CT111 Introduction to Communication Systems
Lecture 2: Models and Functions

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Overview of Today's Talk

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1. Model and Functionalities
   - Types of Communication Systems
2. An Overview of the ARQ at the Data Link Layer
3. An Overview of the Physical Layer

Overview of Today's Talk

Types of Communication Systems

1. Analog Communication Systems: directly transfers messages that are continuous in time and in voltages (e.g., microphone output)
   - Historically, first to be developed
   - Many radio stations today are still analog systems
   - Two important types: Amplitude Modulation (AM), Frequency Modulation (FM)
2. Digital Communication Systems: transfers messages that are discrete (i.e., one of a finite number of messages)
   - Can deal with analog information sources (their output has to be discretized both in time and in voltages)
   - May either transmit the discrete messages directly or convert them to analog signal before transmission. The later scheme is often preferred since it facilitates long-distance communication

Advantages of Digital Communication Systems

as compared to Analog

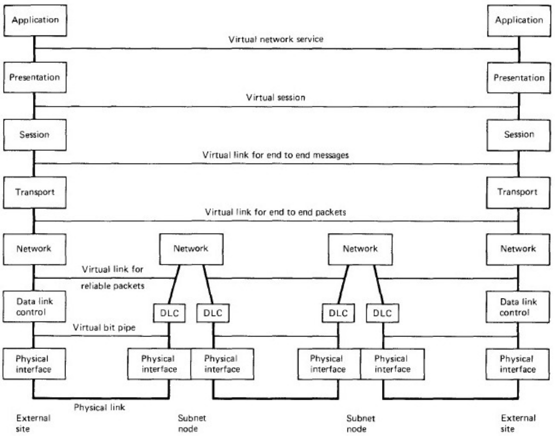
1. Any noise introduces irrecoverable distortion in the analog signal. In comparison, the a digital receiver needs to distinguish only a finite number of transmitted data. Thus, it is possible to completely remove the effect of noise.
2. Many performance enhancing signal processing techniques, such as source coding, channel coding, encryption, etc., require digital processing.
3. Digital technology, for which the primary currency is bits (Digital Integrated Circuits (ICs), and in general, the computers and the smartphones and their networks), has become very powerful and are inexpensive to manufacture.
4. Digital Communications allows integration of voice, video and data on a single packet networking system.
5. Easier to preserve privacy by encryption of digital messages
6. Compared to analog communication systems, digital communications provides a better tradeoff of bandwidth efficiency against energy efficiency (i.e., exchange the power with the bandwidth).

Types of Digital Communication Systems

1. Circuit Switched Systems: the communication link is reserved at a certain fixed data rate between two endpoints (entities)
   - Cannot reuse the capacity of the link for other users even if the reserved session is under utilized or not utilized
2. Store and Forward Systems: no reservation of the communication link is made a-priori (often referred to as packet switched systems, although several variants are possible (message switching, virtual circuit routing, etc.))
   - Better utilization of the communication link
   - However, the packet routing scheme has to be defined, and queuing delays at the routers have to be managed by an appropriate flow control mechanism

A Model of Digital Communication Systems

Seven Layers (Read B&G Chapter 1



A Model of Digital Communication Systems

Seven Layers (Read B&G Chapter 1

- *Application Layer.* This is where the "apps" operate (WhatsApp, facebook, FTP, emails, etc.)
- *Presentation Layer.* Performs encryption, data compression, semantics conversion (also known as code conversion)
- *Session Layer.* Sets up the data session, including the session rights, load sharing, quality of service, etc.
- *Transport Layer.* Performs segmentation of messages into packets and reassembly of packets into message, also provides overall (end-to-end) flow control and error control, may split a high rate session into multiple low-rate sessions and vice versa

A Model of Digital Communication Systems

Seven Layers (Read B&G Chapter 1

- *Network Layer.* Performs routing of the packets, and flow/congestion control. One of the most complex layers. Has Internet Sublayer.
- *Data Link Layer.* Performs segmentation and reassembly of Network packets, performs Automatic Repeat Requests (ARQ), also, with Medium Access Control (MAC) sublayer, provides control mechanisms for the shared access of the communication medium or channel

An Aspect of Operation of Data Link Layer

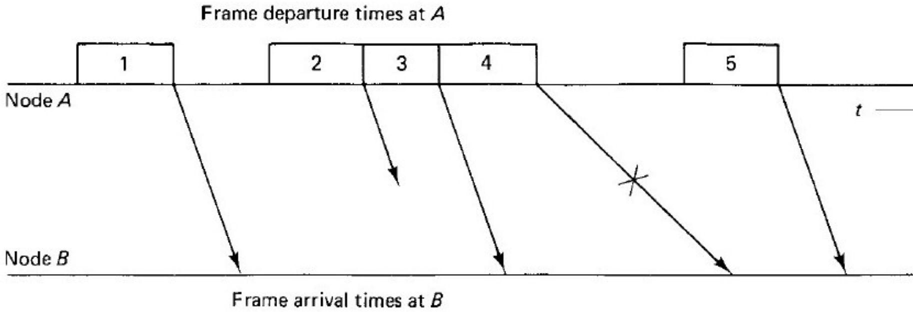
Read B&G Chapter 1

- There are three armies, two colored magenta and one lavender. The lavender army separates the two magenta armies
- If the magenta armies can attack simultaneously, they win, but if they attack separately, the lavender army wins.
- The only communication between the magenta armies is by sending messengers through the lavender army lines, but there is a possibility that any such messenger will be captured, causing the message to go undelivered
- Each magenta army is unwilling to attack unless assured with certainty that the other will also attack.
  - → The first army might send a message saying, "Let us attack on Saturday at noon; please acknowledge if you agree."
  - → The second army, hearing such a message, might send a return message saying, "We agree; send an acknowledgment if you receive our message."

It is not hard to see that this strategy leads to an infinite sequence of messages, with the last army to send a message being unwilling to attack until obtaining a commitment from the other side.

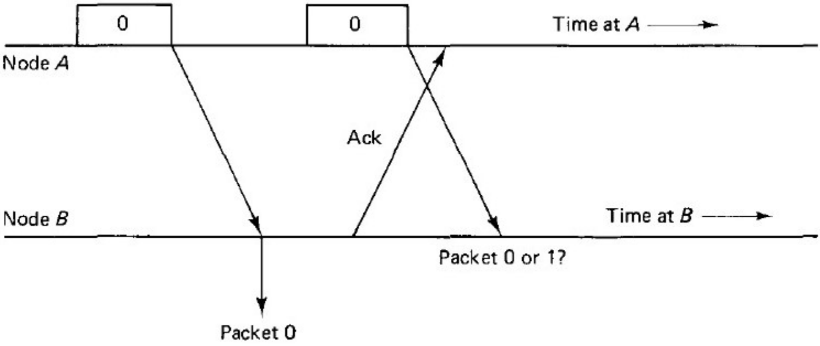
Frame Transmissions at Data Link Layer.

Need of Acknowledgements (ACKs). Fig. 2.17 of B&G



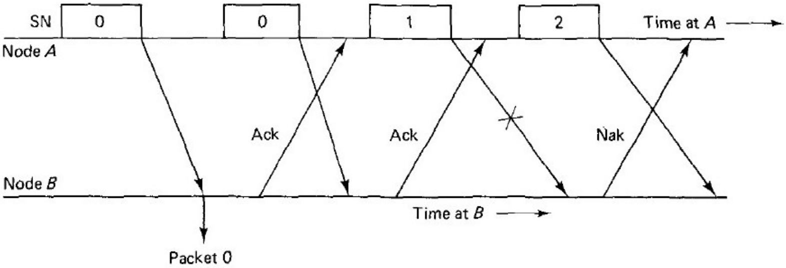
Problem with Unnumbered Packets

Fig. 2.18 of B&G

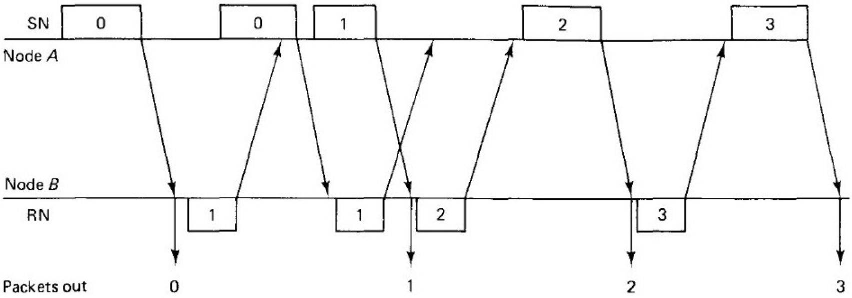


Problem with Unnumbered ACKs

Fig. 2.19 of B&G



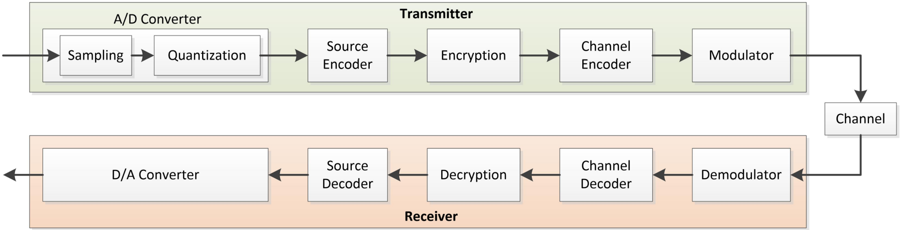
Stop and Wait ARQ Protocol
Fig. 2.21 of B&G



Improvements over Stop and Wait ARQ

- Although the Stop and Wait ARQ works correctly, it is highly inefficient (since both the sender and the receiver spend a lot of time idling)
- Two enhancements: Go Back n ARQ, and Selective Repeat ARQ

A Model of Digital Communication Systems
Physical Layer



Functionalities of Physical Layer

- *Input to digital communication systems is often analog;* and it is often from voice, video, image. Continuous in time and in amplitude.
- *Sampling* makes the signal discrete in time domain. If the signal is bandlimited, there is a theorem (Sampling Theorem) that says that perfect reconstruction of the original signal is possible just from its samples.
- *Quantization* makes the signal discrete in amplitude, typically results in some distortion. The greater the number of quantization levels L (which translates to the bit size of the quantizer $\log_2(L)$), the smaller the distortion. Good designs of the quantizer ensure that the distortion is small while using a small number of bits. We will study both scalar and vector quantizers.
- *Digital data:* In case the input to the communication systems is already in digital format, the above two functions (sampling and quantization) are not needed.

Functionalities of Physical Layer

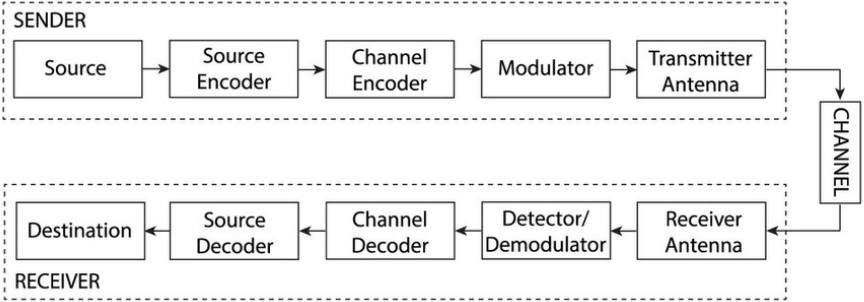
- *Source coding* entails compression of digital data to eliminate redundancies. Can by lossy or lossless compression. Lossy compression is like quantization, introduces distortion but achieves a reduction in the bit rate. Lossless compression schemes reduce the bit rate without introducing the distortion.
- *Encryption* provides data privacy. This course does not talk about encryption in detail.
- *Channel Encoding* provides protection against transmission errors by selectively inserting redundant bits. While quantizer and source encoder work to squeeze out the redundant information, channel encoder inserts redundant information in a selective manner.
- *Modulator* converts digital data to a continuous waveform, usually a sinusoidal wave, suitable for transmission over a channel. Information is transmitted by varying one or more parameters of the waveform.

Functionalities of Physical Layer

- *Channel* carries the signal - could be a telephone wire, free space, etc. Presents distorted signal to the receiver. Effects include attenuation, fading, noise, etc. We will often assume that channel is simple and introduces just additive white Gaussian noise or AWGN.
- *Receiver* functionalities that are mathematical inverses of the transmitter functionalities: demodulation, channel decoding, Decryption, Source Decoding, Digital to Analog Conversion. We will spend a lot of time on the receiver functionalities.

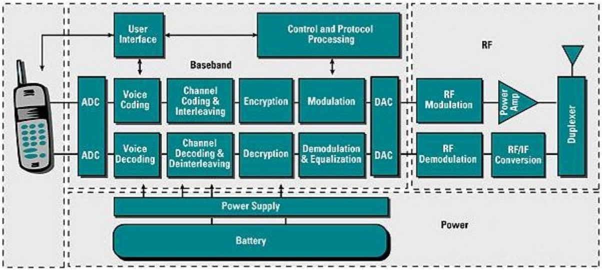
A Model of Digital Communication Systems

Physical Layer: A Practical Block Diagram



A Model of Digital Communication Systems

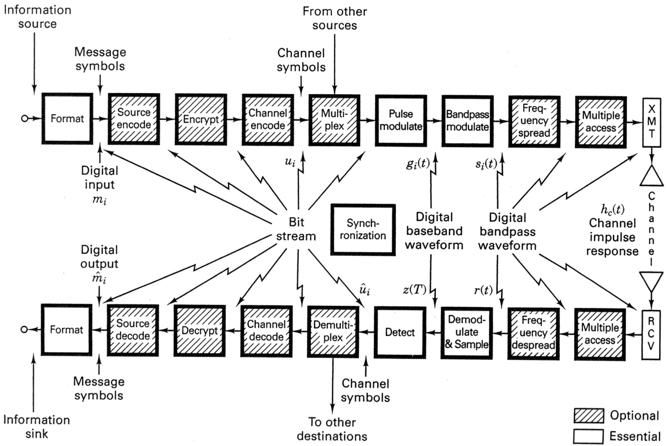
Physical Layer: Another Representative Block Diagram



→ http://ntrg.cs.tcd.ie/mobile/digital_radio_tutorial.html

A Model of Digital Communication Systems

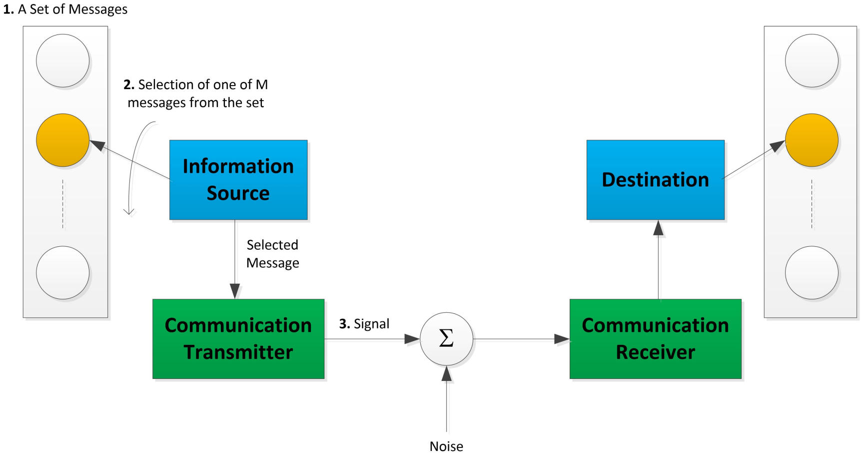
Physical Layer: A Representative Block Diagram



→ https://fypfpga.wordpress.com/2011/07/05/background/

A Model of Digital Communication Systems

Physical Layer: A Conceptual Block Diagram



Functionalities of Physical Layer

Modulation or Conversion of Messages into Signals

Parameters that can be modulated:

- Amplitude: this is called On Off Keying (OOK) or Amplitude Shift Keying (ASK).

$$1 \Rightarrow s(t) = A\cos(2\pi f_c t)$$
$$0 \Rightarrow s(t) = 0$$

- Frequency: this is called Frequency Shift Keying (FSK).

$$1 \Rightarrow s(t) = A\cos(2\pi f_{c,1} t)$$
$$0 \Rightarrow s(t) = A\cos(2\pi f_{c,2} t)$$

- Phase: this is called Phase Shift Keying (PSK).

$$1 \Rightarrow s(t) = A\cos(2\pi f_c t)$$
$$0 \Rightarrow s(t) = A\cos(2\pi f_c t + \pi) = -A\cos(2\pi f_c t)$$

Functionalities of Physical Layer

Parameters that can be modulated:

- Amplitude and Phase: this is called Quadrature Amplitude Modulation (QAM).
- Modern Communications Theory views channel coding and modulation as single operation. This results in Trellis coded modulation.
- Choice of modulation greatly affects the system performance

A Model of Digital Communication Systems

Physical Layer: A Conceptual Block Diagram

Key design parameters:

1. Size M of the message set: determines number of bits N required to convey the message
   - $\rightarrow$ $N = \log_2 M$
2. How fast the messages are selected: determines the number of messages per second
   - $\rightarrow$ the larger the message set size and/or the greater the speed of the message transfer, the bit rate R = the number of bits per second, increases
   - $\rightarrow$ Greater the bit rate R, the greater the information that gets conveyed. However, greater also is the work that the communication system has to do.
3. The power P_s that the communication receiver gets (determined by the power that the transmitter can put in the transmitted signal), the spectral bandwidth W that it has and the power P_n of the noise that the communication channel introduces

A Model of Digital Communication Systems

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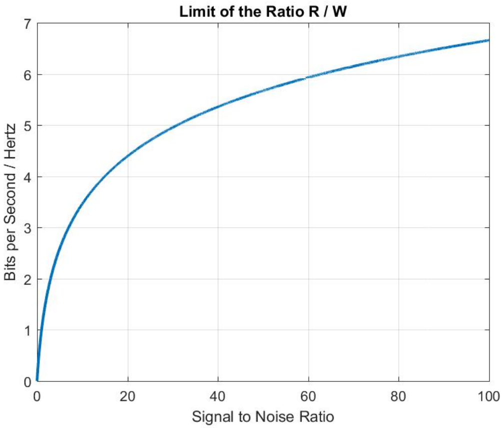
A Fundamental Limit on Communications
Shannon Information Theory

→ The celebrated relationship:
$$R \leq W \log_2 \left(1 + \frac{P_s}{P_n}\right)$$



Bandwidth Efficiency η_B

- As data rate R increases, the pulse width of transmitted signal reduces and therefore the bandwidth B, which is inversely proportional to the transmitted pulse width, increases.
- This cannot be avoided; however some schemes use the available bandwidth more efficiently than the others
- We will denote the ratio R/W as the bandwidth efficiency η_B.
- It is obviously better to have η_B as large as possible. However, there is a cost associated to making η_B large.

Energy Efficiency η_E

- Digital communication systems are characterized by the signal to noise ratio (SNR) P_s/P_n required to attain a certain performance (e.g., bit error probability P_b that is below certain threshold, say, 10^{-6})
  - $\rightarrow$ Often an equivalent metric E_b/N_0, which can be thought of as SNR per transmitted bit, is used
- Typically making η_B large requires E_b/N_0 to be large; this entails a corresponding increase in transmit energy E_b.
- We will define energy efficiency η_E as $\left(\frac{E_b}{N_O}\right)^{-1}$ required to attain some small probability of bit errors (e.g., $P_b = 10^{-6}$). Greater the required $\frac{E_b}{N_O}$, the smaller the energy efficiency.

Fight between η_E and η_B

- As it often is the case in the life, it is hard to get best of both the worlds. Typically an increase in η_B translates to a decrease in η_E and vice versa.
- Binary modulation sends only one bit per use of the channel. $M-$ary modulation sends multiple bits for each use of the channel and provides for an increase in the bandwidth efficiency η_B. However, $M-$ary modulation schemes are typically energy inefficient and have low η_E.
- Channel coding increases redundant bits to provide better bit error rate for a given E_b/N_0 or a reduced E_b/N_0 for a given BER. Thus, channel coding improves η_E. However, the redundant bits require greater bandwidth for transmission, and therefore, channel coding reduces η_B.

Exchange of Power and Bandwidth

- Trade-off between bandwidth and energy efficiencies can be viewed as the *equivalence* between the power and the bandwidth
- If the system designer has a fixed transmit power (i.e., the design is limited or handicapped by the transmit power), this limit can be overcome to some extent by increasing the bandwidth
- Vice versa, if the bandwidth is limited, the power can be increased to obtain the desired data rate