Digital Communications
—— Course Outline

DU, Bing

School of Computer & Communication Engineering

University of Science & Technology of Beijing

Education and Working Experiences

- **Beijing University of Aeronautics & Astronautics Bachelor & Ph.D.**
  - **School of Electronic Information Engineer**
- **04/2010 – 06/2014 Tsinghua University Assistant professor & Postdoc**
  - **Department of Electronic Engineering**
- **10/2015 – present University of Science & Technology Beijing**

  Associate professor
  - **School of Computer and Communication Engineering**
- **03/2017-04/2018 University of British Columbia UBC Canada Visiting Scholar**

Syllabus

- Bing Du
  - Office： Yifu Lou 903
  - Email: dubing@ustb.edu.cn
  - Course website: piazza.com/ustb.edu.cn/fall2022/cs222
    - Everyone needs to log on and register
    - Or you give me your email address and I enroll you
- Prerequisites:
  - Probability, Random Process
  - Introduction to Communication Systems (preferred)

Syllabus

- Textbook:
  - John G. Proakis and Masoud Salehi, *Digital Communications*, 5th edition, McGraw-Hill International Editions, 2008.
- References:
  - Andrew J. Viterbi, CDMA Principles of Spread Spectrum Communication, Addison-Wesley Wireless Communications Series, 1995.
  - R. G. Gallager, Principles of Digital Communication, Cambridge University Press, 2008.
  - A. Lapidoth, A Foundation in Digital Communication, Cambridge, 2009.

Syllabus

- Address: Xinxi Lou 315
- Schedule:
  - Tuesday Thursday 9:55-11:30

Course Content

- Chapter 1: Introduction (brief)
  - 1.1: Elements of a Digital Communication System
  - 1.2: Communication Channels and Their Characteristics
  - 1.3: Mathematical Models for Communications
  - 1.4: A Historical Perspective in the Development of Digital Communications
- Chapter 2: Deterministic and Random Signal Analysis
  - 2.1: Bandpass and Lowpass Signal Representations
  - 2.2: Signal Space Representations of Waveforms
  - 2.7: Random Processes
  - 2.8: Series Expansion of Random Processes
  - 2.9: Bandpass and Lowpass Random Processes

Course Content

- Chapter 3: Digital Modulation Schemes
  - 3.1: Representation of Digitally Modulated Signals
  - 3.2: Memoryless Modulation Methods
  - 3.3: Signaling Schemes with Memory
  - 3.4: Power Spectrum of Digitally Modulated Signals
- Chapter 4: Optimum Receivers for AWGN Channels
  - 4.1: Waveform and Vector Channel Models
  - 4.2: Waveform and Vector AWGN Channels
  - 4.3: Optimal Detection and Error Probability for Band-Limited Signaling
  - 4.4: Optimal Detection and Error Probability for Power-Limited Signaling
  - 4.5: Optimal Detection in Presence of Uncertainty
  - 4.6: A Comparison of Digital Signaling Methods
  - 4.8: Detection of Signaling Schemes with Memory: Maximum Likelihood Sequence Detector

Course Content

- Chapter 6: An Introduction to Information Theory
  - 6.5: Channel Models and Channel Capacity
  - 6.6: Achieving Channel Capacity with Orthogonal Signals (These two sections will be incorporated into Chapter 4.)
- Chapter 13: Fading Channels I: Characterization and Signaling
  - 13.1: Characterization of Fading Multipath Channels
  - 13.2: The Effect of Signal Characteristics on the Choice
  - of a Channel Model
  - 13.3: Frequency-Nonselective, Slowly Fading Channel
  - 13.4: Diversity Techniques for Fading Multipath Channels
  - 13.5: The RAKE Demodulator Digital

Course Content

- Chapter 12: Spread Spectrum Signals for Digital Communications
  - 12.1: Model of Spread Spectrum Digital Communication System
  - 12.2: Direct Sequence Spread Spectrum Signals
- Chapter 9: Digital Communication Through Band-Limited Channels
  - 9.1: Characterization of Band-Limited Channels
  - 2 9.2: Signal Design for Band-Limited Channels
  - 9.3*: Optimum Receiver for Channels with ISI and AWGN (partially covered)
  - 9.4*: Linear Equalization (partially covered)

Course Content

- Chapter 11: Multichannel and Multicarrier Systems
  - 11.1: Multichannel Digital Communications in AWGN Channels
  - 11.2: Multicarrier Communications
- Chapter 5: Carrier and Symbol Synchronization
  - 5.1: Signal Parameter Estimation
  - 5.2: Carrier Phase Estimation
  - 5.3: Symbol Timing Estimation
  - 5.4: Joint Estimation of Carrier Phase and Symbol Timing
  - 5.5: Performance Characteristics of ML Estimators

Course Content

- We will **not** cover . . .
  - Chapter 6: An Introduction to Information Theory
    - Will be covered by Information Theory
    - Will be covered by Error Correcting Codes
  - Chapter 8: Trellis and Graph Based Codes
    - Will be covered by Error Correcting Codes
  - Chapter 10: Adaptive Equalization
    - Special topic in Digital Communications

Course Content

- We will **not** cover . . .
  - Chapter 14: Fading Channels II: Capacity and Coding
    - Advanced topics in Information Theory and Error Correcting Codes
  - Chapter 15: Multiple Antenna Systems
    - Advanced topics in Digital Communications
  - Chapter 16: Multiuser Communications
    - Advanced topics in Digital Communications

Evaluation policy

- Homework: Sample Problems will be given weekly.
- Closed Books: Most of the problems will be from the slides.
- Homework (30%) + Attendance (10%) + Final (60%)
- Final
  - A project report
  - Or an open book exam

Today's Goal

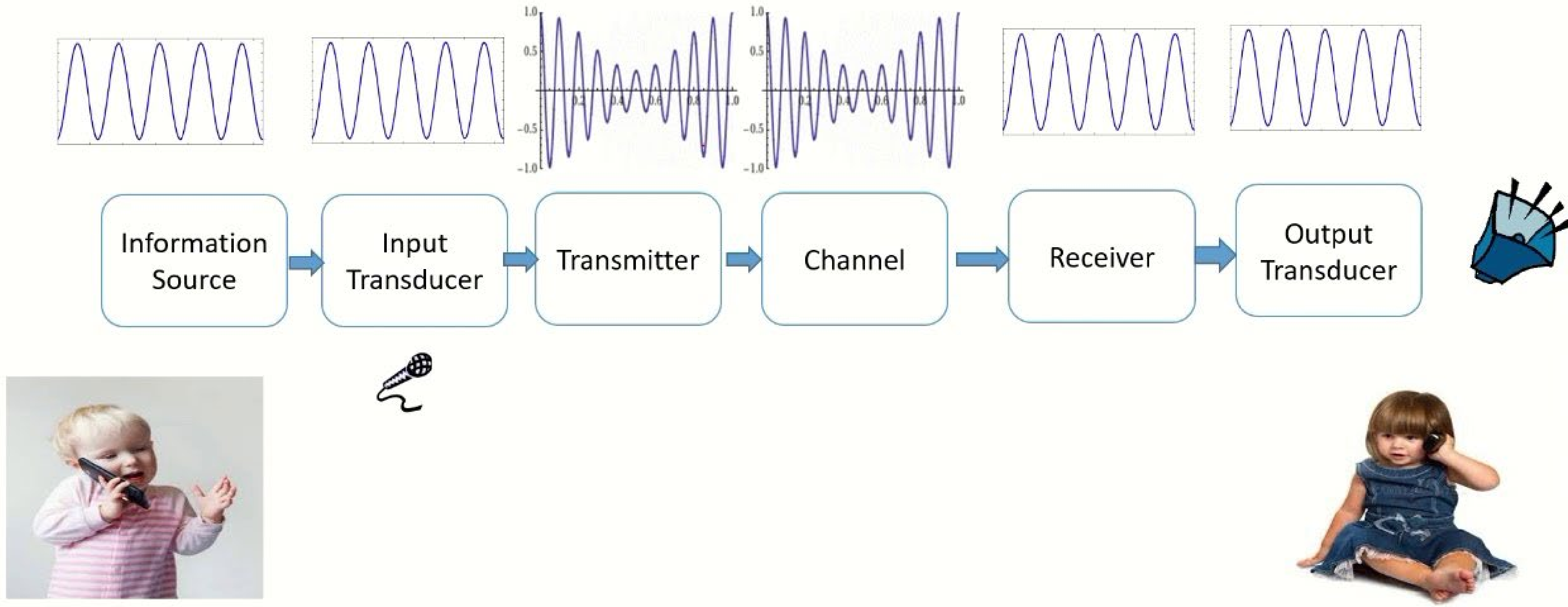
- Digital Communication Basic

Communication

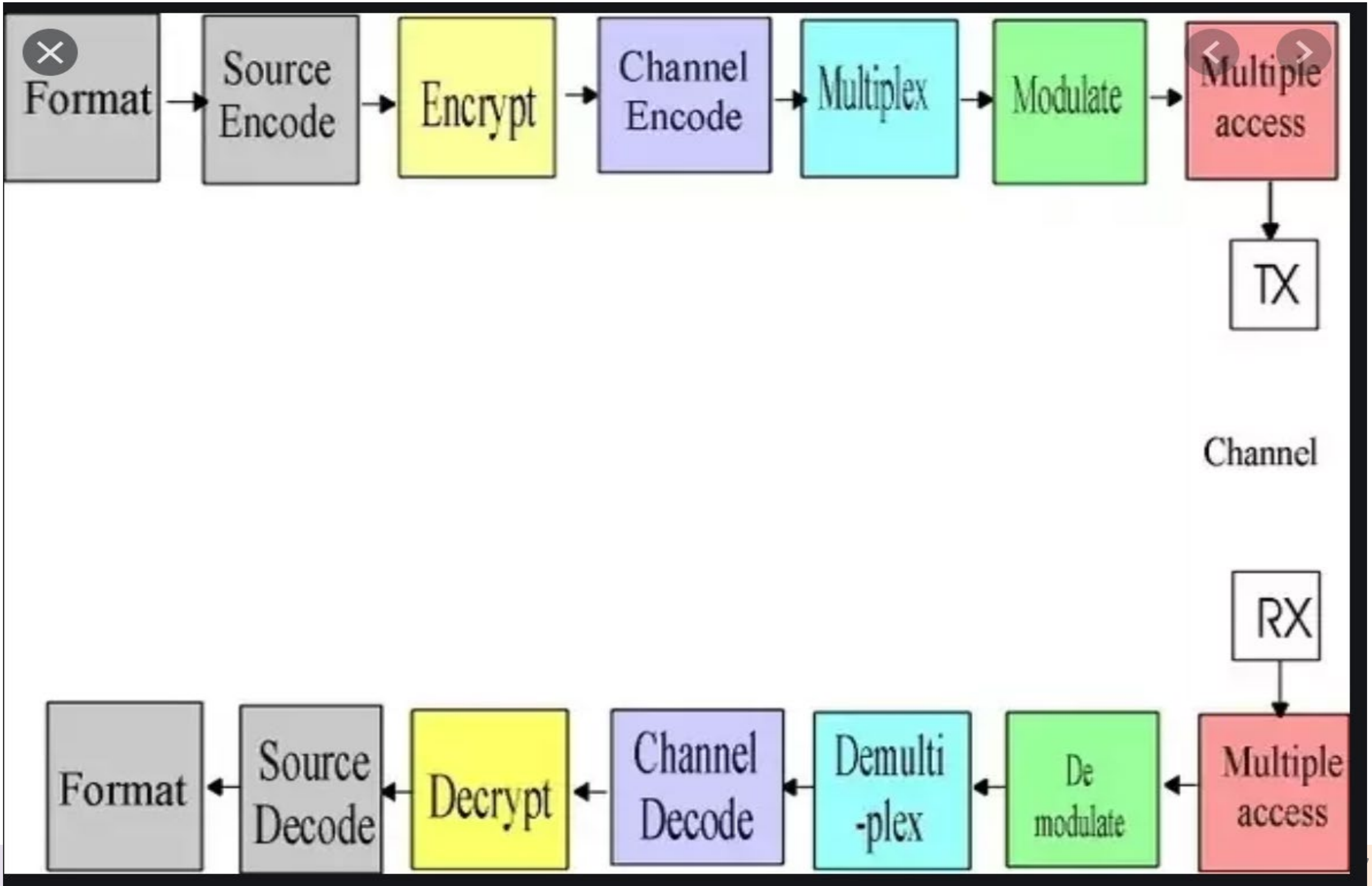
- Main purpose of communication：
  - to transfer information from a source to a recipient via a channel or medium.

- Basic block diagram of a communication system:

Analog Communication system block diagram



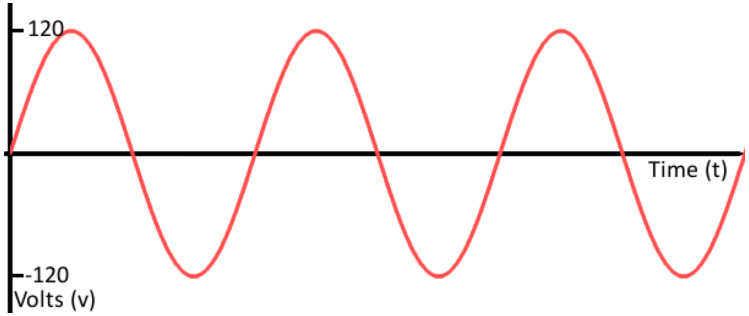
Digital Communication

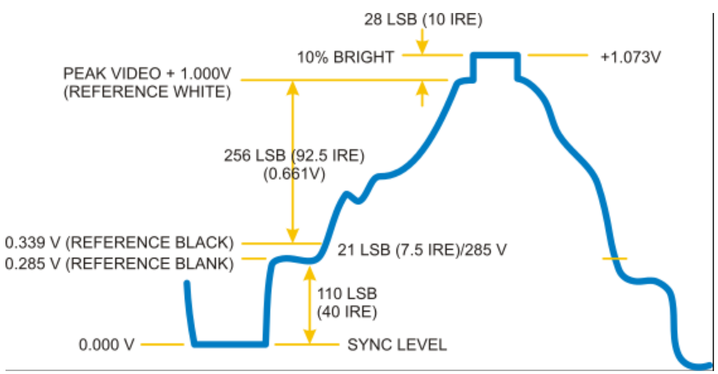


Brief Description

- **Source:** analog or digital

Analog: infinite number of possible values within that range



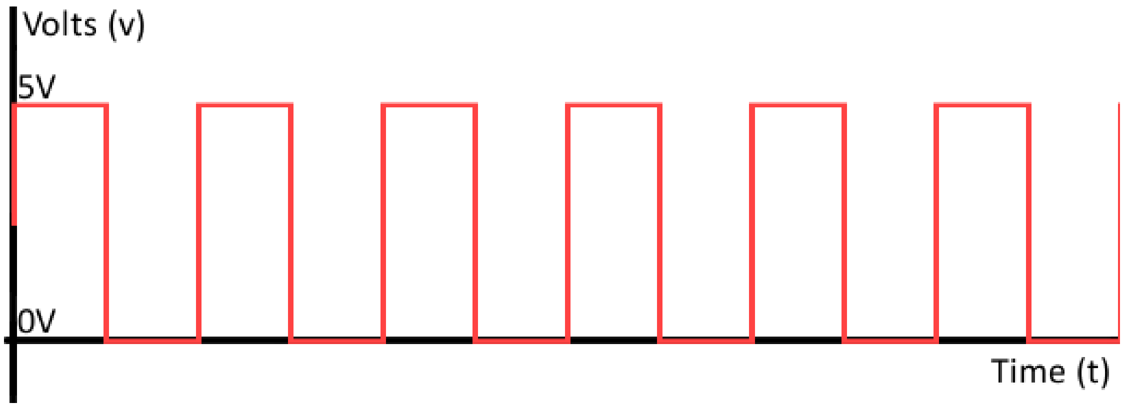


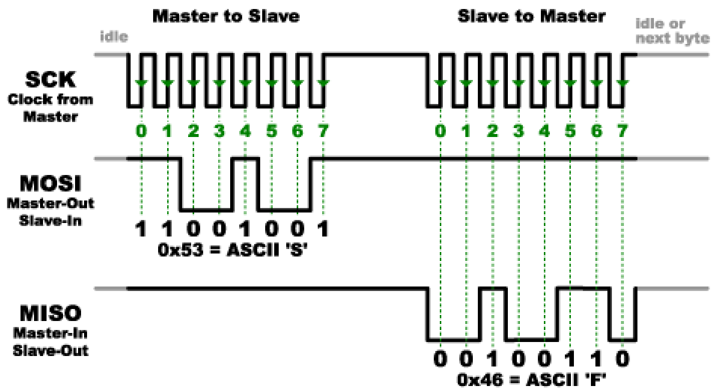
The composite video coming out of an old RCA jack, for example, is a coded analog signal usually ranging between 0 and 1.073V. Tiny changes in the signal have a huge effect on the color or location of the video.

Brief Description

- **Source:** analog or digital

Digital : finite number of possible values within that range





Standardized signals like HDMI for video (and audio) and MIDI, I^2S, or AC'97for audio are all digitally transmitted.
Most communication between integrated circuits is digital. Interfaces like serial, I^2C, and SPI all transmit data via a coded sequence of square waves.

Digital Signal Processors In Products

IP phone

Smart power meters

IP camera

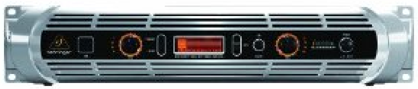
Video conferencing

DSL modems

Consumer audio

Mixing board

Amp



Pro-audio

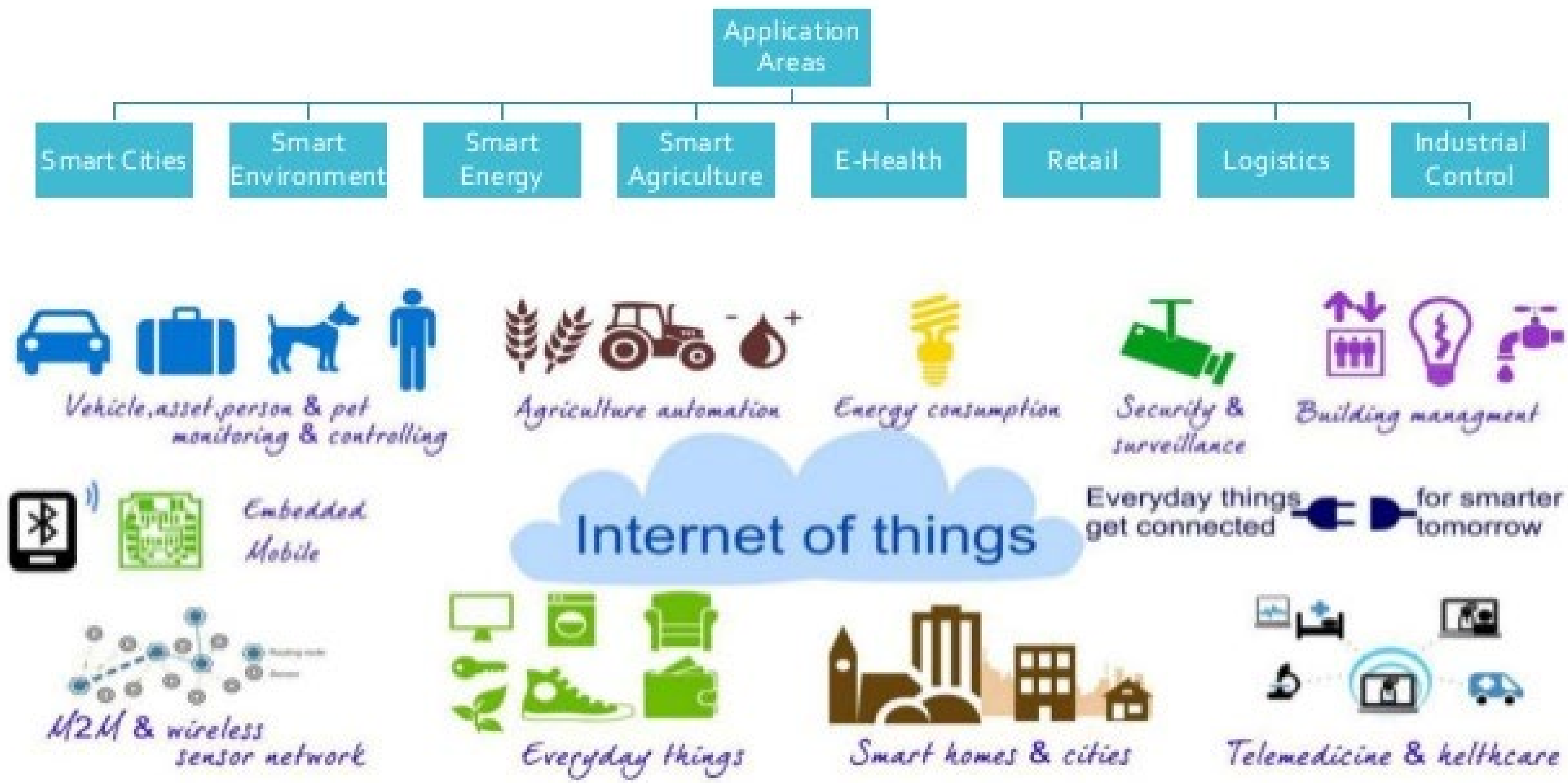
In-car entertainment

Tablets

Multimedia

Communications

Internet of things

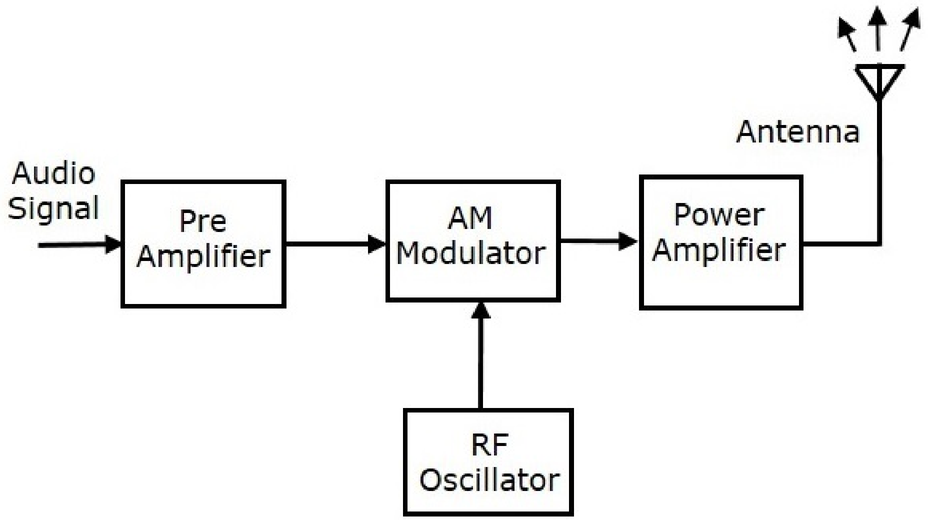


What are the major challenges of communication technologies for IoT?


Security
Connectivity
Compatibility and Longevity
Standards
Intelligent Analysis & Actions

Brief Description

- **Transmitter:** transducer, amplifier, modulator, oscillator, power amp., antenna
- **Channel:** e.g. cable, optical fiber, free space, underwater
- **Receiver:** antenna, amplifier, demodulator, oscillator, power amplifier, transducer
- **Recipient:** e.g. person, (loud) speaker, computer



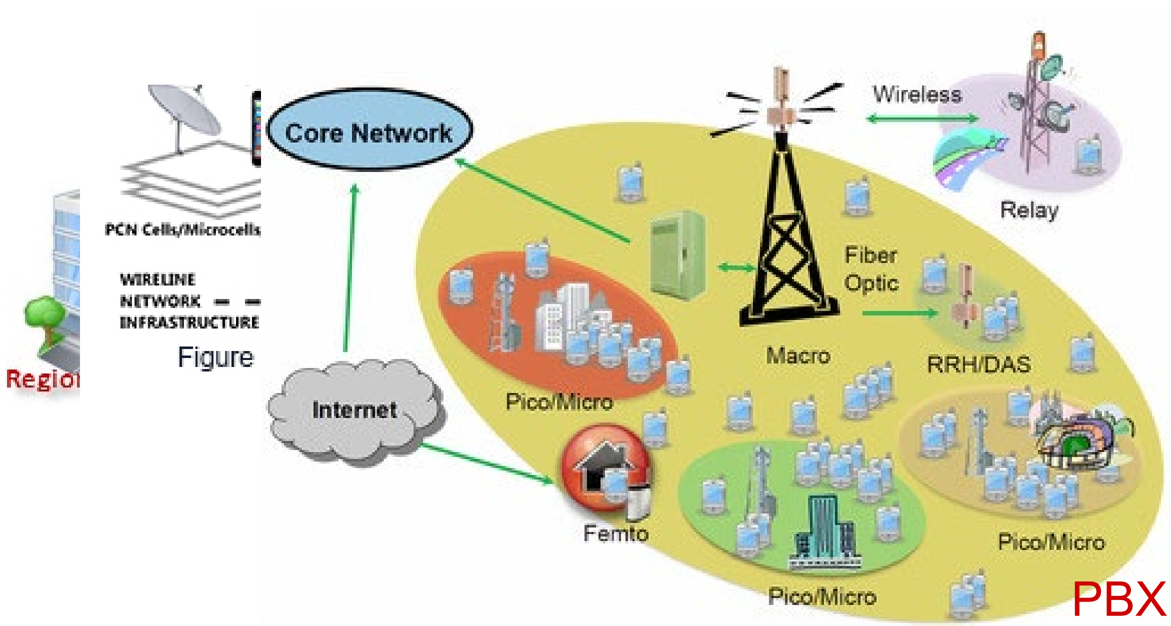
Brief Description

- **Types of information**
  Voice, data, video, streaming, music, email etc.

Almost all sorts of information you can think of can be delivered by the communication systems

Brief Description

- **Types of communication systems**



PBX Private Branch Exchange

Information Representation

- Communication system converts information into
  - Electrical
  - Electromagnetic
  - Optical signals
- Appropriate for the transmission medium.
- Analog systems convert analog message into signals that can propagate through the channel.
- Digital systems convert bits(digits, symbols) into signals
  - Computers naturally generate information as characters/bits
  - Most information can be converted into bits
  - Analog signals converted to bits by sampling and quantizing (A/D conversion)

Why digital?

- Digital techniques need to distinguish between discrete symbols allowing regeneration versus amplification

- Good processing techniques are available for digital signals

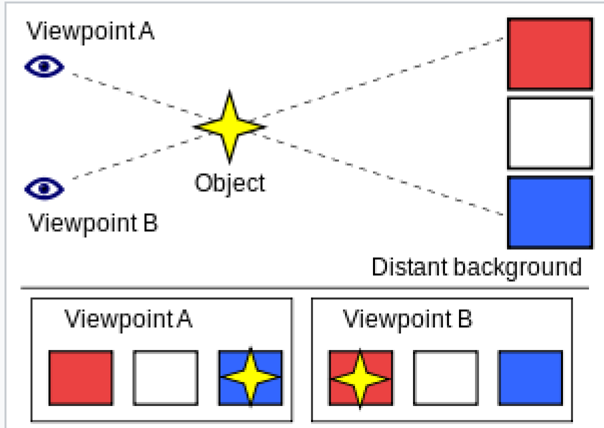
  - Data compression (or source coding)
  - Error Correction (or channel coding)(A/D conversion)
  - Equalization
  - Security

- Easy to mix signals and data using digital techniques

	Analog	Digital
Signal	Analog signal is a continuous signal which represents physical measurements.	Digital signals are discrete time signals generated by digital modulation.
Waves	Denoted by sine waves	Denoted by square waves
Representation	Uses continuous range of values to represent information	Uses discrete or discontinuous values to represent information
Example	Human voice in air, analog electronic devices.	Computers, CDs, DVDs, and other digital electronic devices.
Technology	Analog technology records waveforms as they are.	Samples analog waveforms into a limited set of numbers and records them.
Data transmissions	Subjected to deterioration by noise during transmission and write/read cycle.	Can be noise-immune without deterioration during transmission and write/read cycle.
Response to Noise	More likely to get affected reducing accuracy	Less affected since noise response are analog in nature
Flexibility	Analog hardware is not flexible.	Digital hardware is flexible in implementation.

A/D

Uses	Can be used in analog devices only. Best suited for audio and video transmission.	Best suited for Computing and digital electronics.
Applications	Thermometer	PCs, PDAs
Band	be es	There is no guarantee that digital signal processing can be done in real time and consumes more bandwidth to carry out the same information.
Me	nal	Stored in the form of binary bit
F	e	Digital instrument drawS only negligible power
		Cost is high and not easily portable
Impedance	Low	High order of 100 megaohm
Errors	Analog instruments usually have a scale which is cramped at lower end and give considerable observational errors.	Digital instruments are free from observational errors like parallax and approximation errors.



A simplified illustration of the parallax of an object against a distant background due to a perspective shift. When viewed from "Viewpoint A", the object appears to be in front of the blue square. When the viewpoint is changed to "Viewpoint B", the object *appears* to have moved in front of the red square.

Why Digital Communications?

- Easy to regenerate the distorted signal
  - Regenerative repeaters along the transmission path can detect a digital signal and retransmit a new, clean (noise free) signal
  - These repeaters prevent accumulation of noise along the path
- This is not possible with analog communication systems
  - Two-state signal representation
- The input to a digital system is in the form of a sequence of bits (binary or M_ary)
  - Immunity to distortion and interference
  - Digital communication is rugged in the sense that it is more immune to channel noise and distortion

Why Digital Communications?

- Hardware is more flexible
  - Digital hardware implementation is flexible and permits the use of microprocessors, mini-processors, digital switching and VLSI
- Shorter design and production cycle
  - Low cost
  - The use of LSI and VLSI in the design of components and systems have resulted in lower cost
  - Easier and more efficient to multiplex several digital signals
  - Digital multiplexing techniques – Time & Code Division Multiple Access - are easier to implement than analog techniques such as Frequency Division Multiple Access

Why Digital Communications?

- Can combine different signal types – data, voice, text, etc.
  - Data communication in computers is digital in nature whereas voice communication between people is analog in nature
  - The two types of communication are difficult to combine over the same medium in the analog domain.
  - Using digital techniques, it is possible to combine both format for transmission through a common medium
- Encryption and privacy techniques are easier to implement
  - Better overall performance
  - Digital communication is inherently more efficient than analog in realizing the exchange of SNR for bandwidth
  - Digital signals can be coded to yield extremely low rates and high fidelity as well as privacy

Why Digital Communications?

Disadvantages

- Requires reliable "synchronization"
- Requires A/D conversions at high rate
- Requires larger bandwidth: rates
- Nongraceful degradation: Threshold effect
- Performance Criteria
- Probability of error or Bit Error Rate

Pros of Analog Comm.

- Analog transmission: still very popular, in particular for shorter distances,
- significantly lower costs
- complex multiplexing and timing equipment is unnecessary,
- in small “short-haul” systems that simply do not need multiplexed digital transmission
- However, in situations where a signal often has high signal-to-noise ratio and cannot achieve source linearity, or in long distance, high output systems, analog is unattractive due to attenuation problems.
- Analog systems are very tolerant to noise, make good use of bandwidth, and are easy to manipulate mathematically.

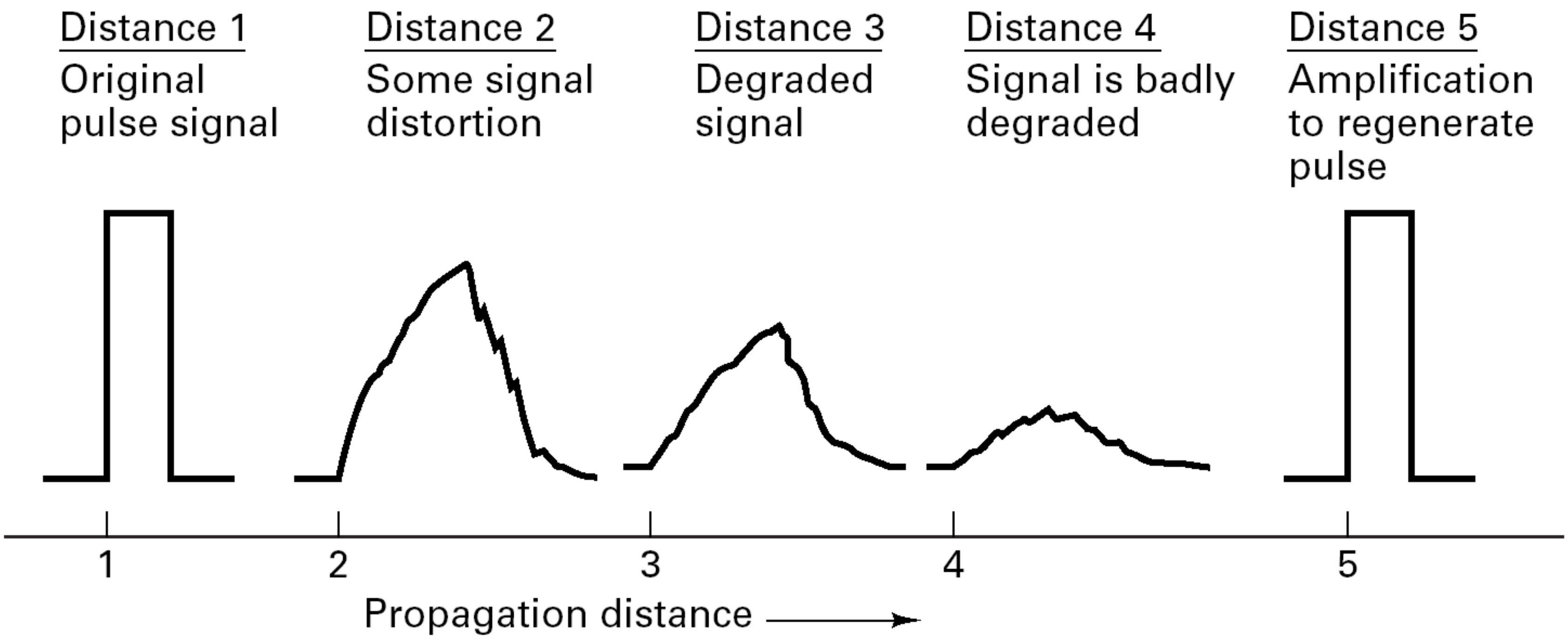


Figure 1.1 Pulse degradation and regeneration.

Review

- Basic concept of Comm.
- Analog VS Digital: Pros and Cons
  - Wave & signal
  - Errors
  - Applications
  - Bandwidth
  - Response to the noise
- The block of Digital Comm. diagram

Source → **Transmitter** → **Channel** → **Receiver** → **Recipient**

Guess of terms

- Module 1
  - Character coding: selects compatible waveforms
  - Sampling
  - Quantization
  - Pulse Code Modulation (PCM)

Formatting:
Transform analog measurement into digital symbols (digitization)

Guess of terms

- Module 2:
  - To reduce the number of symbols in a message to minimum necessary to represent the information in the message
  - As less as possible
  - Make sure to recover the original source info.
  - Popular in video and image, nature language

Source coding

Guess of terms

- Module 3
  - Translating info. bits to transmitter data symbols
  - Techniques used to enhance info. signal so that they are less vulnerable to channel impairment (e.g. noise, fading, jamming, interference)
  - Involves the use of redundant bits to determine the occurrence of error (and sometimes correct it)

Channel coding

Guess of terms

- Module 4:
  - The process of modifying the signal to facilitate transmission
  - Move to the higher frequency band
  - Match to the channel medium

Modulation

Guess of terms

- Module 5:
  - Multiple sources combine together according to certain format to adapt to the transmission rate.

Multiplexing

  - A type of access to the channel medium
  - synonymous with resource sharing with other users

Multiple addressing

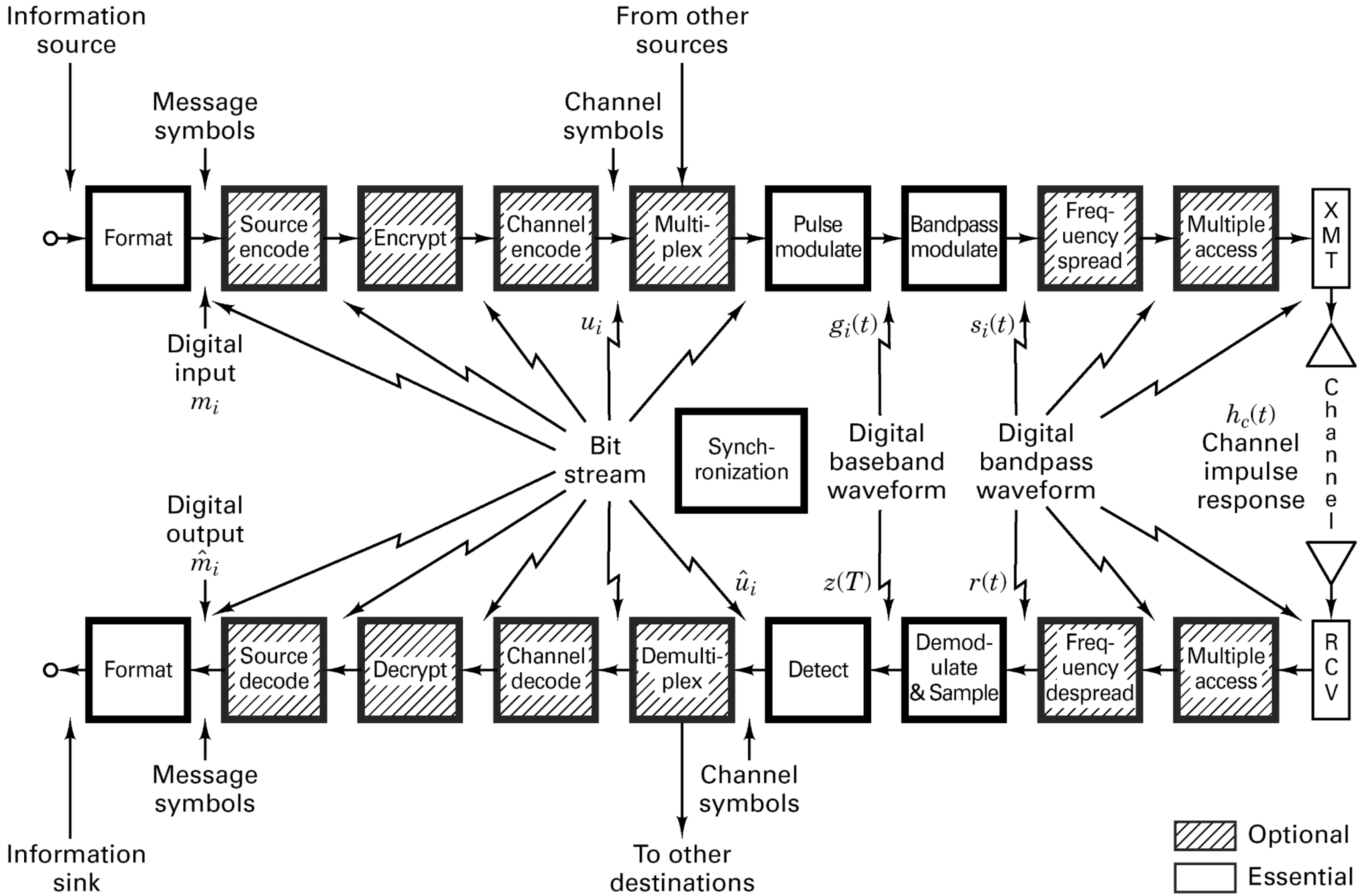


Figure 1.2 Block diagram of a typical digital communication system.

Formatting

Character coding
Sampling
Quantization
Pulse code modulation (PCM)

Source Coding

Predictive coding
Block coding
Variable length coding
Synthesis/analysis coding
Lossless compression
Lossy compression

Baseband Signaling

PCM waveforms (line codes)
- Nonreturn-to-zero (NRZ)
- Return-to-zero (RZ)
- Phase encoded
- Multilevel binary

M-ary pulse modulation
- PAM, PPM, PDM

Equalization

Maximum-likelihood sequence estimation (MLSE)

Equalization with filters
- Transversal or decision feedback
- Preset or Adaptive
- Symbol spaced or fractionally spaced

Bandpass Signaling

Coherent

Phase shift keying (PSK)
Frequency shift keying (FSK)
Amplitude shift keying (ASK)
Continuous phase modulation (CPM)
Hybrids

Noncoherent

Differential phase shift keying (DPSK)
Frequency shift keying (FSK)
Amplitude shift keying (ASK)
Continuous phase modulation (CPM)
Hybrids

Channel Coding

Waveform

M-ary signaling
Antipodal
Orthogonal
Trellis-coded modulation

Structured Sequences

Block
Convolutional
Turbo

Synchronization

Frequency synchronization
Phase synchronization
Symbol synchronization
Frame synchronization
Network synchronization

Multiplexing/Multiple Access

Frequency division (FDM/FDMA)
Time division (TDM/TDMA)
Code division (CDM/CDMA)
Space division (SDMA)
Polarization division (PDMA)

Spreading

Direct sequencing (DS)
Frequency hopping (FH)
Time hopping (TH)
Hybrids

Encryption

Block
Data stream

Figure 1.3 Basic digital communication transformations.

Performance Metrics

- Analog Communication Systems
  - Metric is fidelity: want $\hat{m}(t) \approx m(t)$
  - SNR typically used as a performance metric
- Digital Communication Systems
  - Metrics are data rate (R bps) and probability of bit error

$$\left(P_b = p(\hat{b} \neq b)\right)$$

  - Symbols are already known at the receiver
  - Without noise/distortion/sync. problem, we will never make bit errors

Main Points

- Transmitters modulate analog messages or bits in case of a DCS for transmission over a channel.
- Receivers recreate signals or bits from received signal (mitigate channel effects)
- Performance metric for analog systems is fidelity, for digital it is the bit rate and error probability.

Goals in Communication System Design

- To maximize transmission rate, ***R***
- To maximize system utilization, ***U***
- To minimize bit error rate, P_e
- To minimize required systems bandwidth, ***W***
- To minimize system complexity, C_x
- To minimize required power, E_b/N_o