

Module 5

Carrier Modulation

Lesson 22

Introduction to Carrier Modulation

After reading this lesson, you will learn about

- *Basic concepts of Narrowband Modulation;*
- *BER and SER;*
- *CNR and $\frac{E_b}{N_0}$;*
- *Performance Requirements;*
- *Coherent and Non-Coherent Demodulation;*

In the previous module, we learnt about representing information symbols in suitable signal forms. We used the concepts of orthonormal basis functions to represent information-carrying energy-signals. However, we did not discuss how to prepare the signals further, so that we can transmit information over a large distance with minimal transmission power and very importantly, within a specified frequency band. You may know that well-chosen carriers are used for signal transmission over free space. It is also a common knowledge that sinusoids are used popularly as carriers of message or information.

In fact, the sinusoids can be generated easily and the orthogonality between a sine and a cosine carriers of the same frequency can be exploited to prepare or ‘modulate’ information bearing signals so that the information can be received reliably at a distant receiver. In this module, we will discuss about a few basic yet interesting and popular digital modulation schemes, using sinusoids as carriers. The concepts of Gram-Schmidt Orthogonalization (GSO) are likely to help us, gaining insight into these modulation schemes. The issues of carrier synchronization, which is important for implementing a correlation receiver structure, will also be discussed in this module.

The present lesson will discuss about a few ways to classify digital modulation techniques. We will also introduce some general issues, relevant for appreciating the concepts of digital modulations.

Narrowband Modulation

A modulation scheme is normally categorized as either a narrowband modulation or a wideband modulation. For a linear, time invariant channel model with additive Gaussian noise, if the transmission bandwidth of the carrier-modulated signal is small (typically less than 10%) compared to the carrier frequency, the modulation technique is called a narrowband one. It is easier to describe a narrowband modulation scheme and its performance compared to a wideband modulation scheme, where the bandwidth of the modulated signal may be of the order of the carrier frequency. We will mostly discuss about narrowband digital modulation schemes. Our earlier discussion (Module #4) on equivalent lowpass representation of narrow band pass signals will be useful in this context.

Bandwidth efficient and power efficient modulation schemes

Modulation schemes for digital transmission systems are also categorized as either a) bandwidth efficient or b) power efficient. Bandwidth efficiency means that a modulation scheme (e.g. 8-PSK) is able to accommodate more information (measured in bits/sec) per unit (Hz) transmission bandwidth. Bandwidth efficient modulation schemes are preferred more in digital terrestrial microwave radios, satellite communications and cellular telephony. Power efficiency means the ability of a modulation scheme to reliably send information at low energy per information bit. Some cellular telephony systems and some frequency-hopping spread spectrum communication systems (spread-spectrum systems are wideband type) operate on power-efficient modulation schemes. **Table 5.22.1** names a few digital modulation schemes and some applications. **Table 5.22.2** shows the bandwidth efficiency limits for the modulation techniques.

Some Digital Modulation Schemes	Representative Applications
Binary Phase Shift Keying (BPSK)	Telemetry and telecommand
Quaternary Phase Shift Keying (QPSK)	Satellite, Cellular telephony, Digital Video Broadcasting
Octal Phase Shift Keying (8-PSK)	Satellite communications
16-point Quadrature Amplitude Modulation (16-QAM) / 32 QAM	Digital Video Broadcasting, Microwave digital radio links
64-point Quadrature Amplitude Modulation (64-QAM)	Digital Video Broadcasting, MMDS, Set Top Boxes
Frequency Shift Keying (FSK)	Cordless telephony, Paging services
Minimum Shift Keying (MSK)	Cellular Telephony

Table 5.22.1: Typical applications of some digital modulation schemes

Modulation Scheme	Bandwidth Efficiency (in bits/second/Hz)
Binary Phase Shift Keying (BPSK)	1
Quaternary Phase Shift Keying (QPSK)	2
Octal Phase Shift Keying (8-PSK)	3
16-point Quadrature Amplitude Modulation (16-QAM)	4
32-point Quadrature Amplitude Modulation (32- QAM)	5
256-point Quadrature Amplitude Modulation (256-QAM)	8
Minimum Shift Keying (MSK)	1

Table 5.22.2: Bandwidth efficiency for a few digital modulation schemes

BER and SER

The acronym '**BER**' stands for Bit Error Rate. It is a widely used measure to indicate the quality of information, delivered to the receiving end-user. It is defined as the ratio of total number of bits received in error and the total number of bits received over a fairly large session of information transmission. It is an average figure. It is commonly assumed that the same number of bits is received as has been transmitted from the source. BER is a system-level performance. It is an indication of how good a digital communication system has been designed to perform. It also indicates the quality of service the users of a communication system should expect. As we have noted earlier in Module #2, no practical digital communication system ensures zero BER. Interestingly, it is usually sufficient if a system can ensure a BER below an 'acceptable' level. For example, the accepted BER for toll-quality telephone grade speech signal over land-line telephone system is 10^{-5} , while for second generation cellular telephone systems, the BER is usually less than 10^{-3} only. It is a costlier proposition to expect a BER similar to that enjoyed in landline telephone system because the wireless links in a typical mobile telephone system suffers from signal fading. The acceptable BER values are dependent on the type of information. For example, a BER of 10^{-5} is acceptable for speech signal but is too bad and unacceptable for data service. The BER should be less than 10^{-7} .

'**SER**' stands for Symbol Error Rate. It is also an average figure used to describe the performance of a digital transmission scheme. It is defined as the ratio of total number of symbols detected erroneously in the demodulator and the total number of symbols received by the receiver over a fairly large session of information transmission. Again it is assumed that the same number of symbols is received as has been transmitted by the modulator. Note that this parameter is not necessarily of ultimate interest to the end-users but is important for a communication system designer.

$$\text{CNR and } \frac{E_b}{N_0}$$

Let,

Rate of arrival of information symbols at the input of a modulator = R_s symbols/sec.

Number of different symbols = $M = 2^m$,

Equivalent number of bits grouped to define an information symbol = m

Duration of one symbol = T_s second

Corresponding duration of one bit = $T_b = \frac{T_s}{m}$ second

Double-sided noise power spectral density at the input of an ideal noiseless receiver = $\frac{N_0}{2}$ Watt/Hz

Transmission bandwidth (in the positive frequency region) = B_T Hz

So, the total in-band noise power = N Watt = $\frac{N_0}{2} \cdot (2 \times B_T) = N_0 \cdot B_T$ Watt.

We assume that the transmission bandwidth is decided primarily by the modulation scheme. Let us also assume that total signal power received at the receiver input = C Watt. For many digital modulation schemes, this power is distributed over the transmission bandwidth of the modulated signal. The carrier frequency may not always show up in the modulated signal. However, when no modulating data is present, the unmodulated carrier shows up at the receiver with the same power of 'C Watt'.

The ratio of 'C' and the in-band noise power 'N', i.e. $\frac{C}{N}$ is known as the 'carrier to noise power ratio' (CNR). This is a dimensionless quantity. It is often expressed in decibel as:

$$\text{CNR}|_{dB} = 10 \cdot \log_{10} \left(\frac{C}{N} \right) \quad 5.22.1$$

Let, $\overline{E_s}$ = Energy received on an average per symbol (Joule).

So, the received power can be expressed as,

$$C = \overline{E_s} \cdot R_s = \frac{\overline{E_s}}{T_s} \quad 5.22.2$$

If E_b represents the energy (Joule) received per information bit, $\overline{E_s} = m \cdot E_b$.

Let us now consider another important performance parameter E_b/N_0 , defined as:

$$\frac{E_b}{N_0} = \frac{\text{Energy received per information bit}}{\text{one sided power spectral density of in - band noise}} \quad 5.22.3$$

This is a dimensionless parameter and is often expressed in dB:

$$(E_b/N_0) |_{dB} = 10 \cdot \log_{10} \left(\frac{E_b}{N_0} \right) \quad 5.22.4$$

It should be easy to guess that the CNR and the E_b/N_0 are related.

$$\frac{C}{N} = \frac{C}{N_0 B_T} = \frac{m E_b / T_s}{N_0 B_T} = \left(\frac{E_b}{N_0} \right) \cdot \left(\frac{m}{B_T T_s} \right) \quad 5.22.5$$

If the concept of Nyquist filtering with zero-ISI is followed,

$$B_T = \frac{R_s}{2} = \frac{1}{2T_s}$$

and hence, $\frac{C}{N} = (2 \cdot m) \cdot \left(\frac{E_b}{N_0} \right)$

In logarithmic scale,

$$\text{CNR}|_{\text{dB}} = \left(\frac{E_b}{N_0} \right) \Big|_{\text{dB}} + 10 \cdot \log_{10}(2m) \quad 5.22.6$$

Performance Requirements

Selection of a modulation scheme for an application is not always straightforward. Following are some preferable requirements from a digital transmission system:

- a) Very high data rate should be supported between the end users
- b) Signal transmission should take place over least transmission bandwidth
- c) BER should be well within the specified limit
- d) Minimum transmission power should be used
- e) A digital transmission system should not cause interference beyond specified limit and in turn should also be immune to interference from other potential transmission systems
- f) The system should be cost-competitive

Some of the above requirements are conflicting in nature and a communication system designer attempt a good compromise of the specified requirements by trading off available design parameters.

I/Q Modulation format

A narrowband digital modulation scheme is often expressed in terms of in-phase signal component (I-signal) and quadrature signal component (Q-signal). This approach is especially suitable for describing 2-dimensional modulation schemes and also for their digital implementation. The signal space describing the modulation format is often referred as I/Q diagrams. Often the two independent signals in I and Q exhibit similar statistical properties and can be generated and processed with similar circuitry.

Coherent and non-coherent Demodulation

The approach of correlation receiver calls for ‘coherent’ demodulation scheme where the carrier references are recovered precisely from the received signal and then used for correlation detection of symbols. This approach ensures best (near-optimal) performance, though may be costly for some modulation schemes. We will primarily discuss about coherent demodulation schemes. A non-coherent demodulation scheme does not require precise carrier reference in the receiver and hence is usually of lower-complexity. Performance is expectedly poorer compared to the corresponding coherent demodulation strategy. We will discuss later about non-coherent demodulation strategy for binary phase shift keying (BPSK) modulation.

Power Spectra of N-B modulated signal

A narrowband carrier modulated signal can be expressed in general as:

$$\begin{aligned} s(t) &= u_I(t) \cos w_c t - u_Q(t) \sin w_c t \\ &= R_e \left[\tilde{u}(t) e^{jw_c t} \right], \end{aligned} \quad 5.22.7$$

Where $\tilde{u}(t) = u_I(t) + ju_Q(t)$. is the lowpass complex equivalent of the real band pass signal $s(t)$.

Let, $U_B(f)$ denote the power spectrum of the complex low pass equivalent signal. For example, we have earlier seen (also see **Fig. 5.22.1**) that for a random binary sequence, the power spectral density is of the form: $U_B(f) = 2E_b \cdot \text{sinc}^2(T_b f)$

Now, the power spectrum $S(f)$ of the modulated signal is expressed in terms of $U_B(f)$ as:

$$S(f) = \frac{1}{4} [U_B(f - f_c) + U_B(f + f_c)] \quad 5.22.8$$

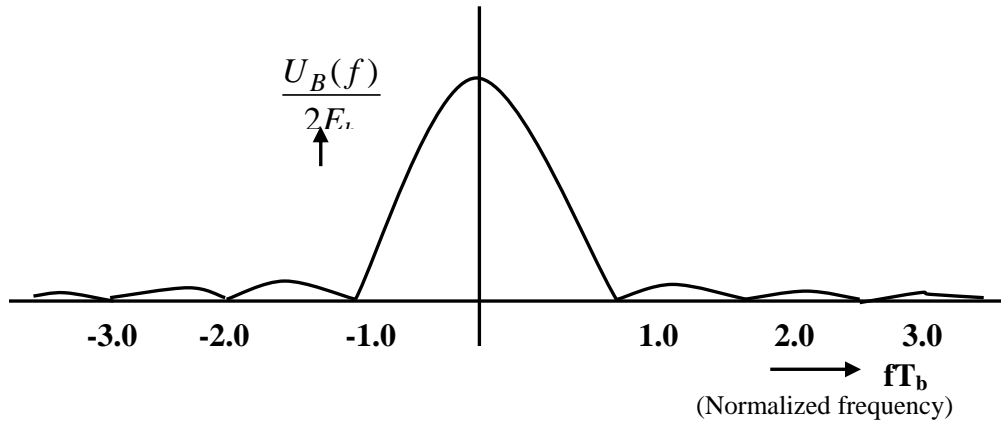


Fig. 5.22.1 Sketch of power spectrum of a random binary sequence

It is a good practice and usually simpler to determine $U_B(f)$ and then obtain the desired form of $S(f)$. Towards a general approach, let us introduce a pulse or symbol shaping function $g(t)$, also known as ‘weighting function’ which, on application to a rectangular time pulse, generates the $u_I(t)$ and $u_Q(t)$. Then we make use of our knowledge of the spectrum of a random sequence of rectangular pulses. As earlier, we assume that all symbols are equally likely at the input to the modulator. The procedure for determining the power spectrum $S(f)$ is summarized below:

- Consider a narrowband modulation scheme
- Identify the shaping pulse $g(t)$, $0 \leq t \leq T_s$

- c) Determine the energy spectral density of $g(t)$
- d) Determine the power spectra of $U_I(t)$ and $U_Q(t)$
- e) Construct $U_B(f)$ and $S(f)$

Problems

- Q5.22.1) What is an acceptable BER for speech signal?
- Q5.22.2) If a modulation scheme has 30 different symbols & if the $\frac{E_b}{N_o}$ is 8 dB at the demodulator, determine the CNR at the receiver.
- Q5.22.3) Mention four performance metrics for a good digital modulation scheme.
- Q5.22.4) Does the narrow band power spectrum of a real band pass signal describe the signal completely?
- Q5.22.5) Mention two applications of QAM scheme.
- Q5.22.6) Mention two bandwidth efficient modulation schemes.