiple antennas relates to space considerations (a terminal should be large enough), hardware concerns (a more complicated receiver or transmitter is required) and price issues (the additional complexity increases the device price). Another disadvantage is that diversity is a process of diminishing returns. This means that the benefit of adding for example a third antenna over having only two antennas is smaller than the benefit from going to two antennas from a single antenna. Moreover, the condition for diversity techniques to be effective is that the copies of the signal have to be independent, so as to minimise the probability that they all face simultaneously bad propagation conditions.

1.1.3 Multiple Input Multiple Output, MIMO

Diversity, and specifically space diversity, relies on the use of multiple antennas at one end of the communication link, either at the transmitter or at the receiver side. The evolution of the diversity ideas has been the use of multiple antennas at both ends of the communications link.

The additional benefit that can be drawn from the use of multiple antennas on both sides of the communications link is so-called spatial multiplexing, that is, the ability to send several data streams simultaneously. Indeed in the examples shown in the previous section, the same data stream exploits the benefit of diversity. Let us take the example

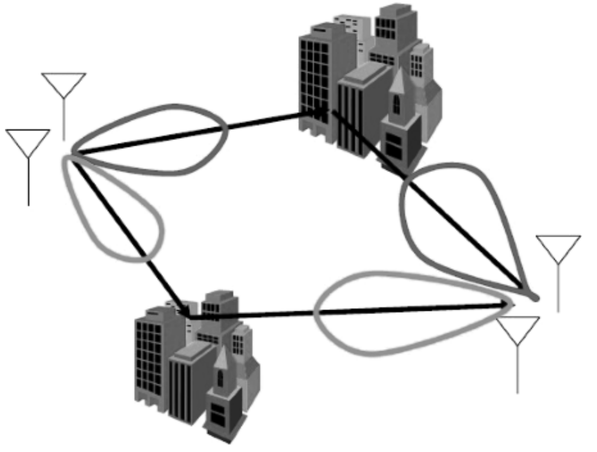

Figure 1.3 Illustration of the principle of a simple 2x2 MIMO link.

of a system with two transmitters and two receivers, each transmitter sending a separate data stream. As shown before, we can perform beamforming to each of the transmitters. If we beamform to both transmitters simultaneously, and the two beams are sufficiently separated, it would be possible to obtain the two streams without them interfering with each other. Indeed, for MIMO to work, it has to be possible for the beams formed at both ends to be able to distinguish different angles from which the antenna can transmit or receive. A simple example is shown in Figure 1.3 where effectively two paths have been created due to reflections of buildings at two different locations and the beams have been formed to transmit and receive down the two orthogonal paths.

Even though MIMO has been in the public domain for several years, it has only recently come into the production line for wireless communication devices. There are two main reasons why this has taken so long. First of all the practical aspects of implementing MIMO have been difficult in terms of building suitable antennas and also the implementation of the complex radio device has eased. Secondly, despite the fact that the cost of such a technology is still not economic, users are now prepared to pay the price if it delivers the desired services over the restricted bandwidth and is a cost-effective option.

1.2 What Do We Need MIMO For?

There are two perspectives from which we can answer this question. The first is from the perspective of a single user, wishing to increase the data rate of the wireless link between their mobile device and an access point or base station. The second is from the perspective that there are normally several users in a wireless system, communicating wirelessly at the same time and using the same frequency. We will therefore address these two points separately.

1.2.1 The Single User Perspective

The most obvious way to increase the rate at which data can be transmitted would be to increase the transmitted power so that the received signal is much stronger. However, transmitting high power signals from a mobile device has safety issues, as well as battery issues: the battery will be depleted extremely fast and the time between charges (which is a common factor in user satisfaction) will be shortened. Therefore this is not a good option.

Another way of enabling a higher data rate to be transmitted through a wireless link is to increase the radio frequency bandwidth. However, at the frequencies suitable for communication links, namely the parts of the spectrum where there are no other conflicting uses and where the propagation losses are not prohibitively high, the bandwidth is extremely precious. There are major financial and legal obstacles involved and it is simply not possible to increase the allocated bandwidth infinitely.

It turns out that MIMO systems have the ability to increase the data rate of the transmitted data without increasing the transmit power and by using the same amount of frequency resources.

1.2.2 The Multiple User Perspective

In any radio environment there is going to be more than one user and all of them need to support simultaneous links. As indicated earlier, the users have conventionally been separated in the time, frequency or code dimensions in order to avoid interference among them.

We therefore need to find methods of accommodating multiple users simultaneously within the constraints of limited frequency bandwidth, and multiple antennas come to the rescue. As explained earlier, MISO and SIMO techniques allow the formation of beams that point the energy in specific directions. By forming two beams pointing in two directions, one can effectively send different signals to two users.

As an example, let us consider one of the simplest forms of antenna array at a receiving base station, while there are two mobile devices at different locations, each transmitting a signal at the same frequency to the receiver illustrated in Figure 1.4. The mobile users, M_1

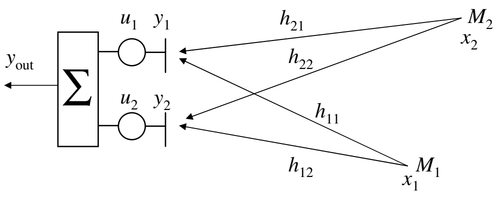

Figure 1.4 Illustration of a basic two element array antenna used to mitigate co-channel interference.

and M_2, are simultaneously transmitting signals x_1 and x_2 respectively. The superposition of the two signals at each of the two receiving the two antennas, y_1 and y_2, can be derived by the following equations:

$$\begin{aligned} y_1 &= h_{11}x_1 + h_{21}x_2 \\ y_2 &= h_{12}x_1 + h_{22}x_2 \end{aligned} \tag{1.5}$$

In reality, there is also receiver noise added to the signals y_1 and y_2, which has for simplicity been omitted.

In the above equation, h_{11} is the complex channel coefficient between mobile M_1 and the receiving antenna 1. Likewise h_{21} is the complex channel coefficient between mobile M_2 and the receiving antenna 1. This works the same way for mobile M_2 with channel coefficients h_{21} and h_{22}.

The receiver can apply weights u_1 and u_2 on the two received signals, y_1 and y_2 and then combine them before reaching the output as shown in Figure 1.4. The resulting signal, y_{out} would be:

$$y_{\text{out}} = u_1y_1 + u_2y_2 = (u_1h_{11} + u_2h_{12})x_1 + (u_1h_{21} + u_2h_{22})x_2 \tag{1.6}$$

The weights can be set appropriately so that the signal contains only terms with x_1 and not x_2, which means only the signal from mobile M_1 is received, while the signal from M_2 is suppressed. For this to be possible, the following criteria therefore has to be met (assuming the channel coefficients are appropriately normalised):

$$\begin{aligned} u_1h_{11} + u_2h_{12} &= 1 \\ u_1h_{21} + u_2h_{22} &= 0 \end{aligned} \tag{1.7}$$

This a simple system of linear equations which can easily be solved to derive the weights u_1 and u_2 that will help isolate signal x_1.

A further step to consider applying also a second set of weights that can help isolate signal x_2 in a simlar fashion as shown in Figure 1.5. By the application of two sets of weights, the receiver has essentially formed two beams, such that y_{out1} only receives from M_1 and y_{out2} only receives from M_2. For simplicity, this technique is referred to as Space Division Multiple Access (SDMA). Therefore MIMO can be seen as an evolution of MISO and SIMO that includes the ability to handle multiple users as well as providing a higher data rate communication link.

Although the selection of the weights shown above to eliminate the interference from the other data streams is not the only, and possibly not the best, way to isolate the data transmitted by the two users, the example is a good illustration of the potential that MIMO systems have to accommodate more than one user simultaneously.

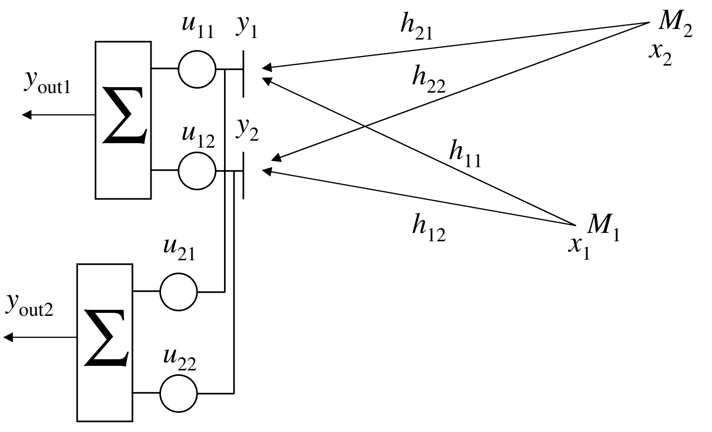

Figure 1.5 Illustration of a basic two element array antenna used for space division multiple access.

1.3 How Does MIMO Work? Two Analogies

Before considering how a MIMO radio channel works using antennas intelligently, we will take two analogies that help to understand the concept in a more visual way. These two ways are going to be analogous to the single and multiple user perspectives presented in the previous section.

1.3.1 The Single User Perspective

Let us first consider the *football match problem*. Supporters on their way to a football match arrive on a bus, train or tram where they exit the station. In the ideal case, they take a wide, direct path to move directly over to the stadium entrance in an orderly queue, thus all walking there as quickly as possible as illustrated in Figure 1.6.

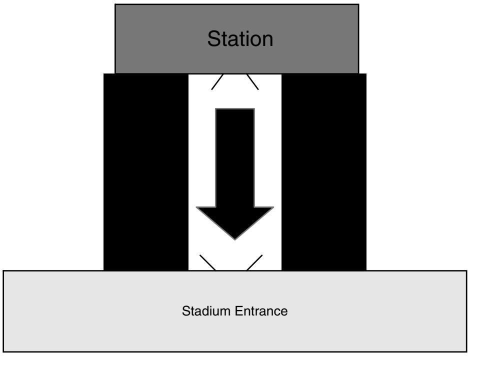

Figure 1.6 Illustration of a perfect scenario of supporters entering a football stadium.

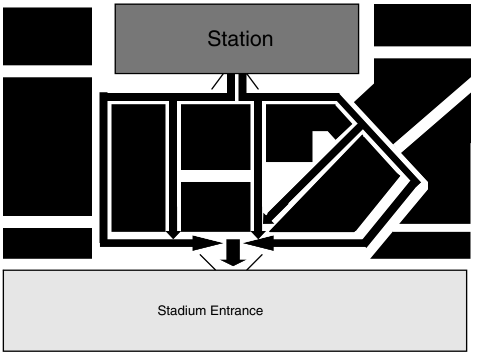

Figure 1.7 Illustration of a real scenario of football supporters entering a stadium without crowd control.

In practice, however, such wide direct maths between the station and the stadium might not exist. Instead, the station may be some distance away and supporters can take several possible routes down different streets to arrive at the same destination as the illustration in Figure 1.7 shows. The picture shows that there are several points where the separate paths that supporters take begin cross, and the traffic can collide. This will slow down the rate at which supporters will enter the building and some will inevitably be stuck for quite some time.

So that a crowd of supporters can walk to and from a station to a stadium quickly and efficiently, it is necessary to enforce crowd control, which will determine which routes the supporters take and which entrances or exits they use. One such example of crowd control is shown in Figure 1.8, where two entrances are opened at the stadium and two exits are opened at the station. Furthermore barriers have been implemented using the dotted lines shown so that the paths between the station exits and the stadium entrances do not collide.

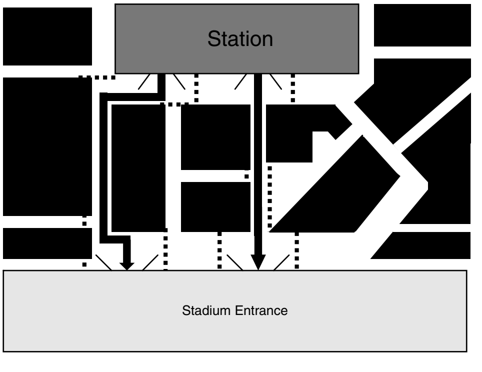

Figure 1.8 Illustration of a real scenario of football supporters entering a stadium with crowd control.

Even though each route individually might only be able to accommodate a portion of the traffic, the collisions that were in Figure 1.7 have now been prevented, and cumulatively the rate at which supporters will enter the stadium will be more efficient.

For wireless radio systems, the transmitted radio signal will encounter many objects that will cause the signal to reflect, refract and diffract causing the signal to arrive at the receiver from many directions. Thus the signal has taken many paths and this is known as *multipath*, which like the case of many football supporters taking several paths to the same destination will cause the resulting signal to fade, which will at the same time limit the rate of data that can be sent to the receiver. MIMO on the other hand uses multiple antennas at the transmitter and receiver to take advantage of the multipath and transmit more data by arterially introducing an isolation of the paths, just like in the case of crowd control at a football match.

1.3.2 The Multiple User Perspective

We will now consider the multiple user perspective by taking the example of the *cocktail party effect* shown in Figure 1.9. There are three groups of people in the picture amongst several other groups in a large hall and everyone is enjoying themselves talking loudly and laughing. Anyone who has lived through such a situation can attest that, despite the ambient noise, one can concentrate on the conversation within one's group. With a bit of effort, one can isolate what the other person is saying, and sometimes, one can even do so for people that are farther away and whose voice is almost lost in the noise. This is because, although the human ear is capable of listening to everything around it no matter what direction the sound is coming from, it can also concentrate on a specific source

Figure 1.9 A cocktail party example of the multiple user perspective.

in a manner very similar to a camera focussing on a single point. In a sense our ears are an array of two elements that can concentrate on the person we are talking to and suppress the noise from others conversing near to us. Therefore the group in the middle of Figure 1.9 can communicate with each other while suppressing the acoustic interference of the two groups either side.

In MIMO, arrays of antennas rather than arrays of ears are used to suppress radio interference at the same frequency. The antenna arrays at both ends of a MIMO link will also concentrate radio signals into different directions to concentrate data into different paths and allow more data to be transmitted.

1.4 Conditions for MIMO to Work

As shown earlier, the derivation of suitable weights that can help isolate the data streams (either from multiple users or from a single user equipped with multiple antennas) relies on the solution of a system of linear equations that involve the channel coefficients. Basic algebra indicates that there cases where the solution is feasible and others where it is not. These conditions translate into requirements for the channel coefficients

To analyse more closely how the channel coefficients should be in order for MIMO to work, the three scenarios can be considered in Figure 1.10. First of all in Figure 1.10 (a), there are are no objects in the vicinity of the transmitting antennas on the left and receiving

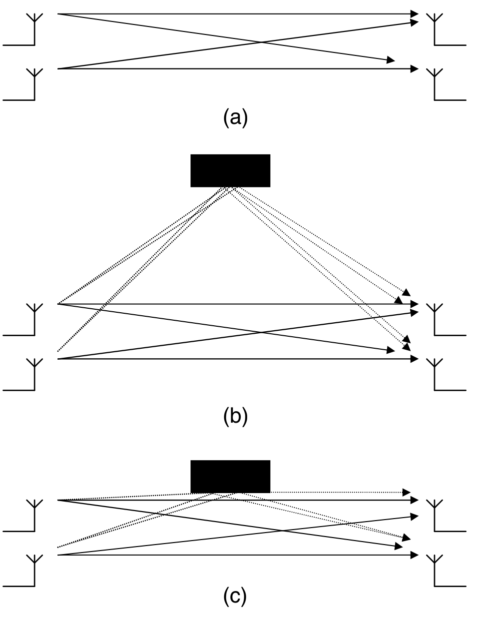

Figure 1.10 Illustration of the scattering scenarios with which MIMO will operate.

antennas on the right, just free space. Therefore if the transmit antennas are close together, and the receive antennas are also close together, then it is difficult to make two beams to isolate the two signals. In this case MIMO communication would not be possible.

If an object is introduced to create some reflected paths as illustrated in Figure 1.10 (b), different paths can be created. The object is known as a *scatterer*, and beams can be formed so that one channel is created that exploits the reflected paths, while the other channel will use the direct link from the transmitter to the receiver. It can now be seen how MIMO will exploit the multipath to create more channels through which it is able to transmit data more rapidly. If there were more scatterers present and more antennas at each end, this would mean there is more multipath available to exploit and also more separate channels could be created to enhance the separation of the signals.

A final point to note regarding the exploitation of multipath by MIMO is that it must also meet certain conditions. Taking Figure 1.10 (c), for example: the scatterer is now very close to the direct path between the transmitter and receiver. Because the paths are then much closer and therefore much more similar to each other (i.e. they are highly correlated) then it becomes too difficult to form unique beams at both ends from which orthogonal channels can be created. Therefore the position of the scatterers as well as their density are very important. This is often quantified by what is known as *scattering richness*, which therefore will be of great benefit to MIMO.

1.5 How Long Has MIMO Been Around?

Although MIMO has had a long history, dating back to 1987 when the first paper was published showing the benefit of using such a technique (Winters 1987). Some of the first related patents were published in the 1990s (Paulraj *et al.* 2003) and then later on some widely cited journals that emerged such as Foschini and Gans (1998) and Telatar and Tse (2000).

In the international research arena, there has been research carried out in MIMO and the research topics considered can be classified into the following categories:

- **Radio** – Channel measurements in terms of how the radio signal propagates through the environment. the goal has been to characterise the channel and derive models of its behaviour. Another important factor in this regard is the design of the array antennas used in MIMO and the study of how they impact the performance.
- **Signal processing** – The MIMO signals will need to be processed such that they have algorithms to detect the incoming MIMO signals and successfully decode them. A variety of algorithms have been developed to achieve that.
- **Coding** – Techniques such as space–time codes, Blast mechanisms and eigen tracking aim at achieving a balance between increasing the data rate and introducing redundancy.
- **Networking** – Linking several mobiles and access points using MIMO simultaneously.
- **Hardware** – Building the actual MIMO systems onto demonstrators, radio frequency (RF) chips and digital signal processing (DSP) chips etc.

The main focus of this book will be the radio and the signal processing involved in MIMO digital communications, including the theoretical limits imposed by information theory.

1.6 Where is MIMO Being Used?

Currently, MIMO is being used in some of the latest wireless routers to enhance the capacity of the wireless local area network (WLAN). This is shown in Figure 1.11 with the multiple antennas spatially separated. Many wireless routers such as this are normally defined under the Institute of Electrical and Electronic Engineers (IEEE) 802.11 standards (IEEE802.11). In the future MIMO will be used in cellular standards such as IEEE 802.16 (known as WiMAX) and Third Generation Partnership Long Term Evolution (3GPP LTE) (3GPP), which will be used in mobile communication devices that have MIMO capabilities. Such a technology will be essential in delivering the wireless broadband and multimedia services that these standards demand.

Figure 1.11 Illustration of a wireless router using MIMO. Reproduced by permission of Belkin Ltd.

1.7 Purpose of the Book

This book has opened up with a brief introduction to MIMO, stating both its function and its purpose. The theory behind MIMO will be explained in greater mathematical detail in the next chapter, paying particular attention to the information theory capacity limits. The book will then consider algorithms with which one can actually allow MIMO to work in practice and measure its performance in the third chapter. As MIMO performance depends on the propagation conditions, Chapters 4 and 5 will respectively address the radio channel and the design of the suitable antennas. Finally the book will conclude by giving specific examples of how MIMO is being used today, future trends and further research still to be carried out.