5730.26 Tráðleyst samskifti V26
Notes

Contents

1 Lecture 1

1.1 Signal and Noise

1.1.1 Material Reference

The material in this lecture is primarily based on:

TSE Book

- Chapter 1 (Sections 1.1 and 1.2): Overview of wireless communication
- Appendix A.1: Gaussian random variables
- Appendix A.2: Signal detection in Gaussian noise

Haykin

- Chapter 2.2 (pp. 8–14)
- Chapter 2.8 (pp. 47–55)

This lecture establishes the physical and mathematical foundations required for analyzing wireless communication systems.

1.2 Fundamental Quantities and Signal Representation

Wireless communication systems operate by transmitting electrical signals that carry information. Two fundamental physical quantities describe these signals:

Voltage is the electrical potential difference (measured in volts), while **Power** is the rate at which energy is transferred (measured in watts).

In a resistive system with resistance R, instantaneous power is

$$P(t) = \frac{v^2(t)}{R}.$$

Because power depends on the square of voltage, small voltage variations can produce large power differences. This quadratic relationship is one reason why wireless systems are analyzed primarily in terms of power rather than voltage.

Wireless signals operate at high frequencies, ranging from kilohertz to gigahertz. Higher frequencies allow:

- Higher data rates
- Smaller antenna sizes
- Greater available bandwidth

However, high frequencies also suffer from:

- Increased path loss
- Stronger attenuation

- Greater susceptibility to noise

Therefore, the **signal-to-noise ratio (SNR)** becomes a central performance metric:

$$\mathrm{SNR} = \frac{P_s}{P_n}.$$

1.3 Noise and the AWGN Model

In any realistic wireless system, the received signal is corrupted by noise. The most important noise source is thermal noise, generated by random electron motion in conductors.

Thermal noise is accurately modeled as **Additive White Gaussian Noise (AWGN)**.

It is:

- **Additive** – it adds to the signal
- **White** – constant power spectral density
- **Gaussian** – normally distributed amplitude

The received signal model becomes:

$$y(t) = x(t) + n(t).$$

This simple model underpins almost all digital communication theory.

1.4 Power in dBm and Logarithmic Representation

Because wireless power levels span many orders of magnitude, logarithmic units are used.

Absolute power in dBm:

$$P_{\mathrm{dBm}} = 10 \log_{10} \left(\frac{P}{1\,\mathrm{mW}} \right).$$

Power ratios are expressed in dB:

$$G_{\mathrm{dB}} = 10 \log_{10} \left(\frac{P_{\mathrm{out}}}{P_{\mathrm{in}}} \right).$$

Important distinction:

- dB $\rightarrow$ ratio
- dBm $\rightarrow$ absolute power

Logarithmic representation simplifies link budget calculations because gains and losses can be added directly.

1.5 Logarithmic Identities

Wireless analysis frequently requires converting between linear and logarithmic domains.

$$\log_{10}(ab) = \log_{10}(a) + \log_{10}(b)$$

$$\log_{10}\left(\frac{a}{b}\right) = \log_{10}(a) - \log_{10}(b)$$

$$\log_{10}(a^n) = n\log_{10}(a)$$

For information theory:

$$\log_2(ab) = \log_2(a) + \log_2(b)$$

Base-2 logarithms naturally arise when measuring information in bits.

1.6 Signal Composition and Spectral Interpretation

Signals may consist of multiple sinusoidal components. For example:

$$x(t) = 2\sin(t) + \sin(5t).$$

This represents a superposition of two frequency components. According to Fourier theory, any physically realizable signal can be decomposed into sinusoids.

This decomposition allows:

- Frequency-domain analysis
- Filter design
- Bandwidth estimation

1.7 Filters and Frequency Selectivity

Filters shape signals in the frequency domain.

A low-pass filter allows frequencies below a cutoff frequency to pass.

A high-pass filter allows frequencies above the cutoff frequency.

Band-pass and notch filters similarly allow or suppress selected frequency regions.

1.8 Link Budget Analysis

A link budget accounts for all gains and losses between transmitter and receiver:

$$P_{\text{rx}} = P_{\text{tx}} + G_{\text{tx}} + G_{\text{rx}} - L_{\text{path}} - L_{\text{other}}.$$

All terms must be expressed consistently in dB or dBm.

This equation allows prediction of whether a communication link will close.

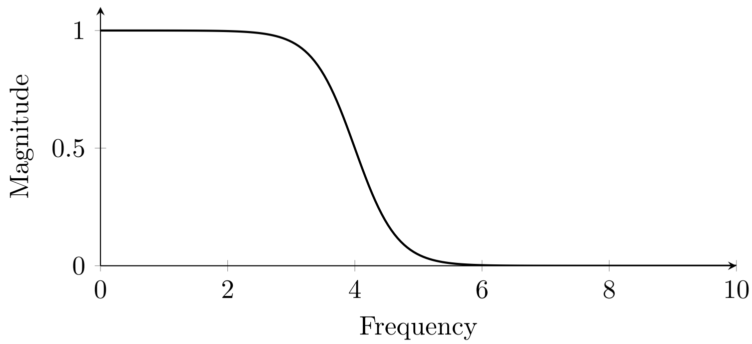


Figure 1: Low-pass filter magnitude response

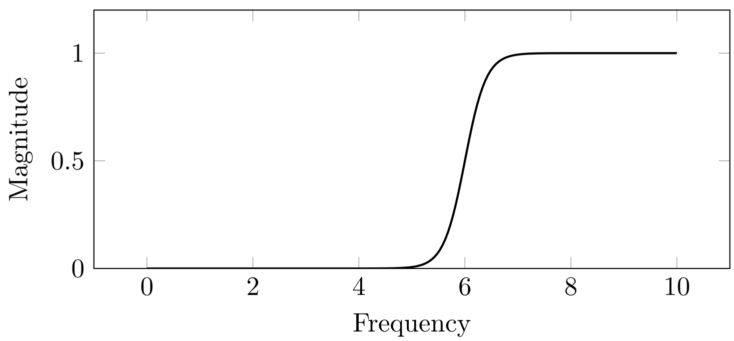


Figure 2: High-pass filter magnitude response

1.9 Thermal Noise, Temperature, and Bandwidth

Thermal noise power in linear units:

$$P_n = k_B T B$$

where:

- k_B = Boltzmann constant
- T = absolute temperature
- B = bandwidth

At room temperature:

$$N_0 \approx -174 \text{ dBm/Hz}.$$

Total noise power:

$$P_n = -174 + 10 \log_{10}(B).$$

Increasing bandwidth increases noise power linearly.

1.10 Shannon Capacity and Fundamental Limits

The maximum achievable data rate is:

$$C = B \log_2(1 + \gamma),$$

where

$$\gamma = \frac{P_s}{P_n}.$$

Key insight:
Capacity increases logarithmically with SNR. Doubling power does not double capacity.

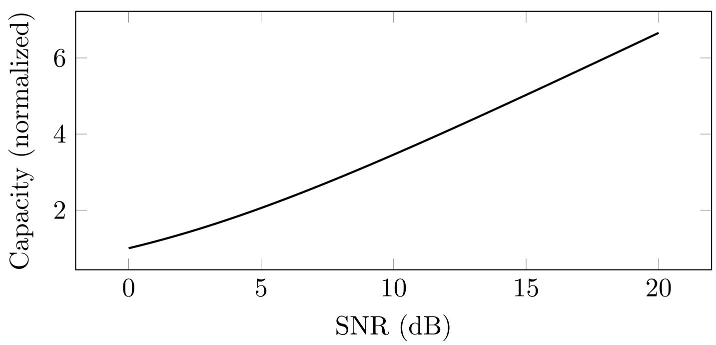


Figure 3: Logarithmic growth of capacity with SNR

1.11 Energy per Bit and BER

Digital systems are commonly analyzed using:

$$\frac{E_b}{N_0}$$

where:

- E_b = energy per bit
- N_0 = noise spectral density

The **Bit Error Rate (BER)** is the probability that a transmitted bit is incorrectly detected.
Higher E_b/N_0 reduces BER.
This metric allows comparison of modulation schemes independent of bandwidth.

2 Lecture 2

2.1 Modulation

In practical wireless systems, information cannot be transmitted directly at baseband over long distances. Antennas are physically inefficient at very low frequencies, and multiple users cannot share the spectrum effectively without frequency separation.

For this reason, a baseband message signal $m(t)$ is shifted to a higher frequency using a carrier wave of frequency f_c. This process is known as modulation.

The simplest modulation process multiplies the baseband signal by a cosine carrier:

$$s(t) = m(t)\cos(2\pi f_c t).$$

Here, f_c is called the carrier frequency, and it determines where the transmitted signal appears in the frequency spectrum.

Modulation therefore performs two key roles:

1. Enables practical radiation through antennas.

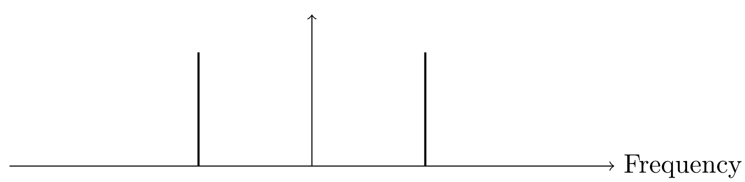
2. Allows multiple signals to coexist at different carrier frequencies.

2.2 Baseband and Bandpass Signals

A baseband signal is centered around 0 Hz in the frequency domain. Its spectrum extends from $-B$ to B, where B is the bandwidth of the signal.

After modulation, the signal becomes a bandpass signal whose spectrum is centered at f_c.

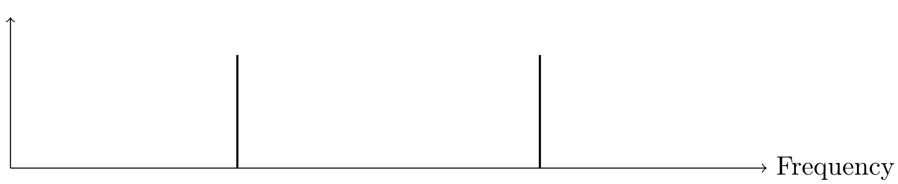
Baseband Spectrum



0 Hz

Baseband

Bandpass Spectrum



f_c

Bandpass

The bandwidth of the bandpass signal remains:

$$B = f_H - f_L.$$

A fundamental efficiency metric is spectral efficiency:

$$\eta = \frac{R_b}{B}.$$

This measures how efficiently bandwidth is used to transmit information.

2.3 Amplitude Modulation (AM)

In amplitude modulation, the amplitude of the carrier is varied proportionally to the message signal:

$$s(t) = A_c[1 + k_a m(t)] \cos(2\pi f_c t).$$

The quantity k_a controls how strongly the message influences the carrier amplitude.

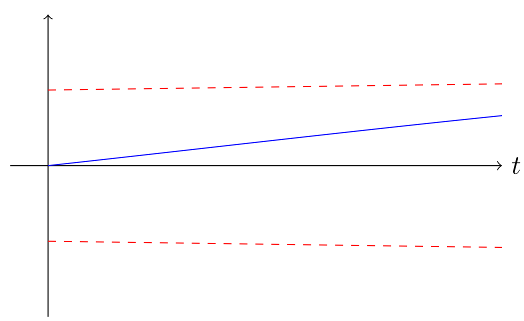
The modulation index is:

$$\mu = k_a \max |m(t)|.$$

If $\mu > 1$, the envelope crosses zero, causing overmodulation and distortion.

AM is simple to implement but inefficient in power because a large portion of transmitted energy resides in the carrier.

AM Envelope



2.4 Double Sideband Suppressed Carrier (DSB-SC)

If the carrier is removed and only the product $m(t) \cos(2\pi f_c t)$ is transmitted, the scheme is called DSB-SC.

$$s(t) = m(t) \cos(2\pi f_c t).$$

The resulting spectrum consists of two shifted copies of the baseband spectrum, producing bandwidth:

$$B_{DSB} = 2B.$$

This improves power efficiency but still occupies twice the baseband bandwidth.

2.5 Frequency Modulation (FM)

In frequency modulation, information is conveyed by varying the instantaneous frequency of the carrier:

$$s(t) = A_c \cos\left(2\pi f_c t + 2\pi k_f \int m(t)dt\right).$$

The peak frequency deviation is:

$$\Delta f = k_f A_m.$$

Unlike AM, FM has constant amplitude, making it more resistant to noise.

Practical bandwidth is estimated using Carson's rule:

$$B_{FM} = 2(\Delta f + B).$$

This shows that FM bandwidth increases with deviation.

2.6 Phase Modulation (PM)

In phase modulation, the carrier phase varies directly with the message:

$$s(t) = A_c \cos(2\pi f_c t + k_p m(t)).$$

FM and PM are closely related. Both belong to the class of angle modulation schemes.

2.7 Complex Baseband Representation

Bandpass signals can be expressed using complex notation:

$$s(t) = I(t) + jQ(t) = Ae^{j\theta}.$$

This representation simplifies analysis and forms the foundation of digital modulation techniques.

Symbols are transmitted over finite intervals:

$$R_s = \frac{1}{T_s}.$$

If M symbols are used:

$$R_b = R_s \log_2 M.$$

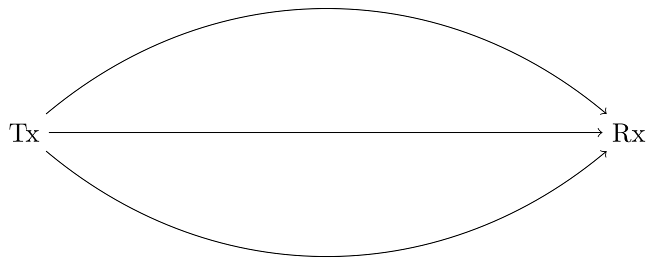
Higher M increases data rate but reduces noise tolerance.

2.8 Multipath Propagation

Wireless signals rarely follow a single direct path. Instead, reflections from buildings, ground, and objects create multiple delayed copies of the signal.

This leads to:

- Inter-Symbol Interference (ISI)
- Fading



2.9 Free Space Propagation Model (Exam Important)

In ideal free space:

$$P_r = P_t \left(\frac{\lambda}{4\pi d} \right)^2 .$$

Since $\lambda = \frac{c}{f_c}$, higher carrier frequencies produce greater path loss.

Received power decays proportionally to:

$$d^2.$$

This quadratic decay is fundamental in link budget design.

2.10 Duplexing

Communication may occur in one or both directions:

Simplex allows one-way communication.

Half-duplex allows two-way communication, but not simultaneously.

Full-duplex allows simultaneous transmission and reception.

2.11 Multiple Access Techniques

To allow multiple users to share limited spectrum, several strategies are used.

FDMA separates users in frequency.

TDMA separates users in time.

CDMA separates users using orthogonal codes:

$$s(t) = m(t)c(t).$$

Modern systems use OFDM and OFDMA to dynamically allocate subcarriers.

2.12 Path Loss Model

Real environments are more complex than free space. A general empirical model is:

$$PL(d) = PL(d_0) + 10n \log_{10} \left(\frac{d}{d_0} \right).$$

The exponent n depends on the environment.

2.13 Channel Behavior

Wireless channels may be: Line-of-sight (LOS), where a direct path exists. Time-invariant, where channel conditions remain stable. Time-variant, where motion causes fading and Doppler effects. Understanding channel behavior is essential for robust system design.