Modulation Techniques for Mm Waves

This document summarizes modern digital communication modulation techniques for millimeter wave communication systems. Digital modulation schemes transform digital signals into millimeter wave signals that are compatible with the nature of the communication channels.

There are two major categories of digital modulations. The first category uses a constant amplitude carrier to carry the information in phase or frequency variations, such as frequency shift keying (FSK) and phase shift keying (PSK). The second category conveys the information in carrier amplitude variations, such as amplitude shift keying (ASK) and quadrature amplitude modulation (QAM).

Millimeter wave radios require high power efficiency with low bit error rate (BER). Power efficiency is the ability of a modulation technique to preserve the fidelity of the digital message at low power levels. As millimeter wave power has high cost, either 64 or 256 QAM is not preferable due to the effect of phase noise and power consumption of the power amplifier (PA).

2.1 ON/OFF KEYING (OOK)

On/off keying (OOK) modulation is a modulation scheme used in control applications. This is in part due to its simplicity and low implementation costs. OOK consists of keying a sinusoidal carrier signal on and off with a unipolar binary signal. OOK is equivalent to two-level ASK. The system diagram of OOK is shown in Figure 2.1. OOK modulation has the advantage of allowing the transmitter to idle during the transmission of a "0", therefore conserving power. Here input signal has two states ("1" and "0") and modulation factor is 100% (from full power to no transmitted power).

The disadvantage of OOK modulation arises in the presence of an undesired signal. The modulated signals can be graphically represented on a two-dimensional orthogonal plot, sometimes referred to as a signal diagram. Consider a set of two basis vectors φ_1 and φ_2. The signal diagrams for OOK are shown in Figure 2.2.

The idea of OOK is that the transmitter is on when logic "1" is transmitted and the transmitter is off when logic "0" is transmitted. OOK receivers require an adaptable threshold and automatic gain controller (AGC) in order to ensure an optimal threshold setting. A logarithm amplifier detector with an averaging bit slicer is employed, as shown in Figure 2.3. This circuit will ensure that the threshold is set between the signal levels of a "0" and a "1" transmission. The above circuit works well as long as the data received is effectively D.C. balanced.

There are two types of demodulation method, namely synchronous demodulation and envelope demodulation.

Synchronous demodulation is also known as coherent demodulation, and the block diagram is shown in Figure 2.4. As shown in Figure 2.4, the coherent carrier for demodulation is $2\cos(2\pi f_c t)$, where the amplitude factor of "2" used here is for calculation convenience, and f_c is the carrier frequency used for the generation of OOK signal. During the following analysis, the carrier phases of the transmitter and receiver are assumed to be the same and they are dropped for notational convenience.

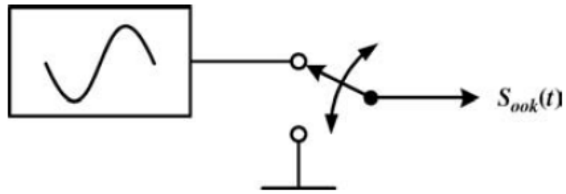


Figure 2.1. System diagram of OOK

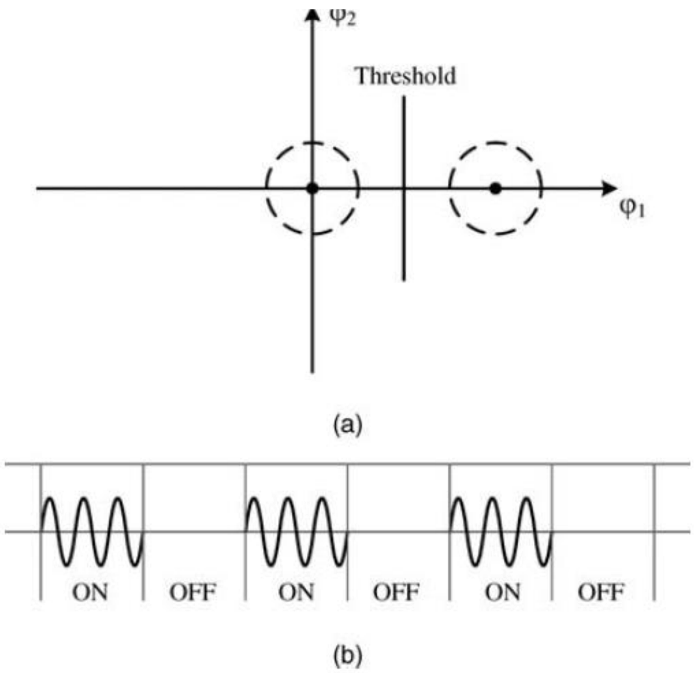


Figure 2.2. (a) OOK signal diagram, (b) OOK signal

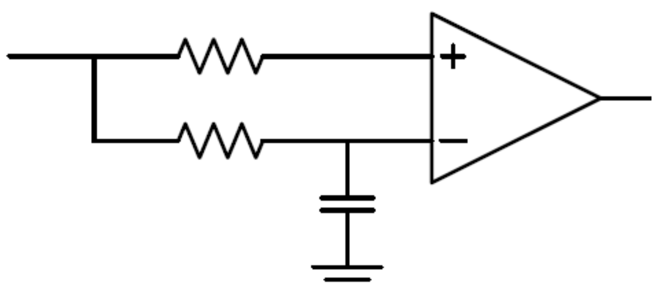


Figure 2.3. OOK receiver

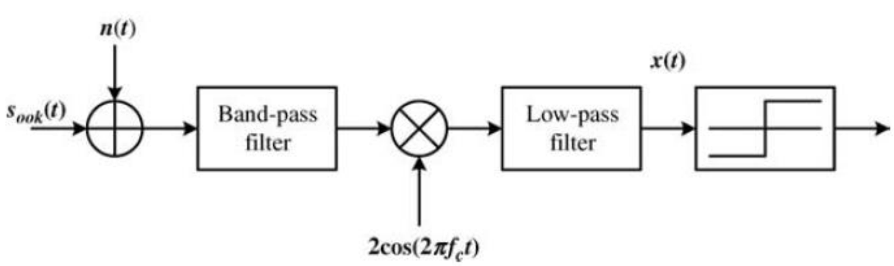


Figure 2.4. Block diagram of synchronous demodulation

Envelope demodulation for OOK signal is a noncoherent demodulation method, as shown in Figure 2.6.

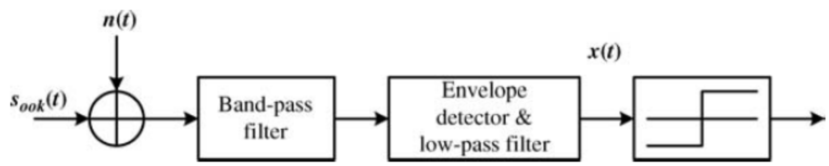


Figure 2.6. Envelope demodulation of OOK system

2.2 PHASE SHIFT KEYING (PSK)

Phase shift keying (PSK) is a large class of digital modulation schemes. PSK is widely used in the communication industry. The simplest form of phase modulation is binary (two-level) phase modulation. For binary phase shift keying (BPSK) the carrier phase has only two states, 0 and π (see Figure 2.8). Obviously the transition from a "1" to a "0", or vice versa, will result in the modulated signal crossing the origin of the constellation diagram, resulting in 100% amplitude modulation.

Quadrature phase shift keying (QPSK) devices modulate input signals by 0°, 90°, 180°, and 270° phase shifts. Figure 2.9 shows three types of constellation diagram for QPSK modulations, (a) conventional QPSK, (b) offset QPSK (OQPSK), and (c) $\pi/4$ QPSK.

Conventional QPSK has transitions through zero (i.e., 180° phase transition). In OQPSK, the transitions on the I and Q channels are staggered. Phase transitions are therefore limited to 90°. In $\pi/4$-QPSK the set of constellation points are toggled each symbol, so transitions through the origin can be avoided. This scheme produces the lowest envelope variations. All these QPSK schemes require linear power amplifiers. In particular, a highly linear amplifier is required for the conventional QPSK.

Both QPSK and BPSK modulators are used in conjunction with demodulators that extract information from the modulated signal. Some QPSK and BPSK modulators

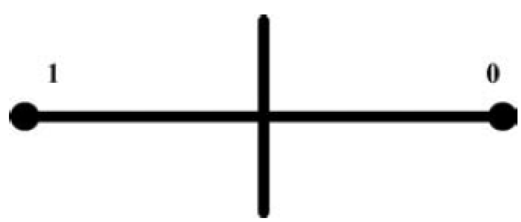


Figure 2.8. Constellation diagram for BPSK

include an integral dielectric resonator oscillator. QPSK and BPSK modulators with root raised cosine (RRC) and Butterworth filters are also available.

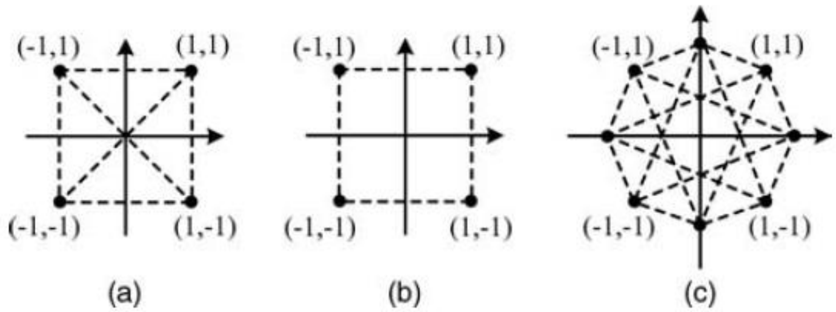


Figure 2.9. Three types of constellation diagram for QPSK: (a) conventional QPSK, (b) OQPSK, (c) $\pi/4$ QPSK

Performance specifications for QPSK and BPSK modulators include input carrier frequency, insertion loss, amplitude unbalance, phase unbalance, and voltage standing wave ratio (VSWR). Insertion loss is the total RF power transmission loss through the device. Amplitude unbalance is the difference in power between the I output signal and the Q output signal. Phase unbalance is the deviation from 90° of the phase angle difference of the I and Q output signals. VSWR is a unitless ratio ranging from 1 to infinity that expresses the amount of reflected energy at the input of the device. A value of 1 indicates that all of the energy passes through. Any other value indicates that a portion of the energy is reflected. Other performance specifications for QPSK and BPSK modulators include frequency range, return loss, and reflected power.

If a sinusoidal carrier is modulated by a bipolar bit stream $a(t)$ according to the scheme illustrated in Figure 2.10, its polarity will be reversed every time the bit stream changes polarity. This, for a sine wave, is equivalent to a phase reversal (shift). The multiplier output is a BPSK signal.

$$a(t) = \sum_{k=-\infty}^{\infty} a_k p(t-kT)$$

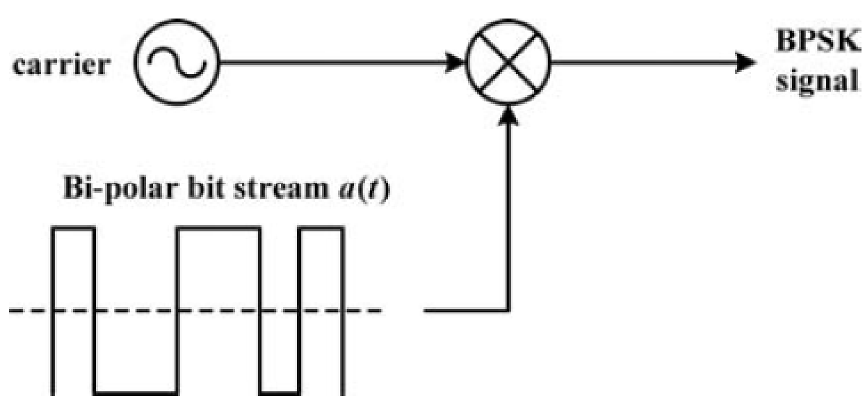


Figure 2.10. BPSK signal generation

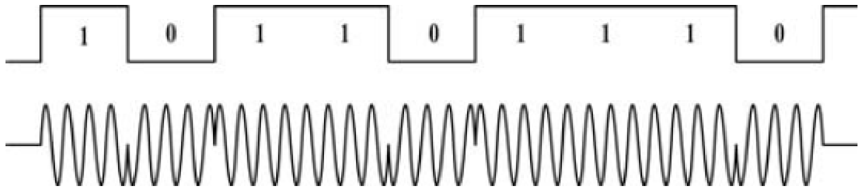


Figure 2.11. BPSK signals in the time domain

where a_k is the bipolar data symbol, T is the bit interval, and $p(t)$ is the rectangular pulse with unit amplitude defined on $[0,T]$. Then the BPSK signal can be expressed as

$$s(t) = Aa(t)\cos(2\pi f_c t) \tag{2.19}$$

where f_c is the carrier frequency and A is the amplitude.

The coherent demodulator for BPSK signal is shown in Figure 2.12.

The BPSK coherent demodulator is one type of binary coherent detectors. The coherent detector could be in the form of a correlator or matched filter with the reference signal of $\cos(2\pi f_c t)$. The frequency and phase between the reference signal and the received signal have to be synchronous. The synchronous reference signal can be generated by the carrier recovery circuit.

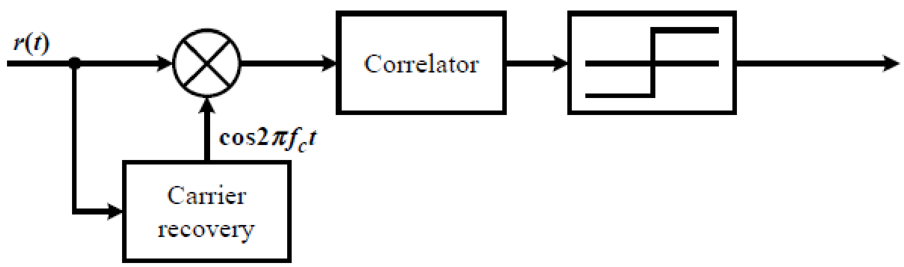
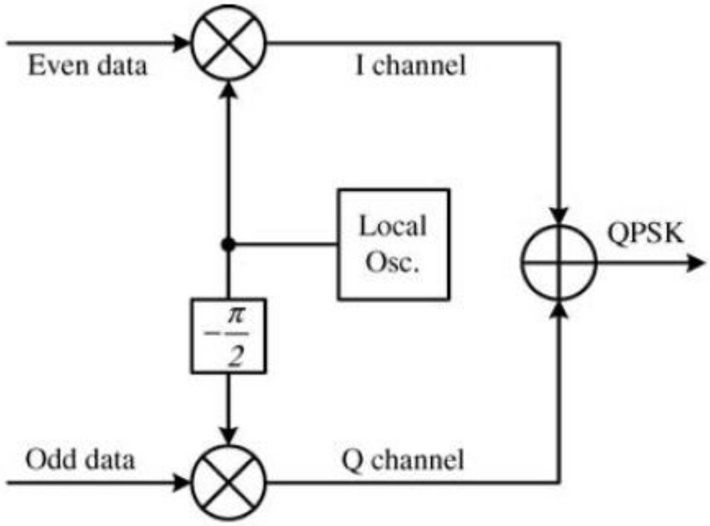


Figure 2.12. Coherent demodulator for BPSK signal

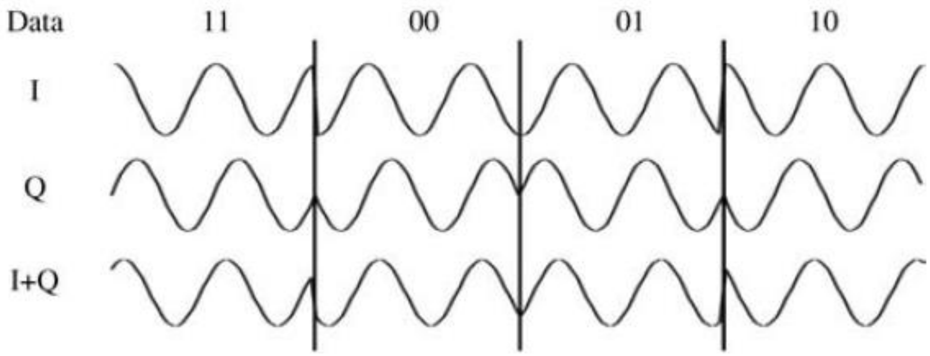
Similar to the case of OOK coherent demodulation, the probability of error for a coherent receiver system with BPSK modulation can be derived as

$$P_e = \frac{1}{2}\operatorname{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right) \tag{2.21}$$

In Figure 2.17(a), QPSK is effectively two independent BPSK systems (I and Q), and therefore exhibits twice bandwidth efficiency. The two signal components with their bit assignments and the total combined signals are shown in Figure 2.17(b). The phase of I or Q signal changes abruptly at some of the bit-period boundaries. QPSK can be filtered using raised cosine filters to achieve excellent out-of-band suppression. Large envelope variations occur during phase transitions, thus requiring linear amplification.



(a)



(b)

2.17. (a) Conventional QPSK signal generation, (b) QPSK signals in the time domain

The coherent demodulator for QPSK signal is shown in Figure 2.18. It consists of two individual BPSK demodulators for both I and Q channels. The two demodulated signals are converted into one data sequence by the parallel to serial converter (P/S). This is possible due to the correspondence and orthogonality between data bits from I and Q channels.

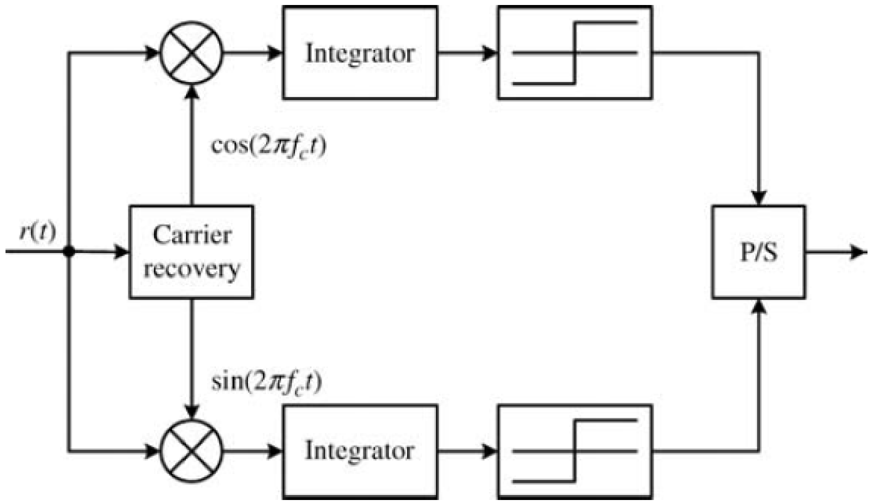


Figure 2.18. QPSK demodulator

For a coherent QPSK receiver system, the probability of error is about [6]

$$P_e = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \tag{2.30}$$

where

$$Q(x) = \int_x^{\infty} \frac{1}{\sqrt{2\pi}} e^{-u^2} du \tag{2.31}$$

FREQUENCY SHIFT KEYING (FSK)

In Figure 2.28(a), the upper trace is the baseband data and the appearance of a FSK signal in the time domain is shown in the lower trace. Bandwidth occupancy of FSK is dependent on the spacing of the two frequencies. A frequency spacing of 0.5 times the symbol period is typically used. FSK can be expanded to an M-ary scheme, employing multiple frequencies as different states, as shown in Figure 2.28(b).

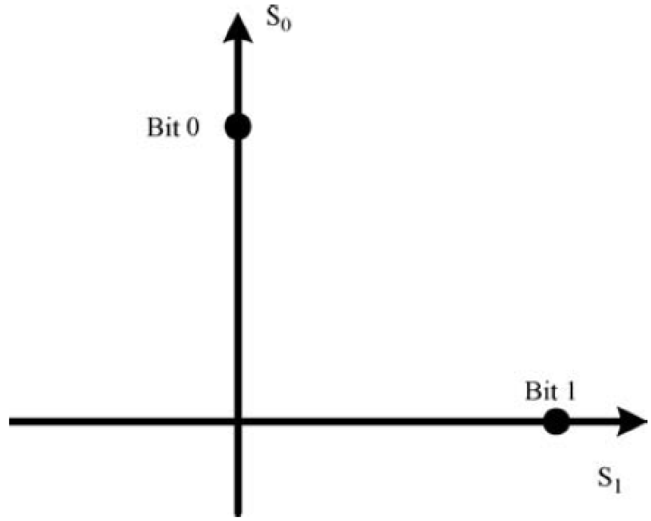


Figure 2.27. FSK constellation

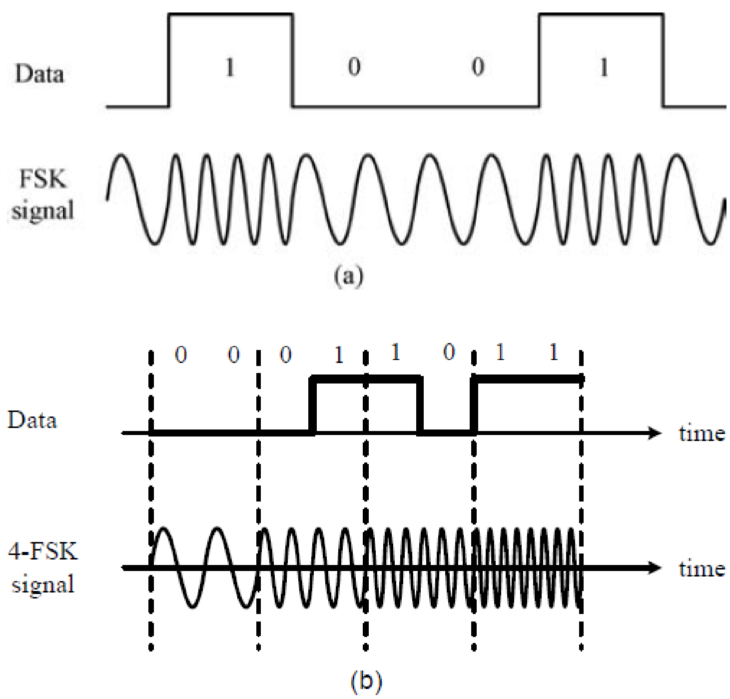


Figure 2.28. (a) BFSK, (b) 4FSK signals in the time domain

FSK signal can be generated both coherently with an IQ modulator and noncoherently with simply a voltage controlled oscillator (VCO) and a digital voltage source,

2.4 QUADRATURE AMPLITUDE MODULATION (QAM)

Quadrature amplitude modulation (QAM) is a complicated name for a simple technique. In the simplest terms, QAM is the combination of amplitude modulation and phase shift keying. A QAM signal can be expressed as

$$\begin{aligned} s_m(t) &= \mathrm{Re}\left[(A_{mc} + jA_{ms})g(t)e^{j2\pi f_c t}\right] \\ &= A_{mc}g(t)\cos(2\pi f_c t) - A_{ms}g(t)\sin(2\pi f_c t) \\ &= V_m g(t)\cos(2\pi f_c t + \theta_m) \end{aligned} \tag{2.56}$$

$$m = 1, 2, \cdots, M \qquad 0 \le t \le T$$

where g(t) is a pulse waveform to control the spectrum, for example, raised cosine, A_{mc} and A_{ms} are the in-phase and quadrature components of the modulating signal, respectively, and V_m and θ_m denote the signal amplitude and phase, given, respectively, by,

$$\begin{aligned} V_m &= \sqrt{A_{mc}^2 + A_{ms}^2} \\ \theta_m &= \tan^{-1}\frac{A_{ms}}{A_{mc}} \end{aligned} \tag{2.57}$$

We can write $s_m(t)$ as a linear combination of two orthogonal waveforms

$$s_m(t) = s_{m1}f_1(t) + s_{m2}f_2(t) \tag{2.58}$$

From (2.58), it can be seen that QAM is a modulation scheme in which data is transferred by modulating the amplitude of two separate orthogonal carrier waves, which are out of phase by 90° (sine and cosine). Due to their 90° phase difference, they are called quadrature carriers.

Figure 2.34, where the lines represent the phase and amplitude transitions from one symbol to another.

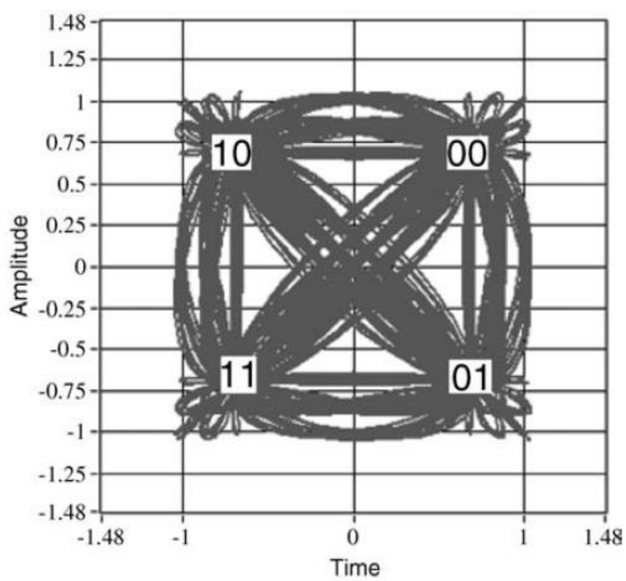


Figure 2.34. Constellation diagram of 4-QAM

The most common QAM constellations, shown in Figure 2.35 include the squared QAMs, 4-QAM, 16-QAM, 64-QAM, and 256-QAM, as well as the odd-bit QAMs, 32-QAM (5-bit per symbol) and 128-QAM (7-bit per symbol).

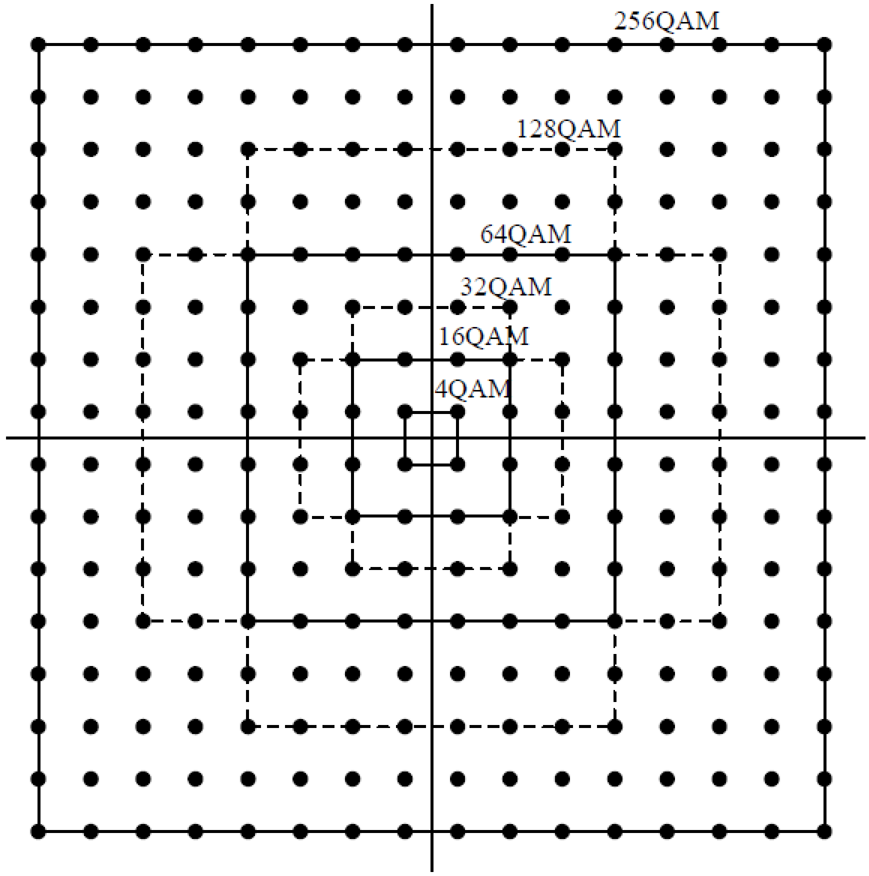
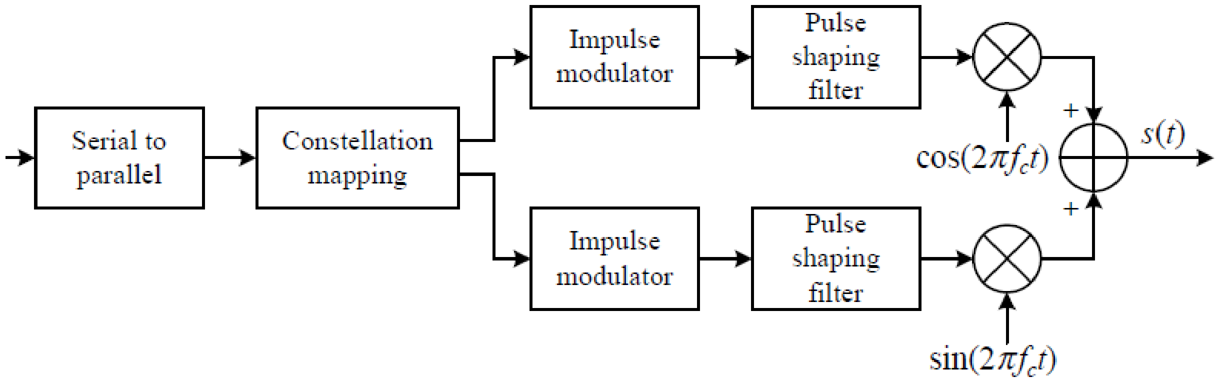


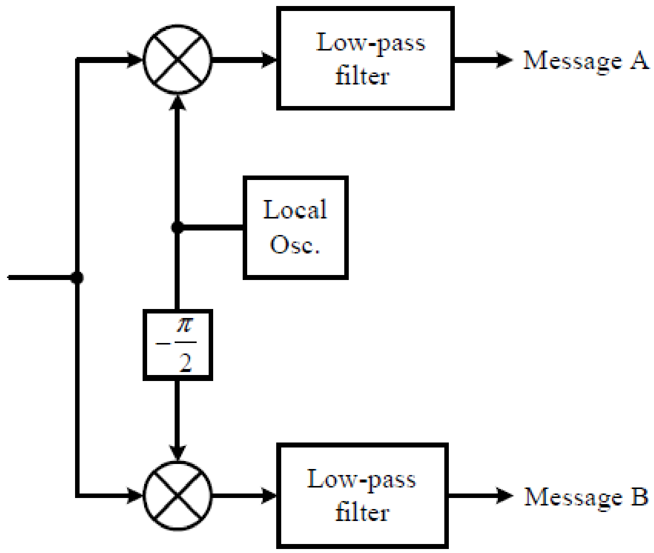
Figure 2.35. QAM constellation

The block diagrams of a QAM modulator and demodulator are shown in Figure 2.36(a) and (b), respectively. A highly stable local oscillator is normally required for a QAM system.

The 64-QAM and 256-QAM are often used in cable modem and digital cable television applications. In millimeter wave communications, neither 64-QAM nor 256-QAM is preferable due to the effect of phase noise and power consumption of PA.



(a)



(b)

Figure 2.36. (a) QAM modulator, (b) QAM demodulator

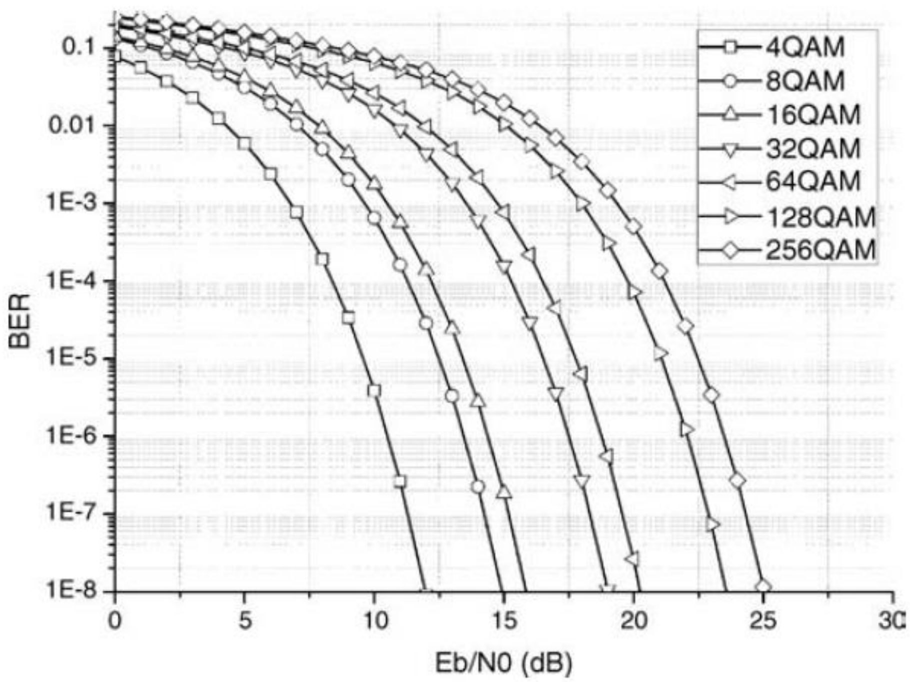


Figure 2.37. Bit error probability of QAM signal

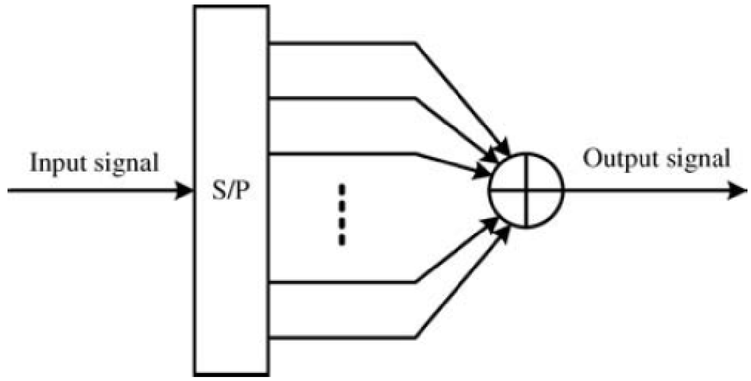


Figure 2.38. OFDM configuration

2.5 ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING (OFDM)

Orthogonal frequency division multiplexing (OFDM) is used widely in the current broadband wireless communication system because of its high data rate transmission and the robustness against frequency selective fading. OFDM technology is to split a high-rate data stream into a number of lower rate streams that are transmitted simultaneously over a number of subcarriers as shown in Figure 2.38 [8]. Because the symbol duration increases with the lower rate parallel subcarrier, the relative amount of dispersion in time caused by multi-path delay spread is decreased. OFDM can be viewed as a multiplexing technique and the output signal is the linear sum of the modulated subcarrier signals. In other words, the radio is transmitting multiple RF subcarriers instead of a single RF carrier. Each of those OFDM subcarriers will still be modulated exactly the same way as using, for example, BPSK, QPSK, or QAM.

At time instant t, the baseband OFDM signal can be expressed as

$$x(t) = \frac{1}{\sqrt{N_c}} \sum_{k=0}^{\infty} p(t-kT_s) \sum_{m=0}^{N_c-1} X_m(k) \exp[\, j2\pi f_m(t-kT_s)] \tag{2.62}$$

where $X_m(k)$ is the modulating signal on the mth subcarrier of the kth OFDM symbol. T_s is the duration of one OFDM symbol, $p(t)$ ($p(t) = 1$ when $0 \leq t < T_s$, otherwise $p(t) = 0$) is the time domain rectangle window function, $f_m = m/T_s$ is the mth subcarrier frequency, and N_c is the total number of subcarriers. $X_m(k)$ can take different values according to the modulation type, such as QPSK, 16-QAM and 64-QAM. Furthermore, $p(t)$ can be any other window functions that obey Nyquist criterion.

The discrete expression of (2.62) is

$$x(n) = \frac{1}{\sqrt{N_c}} \sum_{k=0}^{\infty} p(n-kN_c) \sum_{m=0}^{N_c-1} X_m(k) \exp\left[j\frac{2\pi m(n-kN_c)}{N_c} \right] \tag{2.63}$$

The implementation complexity of OFDM modems can be reduced significantly by employing inverse discrete Fourier transform (IDFT) to replace the bank of sinusoidal generators at transmitter (see Figure 2.39) and using discrete Fourier transform (DFT) to replace the bank of local oscillators at receiver.

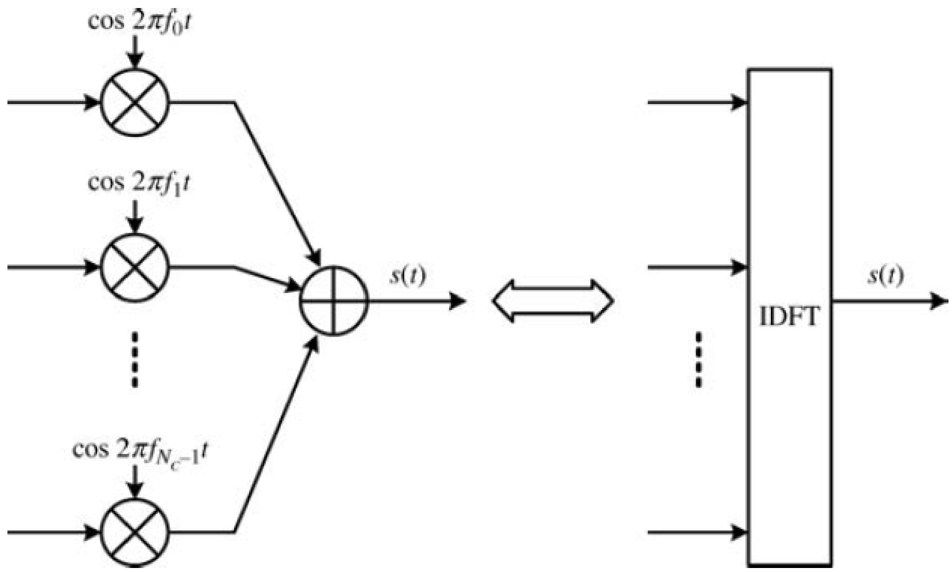


Figure 2.39. Discrete Fourier transformer

In OFDM systems, the spectrum of individual subcarrier is overlapped with minimum frequency spacing, which is carefully designed so that each subcarrier is orthogonal to the other subcarriers. The bandwidth efficiency of OFDM is another advantage.

Figure 2.40 shows an example of one OFDM signal with four subcarriers. In this example, all subcarriers are with the same phase and amplitude. However, in the real system, all the amplitudes and phases could be different according to the modulated symbol for each subcarrier. During the symbol interval T_s, all the subcarriers have integer number of cycles, and the number of cycles between adjacent subcarriers just differs by one. This accounts for the orthogonality between subcarriers.

The spectral shapes for the OFDM signal are shown in Figure 2.41. This figure is based on the rectangle window function. When $p(t)$ are other window functions, the spectral shape will be changed. Therefore, we can use different window functions to adjust the shapes of the subcarriers to reduce the inter-carrier interference (ICI). The subchannel spacing in OFDM signal is $1/T_s$, and the transmission rate of each subchannel is also $1/T_s$, so the subchannels are overlapped. Because of this property, the spectral efficiency of OFDM system is better than the traditional frequency division multiplexing (FDM) system.

One of the main advantages of OFDM is the ability of dealing with the multi-path delay spread. The data to be transmitted over an OFDM signal are spread across N_c subcarriers of the signal, and each subcarrier carrying out the payload. This reduces the data rate for each subcarrier. The lower data rate makes it easy to handle the interference from reflections. This is achieved by adding a guard interval with zero padding between adjacent OFDM symbols. Figure 2.42 gives an example of OFDM signals with zero-padded guard interval. It ensures that the data is only sampled when the signal is stable and no new delayed signals arrive that would alter the timing and phase of the signal. Therefore, the ISI can be eliminated.

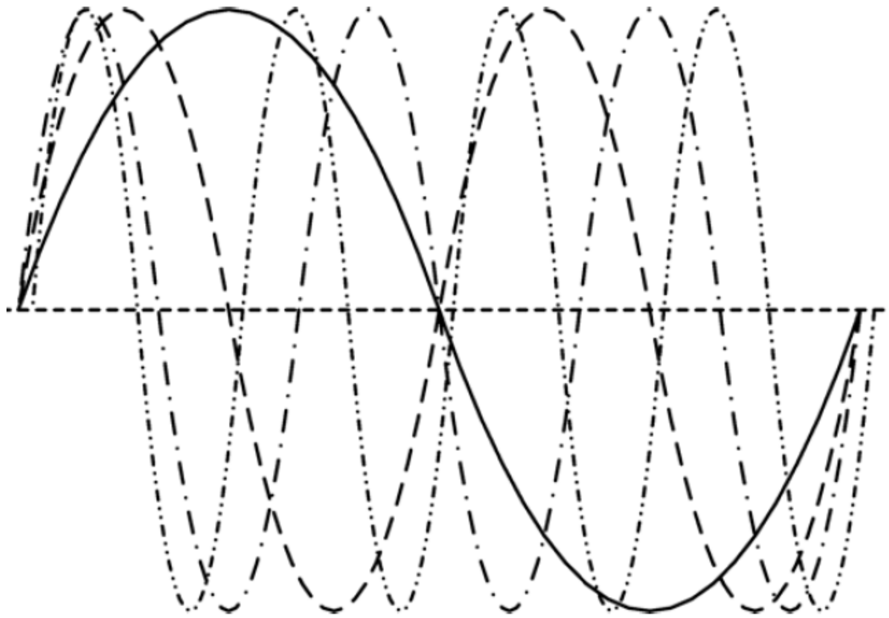


Figure 2.40. Example of four subcarriers within one OFDM symbol

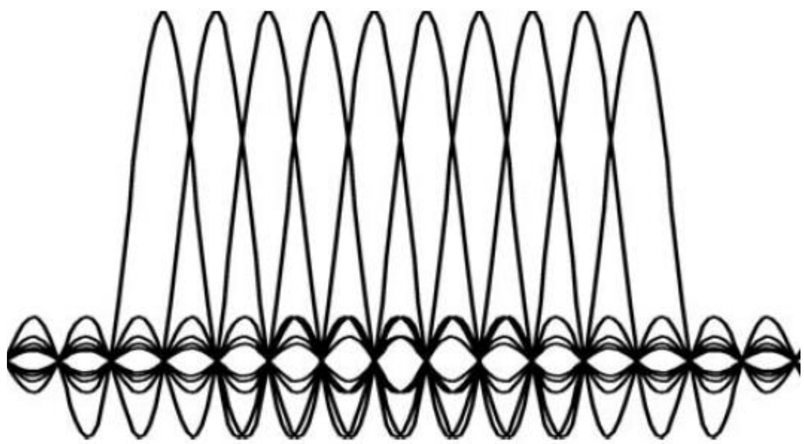


Figure 2.41. Spectral shapes for OFDM signal

The sequence of operations at the transmitter is represented in Figure 2.44

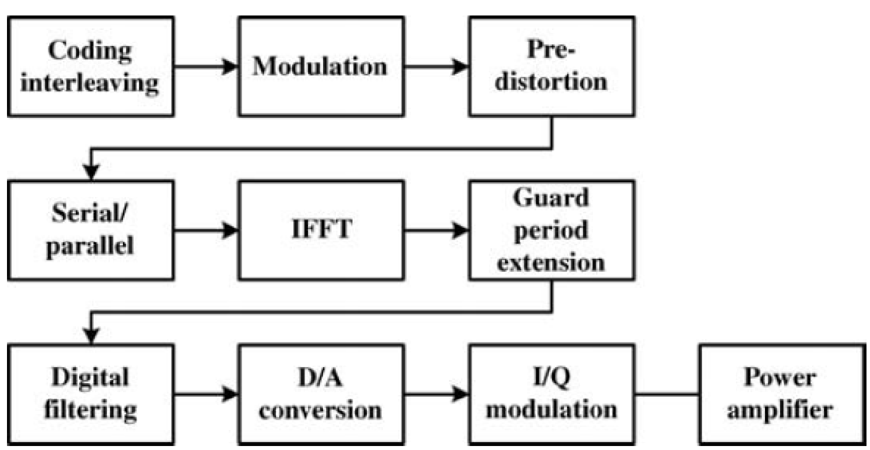


Figure 2.44. Typical OFDM transmitter chain

A typical FFT-based OFDM communication system is described in Figure 2.45. At the transmitter, the serial to parallel converter converts a serial bit stream into several parallel bit streams to be divided among the individual subcarriers. Each subcarrier is modulated as an individual channel before all the subcarriers are combined back together and transmitted as a single signal. The parallel to serial conversion stage is the process of summing all the subcarriers together to form a single signal. The modulation of data into a complex waveform occurs at the IFFT stage of the transmitter. The role of the IFFT is to modulate each subchannel onto the appropriate subcarrier. Here, the modulation scheme can be chosen completely independently of the specific channel and can be chosen based on the channel requirements. In fact, it is possible for each individual subcarrier to use a different modulation scheme.

The receiver performs the reverse process to first divide the incoming signal into the appropriate subcarriers via the S/P converter and then to demodulate them individually via the FFT before reconstructing the original bit stream with the P/S converter [10].

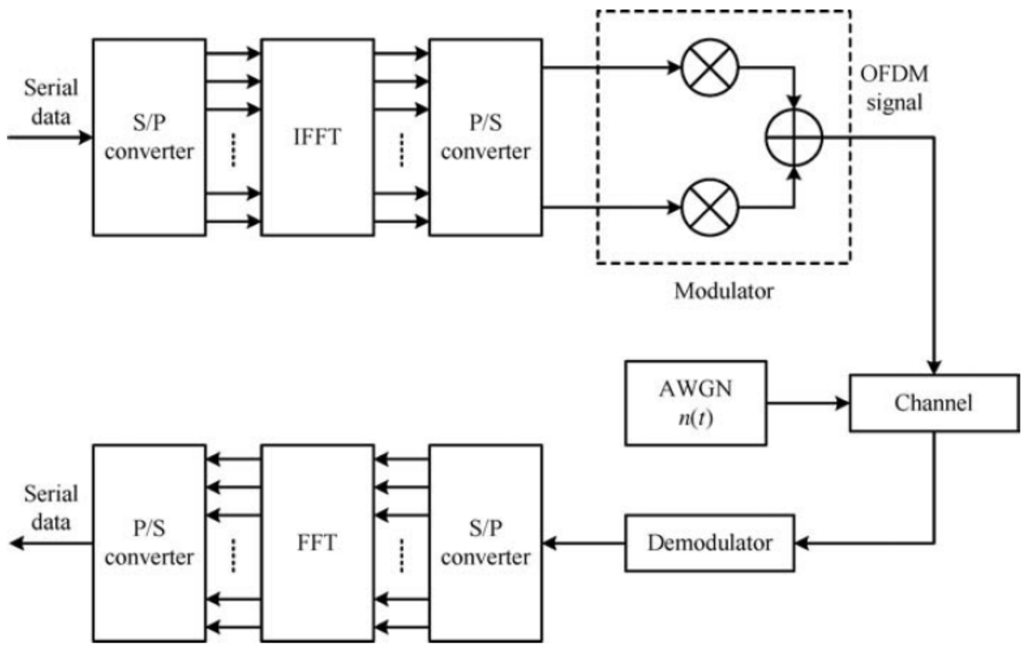


Figure 2.45. OFDM communication system

Recently, OFDM has been used by a plurality of standardization bodies for a wide range of wireless and wire line systems. Applications range from digital video/audio broadcasting to power-line communications. The attractive features of OFDM technology are summarized as follows:

1. The possibility of achieving channel capacity if the transmitted signal is adapted to the state of the wireless channel (i.e., if energy and adaptive bit-loading procedures are adopted),
2. The robustness to multi-path propagation providing a viable low-complexity and an optimal (in the maximum likelihood sense) solution for inter-symbol interference (ISI) mitigation, and
3. The availability of strategies for frequency diversity scheduling in multi-user environment.

Difference between single carrier and OFDM systems.

The single carrier transmission means one Radio Frequency carrier is used to carry the information. Hence information in the form of bits is carried by one single RF carrier. OFDM, also known as multicarrier transmission or modulation, uses multiple carrier signals at different frequencies, sending some of the bits on each channel. This is similar to FDM(Frequency Division Multiplexing) however in the case of OFDM; all of the sub channels are dedicated to a single data source. For OFDM case IFFT is used at the transmitter to accomplish this, which does not exist in Single carrier case.

Single carrier versus OFDM

As shown in the figure, single carrier (SC) system information in the form of voice or data is modulated on single RF carrier frequency. This modulated IF signal is converted to the modulated RF frequency.This is amplified using RF power amplifier before being transmitted over the air using the antenna. One carrier carry data bits based on modulation scheme employed in the modem. For BPSK 1 bit is mapped on this carrier, for QPSK 2 bits , for 16QAM 4bits and for 64QAM 16 bis and so on.

Satellite communication systems, GSM,CDMA,HF and other radio systems use single carrier for transmission and reception.

Unlike SC system, OFDM uses multiple carriers spaced very closed over the band. Each of this carriers carry data bits as per modulation scheme employed. Hence OFDM delivers data rate is higher than the SC system.OFDM technique is used in wlan and wimax broadband technologies. Its variant OFDMA is used in LTE and mobile-wimax systems.

Merits: As explained above in difference between SC and OFDM,OFDM is used to achieve high data rate over single carrier system.

De-merits: Due to multiple carriers OFDM leads to high PAPR(Peak to Average Power Ratio) To overcome PAPR scrambler(randomizer) is used in OFDM based systems which spreads the energy across wide bandwidth. There are various techniques to reduce the PAPR

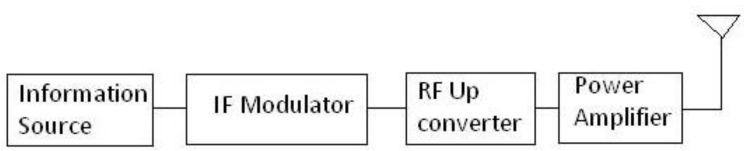


Fig.1 Single carrier system

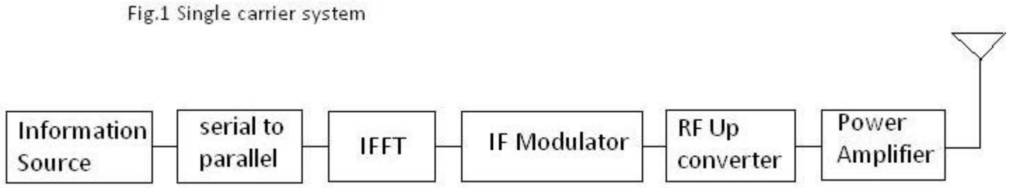


Fig. 2 OFDM based system

www.rfwireless-world.com

Some more additional Info

Modulation Techniques

Due to the relatively large amount of bandwidth available in the 60 GHz band and the propagation characteristics at these frequencies, two main usage scenarios are being considered for the introduction of broadband millimeter-wave technology to the market:

1. Directional, 'point-and-shoot' data-transfer for multi-media kiosk access and peer-to-peer communication among portable devices. For these applications a Gb/s, short distance (1–3 m) line-of-sight (LOS) link is required and the emphasis is on low cost, low complexity and low power consumption.
2. WPAN-like home or office network for high-definition video and/or data transmission. For this application, a nonline-of-sight (NLOS) link (considering radiation-absorbent objects between the receiver and transmitter) over a moderate distance (aproximately 10 m) is required. The emphasis is on robustness to multi-path signal dispersion and system throughput.

More details about specific cases of these scenarios can be found in [1]. Some different modulation options that can be considered for a Gb/s system at 60 GHz include low-complexity single-carrier systems such as on-of keying (OOK) and minimum-shift keying (MSK) [2] with clock-and-data recovery (CDR) based demodulators and higher complexity systems such as single-carrier (SC) quadrature-amplitude modulation (QAM) or multiple-carrier, orthogonal

frequency-division multiplexed (OFDM) QAM [3] with high precision A/D and complex digital-signal processing (DSP). In Sections 19.2 and 19.3, example system architectures for MSK and OFDM based systems are introduced with a discussion of their properties for each usage case. With basis on a survey of the current state-of-the-art for silicon integrated circuits, Section 19.4 presents an analysis of the HW requirements and potential power consumption for the high data-rate systems presented.

19.2 MSK-Based System for LOS Gb/s Communications

A directional channel with low time dispersion from multi-path and/or channel bandwidth limitation permits the use of a low-complexity signaling scheme to realize multiple Gb/s data rates in the 60 GHz band. MSK is an example low-complexity modulation which exhibits many desirable properties for use at these frequencies. A key advantage of this modulation is the constant envelope transmission which enables higher transmit power-amplifier (PA) efficiency compared with OOK or phase-shift-keyed based systems such as differential QPSK (DQPSK). Since no information is modulated on the carrier amplitude, a limiting receiver chain can be used, removing the need for automatic gain-control (AGC). Elimination of the need for receiver AGC enables the potential for fast, efficient packet synchronization.

The MSK signal can be demodulated using either a simple FM discriminator with a low-power clock-and-data recovery (CDR) data slicer or a higher complexity A/D + DSP approach. A block diagram of a MSK system using a FM discriminator/CDR based demodulator is shown in Figure 19.1. At the transmitter, a binary data stream modulates the phase of the 60 GHz carrier at a rate of $+\pi/2$ radians per bit period to transmit a 1 and $-\pi/2$ radians per bit period to transmit a zero. This signal is bandwidth limited, amplified and sent through a directional or otherwise low multi-path dispersion channel. At the receiver, the signal is mixed down to an IF, bandwidth limited and sent to a limiter/discriminator FM detector which produces a nonreturn-to-zero (NRZ) analog waveform. The NRZ waveform is decoded with a clock-and-data recovery slicer, avoiding the need for high-precision A/D while achieving data throughput in the Gb/s range.

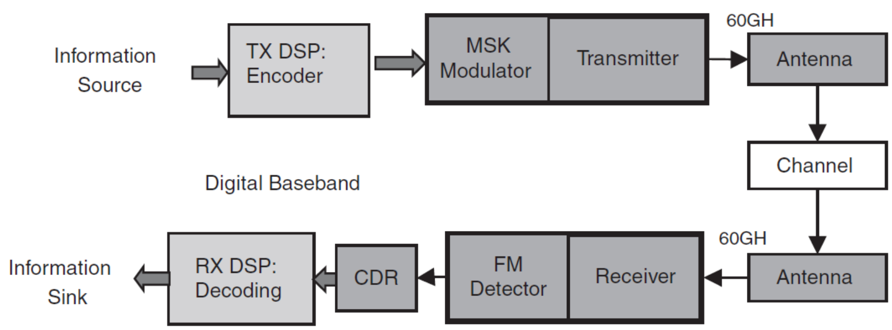


Figure 19.1 System architecture for an MSK-based system to operate in a LOS channel.

Phase noise of the local oscillator in 60 GHz systems can be an important factor to consider in defining an appropriate modulation. A straightforward FM-discriminator demodulation of MSK generates residual-FM at the output from the carrier phase noise, but a combination of data run-length encoding and high-pass filtering the discriminated output can be used to mitigate the degradation from high $1/f$ phase noise near the carrier frequency. Other differential phase SC modulations such as DQPSK or DBPSK inherently filter out the lower-frequency carrier phase noise since the low-frequency noise is common to adjacent high-speed channel symbols. A MSK based modulation can also be demodulated using A/D + DSP in conjunction with a carrier tracking loop to increase the robustness of the system against carrier phase noise.

Possible applications for the MSK system include directional point-to-point links with high-gain antennas to realize wireless point-to-point LAN bridges, and short-range (3 m), directional links to realize power-efficient high-rate modulation in portable 'point-and-shoot' application devices. Without equalization, however, this modulation is not suitable for omnidirectional or low-gain 60 GHz multi-path channels which can exhibit RMS delay spreads up to 25 ns RMS or more.

Millimeter wave radios require high power efficiency with low bit error rate (BER). Power efficiency is the ability of a modulation technique to preserve the fidelity of the digital message at low power levels. As millimeter wave power has high cost, either 64 or 256 QAM is not preferable due to the effect of phase noise and power consumption of the power amplifier (PA). In addition, receiver cost or complexity should also be considered, especially in multiple-input-multiple-output systems as mentioned in

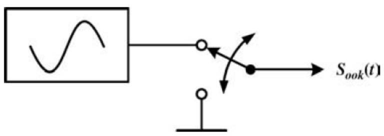


Figure 2.1. System diagram of OOK

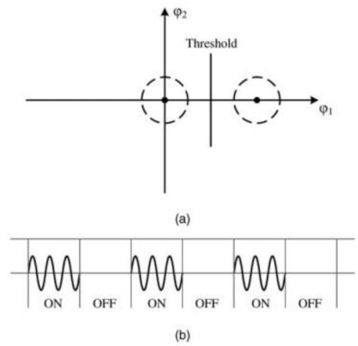


Figure 2.2. (a) OOK signal diagram, (b) OOK signal

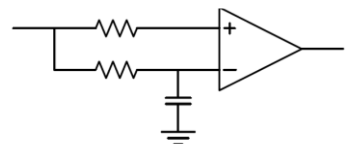


Figure 2.3. OOK receiver

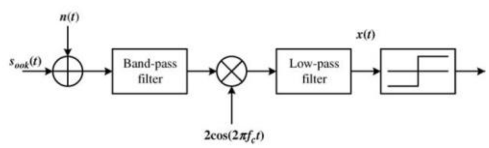


Figure 2.4. Block diagram of synchronous demodulation

2.1 ON/OFF KEYING (OOK)

On/off keying (OOK) modulation is a modulation scheme used in control applications. This is in part due to its simplicity and low implementation costs. OOK consists of keying a sinusoidal carrier signal on and off with a unipolar binary signal. OOK is equivalent to two-level ASK. The system diagram of OOK is shown in Figure 2.1. OOK modulation has the advantage of allowing the transmitter to idle during the transmission of a "0", therefore conserving power. Here input signal has two states ("1" and "0") and modulation factor is 100% (from full power to no transmitted power).

The disadvantage of OOK modulation arises in the presence of an undesired signal. The modulated signals can be graphically represented on a two-dimensional orthogonal plot, sometimes referred to as a signal diagram. Consider a set of two basis vectors φ_1 and φ_2. The signal diagrams for OOK are shown in Figure 2.2.

The idea of OOK is that the transmitter is on when logic "1" is transmitted and the transmitter is off when logic "0" is transmitted. OOK receivers require an adaptable threshold and automatic gain controller (AGC) in order to ensure an optimal threshold setting. A logarithm amplifier detector with an averaging bit slicer is employed, as shown in Figure 2.3. This circuit will ensure that the threshold is set between the signal levels of a "0" and a "1" transmission. The above circuit works well as long as the data received is effectively D.C. balanced.

There are two types of demodulation method, namely synchronous demodulation and envelope demodulation.

Synchronous demodulation is also known as coherent demodulation, and the block diagram is shown in Figure 2.4. As shown in Figure 2.4, the coherent carrier for demodulation is $2\cos(2\pi f_c t)$, where the amplitude factor of "2" used here is for calculation convenience, and f_c is the carrier frequency used for the generation of OOK signal. During the following analysis, the carrier phases of the transmitter and receiver are assumed to be the same and they are dropped for notational convenience.

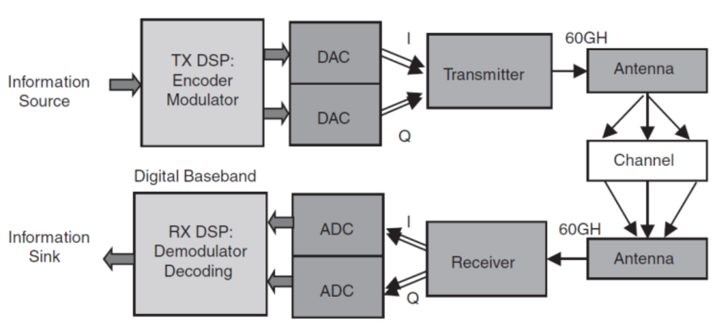


Figure 19.2 System architecture for an OFDM-based system to operate in a NLOS channel.

19.3 OFDM-Based System for NLOS Gb/s Communications

A nondirectional or multi-path channel presents a significant challenge in realizing a robust multi-Gb/s data rate system at 60 GHz. Due to the high channel symbol rate required for data rates in the range 2 Gb/s and above, channel dispersion from multi-path must be addressed by either employing a multi-carrier modulation (OFDM), or using a SC modulation with direct-sequence spread-spectrum (DS-SS) RAKE receiver and/or a powerful multi-path equalizer in the receiver. Since OFDM is already in widespread use at 2.4/5 GHz and in UWB standards, it is considered here for use in 60 GHz broadband NLOS systems also. The primary benefit OFDM brings is reduction of the subchannel symbol rate to a point that the channel delay spread is an acceptable fraction of the symbol period to enable reliable data decoding. However, the OFDM modulation can introduce a significant degradation in PA efficiency, since peak/average power ratio for systems employing 64 subchannels and above can exceed 10 dB. Reduction of the peak/average power through coding or other approaches is a key challenge for deployment of OFDM at 60 GHz where it is difficult to realize high transmitter power.

A high-level block diagram of an OFDM-based 60 GHz system is shown in Figure 19.2. The system requires high rate D/A and A/D (in the range of 1–2 Gs/s) with a FFT-based digital modulator and IDFT based demodulator. Although high rate D/A could be realized with relatively low power and complexity, the A/D presents a challenge since it requires 5–8 bits at a sampling rate in the range of 2 Gs/s to realize 2 Gb/s data rate systems. Although Nyquist sampling ($1 \times$ oversample) can be used to reduce A/D rate, elimination of oversampling reduces the ability of the OFDM system to filter away adjacent channel interference in the demodulator.

Packet synchronization is also an important issue in a broadband OFDM system employing time-division multiple-access protocol. Since the modulation is linear, the receiver must be given time to detect and apply automatic-gain-control (AGC) to the received signal without reducing the maximum throughput of the system significantly. Longer data slots can be used to mitigate this synchronization overhead problem, but may require that the OFDM demodulator implement a time drift tracking algorithm over the longer slot duration to minimize sample error degradation arising from asynchronous transmitter and receiver reference clocks.

Local oscillator phase noise is an important consideration in the design of 60 GHz OFDM systems. Although use of a larger number of subchannels can increase multi-path resistance, the LO phase noise eventually limits performance due to spectral smearing of the subchannels by the phase noise, and the inability to track phase noise at slow subchannel symbol rates. All OFDM demodulators must implement a coherent carrier phase recovery/tracking loop. Use of a lower number of subchannels enables the carrier tracking loop bandwidth to be higher, increasing the tolerance to LO phase noise. Phase noise also directly limits use of high-density QAM constellations in the subcarriers. As an example, a system phase noise level of approximately -90 dBc/Hz or lower at 1 MHz offset is needed to realize 16-QAM OFDM with 512 subchannels supporting a data rate in the range of 2 Gb/s.

A typical high-performance OFDM system employs frequency-domain symbol interleaving and forward-error correction (FEC) coding detected at the receiver with a soft-decision Viterbi algorithm (VA) decoder. Realization of the VA at the receiver is a large challenge for data rates in the 2 Gb/s range. Therefore, alternate coding methods which are robust to subchannel fading while providing lower computational overhead are of interest for development of 60 GHz OFDM based systems.

Applications for the OFDM system include channels with the potential for significant time dispersion from multi-path, including single-bounce delays which can introduce a deep notch in the frequency domain. The OFDM based modulation adds no benefit in a line-of-sight link, and in fact will not perform as well as SC based modulations for these applications due to its higher peak/average power (resulting in lower average power transmission for OFDM) and higher susceptibility to LO phase noise at 60 GHz.