Chapter 1
Introduction
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The subject of digital communications involves the transmission of information in digital form from a source that generates the information to one or more destinations.

Of particular importance in the analysis and design of communication systems are the characteristics of the physical channels through which the information is transmitted.

The characteristics of the channel generally affect the design of the basic building blocks of the communication system.
1.1 Elements of A Digital Communications System
1.2 Communication Channels and Their Characteristics

- Physical channels:
  - A pair of *wires* that carry the electrical signal;
  - An *optical fiber* that carries the information on a modulated light beam;
  - An *underwater ocean channel* in which the information is transmitted acoustically;
  - *Free space* over which the information-bearing signal is radiated by use of an antenna;
  - *Data storage media*, such as magnetic tape, magnetic disks, and optical disks.
1.2 Communication Channels and Their Characteristics

Problems in signal transmission through channels:

- *Thermal noise*: generated internally by components such as resistors and solid-state devices.
- *External noise* and *interference* from other users.
- *Signal attenuation*.
- *Amplitude and phase distortion*.
- *Multi-path distortion*.

Two limitations constrain the amount of data that can be transmitted reliably over any communication channel:

- Power.
- Available channel bandwidth.
Wire-line channels

- *Twisted-pair* wire lines are generally used to connect a customer to a central office with a bandwidth of about 4 kHz.
  - Prone to cross talk interference from physically adjacent channels.
- *Coaxial cable* has a usable bandwidth of several megahertz (MHz).

 Signals transmitted through wireline channels are distorted in both amplitude and phase and further corrupted by additive noise.
1.2 Communication Channels and Their Characteristics
Fiber-optic channels

- Optical fibers offer the communication system designer a channel bandwidth that is several orders of magnitude larger than coaxial cable channels.
- During the past two decades, optical fiber cables have been developed that have a relatively low signal attenuation, and highly reliable photonic devices have been developed for signal generation and signal detection.
- The transmitter or modulator in a fiber-optic communication system is a light source, either a light-emitting diode (LED) or a laser.
- Information is transmitted by varying the intensity of the light source with the message signal.
Fiber-optic channels (cont.)

- The light propagates through the fiber as a light wave and is amplified periodically along the transmission path to compensate for signal attenuation.
- In the case of digital transmission, light is detected and regenerated by *repeaters.*
- At the receiver, the light intensity is detected by a *photodiode,* whose output is an electrical signal that varies in direct proportion to the power of the light impinging on the photodiode.
Wireless electromagnetic channels

Electromagnetic energy is coupled to the propagation medium by an antenna which depends primarily on the frequency of operation.

The physical size and the configuration of the antenna depend primarily on the frequency of operation.

To obtain efficient radiation of electromagnetic energy, the antenna must be longer than $1/10$ of the wavelength.

The mode of propagation of electromagnetic waves in the atmosphere and in free space may be subdivided into three categories:

- Ground-wave propagation;
- Sky-wave propagation;
- Line-of-sight (LOS) propagation.
1.2 Communication Channels and Their Characteristics

Why the available channel bandwidth is limited?
1.2 Communication Channels and Their Characteristics

- **VLF and Audio Band**
  - In the very low frequency (VLF) and audio frequency bands, where the wavelengths exceed 10 km, the earth and the ionosphere (電離層) act as a wave guide for electromagnetic wave propagation.
  - Communication signals practically propagate around the globe and, as a result, these frequency bands are primarily used to provide navigational aids from shore to ships around the world.
  - Channel bandwidths are relatively small and information is generally confined to digital transmission.
  - A dominant type of noise is generated from thunderstorm activity around the globe.
1.2 Communication Channels and Their Characteristics

- **Ground-wave propagation**
  - The dominant mode of propagation for frequencies in the medium frequency (MF) band (0.3 – 3 MHz).
  - Used for AM broadcasting and maritime radio broadcasting.
  - In AM broadcasting, the range is limited to about 150 km.
Sky-wave propagation

- Transmitted signal being reflected from the ionosphere, which consists of several layers of charged particles ranging in altitude from 50 to 400 km above the surface of the earth.
- A frequently occurring problem in the high frequency (HF) range is signal multi-path, which results in inter-symbol interference and signal fading.
Sky-wave propagation (cont.)

During the daytime hours, the heating of the lower atmosphere by the sun causes the formation of the lower layers at altitudes below 120 km.

These lower layers, especially the D-layer, serve to absorb frequencies below 2MHz, thus severely limiting sky-wave propagation of AM radio broadcast.

During the nighttime hours, the electron density in the lower layers of the ionosphere drops sharply and the frequency absorption that occurs during the day time is significantly reduced.

Powerful AM radio broadcast stations can propagate over large distances via sky wave over the F-layer of the ionosphere, which ranges from 140 to 400 km above the surface of the earth.
Sky-wave propagation (cont.)

- Sky-wave ionospheric propagation ceases to exist at frequencies above approximately 30 MHz, which is the end of HF band.
- It is possible to have ionospheric scatter propagation at frequencies in the range 30-60 MHz, resulting from signal scattering from the lower ionosphere.
- It is also possible to communicate over distances of several hundred miles by use of tropospheric (對流層) scattering at frequencies in the range 40-300 MHz.
- Troposcatter results from signal scattering due to particles in the atmosphere at altitudes of 10 miles or less.
- Ionospheric scatter and tropospheric scatter involve large signal propagation losses and require a large amount of transmitter power and relatively large antennas.
1.2 Communication Channels and Their Characteristics

**Line-of-sight propagation (LOS)**

- At frequencies in the very high frequency (VHF) band and higher, the dominant mode of electromagnetic propagation is LOS propagation.
- Frequencies above 30 MHz propagate through the ionosphere with relatively little loss and make satellite and extraterrestrial communications possible.
- For terrestrial communication systems, transmitter and receiver antennas must be in direct LOS with relatively little or no obstruction.
- Television stations transmitting in the VHF and ultra high frequency (UHF) bands mount their antennas on high towers to achieve a broad coverage area.
1.2 Communication Channels and Their Characteristics

- Line-of-sight propagation (LOS)
  - In general, the coverage area for LOS propagation is limited by the curvature of the earth.
  
  \[ d = \sqrt{15h} \text{ km} \]

  where \( d \) is the distance and \( h \) is the antenna height in meter.

  - At frequencies in the super high frequency (SHF) band above 10 GHz, atmospheric conditions play a major role in signal propagation.
    - At 10 GHz, the attenuation ranges from about 0.003 dB/km in light rain to about 0.3 dB/km in heavy rain.
    - At 100 GHz, the attenuation ranges from about 0.1 dB/km in light rain to about 6 dB/km in heavy rain.
Underwater acoustic channels

- Electromagnetic waves do not propagate over long distances under water except at extremely low frequencies.
- Transmission of signals at such low frequencies is prohibitively expensive because of the large and powerful transmitters required.
- The attenuation of electromagnetic waves in water can be expressed in terms of the skin depth, which is the distance a signal is attenuated by $1/e$.
  - For seawater, the skin depth is
    \[ \delta = \frac{250}{\sqrt{f}} \]
    where $f$ is expressed in Hz and $\delta$ is in m.
Underwater acoustic channels

- Acoustic signals propagate over distances of tens and even hundreds of kilometers.
- An underwater acoustic channel is characterized as a multi-path channel due to signal reflections from the surface and the bottom of the sea.
- The signal multi-path components undergo time-varying propagation delays that result in signal fading.
- There is frequency-dependent attenuation, which is approximately proportional to the square of the signal frequency.
- It is possible to implement efficient and highly reliable underwater acoustic communication systems for transmitting digital signals over large distances.
Storage channels

Magnetic tape, including digital audiotape and videotape, magnetic disks used for storing large amounts of computer data, optical disks used for computer data storage, and compact disks are examples of data storage systems that can be characterized as communication channels.

The process of storing data on a magnetic tape or a magnetic or optical disk is equivalent to transmitting a signal over a telephone or a radio channel.

Channel coding and modulation are essential components of a well-designed digital magnetic or optical storage system.

In the readback process, the signal is demodulated and the added redundancy introduced by the channel encoder is used to correct errors in the readback signal.
In the design of communication systems for transmitting information through physical channels, we find it convenient to construct mathematical models that reflect the most important characteristics of the transmission medium.

The mathematical model for the channel is used in the design of the channel encoder and modulator at the transmitter and the demodulator and channel decoder at the receiver.
The additive noise channel

- The transmitted signal $s(t)$ is corrupted by an additive random noise process $n(t)$.
- Thermal noise is characterized statistically as a Gaussian noise process.
- When the signal undergoes attenuation in transmission through the channel, the received signal is

$$r(t) = \alpha \cdot s(t) + n(t)$$

where $\alpha$ is the attenuation factor.
1.3 Mathematical Models for Communication Channels

The linear filter channel

- In some physical channels, such as wire-line telephone channels, filters are used to ensure that the transmitted signals do not exceed specified bandwidth limitations and thus do not interfere with one another.

- Such channels are generally characterized mathematically as linear filter channels with additive noise.

\[ r(t) = s(t) \ast c(t) + n(t) = \int_{-\infty}^{\infty} c(\tau)s(t-\tau)d\tau + n(t) \]
1.3 Mathematical Models for Communication Channels

The linear time-variant filter channel

Physical channels such as underwater acoustic channels and ionospheric radio channels that result in time-variant multi-path propagation of the transmitted signal may be characterized mathematically as time-variant linear filters.

\[ r(t) = s(t) \ast c(\tau; t) + n(t) = \int_{-\infty}^{\infty} c(\tau; t)s(t - \tau)d\tau + n(t) \]
The linear time-variant filter channel (cont.)

Channels such as the ionosphere (at frequencies below 30 MHz) and mobile cellular radio channels have the time-variant impulse response of the form:

\[ c(\tau; t) = \sum_{k=1}^{L} a_k(t) \delta(\tau - \tau_k) \]

\[ r(t) = \sum_{k=1}^{L} a_k(t) s(t - \tau_k) + n(t) \]

where the \( \{a_k(t)\} \) represents the possibly time-variant attenuation factor for the \( L \) multipath propagation paths and \( \{\tau_k\} \) are the corresponding time delays.