Chapter 1. Introduction to Digital Communications

- What is Digital Communication?
- Why Digital?
- Overview of Digital Communication Systems
  - (a) Typical Block Diagram of a DCS
  - (b) Channel Capacity
  - (c) Mathematical Models for Communication Channels
- What shall we learn in this course?

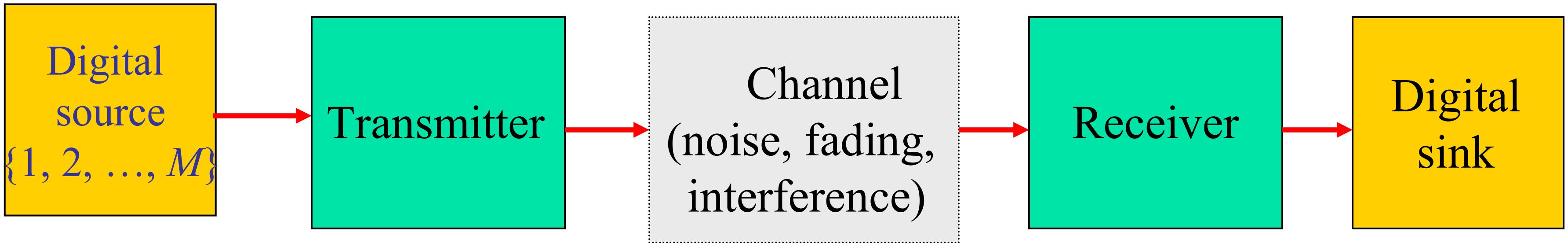
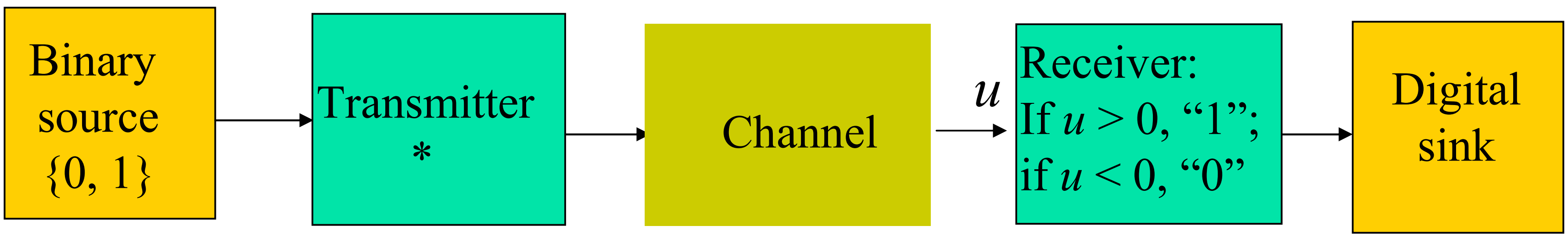
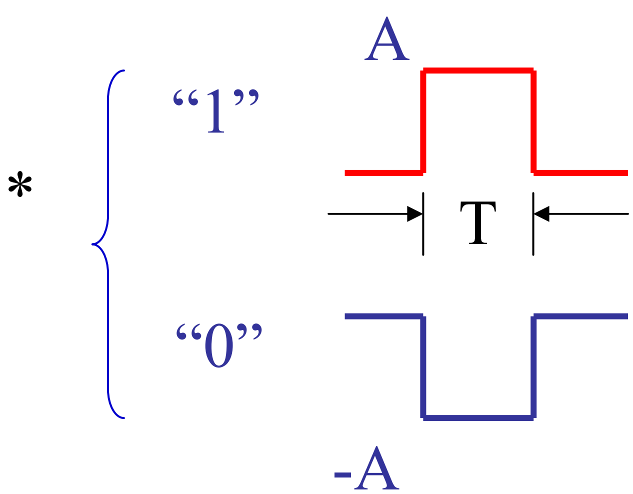


Fig. 1. Simplified Block Diagram for a DCS

- Transmitter: during a finite interval time, it sends a wave form from a finite set of possible waveforms.
- Receiver: the objective of the receiver is to determine from a noise-perturbed signal which waveform from the finite set of waveforms was sent by the transmitter.
- Channel: transmission medium.

Example 1. For $M = 2$, this is a binary source case.





T: bit interval or symbol interval

Objectives in DCS's Design

To design a DCS with reliability (or accuracy), efficiency and simplicity.

- Reliability: to have an accurate transmission or low probability of error
- Efficiency: to efficiently use the resources such as frequency bandwidth and transmission signal power. There are two parameters:

  bandwidth efficiency = data rate /signal bandwidth

  power efficiency = P\{ reception error\}

  a function of signal-to-noise ratio

  (trade-off between these two parameters discussed later)
- Simplicity: simplify transmitter and receiver hardware and software

Classification of Communications

To classify the communications based on the format of the information to be sent:

Analog communication system:
The information to be transmitted is in form of an analog signal.

Digital communication system :
The message signal to be transmitted is in digital form consisting of discrete symbols (both amplitude and time taking on discrete values)

To classify the communication based on the characteristics of the channel.

Wireline communication:
wireline channels

Wireless communication:
wireless channels

Why digital?

Advantages:

- Different type of digitized information sources (audio, video, image, data, …) can be treated as identical signals in transmission and switching: a bit is a bit.
- Control information such as addressing/routing can be easily accommodated.
- Accurate and rapid storage and retrieval.
- Easy to use signal processing functions for protecting against interference and jamming.
- Easy to provide encryption (privacy) and authentication (information integrity or origin). (How hard is it in analog case?).
- Efficient regeneration of the coded signal along the transmission path.
- Redundancy remove (source coding), channel coding and decoding (error correction) .

Disadvantages:

- Increased system complexity
- Increased transmission bandwidth requirements

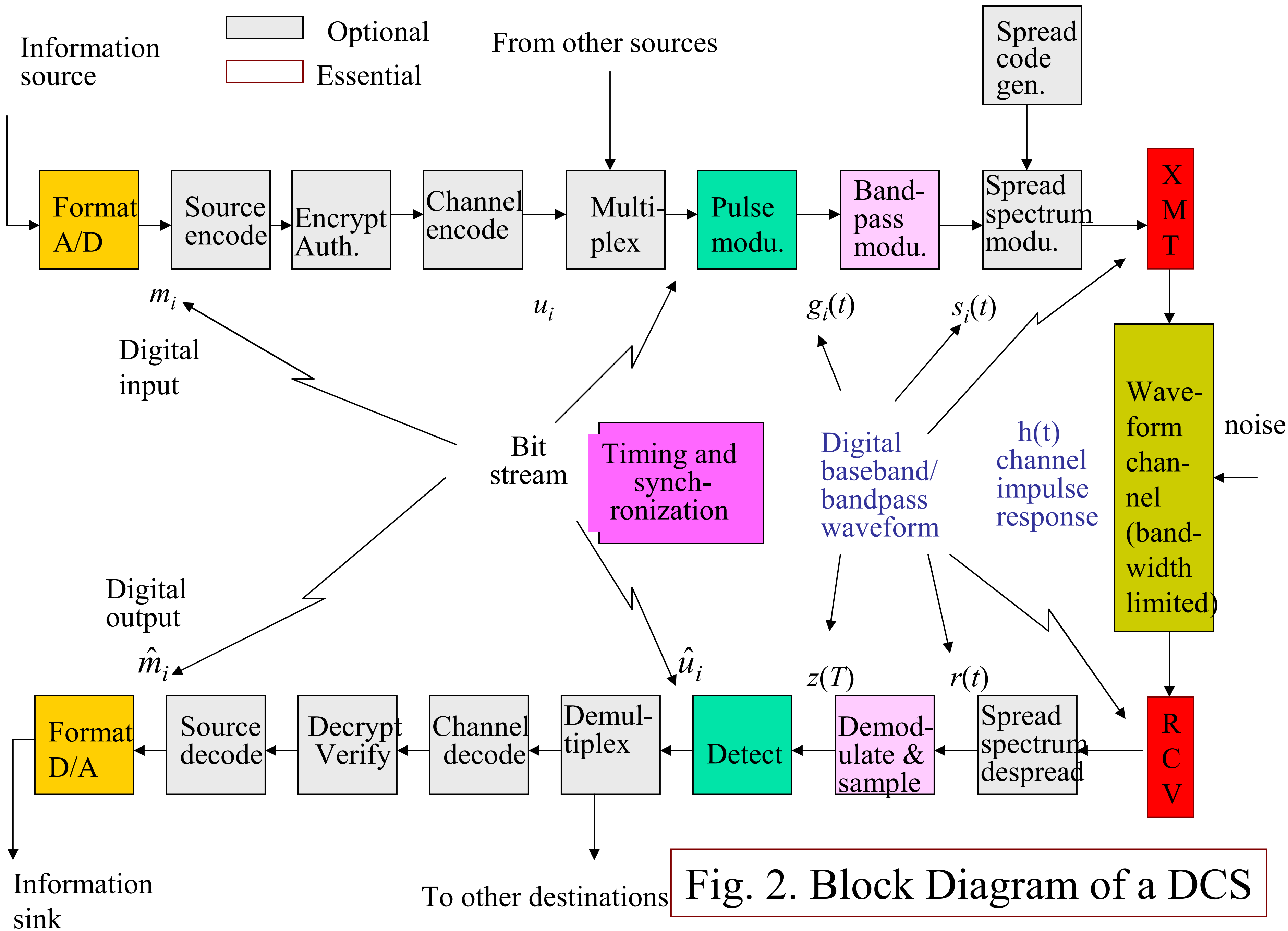


Fig. 2. Block Diagram of a DCS

Format: transforms the source information into bits (A/D converter if it is analog).

Channel encode/decode: add redundancy, in a controlled manner, to message symbols and the decoder can use this redundancy to detect and correct errors.

Source encode/decode: remove redundancy existing in the source information so that it can be represented efficiently.

Modulation, demodulation/detect: generate signal waveform which is suitable for transmission over the channel.

Spread spectrum modulation/Despread: an additional level of modulation beyond pulse modulation. and bandpass modulation. The transmitted signal is much wider than and independent of the bandwidth of the information to be transmitted.

Encrypt/Decryt: protect privacy of the information
Authentication/Verify: provide integrity checking for origin of the information source (this block can be placed after any block before modulation).

Timing and synchronization: a clock signal, is involved in the control of almost every blocks.

Channel Capacity

- Claude Shannon (1948): the inventor of information theory, established the following fundamental limits for DCSs.

  Given a transmitted power constraint P, a bandwidth W, and an additive white Gaussian noise (AWGN) channel with psd N_0, then the channel capacity is given by

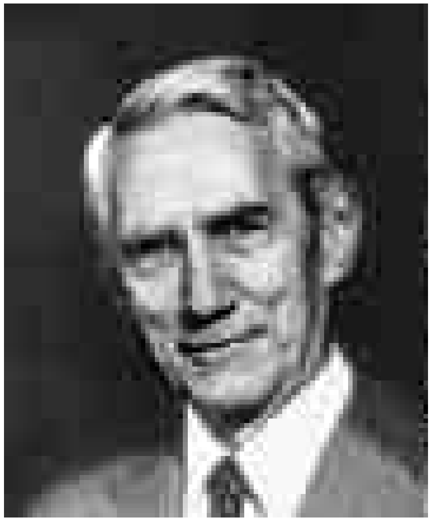
$$C = W \log_2(1 + P/WN_0) \text{ bits/s}$$

- The significant of the channel capacity:
  - If the information rate R from the source is less than C ($R < C$), then it is theoretical possible to achieve reliable transmission through the channel by appropriate coding.
  - If $R > C$, reliable transmission is not possible regardless of the amount of signal processing performed at the transmitter and receiver.

  This result is served as benchmarks relative to which any given communication system is compared.

Claude Elwood Shannon

Born: **30 April 1916 in Gaylord, Michigan, USA**
Died: **24 Feb 2001 in Medford, Massachusetts, USA**



Shannon, a founder of Information Theory, published *A Mathematical Theory of Communication* in the *Bell System Technical Journal* (1948). This paper founded the subject of information theory and he proposed a linear schematic model of a communications system.

Shannon Lecturer of year 2003: Prof.Lloyd Welch, Professor Emeritus, University of Southern California.

Mathematical Models for Communication Channels

Channel is defined as a single path for transmitting signals in one direction or in both directions.

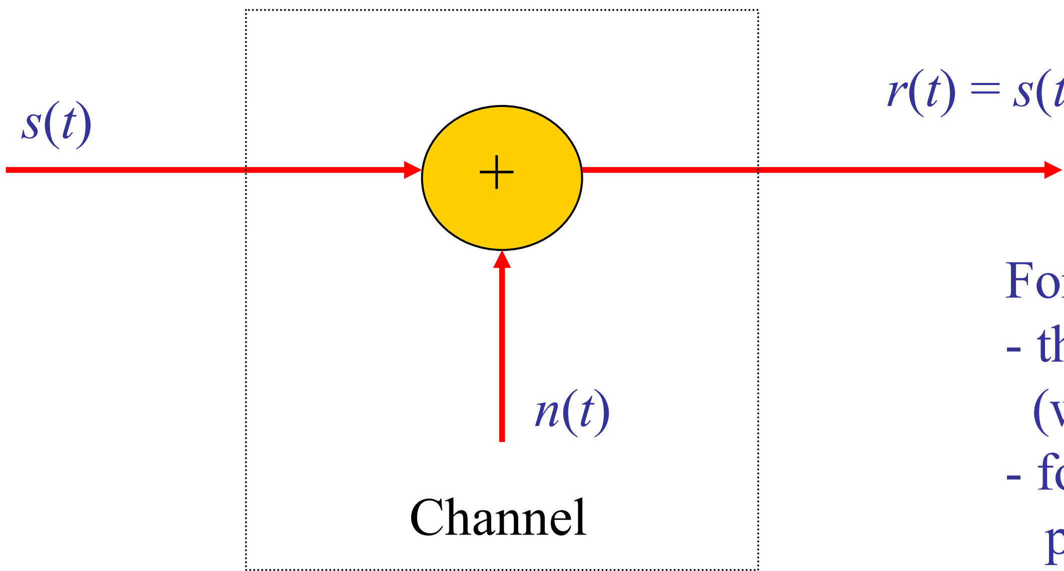
Communication Channels can be classified as:

- Wired channels: telephone line, optical fiber, coaxial cable, etc..
- Wireless channels: radio link (free space), …
- Compact Disc (CD) channels: information storage (modulate) and retrieve (demodulate)

Mathematical Models for Communication Channels

1. The additive white Gaussian noise channel

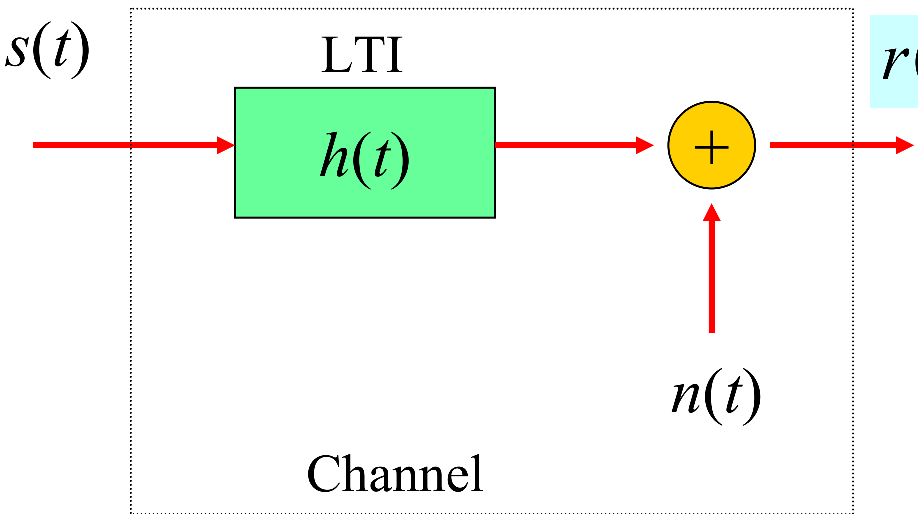
The transmitted signal $s(t)$ is corrupted by an additive white Gaussian noise (AWGN) process $n(t)$ (one of the simplified mathematical models for various physical communication channels including wired channels and some radio channels)



For an AWGN process $n(t)$:
- the psd is a constant (white)
- for any time instance t, the pdf of $n(t)$ is a Gaussian random variable

2. The Linear Time Invariant Filter Channel

In general, a wired channel can be modeled as a linear time invariant (LTI) system which can be mathematically described by the impulse response of the system.



$$r(t) = s(t) * h(t) + n(t)$$

$$= \int_{-\infty}^{\infty} s(t-\tau)h(\tau)d\tau + n(t)$$

The LTI filter channel with an AWGN

For different filter functions, we have the following classifications.

- Memoryless channel (infinite bandwidth): the output at time t only depends on the input at t. In other words, if

  $H(f) = c$, then $h(t) = \delta(t)$.

  In this case, the channel is called memoryless channel.

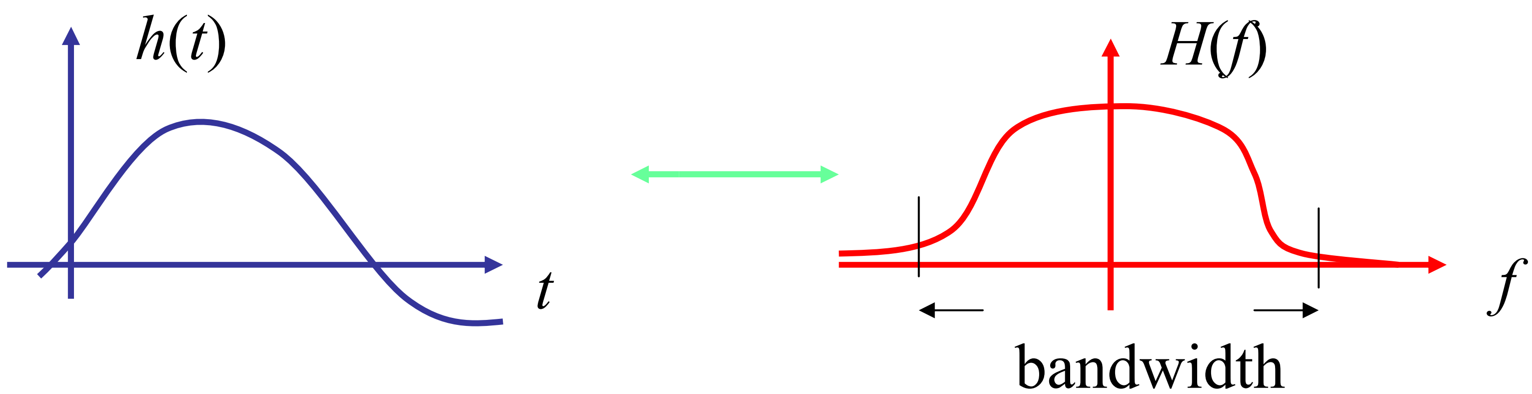
  Note. The AWGN is a memoryless channel.

- With memory: the output at t depends on the input at and before t.

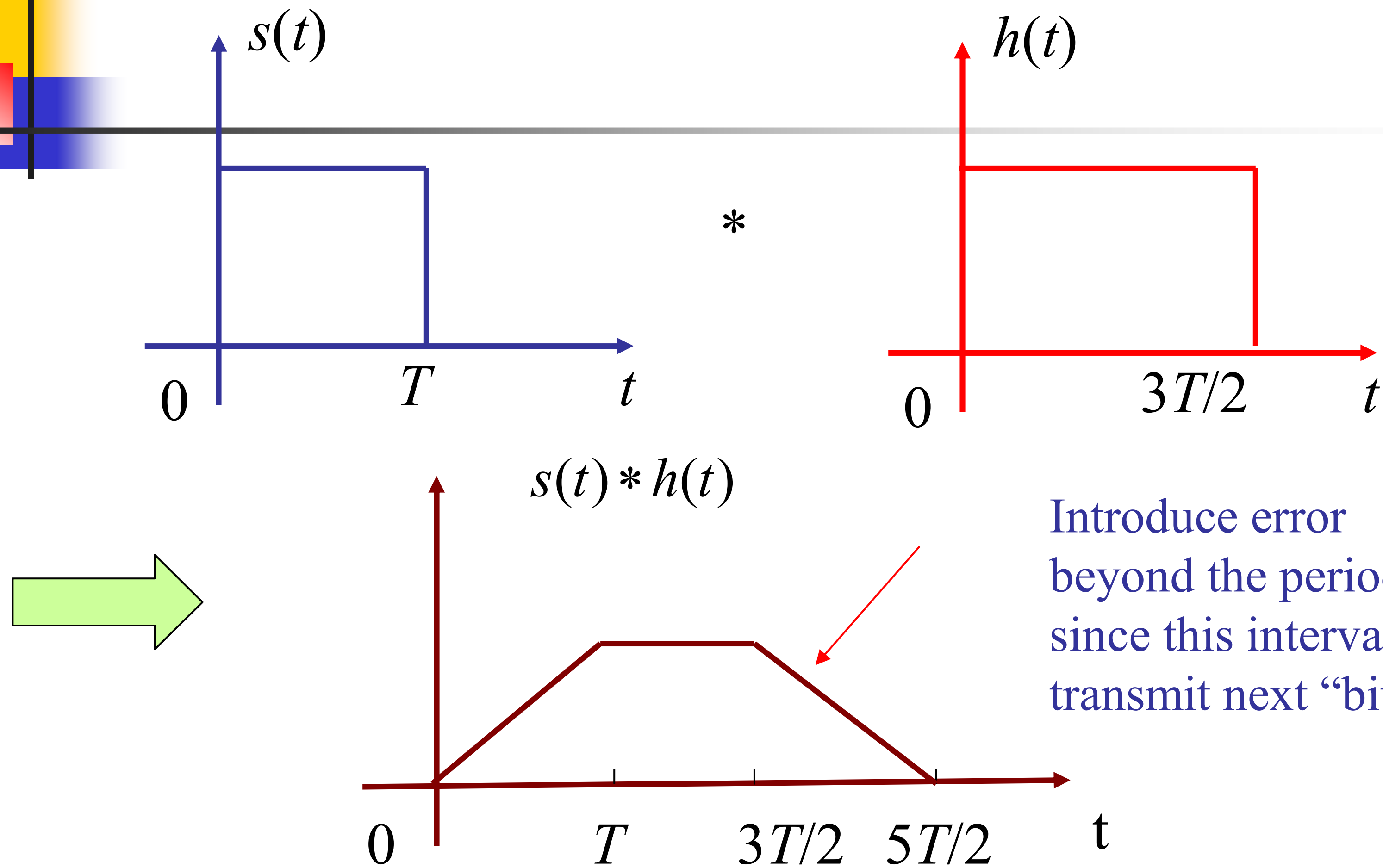
$$h(t) \neq \delta(t)$$

In this case, bandwidth is limited. This limit distorts the transmitted signal, which results in intersymbol interference (ISI) at the output of the demodulation and leads to an increase in the probability of error at the detection.

The channel is always bandlimited. A bandlimited channel disperses or spreads a pulse waveform passing through it. When the channel bandwidth is much greater than the pulse bandwidth, the spreading of the pulse will be slight. When the channel bandwidth is close to the signal bandwidth, the spreading pulses to overlap. This overlapping is called intersymbol interference (ISI).



Example 2.



Introduce error beyond the period since this interval should transmit next “bit”.

Intersymbol Interference (ISI)

LTI Filter Channel

1. AWGN: $h(t) = \delta(t)$

$$r(t) = s(t) * h(t) + n(t) = s(t) + n(t)$$

$r(t)$ has complete information of $s(t)$

2. Bandlimited: (ISI = Intersymbol interference)

$h(t) \neq \delta(t)$

$$r(t) = s(t) * h(t) + n(t)$$

- $r(t)$ does not have complete information of $s(t)$
- If bandwidth of $s(t)$ is narrow, then ISI is large.

Harry Nyquist

Born. Feb. 7, 1889, Nilsby, Sweden
Died. April 4, 1976, Harlingen, Texas, U.S.

American physicist, electrical and communications engineer, a prolific inventor who made fundamental theoretical and practical contributions to telecommunications. In 1924 and 1928, he published "Certain Factors Affecting Telegraph Speed," and "Certain Topics in Telegraph Transmission Theory“. These two papers by Nyquist, along with one by R.V.L. Hartley, are cited in the first paragraph of Claude Shannon's classic essay "The Mathematical Theory of Communication" (1948), where their seminal role in the development of information theory is acknowledged.

Ralph Vinton Lyon Hartley

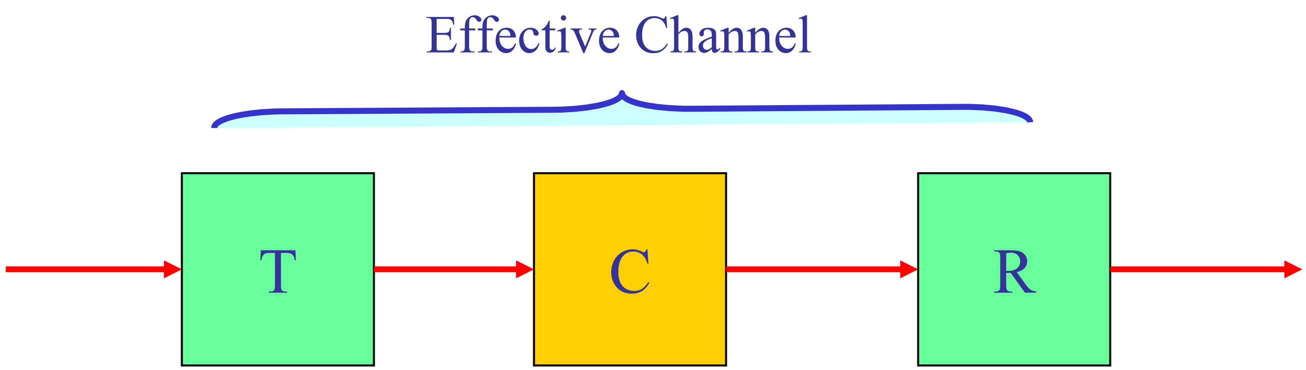
Born. November 30, 1888, Spruce, Nevada, U.S.A.
Died. May 1, 1970, U.S.A.

Ralph V.L. Hartley was inventor of the electronic oscillator circuit that bears his name. He was also a pioneer in the field of Information Theory. He introduced the concept of "information" as random variable and was the first to attempt to define "a measure of information" (1928: "Transmission of Information", in *Bell System Tech. Journal*, vol. 7, pp. 535-563).

What shall we learn in this course?

1) Given an AWGN channel, how to design transmitter and receiver so that the transmission error can be minimized (transmission error means probability of bit error)

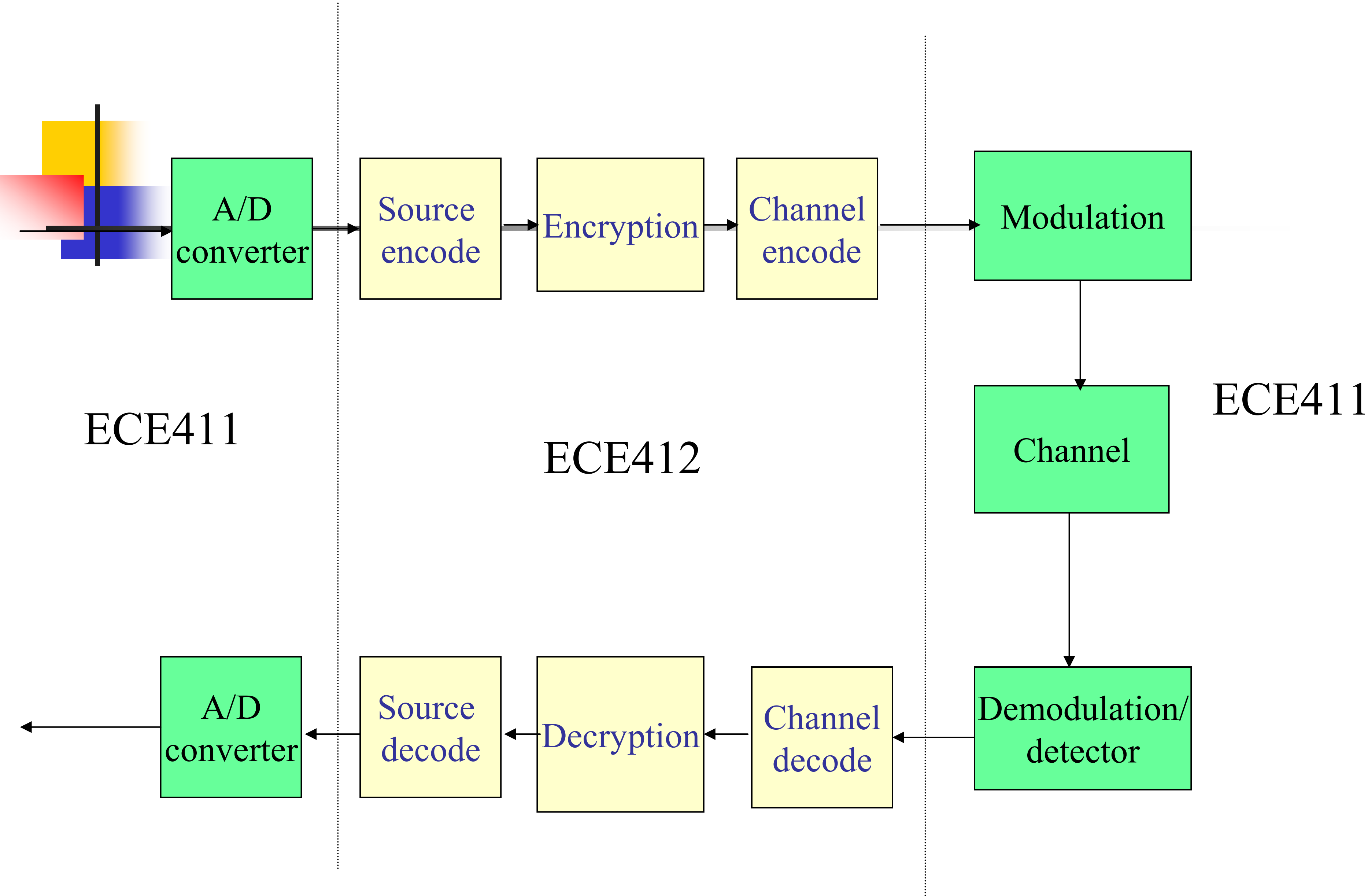
2) Given a bandlimited channel, how to design T & R



such that the "effective channel" is memoryless.

3) How will modulation schemes affect the system performance?

4) How to choose quantization step and how to calculate the quantization error?


A/D converter
Source encode
Encryption
Channel encode
Modulation
ECE411
ECE412
Channel
ECE411
A/D converter
Source decode
Decryption
Channel decode
Demodulation/ detector