Unit 5

# Multiple Access Techniques

Today the rapidly increasing communications systems are operating in an increasingly crowded frequency spectrum. The only solution appears to be sharing the precious frequency resources among different users, and there comes the need for developing various multiple access techniques.

## Text

### Part I: Multiple Access Techniques: FDMA, TDMA and CDMA

Multiple access schemes are used to allow many simultaneous users to use the same fixed bandwidth radio spectrum. In any radio system, the allocated bandwidth is always limited. For mobile phone systems the total bandwidth is typically 50MHz, which is split in half to provide the forward and reverse links of the system. Sharing of the spectrum is required in order to increase the user capacity of any wireless network. FDMA, TDMA and CDMA are the three major methods of sharing the available bandwidth to multiple users in wireless system. There are many extensions, and hybrid techniques for these methods, such as OFDM, and hybrid TDMA and FDMA systems. However, an understanding of the three major methods is required for understanding of any extensions to these methods.

**Frequency division multiple access**

In Frequency Division Multiple Access (FDMA), the available bandwidth is subdivided into a number of narrower bands. Each user is allocated a unique frequency band in which to transmit and receive. During a call, no other user can use the same frequency band. Each user is allocated a forward link channel (from the base station to the mobile phone) and a reverse channel (back to the base station), each being a single way link. The transmitted signal on each of the channels is continuous allowing analog transmissions. The bandwidths of FDMA channels are generally low (30 kHz) as each channel only supports one user. FDMA is used as the primary breakup of large allocated frequency bands and is used as part of most multi-channel systems. Figures 5.1 and 5.2 show the allocation of the available bandwidth into several channels.

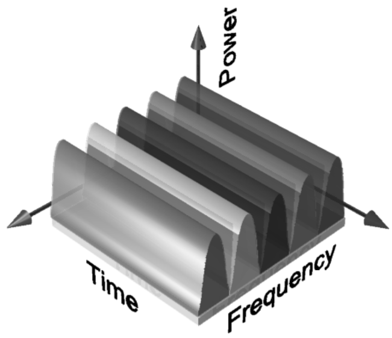


Figure 5.1 FDMA showing that the each narrow band channel is allocated to a single user

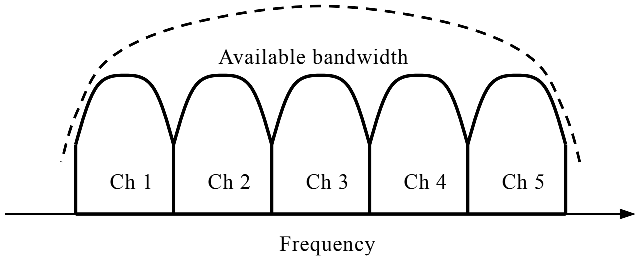


Figure 5.2 FDMA spectrum, where the available bandwidth is subdivided into narrower band channels

**Time division multiple access**

Time Division Multiple Access (TDMA) divides the available spectrum into multiple time slots, by giving each user a time slot in which they can transmit or receive. Figure 5.3 shows how the time slots are provided to users in a round robin fashion, with each user being allotted one time slot per frame.[1]

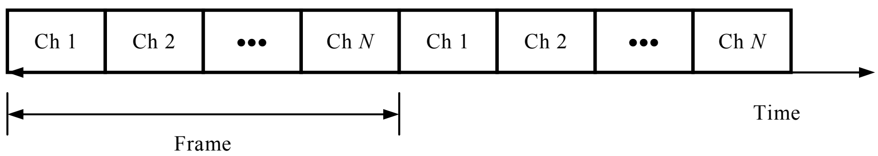


Figure 5.3 TDMA scheme where each user is allocated a small time slot

TDMA systems transmit data in a buffer and burst method, thus the transmission of each channel is non-continuous. The input data to be transmitted is buffered over the previous frame and burst transmitted at a higher rate during the time slot for the channel.[2] TDMA cannot send analog signals directly due to the buffering required, thus is only used for transmitting digital data. TDMA can suffer from multipath effects as the transmission rate is generally very high. This leads the multipath signals causing inter-symbol interference.

TDMA is normally used in conjunction with FDMA to subdivide the total available bandwidth into several channels. This is done to reduce the number of users per channel allowing a lower data rate to be used. This helps reduce the effect of delay spread on the transmission. Figure 5.4 shows the use of TDMA with FDMA. Each channel based on FDMA, is further subdivided using TDMA, so that several users can transmit over one channel. This type of transmission technique is used by most digital second generation mobile phone systems. For GSM, the total allocated bandwidth of 25MHz is divided into 125 channels using FDMA, each having a bandwidth of 200 kHz. These channels are then subdivided further by using TDMA so that each 200 kHz channel allows 8～16 users.

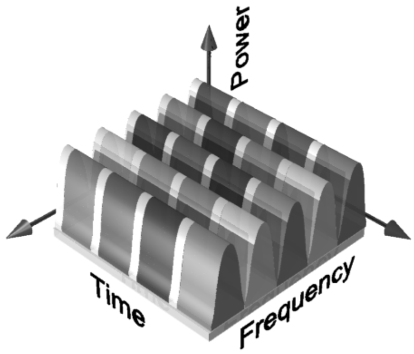


Figure 5.4 TDMA/FDMA hybrid in which the bandwidth is split into frequency channels and time slots

**Code division multiple access**

Code Division Multiple Access (CDMA) is a spread spectrum technique that uses neither frequency channels nor time slots. In CDMA, the narrow band message (typically digitized voice data) is multiplied by a large bandwidth signal which is a pseudo random noise code (PN code). All users in a CDMA system use the same frequency band and transmit simultaneously. The transmitted signal is recovered by correlating the received signal with the PN code used by the transmitter. Figure 5.5 shows the general use of the spectrum using CDMA.

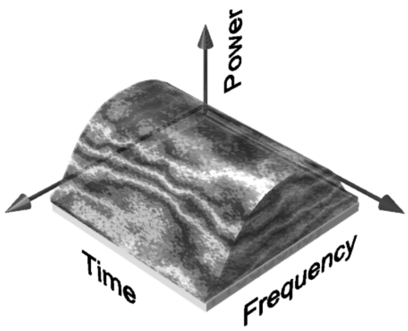


Figure 5.5 Code division multiple access (CDMA)

CDMA technology was originally developed by the military during World War Ⅱ.

Researches were spurred into looking at ways of communicating that would be secure and work in the presence of jamming. Some of the properties that have made CDMA useful are:

- Signal hiding and non-interference with existing systems..
- Anti-jam and interference rejection.
- Information security.
- Accurate ranging.
- Multiple user access.
- Multipath tolerance.

For many years, spread spectrum technology was considered solely for military applications. However, with rapid developments in LSI and VLSI designs, commercial systems are starting to be used.

**CDMA process gain**

One of the most important concepts required in order to understand spread spectrum techniques is the idea of process gain. The process gain of a system indicates the gain or signal to noise improvement exhibited by a spread spectrum system by the nature of the spreading and despreading process.[3] The process gain of a system is equal to the ratio of the spread spectrum bandwidth used, to the original data bit rate. Thus, the process gain can be written as:

$$G_p = \frac{\mathrm{BW}_{\mathrm{RF}}}{\mathrm{BW}_{\mathrm{info}}}$$

where $\mathrm{BW}_{\mathrm{RF}}$ is the transmitted bandwidth after the data is spread, and $\mathrm{BW}_{\mathrm{info}}$ is the bandwidth of the information data being sent.

Figure 5.6 shows the process of a CDMA transmission. The data to be transmitted (a) is spread before transmission by modulating the data using a PN code. This broadens the spectrum as shown in (b). In this example the process gain is 125 as the spread spectrum bandwidth is 125 times greater than the data bandwidth. Part (c) shows the received signal. This consists of the required signal, plus background noise, and any interference from other CDMA users or radio sources. The received signal is recovered by multiplying the signal by the original spreading code. This process causes the wanted received signal to be despread back to the original transmitted data. However, all other signals uncorrelated to the PN spreading code used become more spread. The wanted signal in (d) is then filtered removing the wide spread interference and noise signals.

**CDMA generation**

CDMA is achieved by modulating the data signal by a pseudo random noise sequence (PN code), which has a chip rate higher than the bit rate of the data. The PN code sequence is a sequence of ones and zeros (called chips), which alternate in a random fashion. The data is modulated by modular-2 adding the data with the PN code sequence. This can also be done by multiplying the signals, provided the data and PN code are represented by 1 and

–1 instead of 1 and 0. Figure 5.7 shows a basic CDMA transmitter.

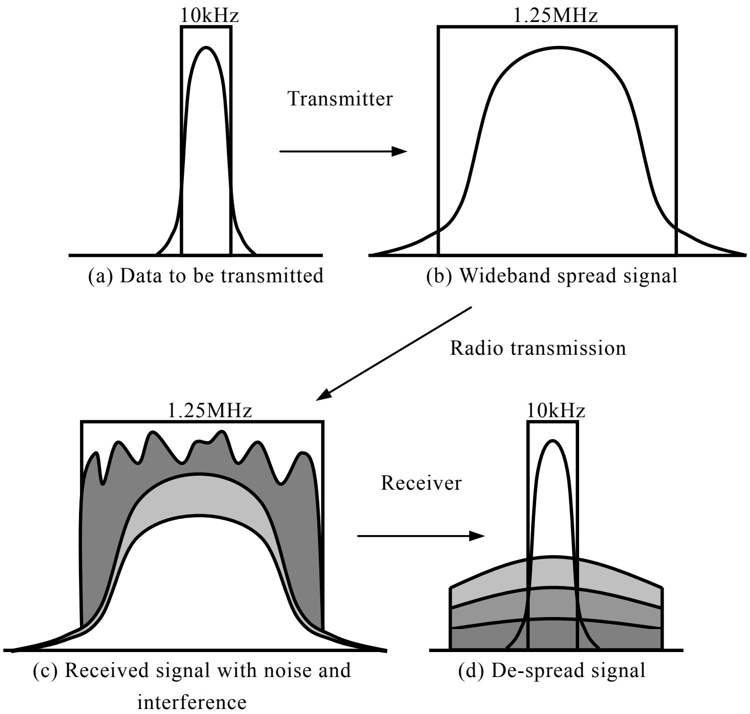


Figure 5.6 Basic CDMA transmission

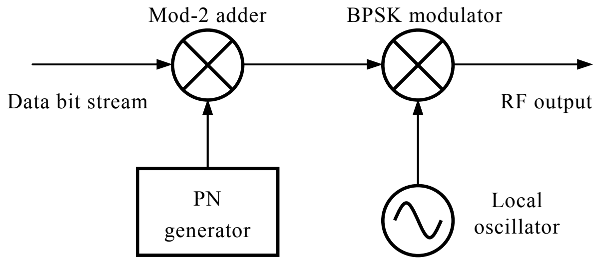


Figure 5.7 Simple direct sequence modulator

The PN code used to spread the data can be of two main types. A short PN code (typically 10～128 chips in length) can be used to modulate each data bit. The short PN code is then repeated for every data bit allowing for quick and simple synchronization of the receiver. Figure 5.8 shows the generation of a CDMA signal using a 10-chip length short code. Alternatively a long PN code can be used. Long codes are generally thousands to millions of chips in length, thus are only repeated infrequently. Because of this they are useful for added security as they are more difficult to decode.

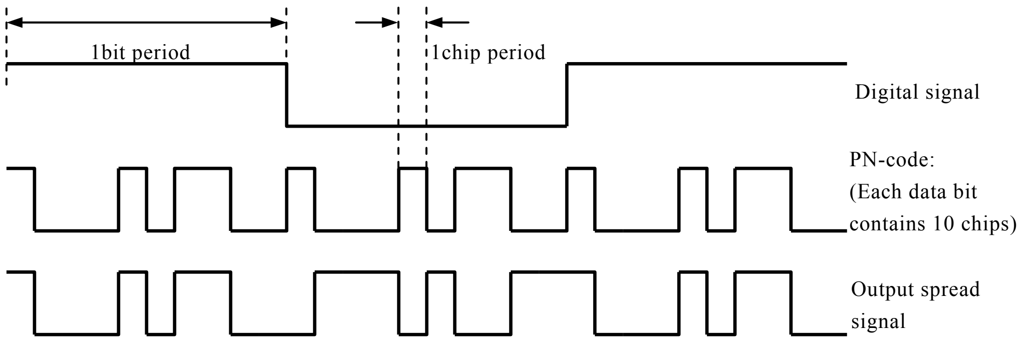


Figure 5.8 Direct sequence signals

**CDMA forward link encoding**

The forward link, from the base station to the mobile, of a CDMA system can use special orthogonal PN codes called Walsh code, for separating the multiple users on the same channel. These are based on a Walsh matrix, which is a square matrix with binary elements, and dimensions which are a power of two. It is generated from the basis $W_1 = 0$ and that:

$$\boldsymbol{W}_{2n} = \begin{bmatrix} \boldsymbol{W}_n & \boldsymbol{W}_n \\ \boldsymbol{W}_n & \overline{\boldsymbol{W}}_n \end{bmatrix}$$

where $\boldsymbol{W}_n$ is the Walsh matrix of dimension $n$. For example:

$$\boldsymbol{W}_2 = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \qquad \boldsymbol{W}_4 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix}$$

Walsh codes are orthogonal, which means that the dot product of any two rows is zero. This is due to the fact that for any two rows exactly half the number of bits match and half do not.

Each row of a Walsh matrix can be used as the PN code of a user in a CDMA system. By doing this the signals from each user is orthogonal to every other user, resulting in no interference between the signals.[4] However, in order for Walsh codes to work the transmitted chips from all users must be synchronized. If the Walsh code used by one user is shifted in time by more than about 1/10 of a chip period with respect to all the other Walsh codes, it loses its orthogonal nature, resulting in inter-user interference.[5] For the forward link signals for all the users originate from the base station, allowing the signals to be easily synchronized.

**CDMA reverse link encoding**

The reverse link is different to the forward link because the signals from each user do not originate from a same source as in the forward link. The transmission from each user will arrive at a different time, due to propagation delay and synchronization errors. Due to the unavoidable timing errors between the users, there is little point in using Walsh codes as they will no longer be orthogonal.[6] For this reason simple pseudo random sequence which are uncorrelated, but not orthogonal are used for the PN codes of each user.

The capacity is different for the forward and the reverse links because of the differences in modulation. The reverse link is not orthogonal, resulting in significant inter-user interference. For this reason the reverse channel sets the capacity of the system.[7]

## Part Ⅱ: Orthogonal Frequency Division Multiplexing

Orthogonal Frequency Division Multiplexing (OFDM)—essentially identical to Coded OFDM (COFDM)—is a digital multi-carrier modulation scheme, which uses a large number of closely-spaced orthogonal sub-carriers. Each sub-carrier is modulated with a conventional modulation scheme (such as quadrature amplitude modulation) at a low symbol rate, maintaining data rates similar to conventional single-carrier modulation schemes in the same bandwidth. In practice, OFDM signals are generated using the fast Fourier transform algorithm.

OFDM has developed into a popular scheme for wideband digital communication systems with a wide range of applications. The primary advantage of OFDM over single-carrier schemes is its ability to cope with severe channel conditions—for example, attenuation of high frequencies at a long copper wire, narrowband interference and frequency-selective fading due to multipath—without complex equalization filters.[1] Channel equalization is simplified because OFDM may be viewed as using many slowly-modulated narrowband signals rather than one rapidly-modulated wideband signal. Low symbol rate makes the use of a guard interval between symbols affordable, making it possible to handle time-spreading and eliminate inter-symbol interference (ISI).

A major disadvantage of OFDM is the high peak-to-average-power ratio (PAPR), requiring more expensive transmitter circuitry, and possibly lowering power efficiency. In addition, it is sensitive to Doppler shift and frequency synchronization problems.

**Orthogonality**

In OFDM, the sub-carrier frequencies are chosen so that the sub-carriers are orthogonal to each other, meaning that cross-talk between the sub-channels is eliminated and inter-carrier guard bands are not required. This greatly simplifies the design of both the transmitter and the receiver; unlike conventional FDM, a separate filter for each sub-channel is not required.

The orthogonality also allows high spectral efficiency, near the Nyquist rate.[2] Almost the whole available frequency band can be utilized. OFDM generally has a nearly "white" spectrum, giving it benign electromagnetic interference properties with respect to other co-channel users.[3]

The orthogonality allows for efficient modulator and demodulator implementation using the FFT algorithm. Although the principles and some of the benefits have been known since the 1960s, OFDM is popular for wideband communications today by way of low-cost digital signal processing components that can efficiently calculate the FFT.

OFDM requires very accurate frequency synchronization between the receiver and the transmitter; with frequency deviation, the sub-carriers shall no longer be orthogonal, causing inter-carrier interference (ICI), i.e. cross-talk between the sub-carriers. Frequency offsets are typically caused by mismatched transmitter and receiver oscillators, or by Doppler shift due to movement. Whilst Doppler shift alone may be compensated for by the receiver, the situation is worsened when combined with multipath, as reflections will appear at various frequency offsets, which is much harder to correct.[4] This effect typically worsens as speed increases, and is an important factor limiting the use of OFDM in high-speed vehicles. Several techniques for ICI suppression are suggested, but they may increase the receiver complexity.

**Guard interval for elimination of inter-symbol interference**

One key principle of OFDM is that since low symbol rate modulation schemes (i.e. where the symbols are relatively long compared to the channel time characteristics) suffer less from intersymbol interference caused by multipath, it is advantageous to transmit a number of low-rate streams in parallel instead of a single high-rate stream.[5] Since the duration of each symbol is long, it is feasible to insert a guard interval between the OFDM symbols, thus eliminating the intersymbol interference.

The guard interval also eliminates the need for a pulse-shaping filter, and it reduces the sensitivity to time synchronization problems.

A simple example: If one sends a million symbols per second using conventional single-carrier modulation over a wireless channel, then the duration of each symbol would be one microsecond or less. This imposes severe constraints on synchronization and necessitates the removal of multipath interference. If the same million symbols per second are spread among one thousand sub-channels, the duration of each symbol can be longer by a factor of thousand, i.e. one millisecond, for orthogonality with approximately the same bandwidth. Assume that a guard interval of 1/8 of the symbol length is inserted between each symbol. Intersymbol interference can be avoided if the multipath time-spreading (the time between the reception of the first and the last echo) is shorter than the guard interval, i.e. 125 microseconds. This corresponds to a maximum difference of 37.5 kilometers between the lengths of the paths. The last 125 microseconds of each symbol are copied and sent in advance of the symbol as a cyclic prefix.

The cyclic prefix, which is transmitted during the guard interval, consists of the end of the OFDM symbol copied into the guard interval, and the guard interval is transmitted followed by the OFDM symbol.[6] Although the guard interval only contains redundant data, which means that it reduces the capacity, some OFDM-based systems, such as some of the broadcasting systems, deliberately use a long guard interval in order to allow the transmitters to be spaced farther apart in a single frequency network (SFN), and longer guard intervals allow larger SFN cell-sizes. A rule of thumb for the maximum distance between transmitters in an SFN is equal to the distance a signal travels during the guard interval — for instance, a guard interval of 200 microseconds would allow transmitters to be spaced 60 km apart.

**Simplified equalization**

The effects of frequency-selective channel conditions, for example fading caused by multipath propagation, can be considered as constant (flat) over an OFDM sub-channel if the sub-channel is sufficiently narrow-banded, i.e. if the number of sub-channels is sufficiently large. This makes equalization far simpler at the receiver in OFDM in comparison to conventional single-carrier modulation. The equalizer only has to multiply each sub-carrier by a constant value, or a rarely changed value.

Our example: The OFDM equalization in the above numerical example would require $N = 1000$ complex multiplications per OFDM symbol, i.e. one million multiplications per second, at the receiver. The FFT algorithm requires $N\log_2 N = 10000$ complex-valued multiplications per OFDM symbol, i.e. 10 million multiplications per second, at both the receiver and transmitter side. This should be compared with the corresponding one million symbols/second single-carrier modulation case mentioned in the example, where the equalization of 125 microseconds time-spreading using a FIR filter would require 125 multiplications per symbol, i.e. 125 million multiplications per second.

Some of the sub-carriers in some of the OFDM symbols may carry pilot signals for measurement of the channel conditions, i.e. the equalizer gain for each sub-carrier. Pilot signals may also be used for synchronization.

If differential modulation such as DPSK or DQPSK is applied to each sub-carrier, equalization can be completely omitted, since these schemes are insensitive to slowly changing amplitude and phase distortion.

**Channel coding and interleaving**

OFDM is invariably used in conjunction with channel coding (forward error correction), and almost always uses frequency and/or time interleaving.

Frequency (subcarrier) interleaving increases resistance to frequency-selective channel conditions such as fading. For example, when a part of the channel bandwidth is faded, frequency interleaving ensures that the bit errors that would result from those subcarriers in the faded part of the bandwidth are spread out in the bit-stream rather than being concentrated.[7] Similarly, time interleaving ensures that bits that are originally close together in the bit-stream are transmitted far apart in time, thus mitigating against severe fading as would happen when traveling at high speed.

However, time interleaving is of little benefit in slowly fading channels, such as for stationary reception, and frequency interleaving offers little to no benefit for narrowband channels that suffer from flat-fading (where the whole channel bandwidth is faded at the same time).

Interleaving is used in OFDM to spread the errors out in the bit-stream that is presented to the error correction decoder, because when such decoders are presented with a high concentration of errors the decoder is unable to correct all the bit errors, and a burst of uncorrected errors occurs.

A common type of error correction coding used with OFDM-based systems is convolutional coding, which is often concatenated with Reed-Solomon coding. Convolutional coding is used as the inner code and Reed-Solomon coding is used for the outer code — usually with additional interleaving (on top of the time and frequency interleaving mentioned above) in between the two layers of coding. The reason why this combination of error correction coding is used is that the Viterbi decoder used for convolutional decoding produces short errors bursts when there is a high concentration of errors, and Reed-Solomon codes are inherently well-suited to correcting bursts of errors.

## New Words

**Part I**

| | | | |
|---|---|---|---|
| simultaneous | 同时的 | hybrid | 混合的 |
| allocate | 分配，指派 | time slot | 时隙 |
| round robin | 循环（复用） | allot | 分配 |
| frame | 帧 | buffer | 缓冲器 |
| burst | 爆发 | multipath | 多径 |
| pseudo random noise | 伪随机噪声 | correlate | 相关，作相关处理 |
| spur | 刺激，激励 | jamming | 干扰 |
| tolerance | 容忍，宽容 | gain | 增益 |
| despread | 解除扩频 | chip | 码片 |
| alternate | 交替 | modular-2 | 模 2 的 |
| synchronization | 同步 | orthogonal | 正交的 |
| matrix | 矩阵 | dimension | 维数 |
| power | 幂 | dot product | 点积，标量积 |
| originate | 发源 | propagation | 传播 |

**Part Ⅱ**

| | | | |
|---|---|---|---|
| multi-carrier | 多载波 | sub-carrier | 子载波 |
| quadrature | 正交，90°相位差 | algorithm | 算法 |

| | | | |
|---|---|---|---|
| attenuation | 衰减 | fading | 衰落 |
| equalization | 均衡 | guard interval | 保护间隔 |
| orthogonality | 正交性 | Doppler shift | 多普勒频移 |
| cross-talk | 串音，干扰 | benign | 良好的，有利的 |
| mismatch | 失配，不匹配 | offset | 偏移 |
| deviation | 偏移，偏差 | parallel | 并行，平行 |
| duration | 持续时间 | sensitivity | 敏感性，灵敏度 |
| prefix | 前缀 | cell-size | 蜂窝大小 |
| redundant | 冗余的，多余的 | pilot signal | 导频信号 |
| numerical | 数值的 | mitigate | 使缓和，减轻 |
| interleaving | 交织，交错 | concatenate | 连在一起，级联 |
| convolutional coding | 卷积编码 | sinusoid | 正弦曲线 |

# Notes on the Text

**Part I**

1. Figure 5.3 shows how the time slots are provided to users in a round robin fashion, with each user being allotted one time slot per frame.
   图 5.3 显示如何以一种循环复用的方式把时隙分配给用户，每个用户每帧分得一个时隙。
2. The input data to be transmitted is buffered over the previous frame and burst transmitted at a higher rate during the time slot for the channel.
   待发送的输入数据在前一帧期间被缓存，在分配给该信道的时隙中以较高速率爆发式发送出去。
3. The process gain of a system indicates the gain or signal to noise improvement exhibited by a spread spectrum system by the nature of the spreading and despreading process.
   系统的处理增益是指扩频系统通过扩频和反扩频的性质所表现出来的增益或信噪比的提高。
4. By doing this the signals from each user is orthogonal to every other user, resulting in no interference between the signals.
   这一处理过程使每一用户的信号与所有其他用户的信号正交，因而相互之间没有干扰。
5. If the Walsh code used by one user is shifted in time by more than about 1/10 of a chip period with respect to all the other Walsh codes, it loses its orthogonal nature, resulting in inter-user interference.
   如果一个用户使用的 Walsh 码在时间上相对于其他所有 Walsh 码移动了超过约十分之一的码片周期，就失去了正交性，导致用户间干扰。

6. Due to the unavoidable timing errors between the users, there is little point in using Walsh codes as they will no longer be orthogonal.
   由于用户之间不可避免的定时偏差，Walsh 码几乎没用，因为它们之间不再正交。
7. The reverse link is not orthogonal, resulting in significant inter-user interference. For this reason the reverse channel sets the capacity of the system.
   反向链接是非正交的，导致用户间的严重干扰。由于这一原因，反向信道限制了系统的容量。

**Part Ⅱ**

1. The primary advantage of OFDM over single-carrier schemes is its ability to cope with severe channel conditions—for example, attenuation of high frequencies at a long copper wire, narrowband interference and frequency-selective fading due to multipath—without complex equalization filters.
   OFDM（正交频分复用）与单载波方案相比的主要优点是不需要复杂的均衡滤波器就能应对严重的信道问题，如：在长铜线中的高频衰减、窄带干扰以及由于多路径而引起的频率选择性衰落。
2. The orthogonality also allows high spectral efficiency, near the Nyquist rate.
   正交性也使 OFDM 的频谱利用率到接近于 Nyquist 频率。
3. OFDM generally has a nearly “white” spectrum, giving it benign electromagnetic interference properties with respect to other co-channel users.
   OFDM 信号一般具有“白的”频谱，使之在与其他用户使用同一信道的情况下具有良好的抗电磁干扰性质。
4. Whilst Doppler shift alone may be compensated for by the receiver, the situation is worsened when combined with multipath, as reflections will appear at various frequency offsets, which is much harder to correct.
   当只有多普勒频移时可以用接收机来补偿，当多普勒频移和多路径结合在一起时，情况就变得更糟，因为反射会出现在不同的频率偏移上，这种偏移很难校正。
5. One key principle of OFDM is that since low symbol rate modulation schemes (i.e. where the symbols are relatively long compared to the channel time characteristics) suffer less from intersymbol interference caused by multipath, it is advantageous to transmit a number of low-rate streams in parallel instead of a single high-rate stream.
   OFDM 的一个关键的特性是因为低符号速率调制方案（也就是与信道时间特性相比，符号的持续时间相对较长）很少受到由多径引起的符号间干扰的影响，并行地传输许多低速率数据流要比传输一个高速率数据流有利。
6. The cyclic prefix, which is transmitted during the guard interval, consists of the end of the OFDM symbol copied into the guard interval, and the guard interval is transmitted followed by the OFDM symbol.
   在保护间隔中传输的循环前缀是由复制到保护间隔中的 OFDM 符号的尾部组成

的，保护间隔是在 OFDM 符号之前传输的。

7. For example, when a part of the channel bandwidth is faded, frequency interleaving ensures that the bit errors that would result from those subcarriers in the faded part of the bandwidth are spread out in the bit-stream rather than being concentrated.
例如，当一部分信道带宽衰减时，频率交织将确保由带宽衰减部分的那些子载波产生的比特误差会分散在整个比特流上而不是集中起来。

# Technical Tips

**GSM**

Global System for Mobile communications is the most popular standard for mobile phones in the world. The GSM Association estimates that 82% of the global mobile market uses the standard. GSM is used by over 2 billion people across more than 212 countries and territories. Its ubiquity makes international roaming very common between mobile phone operators, enabling subscribers to use their phones in many parts of the world. GSM differs from its predecessors in that both signaling and speech channels are digital call quality, and so is considered a second generation (2G) mobile phone system. The key advantage of GSM systems to consumers has been better voice quality and low-cost alternatives to making calls, such as the Short message service. The advantage for network operators has been the ease of deploying equipment from any vendors that implement the standard.

**QAM**

Quadrature amplitude modulation (QAM) is a modulation scheme which conveys data by changing (modulating) the amplitude of two carrier waves. These two waves, usually sinusoids, are out of phase with each other by 90° and are thus called quadrature carriers — hence the name of the scheme.

Like all modulation schemes, QAM conveys data by changing some aspect of a carrier signal, or the carrier wave, (usually a sinusoid) in response to a data signal. In the case of QAM, the amplitude of two waves, 90 degrees out-of-phase with each other (in quadrature) are changed to represent the data signal.

Phase modulation (analog PM) and phase-shift keying (digital PSK) can be regarded as a special case of QAM, where the amplitude of the modulating signal is constant, with only the phase varying. This can also be extended to frequency modulation (FM) and frequency-shift keying (FSK), for these can be regarded a special case of phase modulation.

# Supplementary Readings: Wavelength-Division Multiplexing

In fiber-optic communications, wavelength-division multiplexing (WDM) is a technology which multiplexes multiple optical carrier signals on a single optical fibre by using different wavelengths (colors) of laser light to carry different signals. This allows for a multiplication in capacity, in addition to making it possible to perform bidirectional communications over one strand of fiber. The true potential of optical fiber is fully exploited when multiple beams of light at different frequencies are transmitted on the same fiber. This is a form of frequency division multiplexing (FDM) but is commonly called wavelength division multiplexing. The term wavelength-division multiplexing is commonly applied to an optical carrier (which is typically described by its wavelength), whereas frequency-division multiplexing typically applies to a radio carrier (which is more often described by frequency). However, since wavelength and frequency are inversely proportional, and since radio and light are both forms of electromagnetic radiation, the two terms are equal.

**WDM system**

A WDM system uses a multiplexer at the transmitter to join the signals together, and a demultiplexer at the receiver to split them apart. With the right type of fiber it is possible to have a device that does both simultaneously, and can function as an optical add-drop multiplexer. The optical filtering devices used in the modems are usually etalons, stable solid-state single-frequency Fabry-Perot interferometers in the form of thin-film-coated optical glass.

The concept was first published in 1970, and by 1978 WDM was realized in the laboratory. The first WDM systems only combined two signals. Modern systems can handle up to 160 signals and can thus expand a basic 10 Gbps fiber system to a theoretical total capacity of over 1.6 Tbps over a single fiber pair.

WDM systems are popular with telecommunications companies because they allow them to expand the capacity of the network without laying more fiber. By using WDM and optical amplifiers, they can accommodate several generations of technology development in their optical infrastructure without having to overhaul the backbone network. Capacity of a given link can be expanded by simply upgrading the multiplexers and demultiplexers at each end. This is often done by using optical-to-electrical-to-optical translation at the very edge of the transport network, thus permitting interoperation with existing equipment with optical interfaces.

Most WDM systems operate on single mode fiber optical cables, which have a core diameter of 9 μm. Certain forms of WDM can also be used in multi-mode fiber cables (also known as premises cables) which have core diameters of 50 or 62.5 μm.

Early WDM systems were expensive and complicated to run. However, recent standardization and better understanding of the dynamics of WDM systems have made WDM much cheaper to deploy.

Optical receivers, in contrast to laser sources, tend to be wideband devices. Therefore the demultiplexer must provide the wavelength selectivity of the receiver in the WDM system.

WDM systems are divided in different wavelength patterns, conventional, dense and coarse WDM. Conventional WDM systems provide up to 16 channels in the 3rd transmission window (C-band) of silica fibers around 1550 nm with a channel spacing of 100 GHz. DWDM uses the same transmission window but with less channel spacing enabling up to 31 channels with 50 GHz spacing, 62 channels with 25 GHz spacing sometimes called ultra dense WDM. New amplification options (Raman amplification) enable the extension of the usable wavelengths to the L-band, more or less doubling these numbers.

CWDM in contrast to conventional WDM and DWDM uses increased channel spacing to allow less sophisticated and thus cheaper transceiver designs. To again provide 16 channels on a single fiber CWDM uses the entire frequency band between second and third transmission window (1310/1550 nm respectively) including both windows (minimum dispersion window and minimum attenuation window) but also the critical area where OH scattering may occur, recommending the use of OH-free silica fibers in case the wavelengths between second and third transmission window shall also be used. Avoiding this region, the channels 31, 49, 51, 53, 55, 57, 59, 61 remain and these are the most commonly used.

WDM, DWDM and CWDM are based on the same concept of using multiple wavelengths of light on a single fiber, but differ in the spacing of the wavelengths, number of channels, and the ability to amplify the multiplexed signals in the optical space. EDFA provide efficient wideband amplification for the C-band, Raman amplification adds a mechanism for amplification in the L-band. For CWDM wideband optical amplification is not available, limiting the optical spans to several tens of kilometers.

**Coarse WDM**

Originally, the term “Coarse Wavelength Division Multiplexing” was fairly generic, and meant a number of different things. In general, these things shared the fact that the choice of channel spacings and frequency stability was such that Erbium Doped Fibre Amplifiers (EDFAs) could not be utilized. Prior to the relatively recent ITU standardization of the term, one common meaning for Coarse WDM meant two (or possibly more) signals multiplexed onto a single fiber, where one signal was in the 1550-nm band, and the other in the 1310-nm band.

Recently the ITU has standardized a 20 nanometer channel spacing grid for use with CWDM, using the wavelengths between 1310 nm and 1610 nm. Many CWDM wavelengths below 1470 nm are considered “unusable” on older G.652 specification fibers, due to the increased attenuation in the 1310～1470 nm bands. Newer fibers which conform to the G.652.C and G.652.D standards, such as Corning SMF-28e and Samsung Widepass nearly eliminate the “water peak” attenuation peak and allow for full operation of all twenty ITU

CWDM channels in metropolitan networks.

The Ethernet LX-4 physical layer standard is an example of a CWDM system in which four wavelengths near 1310 nm, each carrying a 3.125 gigabit-per-second (Gbps) data stream, are used to carry 10 gigabit-per-second of aggregate data.

The main characteristic of the recent ITU CWDM standard is that the signals are not spaced appropriately for amplification by EDFAs. This therefore limits the total CWDM optical span to somewhere near 60 km for a 2.5 Gbps signal, which is suitable for use in metropolitan applications. The relaxed optical frequency stabilization requirements allow the associated costs of CWDM to approach those of non-WDM optical components.

CWDM is also being used in cable television networks, where different wavelengths are used for the downstream and upstream signals. In these systems, the wavelengths used are often widely separated, for example the downstream signal might be at 1310 nm while the upstream signal is at 1550 nm.

**Dense WDM**

Dense Wavelength Division Multiplexing, or DWDM for short, refers originally to optical signals multiplexed within the 1550 nm band so as to leverage the capabilities (and cost) of erbium doped fibre amplifiers (EDFAs), which are effective for wavelengths between approximately 1525～1565 nm (C band), or 1570～1610 nm (L band). EDFAs were originally developed to replace SONET/SDH optical-electrical-optical (OEO) regenerators, which they have made practically obsolete. EDFAs can amplify any optical signal in their operating range, regardless of the modulated bit rate. In terms of multi-wavelength signals, so long as the EDFA has enough pump energy available to it, it can amplify as many optical signals as can be multiplexed into its amplification band (though signal densities are limited by choice of modulation format). EDFAs therefore allow a single-channel optical link to be upgraded in bit rate by replacing only equipment at the ends of the link, while retaining the existing EDFA or series of EDFAs along a long haul route. Furthermore, single-wavelength links using EDFAs can similarly be upgraded to WDM links at reasonable cost. The EDFAs cost is thus leveraged across as many channels as can be multiplexed into the 1550 nm band.

# Exercises

**I. Translate the following passage into Chinese.**

OFDM consists of a large number of subcarriers equally spaced in a frequency band. Each band may be digitally modulated by a same scheme such as PSK, QAM, etc., or by different schemes. A serially transmitted sequence is divided into a number of sections, each having $N$ symbols, and the $N$ symbols in each section are used to modulate $N$ carriers for simultaneous transmission. Therefore OFDM is essentially a parallel modulation system. When the number of subcarriers is sufficiently large, the system can resist multipath interference. This is because that, in the time domain, a symbol duration longer than the multipath delay can be chosen, while in the frequency domain, each symbol only occupies a small portion of the channel's frequency band. Thus, the effect of multipath fading spreads over many symbols, resulting in slight distortion to many symbols rather than complete destroy of a few symbols. In this way, correct demodulation is not affected so that the signal can be accurately recovered at the receiver.

In an OFDM system, the principle of choosing the subcarrier interval is to make the subcarriers mutually orthogonal within the entire symbol period. Thus, even if spectral overlap exists between the subcarriers, the symbols can still be recovered without loss. In order to realize maximum spectral efficiency, the interval between subcarriers is usually chosen to equal the reciprocal of the symbol duration $T$. Therefore the subcarrier frequencies in the base band are $f_n = n/T$ ($n$ = 0, 1,⋯, $N$–1). Denoting the $n$-th modulating symbol as $X(n)$, the OFDM waveform within a symbol duration can be expressed as:

$$x(t)=\sum_{n=0}^{N-1}X(n)\exp\left(\mathrm{j}2\pi\frac{n}{T}t\right),\quad 0\le t<T \tag{1}$$

Sampling this waveform at $t = T/N$ yields

$$x(k)=\sum_{n=0}^{N-1}X(n)\exp\left(\mathrm{j}2\pi\frac{kT}{N}\right)=\sum_{n=0}^{N-1}X(n)\exp\left(\mathrm{j}2\pi\frac{nk}{N}\right),\quad k=1,2,\ldots,N-1 \tag{2}$$

It is observed from the above expression that $x(k)$ and $X(n)$ form a discrete Fourier transform pair, therefore the baseband OFDM waveform can be generated from the discrete Fourier transform of $N$ modulating symbols. When $N$=$2^m$ where $m$ is an integer, the fast algorithm of IDFT is easy to implement.

**Ⅱ. Choose the word or phrase that is closest in meaning to the underlined part.**

1. The process gain of a system indicates the gain or signal to noise improvement exhibited by a spread spectrum system by the nature of the spreading and despreading process.
   A. by virtue of the spreading/dispreading process
   B. by processing the spreading/despreading naturally
   C. according to the spreading/despreading characteristics
   D. using the natural spreading/dispreading process
2. Due to the unavoidable timing errors between the users, there is little point in using Walsh codes as they will no longer be orthogonal.
   A. using Walsh codes will have some point due to the absence of orthogonality
   B. using Walsh codes is meaningless since orthogonality will not exist any more
   C. Walsh code cannot be used since they are not orthogonal
   D. it is unnecessary to use Walsh codes because orthogonality is lost
3. For example, when a part of the channel bandwidth is faded, frequency interleaving ensures that the bit errors that would result from those subcarriers in the faded part of the bandwidth are spread out in the bit-stream rather than being concentrated.

A. that would be produced in those subcarriers suffering from frequency selective fading
B. that would cause some subcarriers being faded in some part of the bandwidth
C. that would came from the fading subcarriers falling in part of the bandwidth
D. that would result in those faded subcarrier of the part of the bandwidth

4. Earlier we introduced the concept that the identity of an amplitude modulated message signal <u>may under certain circumstances be communicated by transmitting regular samples of the message</u>, rather than the continuous signal.
A. may transmit samples that are regular in communications under some conditions
B. may be in the circumstances that regular message samples are communicated
C. may be conveyed by sending signal values sampled at regular intervals under certain conditions
D. may communicate with certain customers by sending regular samples of the message

5. Early we introduced the concept that the identity of an amplitude modulated message signal may under certain circumstances be communicated by transmitting <u>regular samples of the message</u>, rather than the continuous signal.
A. values of the message signal taken at regular intervals
B. formally obtained message samples
C. samples of the message produced in a specific manner
D. samples of the regularly obtained message

6. Having defined these functions, we will proceed to show how they can be used to <u>evaluate certain integrals characteristic of system error performance</u>.
A. evaluate characteristics of certain integrals in system error performance
B. assess certain integrals that are typical in describing error performance of the systems
C. decide the value of some characteristic integrals of error performance of the systems
D. carry out evaluations on the integrated characteristics of system error performance

7. Modulation is the systematic variation of some attribute of a carrier waveform such as the amplitude, phase, or frequency <u>in accordance with a function of the message signal</u>.
A. in terms of a message carried by the signal
B. according to the behavior of the signal
C. due to the performance of the signal
D. in relation with a quantity derived from the signal

8. Over recent years this potential has largely been realized in the costs of the optical fiber transmission medium <u>that for bulk purchases is now becoming competitive with copper wires</u>.
A. that is specifically for purchases, and is becoming superior to copper wires
B. that is bulkily comparable in price with copper wires
C. that is competing with copper wires in terms of the scale of purchases
D. that is becoming a challenge to copper wires when bought in a large quantity