- **Transmission range**: Within a certain radius of the sender transmission is possible, i.e., a receiver receives the signals with an error rate low enough to be able to communicate and can also act as sender.
- **Detection range**: Within a second radius, detection of the transmission is possible, i.e., the transmitted power is large enough to differ from background noise. However, the error rate is too high to establish communication.
- **Interference range**: Within a third even larger radius, the sender may interfere with other transmission by adding to the background noise. A receiver will not be able to detect the signals, but the signals may disturb other signals.

This simple and ideal scheme led to the notion of **cells** around a transmitter (as briefly discussed in section 2.8). However, real life does not happen in a vacuum, radio transmission has to contend with our atmosphere, mountains, buildings, moving senders and receivers etc. In reality, the three circles referred to above will be bizarrely-shaped polygons with their shape being time and frequency dependent. The following paragraphs discuss some problems arising in this context, thereby showing the differences between wireless and wired transmission.

2.4.1 Path loss of radio signals

In free space radio signals propagate as light does (independently of their frequency), i.e., they follow a straight line (besides gravitational effects). If such a straight line exists between a sender and a receiver it is called **line-of-sight (LOS)**. Even if no matter exists between the sender and the receiver (i.e., if there is a vacuum), the signal still experiences the **free space loss**. The received power P_r is proportional to $1/d^2$ with d being the distance between sender and receiver (**inverse square law**). The reason for this phenomenon is quite simple. Think of the sender being a point in space. The sender now emits a signal with certain energy. This signal travels away from the sender at the speed of light as a wave with a spherical shape. If there is no obstacle, the sphere continuously grows with the sending energy equally distributed over the sphere's surface. This surface area s grows with the increasing distance d from the center according to the equation $s = 4\pi\, d^2$.

Even without any matter between sender and receiver, additional parameters are important. The received power also depends on the wavelength and the gain of receiver and transmitter antennas. As soon as there is any matter between sender and receiver, the situation becomes more complex. Most radio transmission takes place through the atmosphere – signals travel through air, rain, snow, fog, dust particles, smog etc. While the **path loss** or **attenuation** does not cause too much trouble for short distances, e.g., for LANs (see chapter 7), the atmosphere heavily influences transmission over long distances, e.g., satellite transmission (see chapter 5). Even mobile phone systems are influenced by weather conditions such as heavy rain. Rain can absorb much of the radiated energy of the antenna (this effect is used in a microwave oven to cook), so communication links may break down as soon as the rain sets in.

Depending on the frequency, radio waves can also penetrate objects. Generally the lower the frequency, the better the penetration. Long waves can be transmitted through the oceans to a submarine while high frequencies can be blocked by a tree. The higher the frequency, the more the behavior of the radio waves resemble that of light – a phenomenon which is clear if one considers the spectrum shown in Figure 2.1.

Radio waves can exhibit three fundamental propagation behaviors depending on their frequency:

- **Ground wave** (<2 MHz): Waves with low frequencies follow the earth's surface and can propagate long distances. These waves are used for, e.g., submarine communication or AM radio.
- **Sky wave** (2–30 MHz): Many international broadcasts and amateur radio use these short waves that are reflected[2] at the ionosphere. This way the waves can bounce back and forth between the ionosphere and the earth's surface, travelling around the world.
- **Line-of-sight** (>30 MHz): Mobile phone systems, satellite systems, cordless telephones etc. use even higher frequencies. The emitted waves follow a (more or less) straight line of sight. This enables direct communication with satellites (no reflection at the ionosphere) or microwave links on the ground. However, an additional consideration for ground-based communication is that the waves are bent by the atmosphere due to refraction (see next section).

Almost all communication systems presented in this book work with frequencies above 100 MHz so, we are almost exclusively concerned with LOS communication. But why do mobile phones work even without an LOS?

2.4.2 Additional signal propagation effects

As discussed in the previous section, signal propagation in free space almost follows a straight line, like light. But in real life, we rarely have a line-of-sight between the sender and receiver of radio signals. Mobile phones are typically used in big cities with skyscrapers, on mountains, inside buildings, while driving through an alley etc. Hare several effects occur in addition to the attenuation caused by the distance between sender and receiver, which are again very much frequency dependent.

An extreme form of attenuation is **blocking** or **shadowing** of radio signals due to large obstacles (see Figure 2.12, left side). The higher the frequency of a signal, the more it behaves like light. Even small obstacles like a simple wall, a truck on the street, or trees in an alley may block the signal. Another effect is the **reflection** of signals as shown in the middle of Figure 2.12. If an object is large compared to the wavelength of the signal, e.g., huge buildings, mountains,

2 Compared to, e.g., the surface of a building, the ionosphere is not really a hard reflecting surface. In the case of sky waves the 'reflection' is caused by refraction.

or the surface of the earth, the signal is reflected. The reflected signal is not as strong as the original, as objects can absorb some of the signal's power. Reflection helps transmitting signals as soon as no LOS exists. This is the standard case for radio transmission in cities or mountain areas. Signals transmitted from a sender may bounce off the walls of buildings several times before they reach the receiver. The more often the signal is reflected, the weaker it becomes. Finally, the right side of Figure 2.12 shows the effect of **refraction**. This effect occurs because the velocity of the electromagnetic waves depends on the density of the medium through which it travels. Only in vacuum does it equal *c*. As the figure shows, waves that travel into a denser medium are bent towards the medium. This is the reason for LOS radio waves being bent towards the earth: the density of the atmosphere is higher closer to the ground.

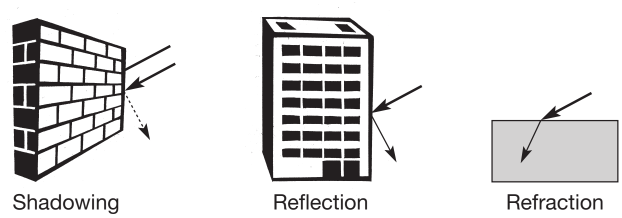


Figure 2.12
Blocking (shadowing), reflection and refraction of waves

While shadowing and reflection are caused by objects much larger than the wavelength of the signals (and demonstrate the typical 'particle' behavior of radio signals), the following two effects exhibit the 'wave' character of radio signals. If the size of an obstacle is in the order of the wavelength or less, then waves can be **scattered** (see Figure 2.13, left side). An incoming signal is scattered into several weaker outgoing signals. In school experiments, this is typically demonstrated with laser light and a very small opening or obstacle, but here we have to take into consideration that the typical wavelength of radio transmission for, e.g., GSM or AMPS is in the order of some 10 cm. Thus, many objects in the environment can cause these scattering effects. Another effect is **diffraction** of waves. As shown on the right side of Figure 2.13, this effect is very similar to scattering. Radio waves will be deflected at an edge and propagate in different directions. The result of scattering and diffraction are patterns with varying signal strengths depending on the location of the receiver.

Effects like attenuation, scattering, diffraction, and refraction all happen simultaneously and are frequency and time dependent. It is very difficult to predict the precise strength of signals at a certain point in space. How do mobile phone operators plan the coverage of their antennas, the location of the antennas, the direction of the beams etc.? Two or three dimensional maps are used with a resolution down to several meters. With the help of, e.g., ray tracing or radiosity techniques similar to rendering 3D graphics, the signal quality can roughly be calculated in advance. Additionally, operators perform a lot of measurements during and after installation of antennas to fill gaps in the coverage.

Figure 2.13
Scattering and diffraction of waves

2.4.3 Multi-path propagation

Together with the direct transmission from a sender to a receiver, the propagation effects mentioned in the previous section lead to one of the most severe radio channel impairments, called **multi-path propagation**. Figure 2.14 shows a sender on the left and one possible receiver on the right. Radio waves emitted by the sender can either travel along a straight line, or they may be reflected at a large building, or scattered at smaller obstacles. This simplified figure only shows three possible paths for the signal. In reality, many more paths are possible. Due to the finite speed of light, signals travelling along different paths with different lengths arrive at the receiver at different times. This effect (caused by multi-path propagation) is called **delay spread**: the original signal is spread due to different delays of parts of the signal. This delay spread is a typical effect of radio transmission, because no wire guides the waves along a single path as in the case of wired networks (however, a similar effect, dispersion, is known for high bit-rate optical transmission over multi-mode fiber, see Halsall, 1996, or Stallings, 1997). Notice that this effect has nothing to do with possible movements of the sender or receiver. Typical values for delay spread are approximately 3 μs in cities, up to 12 μs can be observed. GSM, for example, can tolerate up to 16 μs of delay spread, i.e., almost a 5 km path difference.

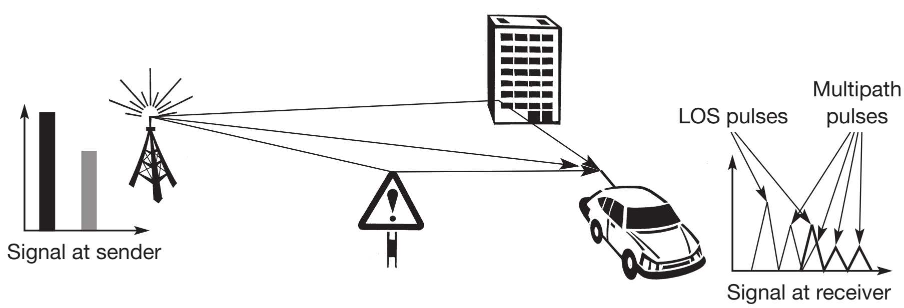


Figure 2.14
Multi-path propagation and intersymbol interference

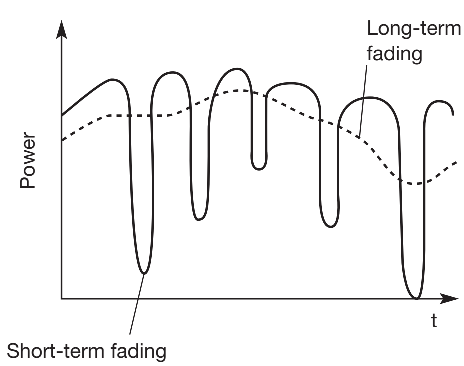
What are the **effects** of this delay spread on the signals representing the data? The first effect is that a short impulse will be smeared out into a broader impulse, or rather into several weaker impulses. In Figure 2.14 only three possible paths are shown and, thus, the impulse at the sender will result in three smaller impulses at the receiver. For a real situation with hundreds of different paths, this implies that a single impulse will result in many weaker impulses at the receiver. Each path has a different attenuation and, the received pulses have different power. Some of the received pulses will be too weak even to be detected (i.e., they will appear as noise).

Now consider the second impulse shown in Figure 2.14. On the sender side, both impulses are separated. At the receiver, both impulses interfere, i.e., they overlap in time. Now consider that each impulse should represent a symbol, and that one or several symbols could represent a bit. The energy intended for one symbol now spills over to the adjacent symbol, an effect which is called **intersymbol interference (ISI)**. The higher the symbol rate to be transmitted, the worse the effects of ISI will be, as the original symbols are moved closer and closer to each other. ISI limits the bandwidth of a radio channel with multi-path propagation (which is the standard case). Due to this interference, the signals of different symbols can cancel each other out leading to misinterpretations at the receiver and causing transmission errors.

In this case, knowing the channel characteristics can be a great help. If the receiver knows the delays of the different paths (or at least the main paths the signal takes), it can compensate for the distortion caused by the channel. The sender may first transmit a **training sequence** known by the receiver. The receiver then compares the received signal to the original training sequence and programs an **equalizer** that compensates for the distortion (Wesel, 1998), (Pahlavan, 2002), (Stallings, 2002).

While ISI and delay spread already occur in the case of fixed radio transmitters and receivers, the situation is even worse if receivers, or senders, or both, move. Then the channel characteristics change over time, and the paths a signal can travel along vary. This effect is well known (and audible) with analog radios while driving. The power of the received signal changes considerably over time. These quick changes in the received power are also called **short-term fading**. Depending on the different paths the signals take, these signals may have a different phase and cancel each other as shown in Figure 2.15. The receiver now has to try to constantly adapt to the varying channel characteristics, e.g., by changing the parameters of the equalizer. However, if these changes are too fast, such as driving on a highway through a city, the receiver cannot adapt fast enough and the error rate of transmission increases dramatically.

Figure 2.15
Short-term and long-term fading



An additional effect shown in Figure 2.15 is the **long-term fading** of the received signal. This long-term fading, shown here as the average power over time, is caused by, for example, varying distance to the sender or more remote obstacles. Typically, senders can compensate for long-term fading by increasing/decreasing sending power so that the received signal always stays within certain limits.

There are many more effects influencing radio transmission which will not be discussed in detail – for example, the **Doppler shift** caused by a moving sender or receiver. While this effect is audible for acoustic waves already at low speed, it is also a topic for radio transmission from or to fast moving transceivers. One example of such a transceiver could be a satellite (see chapter 5) – there Doppler shift causes random frequency shifts. The interested reader is referred to Anderson (1995), (Pahlavan, 2002), and (Stallings, 2002) for more information about the characteristics of wireless communication channels. For the present it will suffice to know that multi-path propagation limits the maximum bandwidth due to ISI and that moving transceivers cause additional problems due to varying channel characteristics.

2.5 Multiplexing

Multiplexing is not only a fundamental mechanism in communication systems but also in everyday life. Multiplexing describes how several users can share a medium with minimum or no interference. One example, is highways with several lanes. Many users (car drivers) use the same medium (the highways) with hopefully no interference (i.e., accidents). This is possible due to the provision of several lanes (space division multiplexing) separating the traffic. In addition, different cars use the same medium (i.e., the same lane) at different points in time (time division multiplexing).

While this simple example illustrates our everyday use of multiplexing, the following examples will deal with the use of multiplexing in wireless communications. Mechanisms controlling the use of multiplexing and the assignment of a medium to users (the traffic regulations), are discussed in chapter 3 under the aspect of medium access control.

2.5.1 Space division multiplexing

For wireless communication, multiplexing can be carried out in four dimensions: **space**, **time**, **frequency**, and **code**. In this field, the task of multiplexing is to assign space, time, frequency, and code to each communication channel with a minimum of interference and a maximum of medium utilization. The term communication channel here only refers to an association of sender(s) and receiver(s) who want to exchange data. Characteristics of communication channels (e.g., bandwidth, error rate) will be discussed together with certain technologies in chapters 4 to 7.