10.1 Multiplex vs. Multiple Access

Consider a situation where there are a huge number of potential users that all have access to a common channel. Assume that only a small fraction of those users are active simultaneously. Traditionally, this type of sharing of a wire bound channel is referred to as multiplex or multiplexing, while the sharing of a wireless channel is referred to as multiple access. The principles of multiplexing and multiple access are the same, but there are a few differences, that are due to the nature of the different channels.

It can be shown that a band-limited channel of bandwidth $W$, and a signal interval $T$, offers approximately $2WT$ dimensions per signal interval. The methods of this chapter all aim at sharing those dimensions among the active users by assigning a subset of the available dimensions to each user.

Wire Bound – Multiplex

Telephone companies have long used multiplexing to transmit several telephone calls over a single wire. Traditionally, the channel has been a coaxial wire or a radio link, but optical fibers have been common for some years. The calls are gathered (multiplexed) by a telephone company in one point, each given its own part of the channel. The calls are then taken apart (demultiplexed) in the other end, and distributed. In this situation, the telephone company has full control over all technical aspects of the transmission and the sharing of the channel.
Wireless – Multiple Access

With the advent of mobile communication, we have been blessed with yet another term: Multiple access. When a mobile wants access to the channel, it tells the nearest base station so, typically over a separate channel. The base station assigns a part of the channel for the call, but it is up to the mobile to actually use the assigned part of the channel.

There are a number of special problems connected to mobile wireless communication. One is the near-far effect. Mobiles that are on different distances from the base station result in different signal power at the base station. The difference can be huge, which means that the stronger signal may cause cross-talk to the weaker signal if the corresponding parts of the channel are not enough separated. This problem is dealt with by power control, by estimating the channel.

Another problem is time accuracy. Again, mobiles can be located at different distances from the base station, which causes different delays. The time references of the mobiles may also differ. A third problem frequency accuracy. The moving property of mobiles may cause doppler shifts, which means that the spectrum is shifted. The frequency reference of the mobiles may also differ. Finally, multipath transmission causes problems. This causes frequency selective fading, which tends to make individual frequency bands useless for longer or shorter time intervals.

10.2 Frequency Division

Basic Idea

One way to supply several parts of the available channel is to divide the frequency band into several smaller frequency bands. The methods based on this idea are called

- **FDM – Frequency Division Multiplex**
- **FDMA – Frequency Division Multiple Access**

The sharing of the common channel is displayed in Figure 10.1. A simple example of frequency division is ordinary radio broadcasts. Each radio station uses a certain frequency band, decided upon by some authority. A receiver is tuned in on a desired radio station, and simply works as a BP filter, where the tuning determines the center frequency of that filter.
10.2. Frequency Division

Figure 10.1: The sharing of a common channel in FDM(A).

Figure 10.2: The overall structure of the multiplexing in the Bell FDM system.

An Example: The Bell FDM System

The Bell FDM system for multiplexing ordinary telephone calls is widely used. It is a purely analog system that is based on repeated amplitude modulation, as shown in Figure 10.2. A detailed picture of the first step, the channel group generation, is given in Figure 10.3. The other steps are performed in similar ways. The spectrum of a supergroup is indicated in Figure 10.4. Totally, 10 800 one-directional voice channels can be distributed over a single channel. Those voice channels share a bandwidth of a little over 40 MHz.

This system is used in a telephone exchange office to transmit phone calls to another telephone exchange office, where the phone calls are demultiplexed by filtering and demodulation. The pilot signals indicated in Figures 10.3 and 10.4 are used at the receiving
Figure 10.3: Generation of a channel group in the Bell FDM system. The carrier frequency $f_k$ used for channel number $k$, $1 \leq k \leq 12$, is given by $f_k = 112 - 4k$ kHz. The frequency scale of the indicated spectra is in kHz.

Figure 10.4: A supergroup in the Bell FDM system formed from five channel groups, totally 60 voice channels. The frequency scale of the spectrum is in kHz.
end to generate carriers of the correct frequencies. The demultiplexed signals are then further distributed, some of them possibly multiplexed again to be transmitted to another exchange office.

The system is obviously one-directional, while phone calls are two-directional. Therefore those systems are used in pairs, one system for each direction.

Advantages and Disadvantages

The advantages of FDM(A) include the following.

- The assigned frequency band is continuously available. This means that this method is insensitive to delays. Also, that means that an individual mobile does not need to be synchronized to other mobiles.

- The narrow-band subchannel that is used for the communication poses low demands on the radio parts, including modulators and demodulators. These parts need only to deliver linearity within a narrow-band subchannel.

- The peak power is approximately the same as the average power, since each mobile uses its subchannel continuously.

The disadvantages of FDM(A) include the following.

- The narrow-band subchannel poses high demands on frequency stability. Due to the problem with frequency inaccuracy in the mobile case, this method needs a guard band between the used frequency bands, in order to avoid cross-talk. These guard bands cost dimensions.

- A related issue is high demands on filters. These typically need to be of high degree, and the cutoff frequencies of those filters need to be exact.

- The method is sensitive to frequency selective fading, since each mobile is assigned a narrow-band subchannel. This means that the channel can be completely blocked during relatively long periods of time.
10.3 Wavelength Division

In the optical case, where we use an optical fibre as the channel, it is possible to communicate over the channel using light of more than one wavelength. Even though this is the same idea as FDM (or FDMA), the methods are then called

- **WDM** – *Wavelength Division Multiplex*,
- **WDMA** – *Wavelength Division Multiple Access*.

The choice of carrier wavelengths is then limited to the wavelengths for which there exist good laser diodes. One obvious difference between WDM(A) and FDM(A) is that the frequencies used in WDM(A) are much higher than the frequencies used in FDM(A), since we are transmitting visible light.

10.4 Time Division

Basic Idea

Another way to supply several parts of the available channel is to divide the time axis into several disjoint intervals, one interval for each mobile. These intervals are then repeated, so that each mobile is given access to all of the available bandwidth during a short period of time, which is repeated after a while. The methods based on this idea are called

- **TDM** – *Time Division Multiplex*
- **TDMA** – *Time Division Multiple Access*

The sharing of the common channel is displayed in Figure 10.5. In digital electronics, this method is often used to transmit binary data from one part of a device to another. It is then simply referred to as multiplexing/demultiplexing or parallel-to-serial conversion and serial-to-parallel conversion.

An Example: The Bell TDM System

The Bell TDM system is a digital system based on TDM for multiplexing phone calls. The over-all structure of the system is given in Figure 10.6. The analog voice channel is sampled using the sampling frequency 8 kHz, and each sample is quantized to 8 b/sample using non-uniform quantization, and those bits are transmitted. This results in a data rate of 64 kb/s for one channel. This is done by a digitizer as in Figure 10.7.
10.4. Time Division

Figure 10.5: The sharing of a common channel in TDM(A).

Figure 10.6: The overall structure of the multiplexing in the Bell TDM system. Systems may not use all of those steps, depending on the bandwidth of the channel at hand.

Figure 10.7: A voice channel digitizer for the Bell TDM system. The sampling frequency is 8 kHz, and each sample is converted to eight bits by the A/D converter.
Twentyfour digital voice channels are multiplexed to form a T1 frame together with an extra framing bit for synchronization. Such a frame is depicted in Figure 10.8. The following formations of T2 through T5 frames are done in similar ways as the formation of a T1 frame, i.e. by multiplexing the smaller frames and appending synchronization bits. Each frame is 125 μs long, since the sample frequency is 8 kHz.

Twelve consecutive T1 frames form a T1 superframe. Things vary between the individual frames within a superframe. For instance, the least significant bit is ignored in frames six and twelve. Those bits are instead used as control bits. The framing bit varies between consecutive T1 frames in a superframe according to the pattern 1000 1101 1100. The demultiplexer has a time reference that is synchronized by correlating against this pattern. Each superframe is 1.5 ms long.

This system is one-directional just as the Bell FDM system, while phone calls still are two-directional. Therefore those systems are also used in pairs, one system for each direction.

**Advantages and Disadvantages**

The advantages of TDM(A) include the following.

- The bandwidth is large, since the mobiles are not separated in terms of frequencies. This poses *low demands on filters*.

- Each mobile uses the same bandwidth. Thus, the radio parts of the base station can be reused for each mobile, which simplifies the implementation of those parts.

- The method is insensitive to frequency selective fading, since each mobile has access to all of the available bandwidth, during its time interval. A suitable error correcting code and/or modulation scheme can be used to eliminate the effects of this fading.

**Figure 10.8:** A frame in the Bell TDM system formed from 24 digital voice channels. The slot labelled “F” is the framing bit. A frame consists of 192 data bits (24 × 8) and one framing bit, totally 193 bits. The bits of each channel is transmitted with most significant bit first.
The disadvantages of TDM(A) include the following.

- The method poses high demands on synchronization. Due to the problem with time inaccuracy in the mobile case, this method needs a guard interval between the used intervals, in order to avoid cross-talk. These guard intervals cost dimensions.

- The average power in TDM(A) is the same as in FDM(A), in order to reach the same error probability. However, the peak power in TDM(A) is considerably larger than in FDM(A), since each mobile is only active part of the time.

- The high bandwidth causes linearity problems in radio parts.

## 10.5 Code Division

### Basic Idea

The idea of code division is based on using the whole available bandwidth for every mobile, still letting them communicate simultaneously. This is achieved by assigning each mobile a code, that identifies it. These methods are called

- **CDM** – *Code Division Multiplex*,

- **CDMA** – *Code Division Multiple Access*.

There are a number code division methods. Some of them will be dealt with in this section.

### Frequency Hopping

A major disadvantage of FDMA is the sensitivity of frequency selective fading. A simple way to deal with that problem is to change frequency band on a regular basis. A method where all mobiles change frequencies regularly, in a synchronized manner is referred to as

- **FH-CDMA** – *Frequency Hopping Code Division Multiple Access*

The sharing of the common channel is displayed in Figure 10.9. This simple spreading technique shares the need for guard bands with FDMA, and the need of guard intervals with TDMA. Thus, the loss of dimensions may be even larger than in both those methods.
Advantages and Disadvantages of Frequency Hopping

FH-CDMA can be viewed as a mixture of FDMA and TDMA. Therefore FH-CDMA inherits properties from both those methods.

The advantages of FH-CDMA include the following.

- The method is *insensitive to frequency selective fading*, since each mobile uses all of the available bandwidth. Inherited from TDMA.

- The peak power is approximately the same as the average power, since each mobile uses its subchannel almost continuously. Inherited from FDM(A).

Disadvantages of FH-CDMA inherited from TDMA:

- The method poses equally *high demands on synchronization* as TDM(A). Due to the problem with time inaccuracy in the mobile case, this method needs a guard interval between the used intervals, in order to avoid cross-talk. These guard intervals cost dimensions.

- The high total bandwidth may cause *linearity problems in radio parts.*
Disadvantages of FH-CDM(A) inherited from FDMA:

- The small bandwidth in each interval poses high demands on filters.
- The narrow-band subchannel poses high demands on frequency stability. Due to the problem with frequency inaccuracy in the mobile case, this method needs a guard band between the used frequency bands, in order to avoid cross-talk. These guard bands cost dimensions.

An additional disadvantage of FH-CDM(A):

- The signal processing overhead is somewhat larger than for TDM(A) and FDM(A), both in the base station and in the mobile.

**Spreading Sequencies**

The available dimensions must be shared among the active mobiles. Even if all mobiles use the whole bandwidth all the time, each mobile’s signal must still be representable using the same small number of dimensions as in all previous methods. Thus, each mobile’s signal must be representable as a narrowband signal. This narrowband signal is then spread in the frequency domain by multiplying it with a spread sequence of ±1. This method is referred to as

- **DS-CDMA – Direct Sequence Code Division Multiple Access**

A popular method to create the spread sequence is to use feedback shift registers. A feedback shift register of length $m$ can at most generate a sequence of length $N = 2^m - 1$. By properly choosing the feedback shift register, it is also possible to get $N = 2^m - 1$. Such a feed back shift register is normally referred to as a maximum length feedback shift register, and the sequence is called an $m$-sequence. The generation of an $m$-sequence of length 15 is displayed in Figure 10.10. The used sequence is then generated from the original sequence by mapping $0, 1$ on ±1.

M-sequences are often referred to as pseudo-noise. As such, they have properties that we are interested in. The individual bits can be shown to be almost uncorrelated. That in turn means that the spectrum of the sequence resembles the spectrum of one single rectangular pulse corresponding to one bit. Since the message is multiplied by the $m$-sequence, their spectra are convoluted, which means that the spectrum of the message is spread. On the receiver side, the signal is again multiplied by the same sequence, which gives us the original message back.
Advantages and Disadvantages of Direct Sequence Code Division

The advantages of DS-CDM(A) include the following.

- The method is *insensitive to frequency selective fading*, since each mobile uses all of the available bandwidth.
- The high bandwidth poses *low demands on filters*.
- The method is said to be more *flexible for varying mobile rates*, compared to other methods. This claim can definitely be subject to debate.
- *No dimensions are lost*, since there is no need for guard intervals or guard bands.
- A slight *oversubscription of the number of mobiles* is possible in situations where users are inactive from time to time.
The disadvantages of DS-CDM(A) include the following.

- The signal processing overhead is larger than for other methods, both in the base station and in the mobile.
- The method poses even *higher demands on synchronization* than TDM(A).
- The high bandwidth may cause *linearity problems in radio parts*.

### 10.6 Practical Systems

Several practical multiple access systems are implemented as a combination of two of the described methods. For example:

- **TDMA/FDMA:** Split the time-frequency domain both in time and in frequency. TETRA, the Trans European Trunked Radio Access system, uses this combination.
- **FDMA/CDMA:** Split the frequency band into a number of sub-bands, and use CDMA in each sub-band. The IS-95 standard for cellular telephone applications is an example where this combination is used.
- **TDMA/CDMA:** FH-CDMA, with TDMA in each block. This combination is used in the mobile telephone standard GSM.