Chapter Two

WIRELESS COMMUNICATIONS

Content of Lecture Three

Chapter Two

2.1 Wireless transmission

While transmission over different wires typically does not cause interference, this is an important topic in wireless transmission. The frequencies used for transmission are all regulated. The first section gives a general overview of these frequencies. The following sections recall some basic facts about signals, antennas, and signal propagation. The varying propagation characteristics create particular complications for radio transmission, frequently causing transmission errors. Multiplexing is a major design topic in this context, because the medium is always shared. Multiplexing schemes have to ensure low interference between different senders. Modulation is needed to transmit digital data via certain frequencies. A separate section presents standard modulation schemes that will reoccur together with the wireless communication systems.

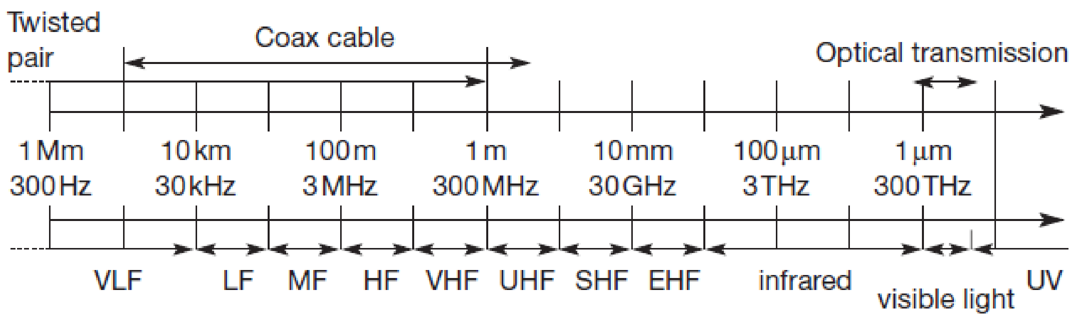


Figure 2.1: Frequency spectrum

2.1.1 Frequencies for radio transmission

Radio transmission can take place using many different frequency bands. Each frequency band exhibits certain advantages and disadvantages. Figure above gives a rough overview of the frequency spectrum that can be used for data transmission. The figure shows frequencies starting at 300 Hz and going up to over 300 THz. directly coupled to the frequency is the wavelength λ.

$$\lambda = c/f, \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.1)$$

where $c \cong 3 \cdot 108$ m/s (the speed of light in vacuum) and f the frequency. For traditional wired networks, frequencies of up to several hundred kHz are used for distances up to some km with twisted pair copper wires, while frequencies of several hundred MHz are used with coaxial cable (new coding schemes work with several hundred MHz even with twisted pair copper wires over distances of some 100 m). Fiber optics are used for frequency ranges of several hundred THz, but here one typically refers to the wavelength which is, e.g., 1500 nm, 1350 nm etc. (infra red).

2.1.2 Signals

Signals are the physical representation of data. Users of a communication system can only exchange data through the transmission of signals. Layer 1 of the ISO/OSI basic reference model is responsible for the conversion of data, i.e., bits, into signals and vice versa. Signals are functions of time and location. Signal parameters represent the data values. The most interesting types of signals for radio transmission are periodic signals, especially sine waves as carriers. The general function of a sine wave is:

$$g(t) = A_t \sin(2 \pi f_t t + \varphi_t) \ldots\ldots\ldots\ldots\ldots\ldots.. \quad (2.2)$$

Signal parameters are the amplitude A, the frequency f, and the phase shift φ. The phase shift determines the shift of the signal relative to the same signal without a shift. An example for shifting a function is shown in Figure 2.2. A typical way to represent signals is the time domain (see Figure 2.2).

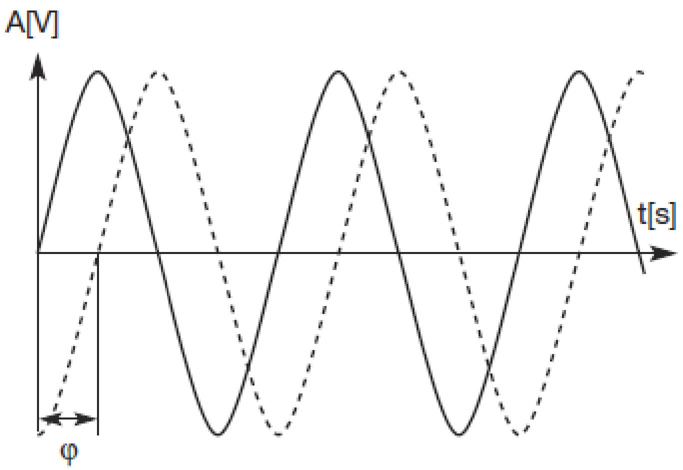


Figure 2.2: Time domain representation of a signal

Representations in the time domain are problematic if a signal consists of many different frequencies. In this case, a better representation of a signal is the frequency domain (see Figure 2.3).

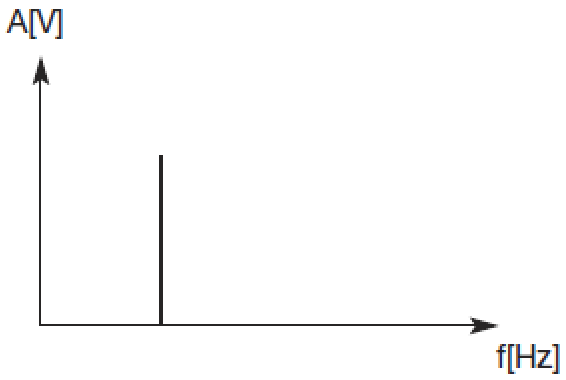


Figure 2.3: Frequency domain representation of a signal

2.1.3 Antennas

As the name wireless already indicates, this communication mode involves 'getting rid' of wires and transmitting signals through space without guidance. We do not need any 'medium' (such as an ether) for the transport of electromagnetic waves. Somehow, we have to couple the energy from the transmitter to the out-side world and, in reverse, from the outside world to the receiver. This is exactly what antennas do. Antennas couple electromagnetic energy to and from space to and from a wire or coaxial cable (or any other appropriate conductor).

A theoretical reference antenna is the **isotropic radiator**, a point in space radiating equal power in all directions, i.e., all points with equal power are located on a sphere with the antenna as its center. The **radiation pattern** is symmetric in all directions (see Figure 2.4, a two dimensional cross-section of the real three-dimensional pattern).

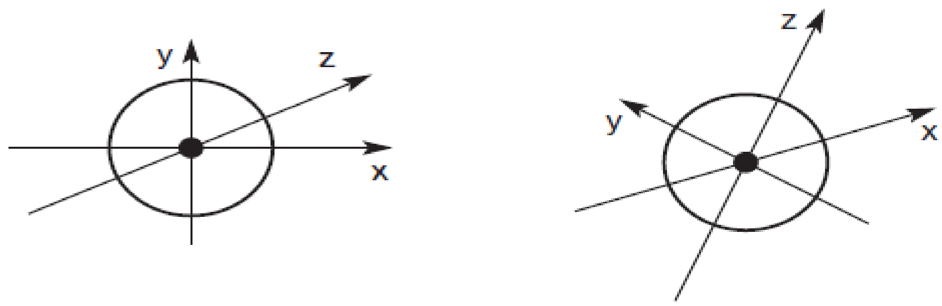


Figure 2.4: Radiation pattern of an isotropic radiator

2.1.4 Signal propagation

Like wired networks, wireless communication networks also have senders and receivers of signals. However, in connection with signal propagation, these two networks exhibit considerable differences. In wireless networks, the signal has no wire to determine the direction of propagation, whereas signals in wired networks only travel along the wire (which can be twisted pair copper wires, a coax cable, but also a fiber etc.). As long as the wire is not interrupted or damaged, it typically exhibits the same characteristics at each point. For wireless transmission, this predictable behavior is only valid in a vacuum, i.e., without matter between the sender and the receiver. The situation would be as follows (Figure 2.5):

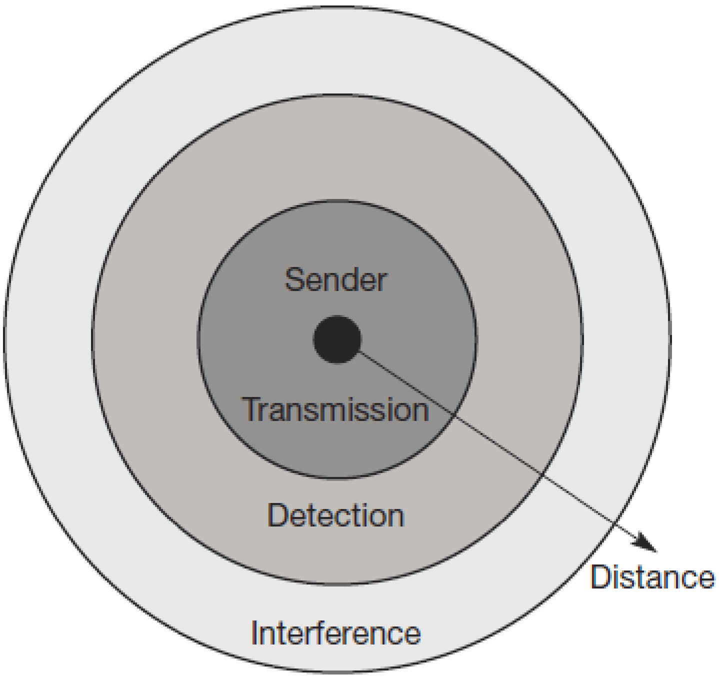


Figure 2.5: Ranges for transmission, detection, and interference of signals

2.1.4.1 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 Pr is proportional to 1/d2 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 = 4π d2.

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 reflected2 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

2.1.4.2 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.

The more often the signal is reflected, the weaker it becomes. Finally, the right side of Figure 2.6 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.

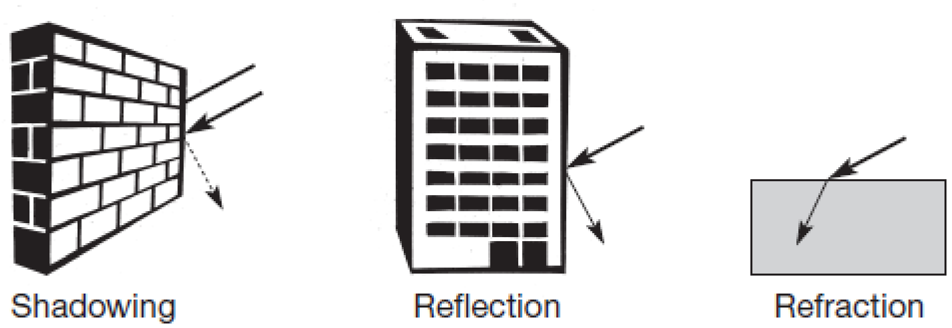


Figure 2.6: Blocking (shadowing), reflection and refraction of waves

2.1.4.3 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 2.7 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 he case of wired networks (however, a similar effect, dispersion, is known for high bit-rate optical transmission over multi-mode fiber. 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.

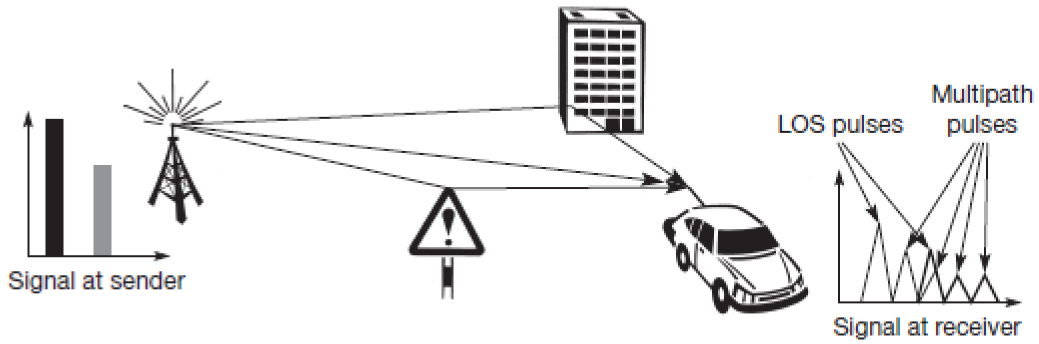


Figure 2.7 Multi-path propagation and intersymbol interference

2.1.5 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.

2.1.5.1 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 Figure 2.8 shows six channels ki and introduces a three dimensional coordinate system. This system shows the dimensions of code c, time t and frequency f. For this first type of multiplexing, **space division multiplexing (SDM)**, the (three dimensional) space si is also shown. Here space is represented via circles indicating the interference range. How is the separation of the different channels achieved? The channels k1 to k3 can be mapped onto the three 'spaces' s1 to s3 which clearly separate the channels and prevent the interference ranges from overlapping. The space between the interference ranges is sometimes called **guard space**. Such a guard space is needed in all four multiplexing schemes presented.

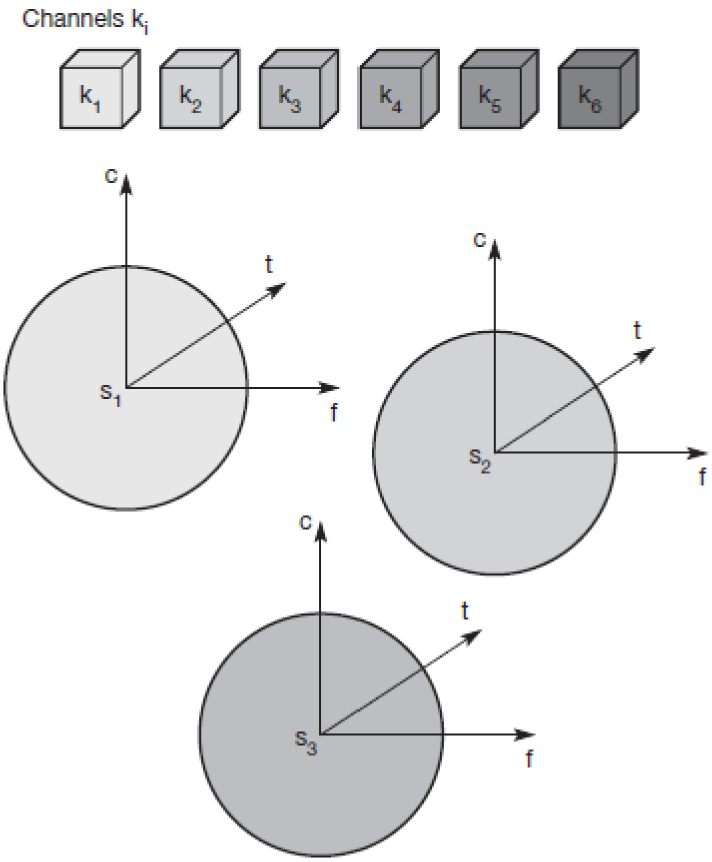


Figure 2.8: Space division multiplexing (SDM)

2.1.5.2 Frequency division multiplexing

Frequency division multiplexing (FDM) describes schemes to subdivide the frequency dimension into several non-overlapping frequency bands as shown in Figure 2.9. Each channel ki is now allotted its own frequency band as indicated. Senders using a certain frequency band can use this band continuously. Again, **guard spaces** are needed to avoid frequency band overlapping (also called **adjacent channel interference**). This scheme is used for radio stations within the same region, where each radio station has its own frequency. This very simple multiplexing scheme does not need complex coordination between sender and receiver: the receiver only has to tune in to the specific sender.

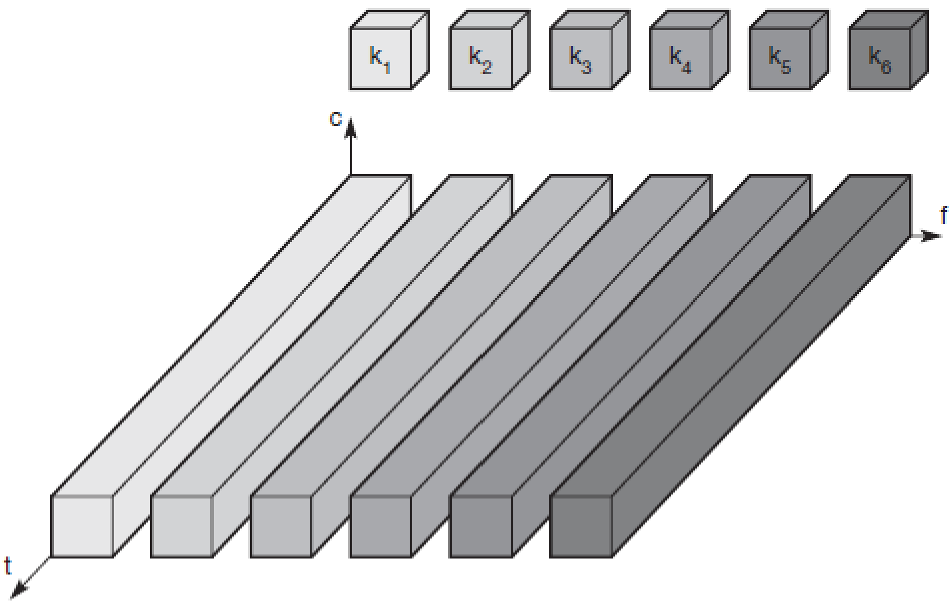


Figure 2.9: Frequency division multiplexing (FDM)

2.1.5.3 Time division multiplexing

A more flexible multiplexing scheme for typical mobile communications is **time division multiplexing (TDM)**. Here a channel ki is given the whole bandwidth for a certain amount of time, i.e., all senders use the same frequency but at different points in time (see Figure 2.10). Again, **guard spaces**, which now represent time gaps, have to separate the different periods when the senders use the medium. In our highway example, this would refer to the gap between two cars. If two transmissions overlap in time, this is called co-channel interference.

(In the highway example, interference between two cars results in an accident.) To avoid this type of interference, precise synchronization between different senders is necessary. This is clearly a disadvantage, as all senders need precise clocks or, alternatively, a way has to be found to distribute a synchronization signal to all senders. For a receiver tuning in to a sender this does not just involve adjusting the frequency, but involves listening at exactly the right point in time. However, this scheme is quite flexible as one can assign more sending time to senders with a heavy load and less to those with a light load.

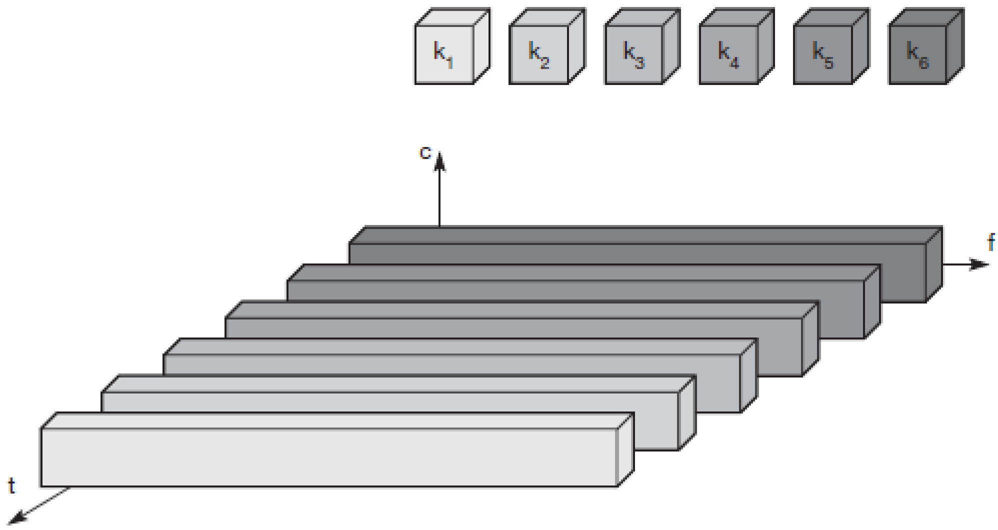


Figure 2.10: Time division multiplexing (TDM)

2.1.5.4 Code division multiplexing

While SDM and FDM are well known from the early days of radio transmission and TDM is used in connection with many applications, **code division multiplexing (CDM)** is a relatively new scheme in commercial communication systems. First used in military applications due to its inherent security features (together with spread spectrum techniques), it now features in many civil wireless transmission scenarios thanks to the availability of cheap processing power. Figure 2.11 shows how all channels ki use the same frequency at the same time for transmission. Separation is now achieved by assigning each channel its own ‘code’, **guard spaces** are realized by using codes with the necessary 'distance' in code space, e.g., **orthogonal codes**. The technical realization of CDM together with the medium access mechanisms.

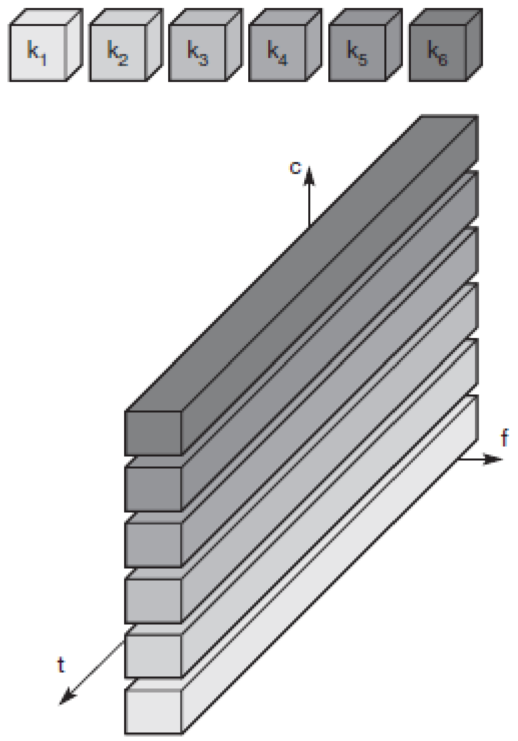


Figure 2.11: Code division multiplexing (CDM)

The main advantage of CDM for wireless transmission is that it gives good protection against interference and tapping. Different codes have to be assigned, but code space is huge compared to the frequency space. Assigning individual codes to each sender does not usually cause problems.

The main disadvantage of this scheme is the relatively high complexity of the receiver. A receiver has to know the code and must separate the channel with user data from the background noise composed of other signals and environmental noise. Additionally, a receiver must be precisely synchronized with the transmitter to apply the decoding correctly. The voice example also gives a hint to another problem of CDM receivers. All signals should reach a receiver with almost equal strength, otherwise some signals could drain others. If some people close to a receiver talk very loudly the language does not matter. The receiver cannot listen to any other person. To apply CDM, precise power control is required.

2.1.6 Modulation

This section introduced the basic function of a sine wave which already indicates the three basic modulation schemes (typically, the cosine function is used for explanation):

$$g(t) = A_t \cos(2\pi f_t t + \varphi_t)$$

This function has three parameters: amplitude A_t, frequency f_t, and phase φ_t which may be varied in accordance with data or another modulating signal. For **digital modulation**, which is the main topic in this section, digital data (0 and 1) is translated into an analog signal (baseband signal). Digital modulation is required if digital data has to be transmitted over a medium that only allows for analog transmission. One example for wired networks is the old analog telephone system – to connect a computer to this system a modem is needed. The modem then performs the translation of digital data into analog signals and vice versa. Digital transmission is used, for example, in wired local area networks or within a computer .

In wireless networks, however, digital transmission cannot be used. Here, the binary bit-stream has to be translated into an analog signal first. The three basic methods for this translation are **amplitude shift keying (ASK)**, **frequency shift keying (FSK)**, and **phase shift keying (PSK)**. These are discussed in more detail in the following sections.

There are several reasons why this baseband signal cannot be directly transmitted in a wireless system:

● **Antennas**: this section, an antenna must be the order of magnitude of the signal's wavelength in size to be effective. For the 1 MHz signal in the example this would result in an antenna some hundred meters high, which is obviously not very practical for handheld devices. With 1 GHz, antennas a few centimeters in length can be used.

● **Frequency division multiplexing**: Using only baseband transmission, FDM could not be applied. Analog modulation shifts the baseband signals to different carrier frequencies as required in section. The higher the carrier frequency, the more bandwidth that is available for many baseband signals.

● **Medium characteristics**: Path-loss, penetration of obstacles, reflection, scattering, and diffraction. Depending on the application, the right carrier frequency with the desired characteristics has to be chosen: long waves for submarines, short waves for handheld devices, very short waves for directed microwave transmission etc.

2.1.6.1 Amplitude shift keying

Figure 2.12 illustrates **amplitude shift keying (ASK)**, the most simple digital modulation scheme. The two binary values, 1 and 0, are represented by two different amplitudes. In the example, one of the amplitudes is 0 (representing the binary 0). This simple scheme only requires low bandwidth, but is very susceptible to interference. Effects like multi-path propagation, noise, or path loss heavily influence the amplitude. In a wireless environment, a constant amplitude cannot be guaranteed, so ASK is typically not used for wireless radio transmission. However, the wired transmission scheme with the highest performance, namely optical transmission, uses ASK. Here, a light pulse may represent a 1, while the absence of light represents a 0. The carrier frequency in optical systems is some hundred THz. ASK can also be applied to wireless infrared transmission, using a directed beam or diffuse light (Wireless LANs).

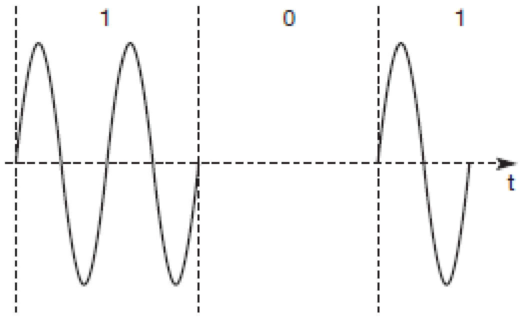


Figure 2.12: Amplitude shift keying (ASK)

2.1.6.2 Frequency shift keying

A modulation scheme often used for wireless transmission is **frequency shift keying (FSK)** (see Figure 2.13). The simplest form of FSK, also called **binary FSK (BFSK)**, assigns one frequency f1 to the binary 1 and another frequency f2 to the binary 0. A very simple way to implement FSK is to switch between two oscillators, one with the frequency f1 and the other with f2, depending on the input. To avoid sudden changes in phase, special frequency modulators with **continuous phase modulation**, **(CPM)** can be used. Sudden changes in phase cause high frequencies, which is an undesired side-effect. A simple way to implement demodulation is by using two bandpass filters, one for f1 the other for f2. A comparator can then compare the signal levels of the filter outputs to decide which of them is stronger. FSK needs a larger bandwidth compared to ASK but is much less susceptible to errors.

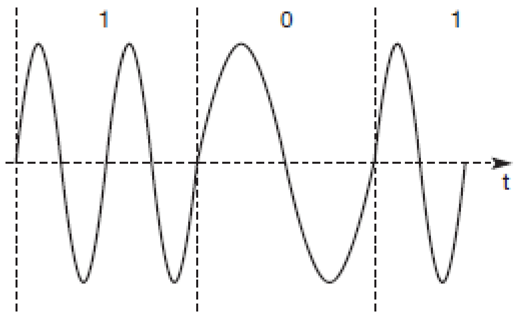


Figure 2.13: Frequency shift keying (FSK)

2.1.6.3 Phase shift keying

Finally, **phase shift keying (PSK)** uses shifts in the phase of a signal to represent data. Figure 2.14 shows a phase shift of 180° or π as the 0 follows the 1 (the same happens as the 1 follows the 0). This simple scheme, shifting the phase by 180° each time the value of data changes, is also called **binary PSK (BPSK)**.

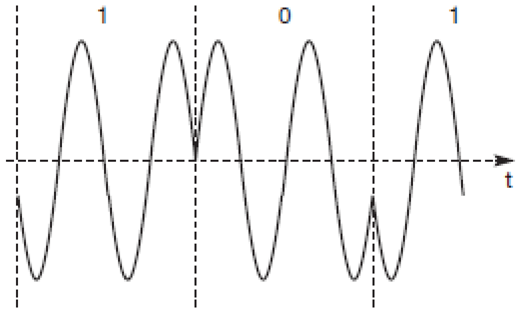


Figure 2.14: Phase shift keying (PSK)

2.1.6.4 Multi-carrier modulation

Special modulation schemes that stand somewhat apart from the others are **multi-carrier modulation (MCM)**, **orthogonal frequency division multiplexing (OFDM)** or **coded OFDM (COFDM)** that are used in the context of the European digital radio system DAB and the WLAN standards IEEE 802.11a and HiperLAN2. The main attraction of MCM is its good ISI mitigation property. higher bit rates are more vulnerable to ISI. MCM splits the high bit rate stream into many lower bit rate streams (see Figure 2.15), each stream being sent using an independent carrier frequency. If, for example, n symbols/s have to be transmitted, each subcarrier transmits n/c symbols/s with c being the number of subcarriers. One symbol could, for example represent 2 bit as in QPSK. DAB, for example, uses between 192 and 1,536 of these subcarriers. The physical layer of HiperLAN2 and IEEE 802.11a uses 48 subcarriers for data.

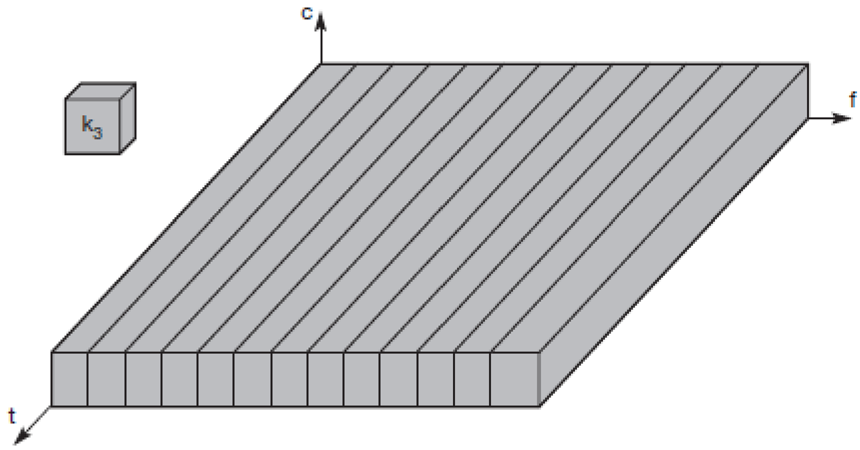


Figure 2.15: Parallel data transmission on several subcarriers with lower rate

2.1.7 Cellular systems

Cellular systems for mobile communications implement SDM. Each transmitter, typically called a **base station**, covers a certain area, a **cell**. Cell radii can vary from tens of meters in buildings, and hundreds of meters in cities, up to tens of kilometers in the countryside. The shape of cells are never perfect circles or hexagons (as shown in Figure), but depend on the environment (buildings, mountains, valleys etc.), on weather conditions, and sometimes even on system load. Typical systems using this approach are mobile telecommunication systems, where a mobile station within the cell around a base station communicates with this base station and vice versa.

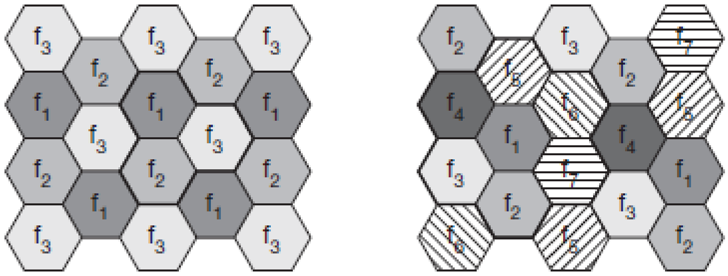


Figure 2.16 Cellular system with three and seven cell clusters

Cellular systems using CDM instead of FDM do not need such elaborate channel allocation schemes and complex frequency planning. Here, users are separated through the code they use, not through the frequency. Cell planning faces another problem – the cell size depends on the current load. Accordingly, **CDM cells** are commonly said to '**breathe**'. While a cell can cover a larger area under a light load, it shrinks if the load increases. The reason for this is the growing noise level if more users are in a cell. (Remember, if you do not know the code, other signals appear as noise, i.e., more and more people join the party.) The higher the noise, the higher the path loss and the higher the transmission errors. Finally, mobile stations further away from the base station drop out of the cell. (This is similar to trying to talk to someone far away at a crowded party.)

Figure below illustrates this phenomenon with a user transmitting a high bit rate stream within a CDM cell. This additional user lets the cell shrink with the result that two users drop out of the cell. In a real-life scenario this additional user could request a video stream (high bit rate) while the others use standard voice communication (low bit rate).

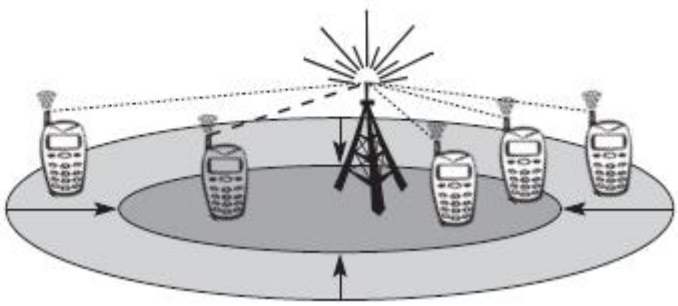


Figure 2.17: Cell breathing depending on the current load

2.2 Medium access control

MAC belongs to layer 2 of the ISO/OSI reference model, the data link control layer (DLC). Layer 2 is subdivided into the logical link control (LLC), and the medium access control (MAC) . The task of DLC is to establish a reliable point to point or point to multi-point connection between different devices over a wired or wireless medium. Medium access control comprises all mechanisms that regulate user access to a medium using SDM, TDM, FDM, or CDM. In the following sections we will talk about several medium access control (MAC) algorithms which are specifically adapted to the wireless domain.

2.2.1 SDMA

Space Division Multiple Access (SDMA) is used for allocating a separated space to users in wireless networks. A typical application involves assigning an optimal base station to a mobile phone user. The mobile phone may receive several base stations with different quality. A MAC algorithm could now decide which base station is best, taking into account which frequencies (FDM), time slots (TDM) or code (CDM) are still available (depending on the technology). Typically, SDMA is never used in isolation but always in combination with one or more other schemes.

The basis for the SDMA algorithm is formed by cells and sectorized antennas which constitute the infrastructure implementing space division multiplexing (SDM). A new application of SDMA comes up together with beam-forming antenna arrays. Single users are separated in space by individual beams. This can improve the overall capacity of a cell .

2.2.2 FDMA

Frequency division multiple access (FDMA) comprises all algorithms allocating frequencies to transmission channels. Allocation can either be fixed (as for radio stations or the general planning and regulation of frequencies) or dynamic (i.e., demand driven). Channels can be assigned to the same frequency at all times, i.e., pure FDMA, or change frequencies according to a certain pattern, i.e., FDMA combined with TDMA.

FDMA assigns individual channels to individual users. Figure 2.18 shows that in FDMA, each user is allocated a unique frequency band or channel. These channels are assigned on demand to users who request service. During the period of the call, no other user can share the same channel. Furthermore, FDM is often used for simultaneous access to the medium by base station and mobile station in cellular networks. Here the two partners typically establish a duplex channel, i.e., a channel that allows for simultaneous transmission in both directions. The two directions, mobile station to base station and vice versa are now separated using different frequencies. This scheme is then called frequency division duplex (FDD).

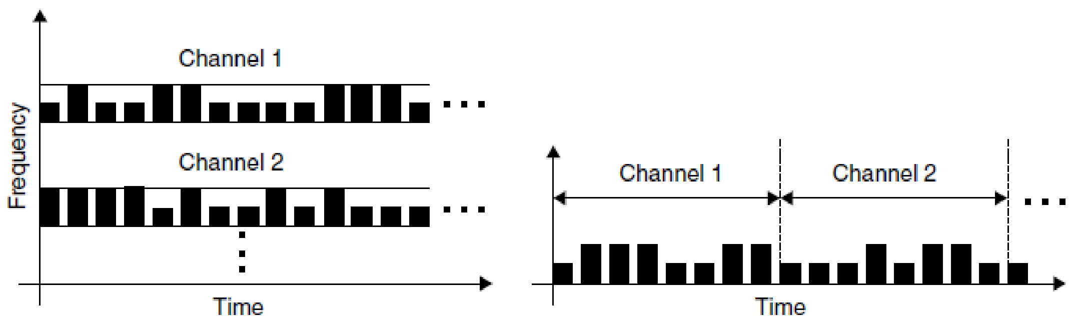


Figure 2.18: Digital data transmitted using FDMA and TDMA

2.2.3 TDMA

Compared to FDMA, time division multiple access (TDMA) offers a much more flexible scheme, which comprises all technologies that allocate certain time slots for communication, i.e., controlling TDM. Now tuning in to a certain frequency is not necessary, i.e., the receiver can stay at the same frequency the whole time. Using only one frequency, and thus very simple receivers and transmitters, many different algorithms exist to control medium access.

Listening to different frequencies at the same time is quite difficult, but listening to many channels separated in time at the same frequency is simple. Almost all MAC schemes for wired networks work according to this principle, e.g., Ethernet, Token Ring, ATM etc.

Now synchronization between sender and receiver has to be achieved in the time domain. Again this can be done by using a fixed pattern similar to FDMA techniques, i.e., allocating a certain time slot for a channel, or by using a dynamic allocation scheme. Dynamic allocation schemes require an identification for each transmission as this is the case for typical wired MAC schemes (e.g., sender address) or the transmission has to be announced beforehand. MAC addresses are quite often used as identification. This enables a receiver in a broadcast medium to recognize if it really is the intended receiver of a message. Fixed schemes do not need identification, but are not as flexible considering varying bandwidth requirements.

2.2.3.1 Fixed TDM

The simplest algorithm for using TDM is allocating time slots for channels in a fixed pattern. This results in a fixed bandwidth and is the typical solution for wireless phone systems. MAC is quite simple, as the only crucial factor is accessing the reserved time slot at the right moment. If this synchronization is assured, each mobile station knows its turn and no interference will happen. The fixed pattern can be assigned by the base station, where competition between different mobile stations that want to access the medium is solved. Fixed access patterns (at least fixed for some period in time) fit perfectly well for connections with a fixed bandwidth. Furthermore, these patterns guarantee a fixed delay – one can transmit, e.g., every 10 ms as this is the case for standard DECT systems. TDMA schemes with fixed access patterns are used for many digital mobile phone systems like IS-54, IS-136, GSM, DECT, PHS, and PACS.

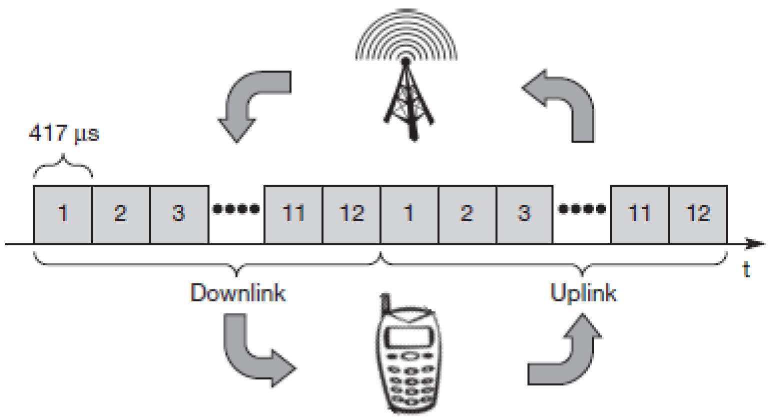


Figure 2.19: Time division multiplexing for multiple access and duplex

2.2.3.2 Classical Aloha

As mentioned above, TDMA comprises all mechanisms controlling medium access according to TDM. But what happens if TDM is applied without controlling access? This is exactly what the classical **Aloha** scheme does, a scheme which was invented at the University of Hawaii and was used in the ALOHANET for wireless connection of several stations. Aloha neither coordinates medium access nor does it resolve contention on the MAC layer. Instead, each station can access the medium at any time as shown in Figure 2.20. This is a random access scheme, without a central arbiter controlling access and without coordination among the stations. If two or more stations access the medium at the same time, a **collision** occurs and the transmitted data is destroyed. Resolving this problem is left to higher layers (e.g., retransmission of data).

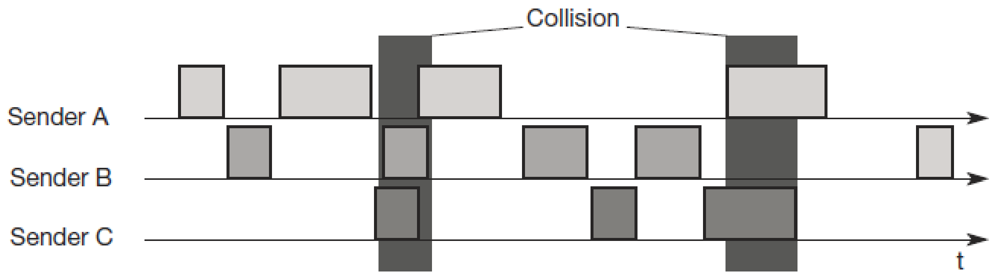


Figure 2.20 Classical Aloha multiple access

2.2.3.3 Slotted Aloha

The first refinement of the classical Aloha scheme is provided by the introduction of time slots (**slotted Aloha**). In this case, all senders have to be synchronized, transmission can only start at the beginning of a **time slot** as shown in Figure 2.21. Still, access is not coordinated. Under the assumption stated above, the introduction of slots raises the throughput from 18 per cent to 36 per cent, i.e., slotting doubles the throughput.

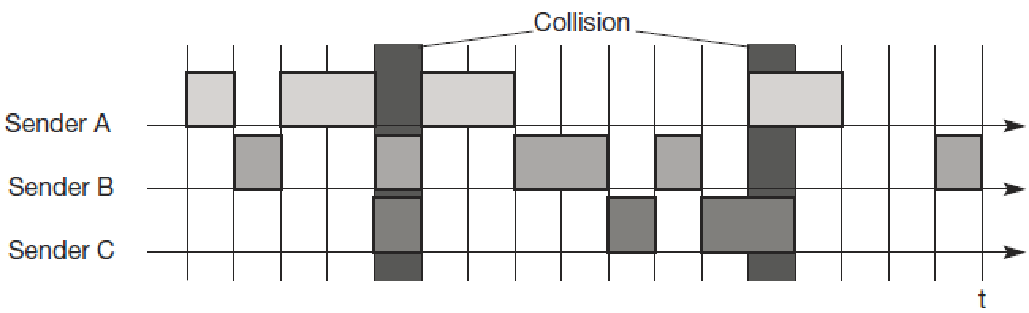


Figure 2.21 Slotted Aloha multiple access

2.2.3.4 Carrier sense multiple access

One improvement to the basic Aloha is sensing the carrier before accessing the medium. This is what **carrier sense multiple access (CSMA)** schemes generally do. Sensing the carrier and accessing the medium only if the carrier is idle decreases the probability of a collision. But, hidden terminals cannot be detected, so, if a hidden terminal transmits at the same time as another sender, a collision might occur at the receiver.

2.2.3.5 Demand assigned multiple access

A general improvement of Aloha access systems can also be achieved by **reservation** mechanisms and combinations with some (fixed) TDM patterns. These schemes typically have a reservation period followed by a transmission period. During the reservation period, stations can reserve future slots in the transmission period. While, depending on the scheme, collisions may occur during the reservation period, the transmission period can then be accessed without collision. Alternatively, the transmission period can be split into periods with and without collision. In general, these schemes cause a higher delay under a light load (first the reservation has to take place), but allow higher throughput due to less collisions.

2.2.3.6 Reservation TDMA

An even more fixed pattern that still allows some random access is exhibited by **reservation TDMA** (see Figure 2.22). In a fixed TDM scheme N mini-slots followed by N·k data-slots form a frame that is repeated. Each station is allotted its own mini-slot and can use it to reserve up to k data-slots. This guarantees each station a certain bandwidth and a fixed delay. Other stations can now send data in unused data-slots as shown. Using these free slots can be based on a simple round-robin scheme or can be uncoordinated using an Aloha scheme. This scheme allows for the combination of, e.g., isochronous traffic with fixed bitrates and best-effort traffic without any guarantees.

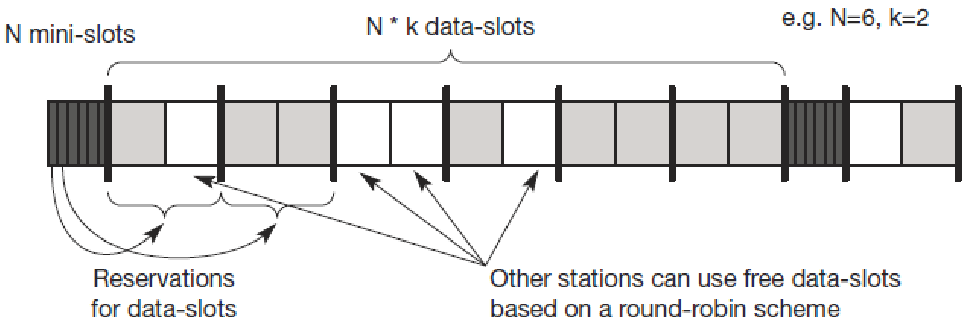
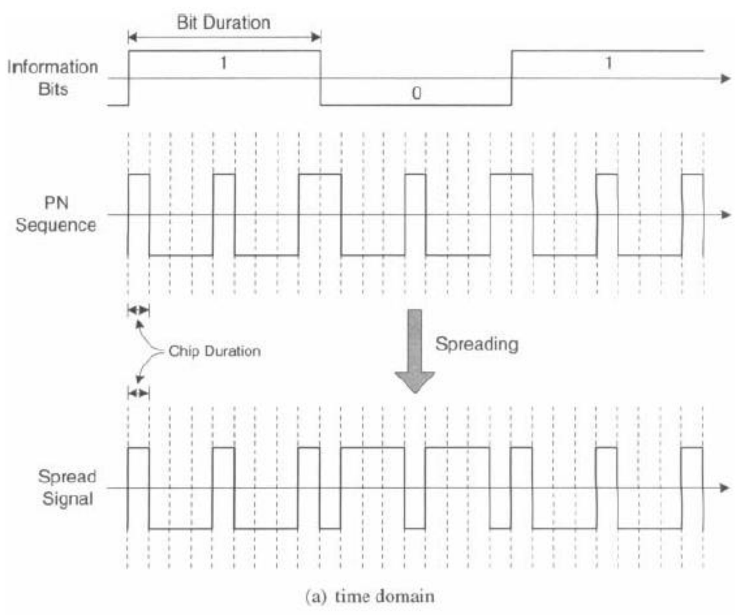


Figure 2.22 Reservation TDMA access scheme

2.2.4 CDMA

While FDMA and TDMA partition the system resource based on the frequency dimension and time dimension of the signal space, CDMA partition the system resource based on the ***code-dimension*** of the signal space. In other words, all the user signals share the entire bandwidth and the entire time duration but differentiate among themselves based on different ***code*** *channels*. This extra code dimension is introduced through the *spreading* ***process*** as illustrated in figure 2.23



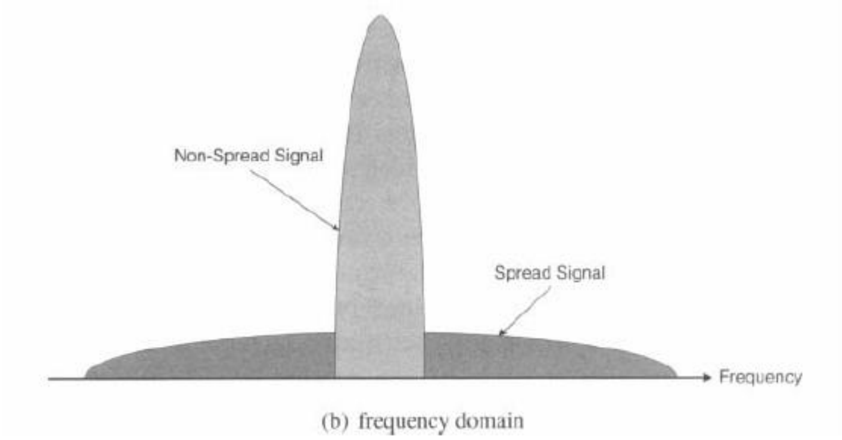


Figure 2.23: Principle of CDMA spreading

Now let us translate this into code space and explain what we mean by a good **autocorrelation**. The Barker code (+1, –1, +1, +1, –1, +1, +1, +1, –1, –1, –1), for example, has a good autocorrelation, i.e., the inner product with itself is large, the result is 11. This code is used for ISDN and IEEE 802.11. But as soon as this Barker code is shifted 1 chip further (think of shifting the 11 chip Barker code over itself concatenated several times), the correlation drops to an absolute value of 1. It stays at this low value until the code matches itself again perfectly. This helps, for example, to synchronize a receiver with the incoming data stream. The peak in the matching process helps the receiver to reconstruct the original data precisely, even if noise distorts the original signal up to a certain level.

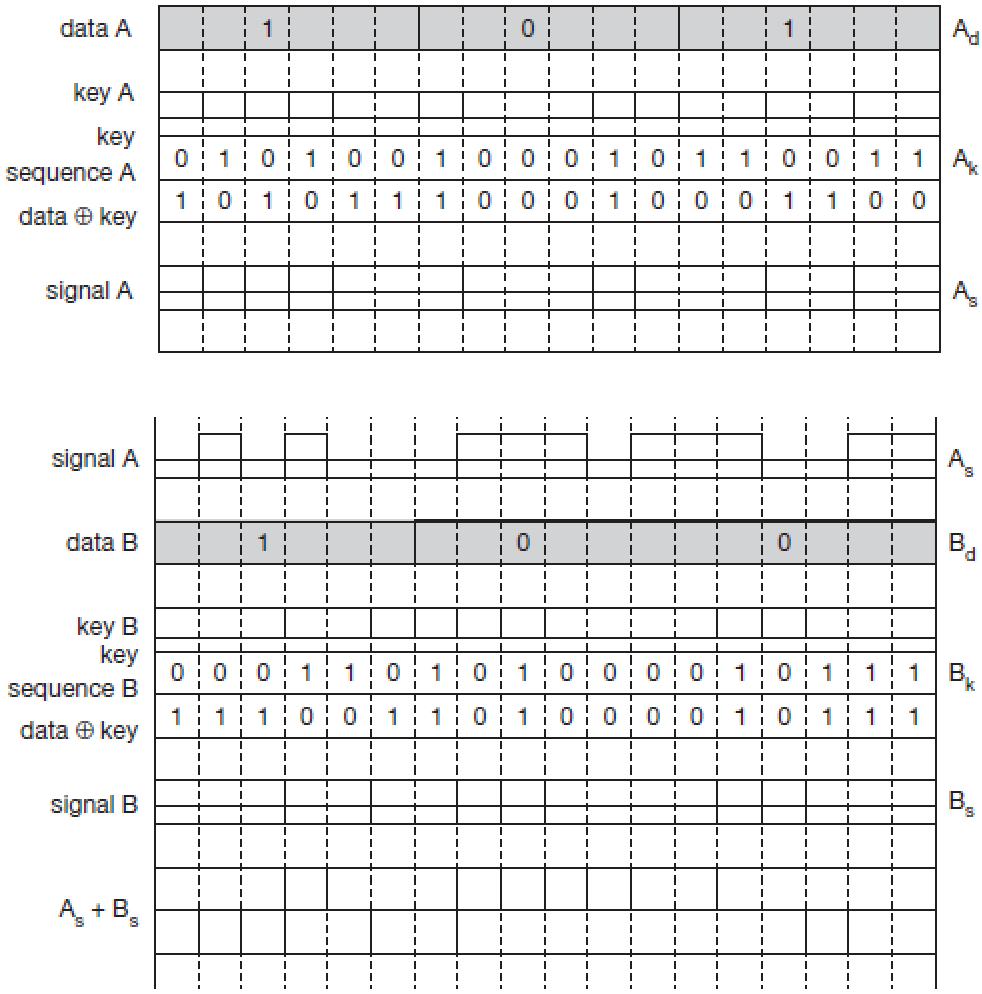


Figure 2.24: Coding and spreading of data from sender A and B

2.3 Telecommunications systems

Digital cellular networks are the segment of the market for mobile and wireless devices which are growing most rapidly. They are the wireless extensions of traditional PSTN or ISDN networks and allow for seamless roaming with the same mobile phone nation or even worldwide. Today, these systems are mainly used for voice traffic. However, data traffic is continuously growing and, therefore, the following sections will be presents several technologies for wireless data transmission using cellular systems.

2.3.1 GSM

GSM is the most successful digital mobile telecommunication system in the world today. Global System for Mobile Communications (GSM) is a digital wireless network standard designed by standization committees of the European telecommunication operators and vendors. The objective is to design a high capacity cellular system to operate in the 900MHz cellular band with service portability, quality of service and security, high spectral efficiency as well as low cost design.

The GSM system offers a common set of compatible circuit-switched services to all mobile users across European and the rest of the world. More than 70% of the mobile populations in the world are GSM-based system. Hence, GSM represents a very important and successful deployment of digital cellular system and is one typical example of 2G cellular system.

Around year 2000, the GSM system was evolved to GPRS system tooffer high speed packet switched data service. This refers to the so-called 2.5G system where packet-switched connection is the key new element. After GPRS, we have the EDGE system which further enhances the radio interface of the GPRS system to offer higher bit rate data services. Eventually, the GSM system will be evolved into UMTS system (today’s 3G networks) to offer high quality wireless packet data access with quality of services.

2.3.1.1 Mobile services

GSM permits the integration of different voice and data services and the interworking with existing networks. Services make a network interesting for customers. GSM has defined three different categories of services: bearer, tele, and supplementary services.

Figure 2.25 shows a reference model for GSM services. A mobile station **(MS)** is connected to the **GSM** public land mobile network **(PLMN)** via the Um interface. (GSM-PLMN is the infrastructure needed for the GSM network.) This network is connected to transit networks, e.g., integrated services digital network **(**ISDN**)** or traditional public switched telephone network **(PSTN)**. There might be an additional network, the source/destination network, before another terminal **TE** is connected.

Bearer services now comprise all services that enable the transparent transmission of data between the interfaces to the network, i.e., S in case of the mobile station, and a similar interface for the other terminal (e.g., S0 for ISDN terminals). Interfaces like U, S, and R in case of ISDN have not been defined for all networks, so it depends on the specific network which interface is used as a reference for the transparent transmission of data. In the classical GSM model, bearer services are connection-oriented and circuit- or packet-switched. These services only need the lower three layers of the ISO/OSI reference model.

Within the mobile station MS, the **mobile termination (MT)** performs all network specific tasks (TDMA, FDMA, coding etc.) and offers an interface for data transmission (S) to the terminal TE which can then be network independent. Depending on the capabilities of TE, further interfaces may be needed, such as R, according to the ISDN reference model. **Tele services** are application specific and may thus need all seven layers of the ISO/OSI reference model. These services are specified end-to-end, i.e., from one terminal TE to another.

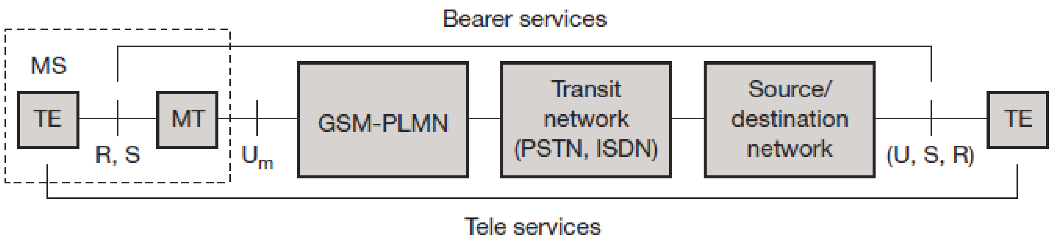


Figure 2.25: Bearer and tele services reference model

2.3.1.2 System architecture

As with all systems in the telecommunication area, GSM comes with a hierarchical, complex system architecture comprising many entities, interfaces, and acronyms. Figure 2.26 gives a simplified overview of the GSM . A GSM system consists of three subsystems, the radio sub system (RSS), the network and switching subsystem (NSS), and the operation subsystem (OSS). Generally, a GSM customer only notices a very small fraction of the whole network – the mobile stations (MS) and some antenna masts of the base transceiver stations (BTS).

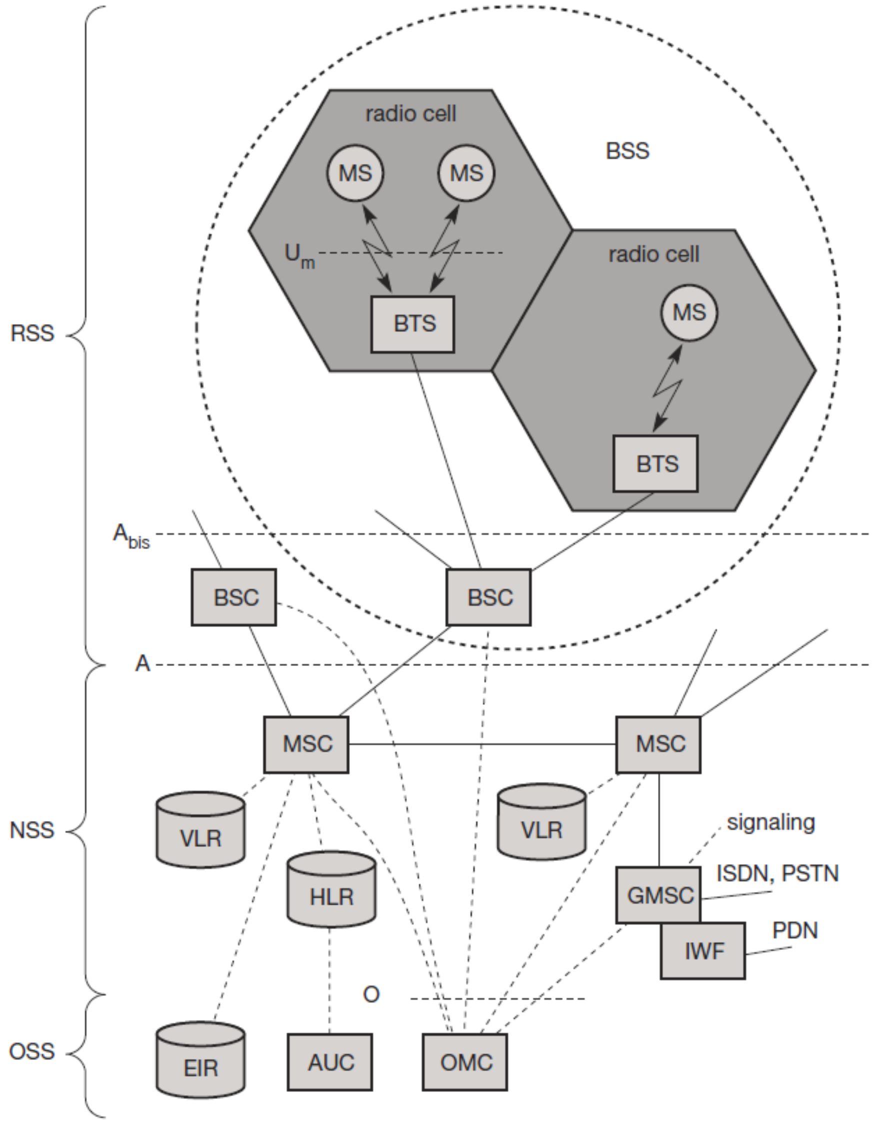


Figure 2.26: Functional architecture of a GSM system

2.3.1.2.1 Radio subsystem

As the name implies, the **radio subsystem (RSS)** comprises all radio specific entities, i.e., the **mobile stations (MS)** and the **base station subsystem (BSS)**. Figure 2.26 shows the connection between the RSS and the NSS via the **A interface** (solid lines) and the connection to the

OSS via the **O interface** (dashed lines). The A interface is typically based on circuit-switched PCM-30 systems (2.048 Mbit/s), carrying up to 30 64 kbit/s connections, whereas the O interface uses the Signalling System No. 7 (SS7) based on X.25 carrying management data to/from the RSS.

● **Base station subsystem (BSS)**: A GSM network comprises many BSSs, each controlled by a base station controller (BSC). The BSS performs all functions necessary to maintain radio connections to an MS, coding/decoding of voice, and rate adaptation to/from the wireless network part.

● **Base transceiver station (BTS)**: A BTS comprises all radio equipment, i.e., antennas, signal processing, amplifiers necessary for radio transmission.

● **Base station controller (BSC)**: The BSC basically manages the BTSs. It reserves radio frequencies, handles the handover from one BTS to another within the BSS, and performs paging of the MS.

2.3.1.2.2 Network and switching subsystem

The "heart" of the GSM system is formed by the **network and switching subsystem (NSS)**. The NSS connects the wireless network with standard public networks, performs handovers between different BSSs, comprises functions for worldwide localization of users and supports charging, accounting, and roaming of users between different providers in different countries. The NSS consists of the following switches and databases:

- **Mobile services switching center (MSC):** MSCs are high-performance digital ISDN switches. They set up connections to other MSCs and to the BSCs via the A interface, and form the fixed backbone network of a GSM system. Typically, an MSC manages several BSCs in a geographical region.
- **Home location register (HLR):** The HLR is the most important database in a GSM system as it stores all user-relevant information.
- **Visitor location register (VLR)**: The VLR associated to each MSC is a dynamic database which stores all important information needed for the MS users currently in the LA that is associated to the MSC.

2.3.1.2.3 Operation subsystem

The third part of a GSM system, the **operation subsystem (OSS)**, contains the necessary functions for network operation and maintenance. The OSS possesses network entities of its own and accesses other entities via SS7 signaling. The following entities have been defined:

- **Operation and maintenance center (OMC)**: The OMC monitors and controls all other network entities via the O interface (SS7 with X.25). Typical OMC management functions are traffic monitoring, status reports of network entities, subscriber and security management, or accounting and billing.
- **Authentication centre (AuC)**: As the radio interface and mobile stations are particularly vulnerable, a separate AuC has been defined to protect user identity and data transmission. The AuC contains the algorithms for authentication as well as the keys for encryption and generates the values needed for user authentication in the HLR. The AuC may, in fact, be situated in a special protected part of the HLR.
- **Equipment identity register (EIR)**: The EIR is a database for all IMEIs, i.e., it stores all device identifications registered for this network. As MSs are mobile, they can be easily stolen. With a valid SIM, anyone could use the stolen MS. The EIR has a blacklist of stolen (or locked) devices. In theory an MS is useless as soon as the owner has reported a theft. Unfortunately, the blacklists of different providers are not usually synchronized and the illegal use of a device in another operator’s network is possible (the reader may speculate as to why this is the case). The EIR also contains a list of valid IMEIs (white list), and a list of malfunctioning devices (gray list).

2.3.1.3 Protocols

Figure 2.27 shows the protocol architecture of GSM with signaling protocols, interfaces, as well as the entities already shown in Figure 2.26. The main interest lies in the Um interface, as the other interfaces occur between entities in a fixed network. **Layer 1**, the physical layer, handles all **radio**-specific functions. This includes the creation of bursts according to the five different formats, **multiplexing** of bursts into a TDMA frame, **synchronization** with the BTS, detection of idle channels, and measurement of the **channel quality** on the downlink. The physical layer at Um uses GMSK for digital **modulation** and performs **encryption/decryption** of data, i.e., encryption is not performed end-to-end, but only between MS and BSS over the air interface.

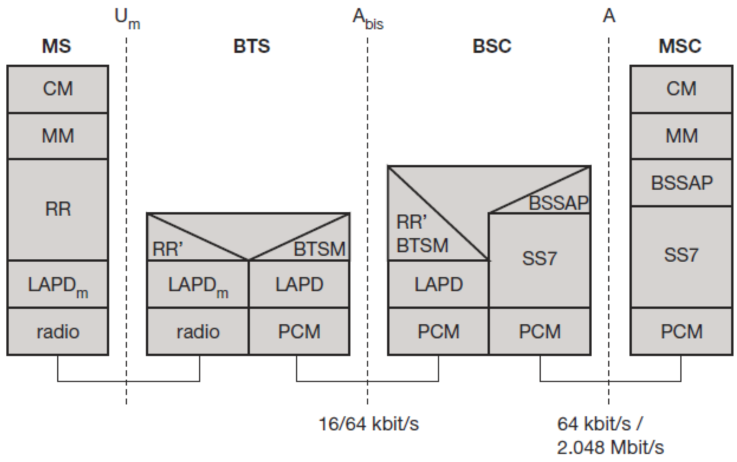


Figure 2.27: Protocol architecture for signaling

2.3.1.4 Localization and calling

One fundamental feature of the GSM system is the automatic, worldwide localization of users. The system always knows where a user currently is, and the same phone number is valid worldwide. To provide this service, GSM performs periodic location updates even if a user does not use the mobile station (provided that the MS is still logged into the GSM network and is not completely switched off). The HLR always contains information about the current location (only the location area, not the precise geographical location), and the VLR currently responsible for the MS informs the HLR about location changes.

2.3.1.5 Handover

Cellular systems require **handover** procedures, as single cells do not cover the whole service area, but, e.g., only up to 35 km around each antenna on the countryside and some hundred meters in cities. The smaller the cell size and the faster the movement of a mobile station through the cells (up to 250 km/h for GSM), the more handovers of ongoing calls are required. However, a handover should not cause a cut-off, also called **call drop**. GSM aims at maximum handover duration of 60 ms.

2.3.2 DECT

Digital Enhanced Cordless Telecommunications (DECT) is a digital wireless telephone technology with a more ambitious goal than just telephony. DECT was designed especially to operate on a small area with a large number of users such as a corporation or even a city, using TDMA to transmit radio signals to phones. A user equipped with a DECT/GSM dual-mode telephone can operate seamlessly in both networks. In this case, a dual-mode phone would automatically search first for a DECT network, then for a GSM network if DECT is not available.

A big difference between DECT and GSM exists in terms of cell diameter and cell capacity. While GSM is designed for outdoor use with a cell diameter of up to 70 km, the range of DECT is limited to about 300 m from the base station (only around 50 m are feasible inside buildings depending on the walls). Due to this limited range and additional multiplexing techniques, DECT can offer its service to some 10,000 people within one km2.

2.3.2.1 System architecture

A DECT system may have various different physical implementations depending on its actual use. Different DECT entities can be integrated into one physical unit; entities can be distributed, replicated etc. However, all implementations are based on the same logical reference model of the system architecture as shown in Figure 2.28.

A global network connects the local communication structure to the outside world and offers its services via the interface D1. Global networks could be integrated services digital networks (ISDN), public switched telephone networks (PSTN), public land mobile networks (PLMN), e.g., GSM, or packet switched public data network (PSPDN). The services offered by these networks include transportation of data and the translation of addresses and routing of data between the local networks.

Local networks in the DECT context offer local telecommunication services that can include everything from simple switching to intelligent call forwarding, address translation etc. Examples for such networks are analog or digital private branch exchanges (PBXs) or LANs.

The DECT core network consists of the fixed radio termination (FT) and the portable radio termination (PT), and basically only provides a multiplexing service. FT and PT cover layers one to three at the fixed network side and mobile network side respectively. Additionally, several portable applications (PA) can be implemented on a device.

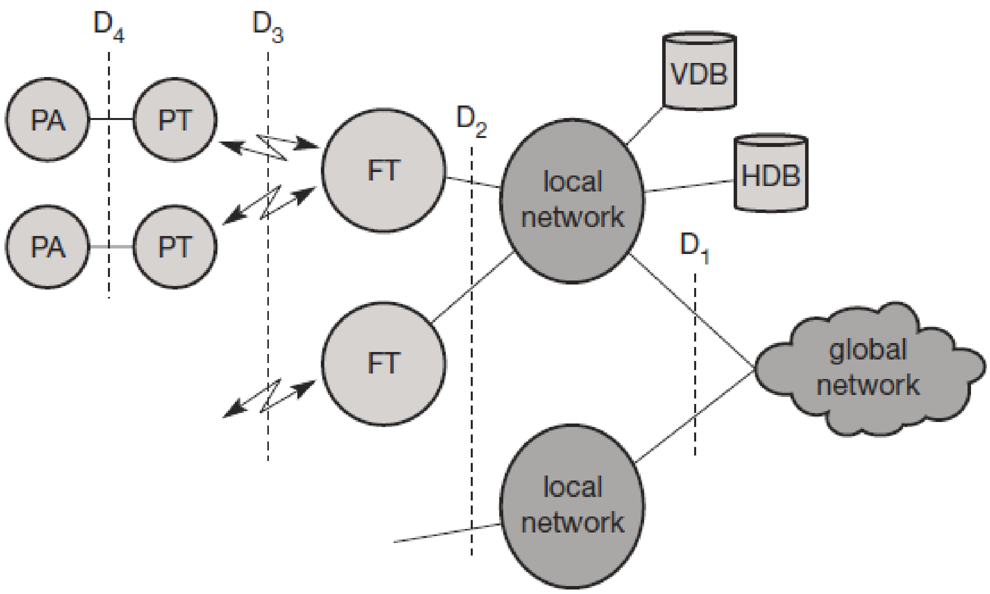


Figure 2.28: DECT system architecture reference model

2.3.2.2 Protocol architecture

The DECT protocol reference architecture follows the OSI reference model. Figure 2.29 shows the layers covered by the standard: the physical layer, medium access control, and data link control8 for both the control plane (C-Plane) and the user plane (U-Plane). An additional network layer has been specified for the C-Plane, so that user data from layer two is directly forwarded to the U-Plane. A management plane vertically covers all lower layers of a DECT system.

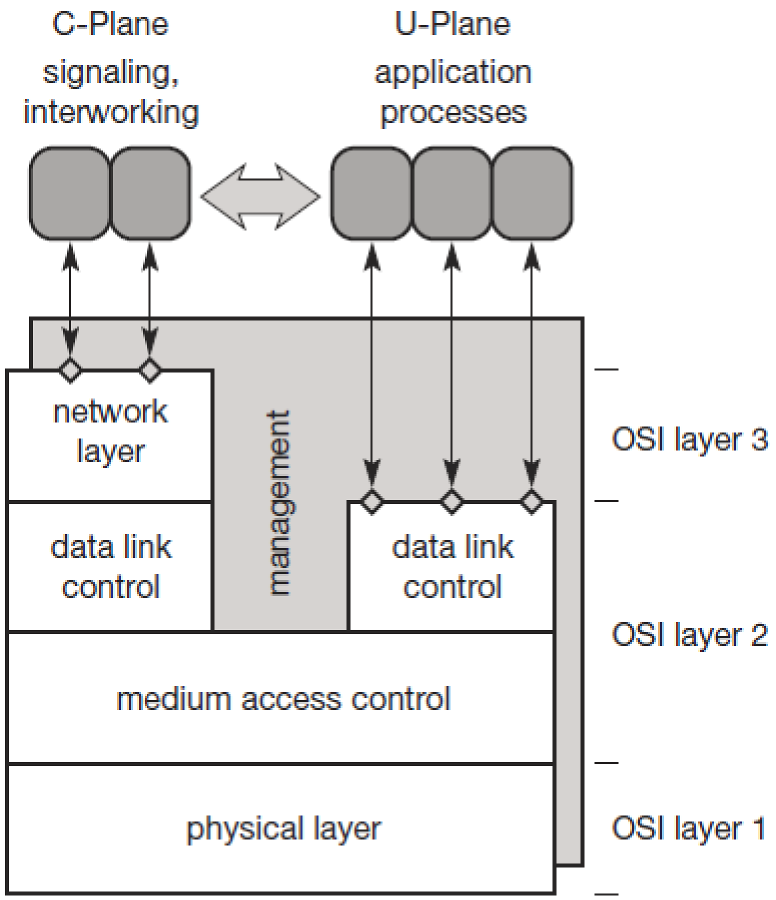


Figure 2.29: DECT protocol Layers

2.3.2.2.1 Physical layer

As in all wireless networks, the **physical layer** comprises all functions for modulation/ demodulation, incoming signal detection, sender/receiver synchronization, and collection of status information for the management plane. This layer generates the physical channel structure with a certain, guaranteed throughput. On request from the MAC layer, the physical layer assigns a channel for data transmission.

2.3.2.2.2 Medium access control layer

The **medium access control (MAC**) layer establishes, maintains, and releases channels for higher layers by activating and deactivating physical channels. MAC multiplexes several logical channels onto physical channels. Logical channels exist for signaling network control, user data transmission, paging, or sending broadcast messages.

Additional services offered include segmentation/reassembly of packets and error control/error correction.

2.3.2.2.3 Data link control layer

The **data link control (DLC)** layer creates and maintains reliable connections between the mobile terminal and the base station. Two services have been defined for the **C-Plane**: a **connectionless broadcast** service for paging (called **Lb**) and a **point-to-point** protocol similar to LAPD in ISDN, but adapted to the underlying MAC (called **LAPC+Lc**).

Several services exist for the **U-Plane**, e.g., a transparent unprotected service (basically a null service), a forward error correction service, rate adaptation services, and services for future enhancements. If services are used, e.g., to transfer ISDN data at 64 kbit/s, then DECT also tries to transfer 64 kbit/s. However, in case of errors, DECT raises the transfer rate to 72 kbit/s, and includes FEC and a buffer for up to eight blocks to perform ARQ. This buffer then introduces an additional delay of up to 80 ms.

2.3.2.2.4 Network layer

The **network laye**r of DECT is similar to those in ISDN and GSM and only exists for the **C-Plane**. This layer provides services to request, check, reserve, control, and release resources at the fixed station (connection to the fixed network, wireless connection) and the mobile terminal (wireless connection). The **mobility management (MM)** within the network layer is responsible for identity management, authentication, and the management of the location data bases. **Call control (CC)** handles connection setup, release, and negotiation. Two message services, the **connection oriented message service (COMS)** and the **connectionless message service (CLMS)** transfer data to and from the interworking unit that connects the DECT system with the outside world.

2.3.3 TETRA

Trunked radio systems constitute another method of wireless data transmission. These systems use many different radio carriers but only assign a specific carrier to a certain user for a short period of time according to demand. These types of radio systems typically offer interfaces to the fixed telephone network, i.e., voice and data services, but are not publicly accessible. These systems are not only simpler than most other networks, they are also reliable and relatively cheap to set up and operate, as they only have to cover the region where the local users operate, e.g., a city taxi service.

TETRA also offers bearer services of up to 28.8 kbit/s for unprotected data transmission and 9.6 kbit/s for protected transmission. Examples for end-to-end services are call forwarding, call barring, identification, call hold, call priorities, emergency calls and group joins. The system architecture of TETRA is very similar to GSM.

Figure below shows the typical TDMA frame structure of TETRA. Each frame consists of four slots, with a frame duration of 56.67 ms. Each slot carries 510 bits within 14.17 ms, i.e., 36 kbit/s. 16 frames together with one control frame (CF) form a multi frame, and finally, a hyper frame contains 60 multi frames. To avoid sending and receiving at the same time, TETRA shifts the uplink for a period of two slots compared to the downlink.

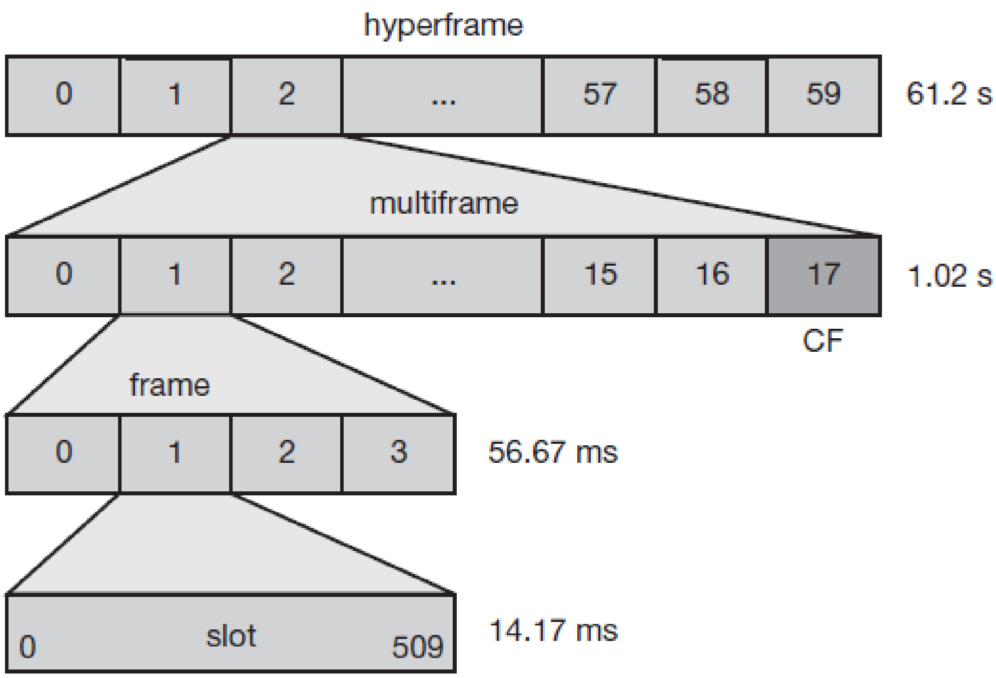


Figure 2.30: TETRA frame Structure

TETRA offers additional services like group call, acknowledged group call, broadcast call, and discreet listening. Emergency services need a sub-second group-call setup in harsh environments which possibly lack all infrastructure. These features are currently not available in GSM or other typical mobile telephone networks, so TETRA is complementary to other systems.

2.3.4 UMTS releases and standardization

UMTS as discussed today and introduced in many countries relies on the initial release of the UMTS standard called **release 99** or **R99** for short. This release of the specification describes the new radio access technologies UTRA FDD and UTRA TDD, and standardizes the use of a GSM/GPRS network as core within 440 separate specifications. This enables a cost effective migration from GSM to UMTS. The initial installations will even offer the FDD mode only. This release was (almost) finalized in 1999 – hence the name R99.

The following sections will focus on this release as it is unclear when, and to what extent, the following releases will be realized. After R99 the release 2000 or R00 followed. However, in September 2000 3GPP realized that it would be impossible to finalize the standard within the year 2000. 3GPP decided to split R2000 into two standards and call them release 4 (Rel-4) and release 5 (Rel-5). The version of all standards finalized for R99 start with 3.x.y (a reason for renaming R99 into Rel-3), Rel-4 and Rel-5 versions start with 4.x.y and 5.x.y, respectively. The standards are grouped into series. For example, radio aspects are specified in series 25, technical realization in series 23, and codecs in series 26. The complete standard number (e.g., TS 25.401 V3.10.0) then identifies the series (25), the standard itself (401), the release (3), and the version within the release (10.0).

2.3.4.1 UMTS system architecture

Figure 2.31 shows the very simplified UMTS reference architecture which applies to both UTRA solutions (3GPP, 2000). The **UTRA network (UTRAN)** handles cell level mobility and comprises several **radio network subsystems (RNS)**. The functions of the RNS include radio channel ciphering and deciphering, handover control, radio resource management etc. The UTRAN is connected to the **user**

equipment (UE) via the radio interface **Uu** (which is comparable to the Um interface in GSM). Via the **Iu** interface (which is similar to the A interface in GSM), UTRAN communicates with the **core network (CN)**. The CN contains functions for inter-system handover, gateways to other networks (fixed or wireless), and performs location management if there is no dedicated connection between UE and UTRAN.

UMTS further subdivides the above simplified architecture into so-called **domains**. The **user equipment** domain is assigned to a single user and comprises all the functions that are needed to access UMTS services. The **infrastructure** domain is shared among all users and offers UMTS services to all accepted users. This domain consists of the **access network** domain, which contains the radio access networks (RAN), and the core network domain, which contains access network independent functions. The **core network** domain can be separated into three domains with specific tasks. The **serving network** domain comprises all functions currently used by a user for accessing UMTS services.

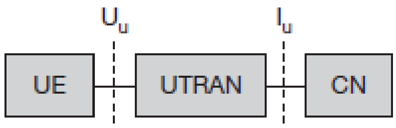


Figure 2.31: Main components of the UMTS reference architecture

All functions related to the home network of a user, e.g., user data look-up, fall into the **home network** domain. Finally, the **transit network** domain may be necessary if, for example, the serving network cannot directly contact the home network. All three domains within the core network may be in fact the same physical network. These domains only describe functionalities.

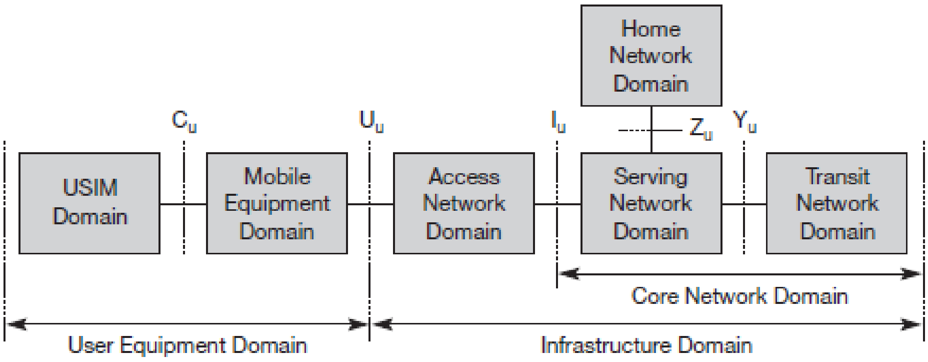


Figure 2.32: UMTS domains and interfaces

2.3.4.2 UTRAN

Figure 2.33 shows the basic architecture of the UTRA network (UTRAN; 3GPP, 2002b). This consists of several **radio network subsystems (RNS)**. Each RNS is controlled by a **radio network controller (RNC)** and comprises several components that are called node B. An RNC in UMTS can be compared with the BSC; a node B is similar to a BTS. Each **node B** can control several antennas which make a radio cell. The mobile device, UE, can be connected to one or more antennas. Each RNC is connected with the core network (CN) over the interface **Iu** (similar to the role of the A interface in GSM) and with a node B over the interface **Iub**. A new interface, which has no counterpart in GSM, is the interface **Iur** connecting two RNCs with each other.

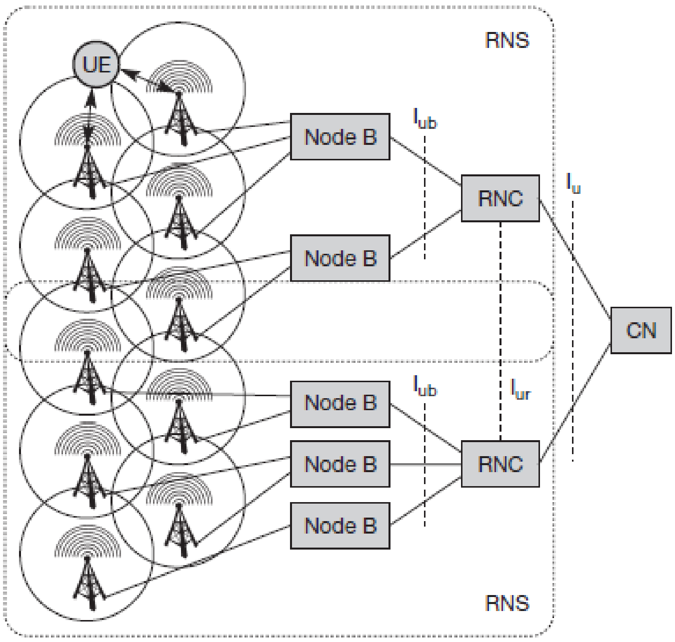


Figure 2.33 Basic architecture of the UTRA network

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