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REVIEW OF DIGITAL COMMUNICATIONS

Notes prepared for EE 6310

by

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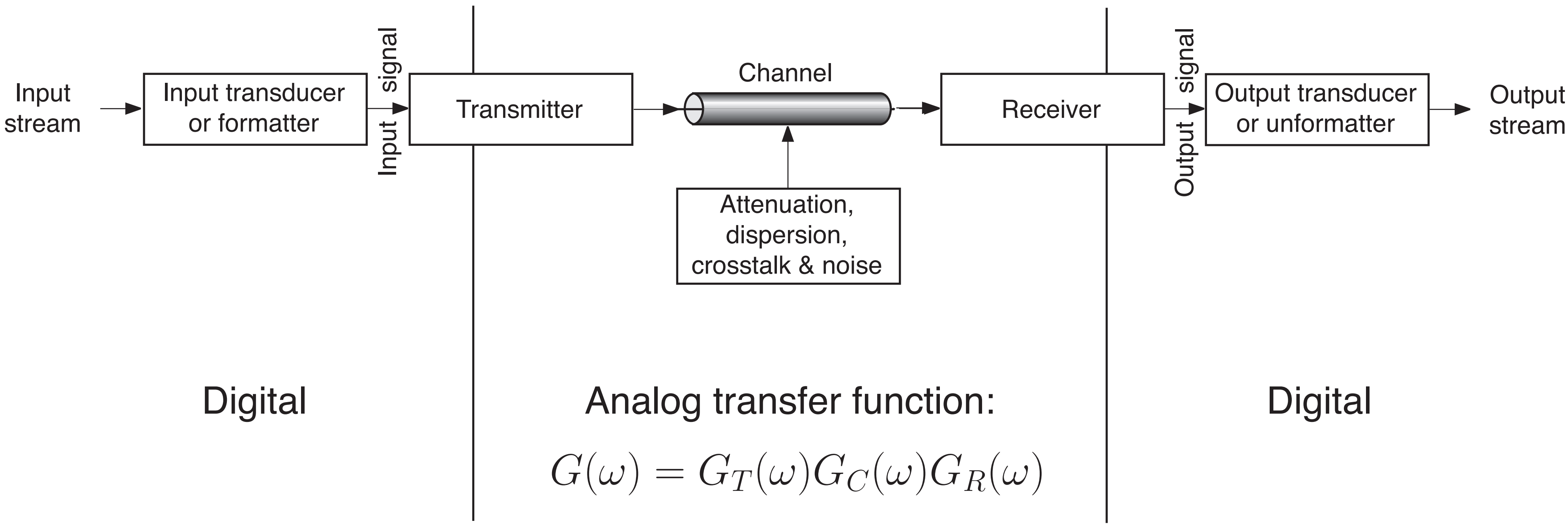
ANALOG vs. DIGITAL COMMUNICATION

- **Analog communication** uses continuous-time signals that:
  - ▷ Can (in principle) take any real value
  - ▷ When received, produce an output that also varies continuously
  - ▷ Degrade gradually in the presence of physical effects such as attenuation, dispersion, low bandwidth, or noise
    - ◦ A high point of analog communication technology: The superheterodyne receiver
- **Digital communication** uses continuous-time signals that:
  - ▷ Represent bits or bit groups using a finite, standard alphabet
    - ◦ Continuous-time inputs are sampled, giving discrete-time series that are digitized and encoded before being transmitted
  - ▷ When received, produce an output that is interpreted as bits or bit groups
  - ▷ Can be "cleaned up" from some distortion and noise, but generally do not degrade gracefully below a minimum signal-to-noise ratio
- In simple words, digital is profoundly different from analog

A DIGITAL COMMUNICATION LINK



$$G(\omega) = G_T(\omega)G_C(\omega)G_R(\omega)$$

- The link includes both analog and digital parts
  - ▷ For a digital link, the analog part is the transmitter, channel and receiver
  - ▷ For a linear, time-shift-invariant link, the transfer function defines the bandwidth, total attenuation and dispersion from transmitter input to receiver output

WHY *DIGITAL* COMMUNICATIONS?

- Digital encoding and decoding uses a finite **alphabet** of standard waveforms to represent bits or bit groups
- Digital techniques greatly reduce the effects of noise and distortion, and make it possible to approach theoretical information-capacity limits
  - ▷ Attenuation reduces the signal amplitude, but does not reduce the noise inserted by the channel in the same frequency band that the signal uses
  - ▷ Dispersion changes the waveform's shape in the course of propagation
- An analog system designer has very few means to disentangle the signal from the noise or the distortion
  - ▷ Remember long-distance calls carried on analog channels?
- Digital communication changes the paradigm from **waveform replication** to **waveform recognition**
  - ▷ Distortion and noise don't matter, as long as each digital waveform can be recognized and distinguished from a small set of other waveforms

ADVANTAGES OF DIGITAL COMMUNICATIONS

- Fewer errors than analog transmission
- Higher efficency
- Higher maximum transmission rates
- A digital bitstream is easier to encrypt than an analog stream $\Rightarrow$ better security
- Integrating voice, video and data is simpler with digital transmission than with analog transmission

LOGICAL vs. PHYSICAL LINKS

- Physical channels can be baseband or broadband
  - ▷ A broadband channel can share the medium with other physical channels
- Each physical channel supports one or more logical links
  - ▷ If several logical links originate at one host, one speaks of **multiplexing** the logical links onto the physical link
  - ▷ If several logical links originate from different hosts, one speaks of **multiple access** to the physical link
- Multiplexing and switching technologies drive the architecture of the network
  Example:
  - ▷ Multiple wavelengths in a single fiber (with one logical channel per wavelength) permits optical amplification and switched all-optical datapaths
  - ▷ One wavelength per fiber (with time-division-multiplexed logical channels) requires opto-electronic conversion at every node

PHYSICAL CHANNELS

- Types of physical channels that support data communication:
  - ▷ Point-to-point: A channel between exactly two hosts (or one host and one peripheral device)
    - ◦ Examples:
      - ◇ Cable connection from PC serial port to printer
      - ◇ Crossover cable Ethernet connection between two PCs
      - ◇ Telephone call set up between a home PC and an ISP's server
  - ▷ Multipoint: A channel shared by more than two hosts or peripherals
    - ◦ Examples:
      - ◇ An external SCSI bus
      - ◇ An external USB or Firewire bus
      - ◇ An Ethernet
      - ◇ A wireless LAN

POINT-TO-POINT LINKS

- A **point-to-point link** uses a physical channel between two only 2 host computers over which information can be transmitted
  - ▷ Channels are transmission lines or waveguides
    - ◦ Linear, time-shift-invariant systems (for most purposes)
  - ▷ Main physical properties for purposes of communication:
    - ◦ Bandwidth
    - ◦ Maximum transmission distance
  - ▷ Electrical/electromagnetic properties that determine data bandwidth and maximum transmission distance:
    - ◦ Delay
    - ◦ Transmission-line effects
    - ◦ Attenuation
    - ◦ Crosstalk and noise

PROPERTIES OF COMMUNICATION CHANNELS (1)

- **Delay**
  - ▷ **Propagation time**:

$$(\text{propagation time across a channel of length } L) = \frac{L}{v_g}$$

  - ∘ v_g is the **group velocity**, i.e., the velocity of a pulse
  - ∘ v_g is usually almost equal to the **phase velocity**, i.e., the velocity of a theoretical monochromatic wave of infinite duration

  - ▷ **Transmission time**

$$(\text{transmission time for } N \text{ bits into a channel of bandwidth } \Delta f) = \frac{N}{\Delta f}$$

  - ▷ **Total delay**

$$\begin{aligned}\text{total delay} =& \text{transmission time} + \text{propagation time} \\ &+ \text{buffering time} + \text{processing time}\end{aligned}$$

PROPERTIES OF COMMUNICATION CHANNELS (2)

- **Transmission-line effects**
  - ▷ **Characteristic impedance**:

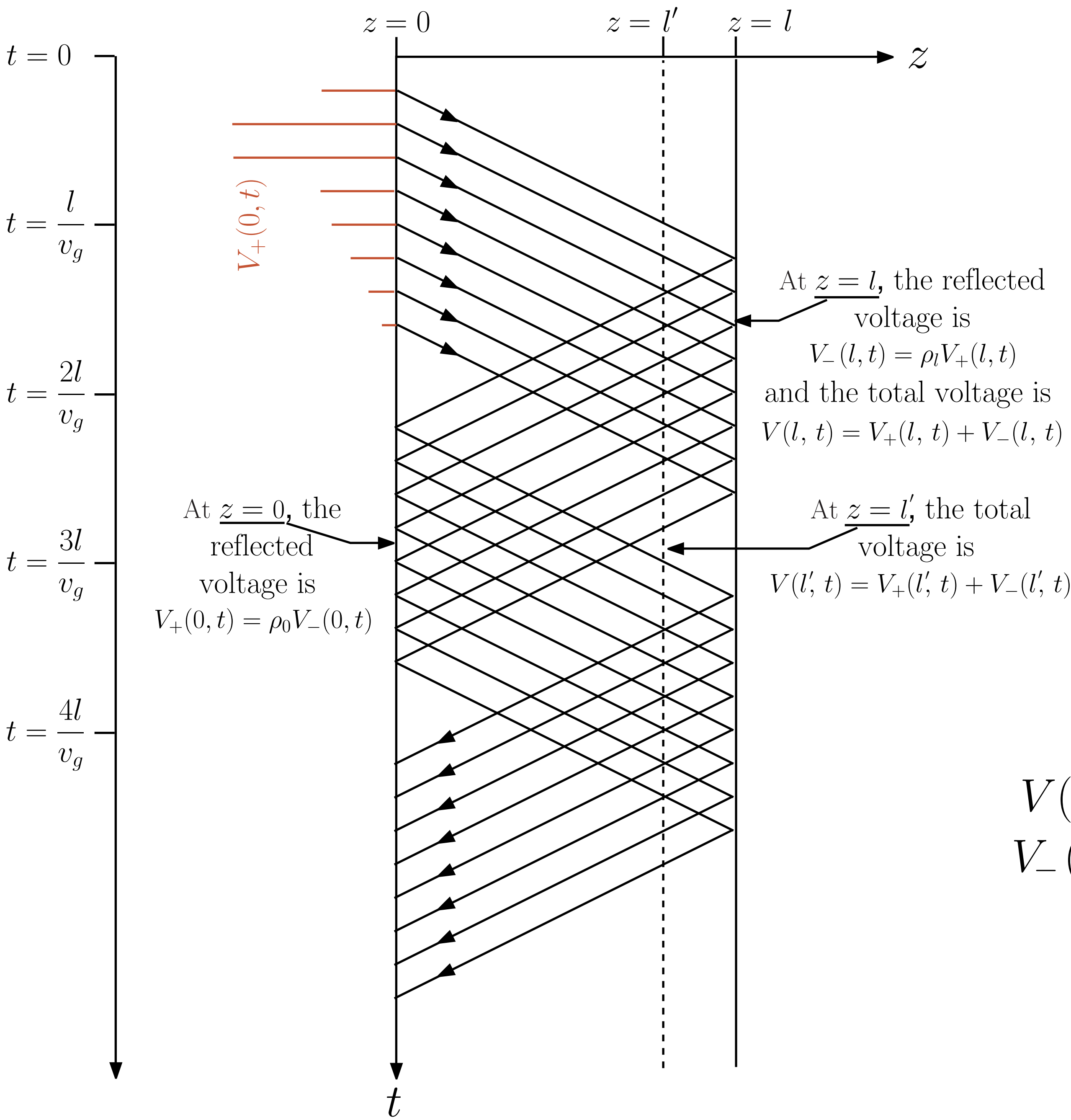
$$Z_0 = \sqrt{\frac{L}{C}}$$

    - ○ If the line is terminated with an impedance Z_L that is not equal to Z_0, then energy is reflected back towards the transmitter
    - ○ Improperly terminated lines may be unusable for communications
  - ▷ **Reflection coefficient**:

$$\rho = \frac{Z_L - Z_0}{Z_L + Z_0}$$

    - ○ Reflections can be analyzed in the time domain by using a bounce diagram

Visualization of a pulse on a transmission line using a bounce diagram

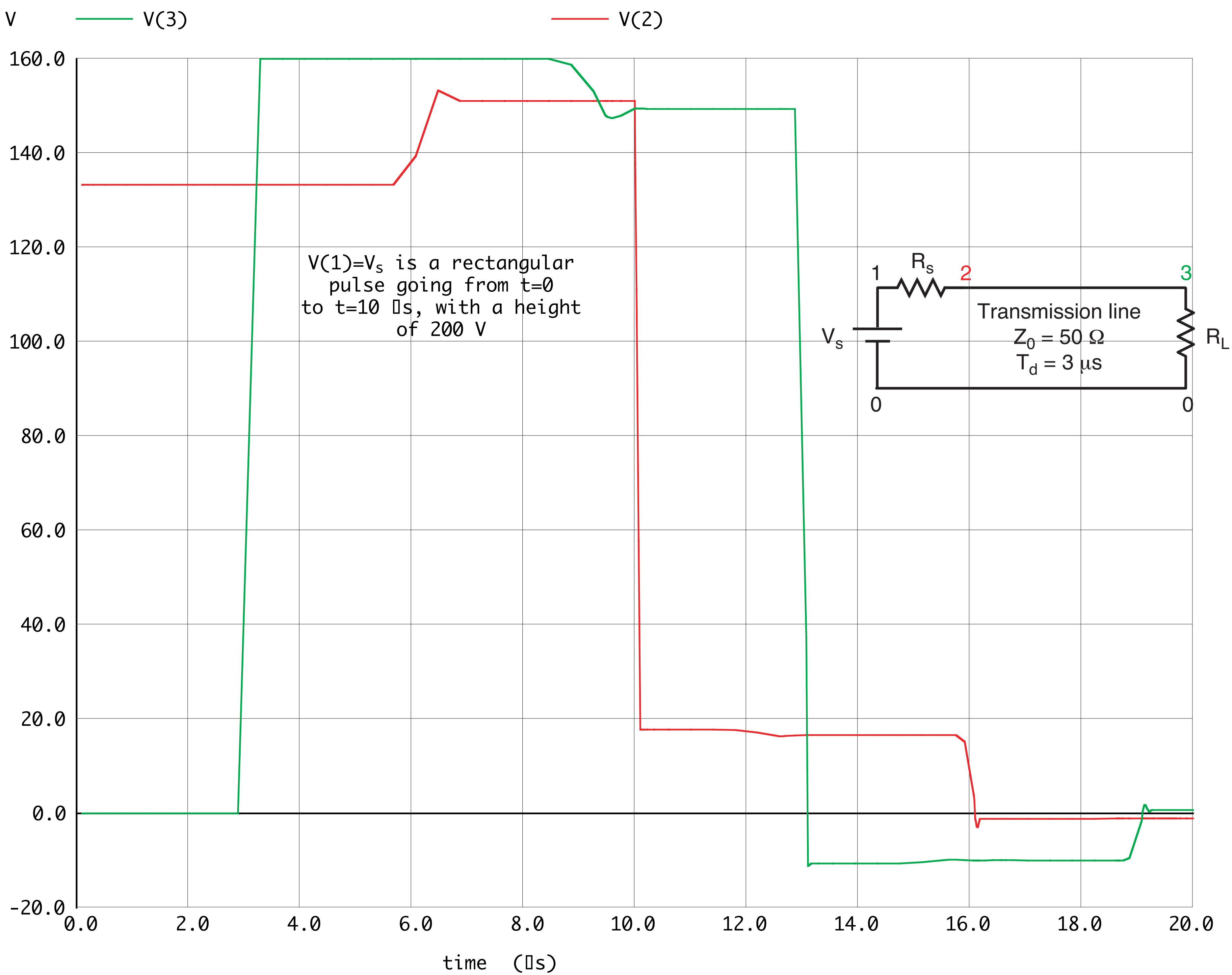


Basic equations:

$$V(z,t) = V_+(z,t) + V_-(z,t)$$

$$V_-(l,t) = \rho_l V_+(l,t)$$

$$\rho = \frac{Z_L - Z_0}{Z_L + Z_0}$$



V
V(3)
V(2)
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
time (μs)
V(1)=Vs is a rectangular pulse going from t=0 to t=10 μs, with a height of 200 V
1
Rs
2
3
Vs
Transmission line
Z0 = 50 Ω
Td = 3 μs
RL
0
0

PROPERTIES OF COMMUNICATION CHANNELS (3)

- **Attenuation**

$$\frac{\text{Power received at a distance } L \text{ from the transmitter}}{\text{Power transmitted}} = e^{-\alpha L}$$

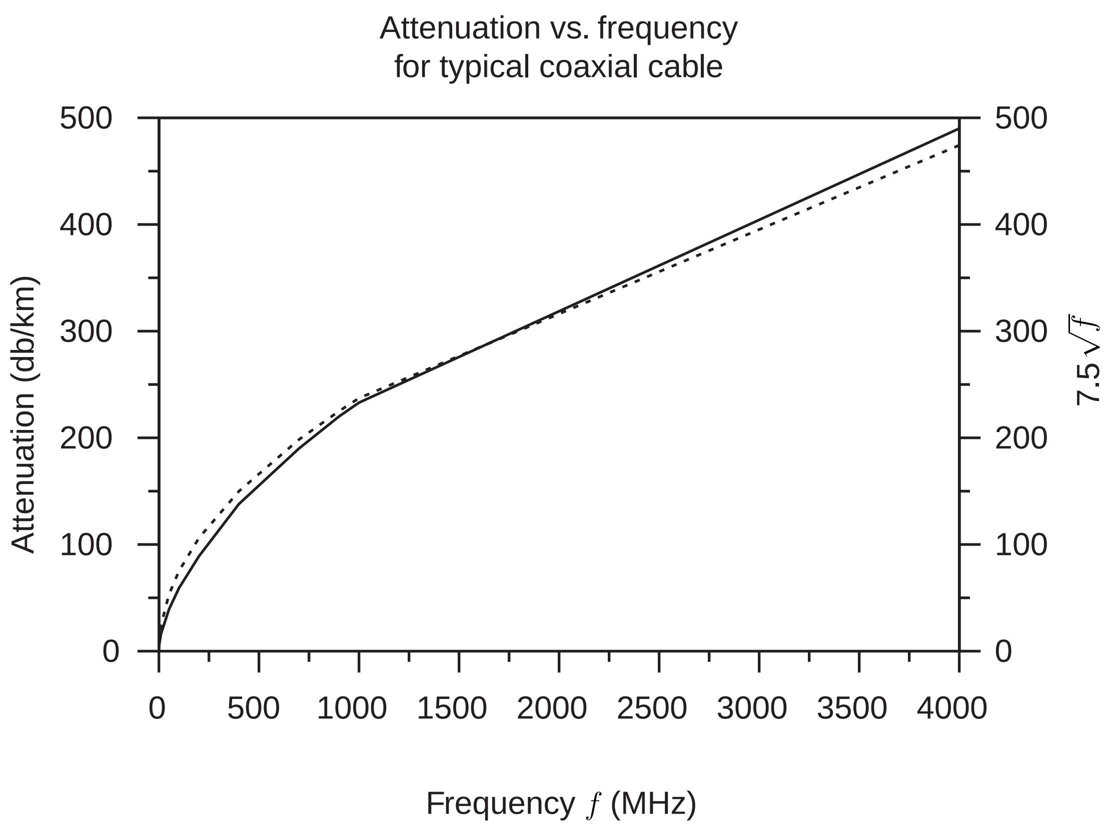
  - ▷ α is the **attenuation coefficient** (units are cm^{-1} or m^{-1})
  - ▷ Loss in dB $= 10(\log_{10} e)\alpha L \approx 4.343\,\alpha L$
  - ▷ Practical units of the attenuation coefficient are dB/km or dB/m
  - ▷ In metallic transmission lines, α depends on the frequency f, mainly because of the skin effect
    - ∘ Skin depth $\delta(f) = 1/\sqrt{\pi f \mu \sigma}$
    - ∘ For a coaxial transmission line with inner radius r_i and outer radius r_o,

$$\alpha(f) \approx \frac{R_s(f)}{2\eta \ln(r_o/r_i)} \left(\frac{1}{r_o} + \frac{1}{r_i} \right) \quad \text{m}^{-1}$$

where the surface resistance is

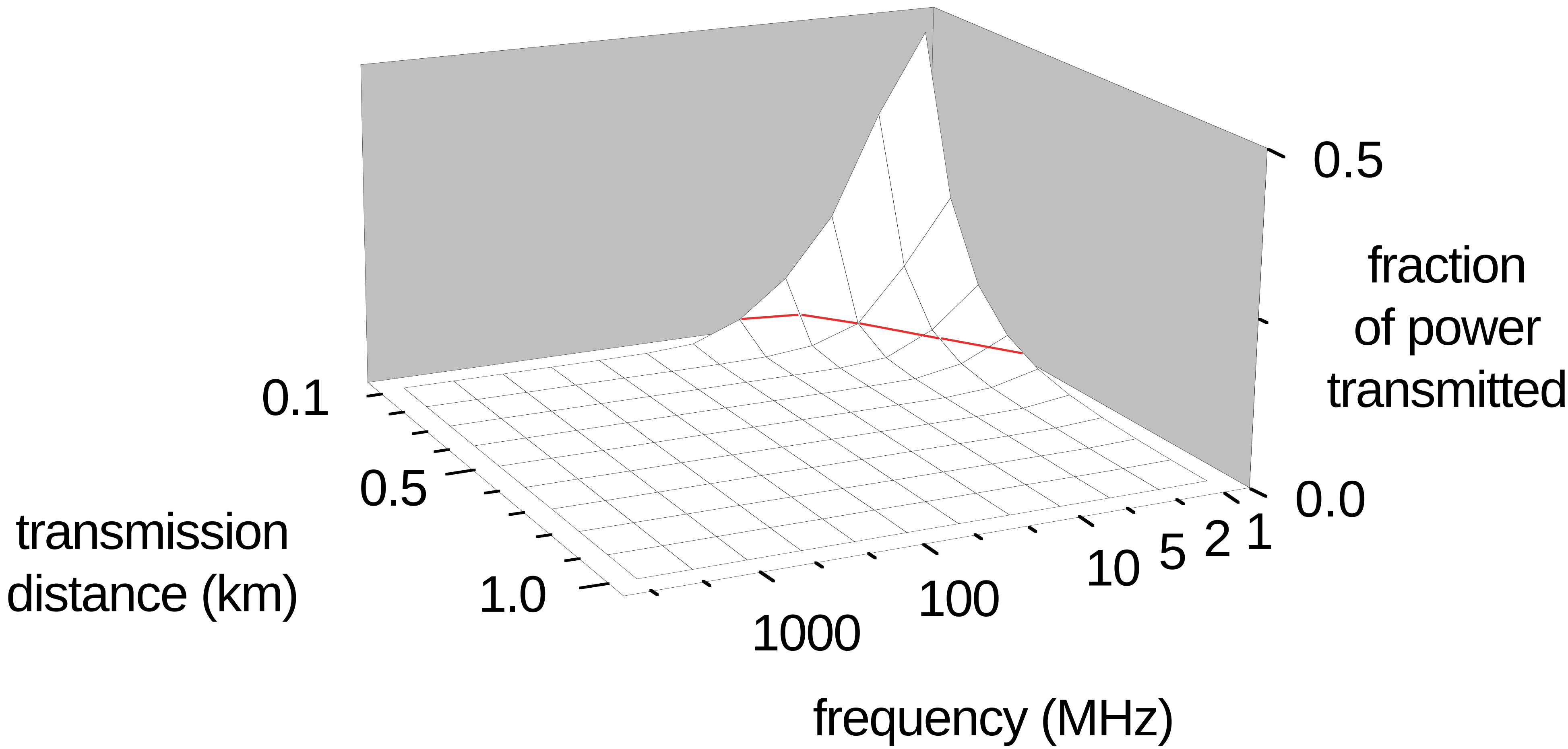
$$R_s(f) = \sqrt{\frac{\pi f \mu}{\sigma}} \quad \text{ohms}$$

ATTENUATION IN COAXIAL CABLE



- The dashed line shows a constant times $\sqrt{f}$

BANDWIDTH DEPENDS ON TRANSMISSION DISTANCE



- The red curve indicates a constant value of attenuation in copper cable

PROPERTIES OF COMMUNICATION CHANNELS (4)

- **Crosstalk**
  - ▷ Crosstalk = unwanted waveforms induced in a channel by waveforms in adjacent channels
  - ▷ Crosstalk cannot be cancelled easily, because a crosstalk waveform is not related to the transmitted waveform in the target channel
  - ▷ Origin in electrical transmission lines: (Mostly) capacitive coupling
    - ∘ Inductive or radiative coupling may occur at high frequencies
  - ▷ Crosstalk between WDM channels in fiber is due to cross-phase modulation or 4-wave mixing
- **Noise**
  - ▷ Information is carried by a pulse train or an analog waveform
  - ▷ **Bit error rate** = probability that a waveform that was transmitted as a 1 bit will be detected as representing a 0 bit (or vice versa)

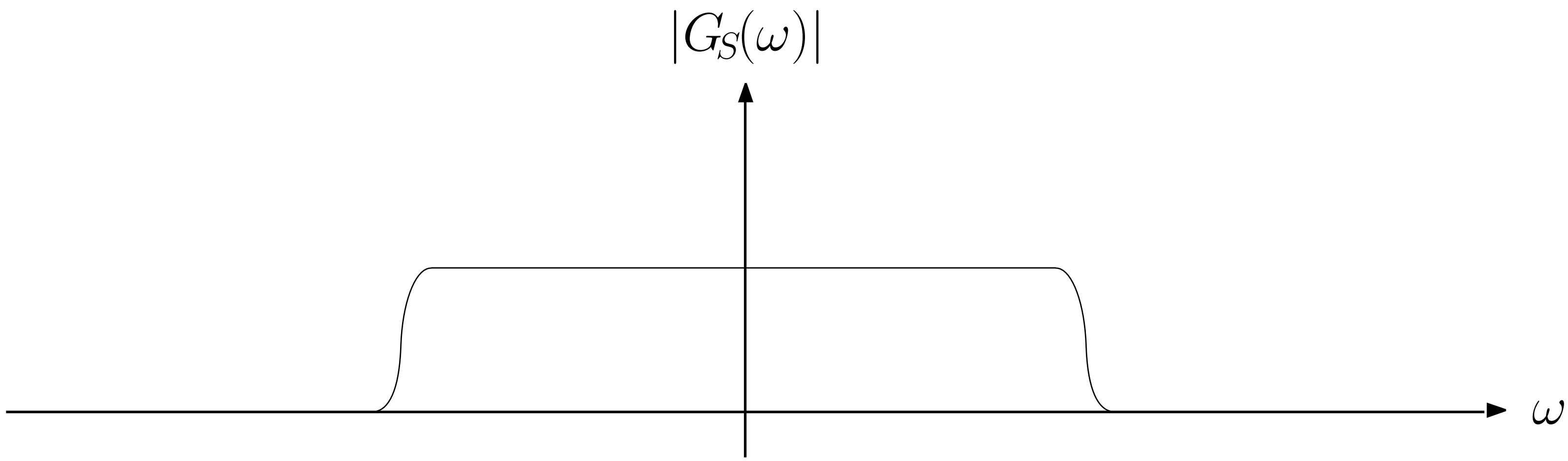
BANDWIDTH USAGE OF COMMUNICATION LINKS (1)

- Baseband
  - ▷ Information is carried by a pulse train or an analog waveform
  - ▷ Digital baseband is bit-serial or bit-group-serial
  - ▷ Optimal when

$$\text{spectral width of channel} \approx \text{spectral width of link}$$

  - ▷ Examples:
    - ∘ RS-232, RS-422 over multiconductor cable
    - ∘ Ethernet over 2- or 4-twisted pair cable or multimode optical fiber
    - ∘ DS-1 transmission of multiplexed, digitized voice circuits over repeatered twisted-pair cable
    - ∘ Long-haul, OC-12c or OC-48c data transmission over repeatered single-mode optical fiber

BASEBAND SPECTRUM



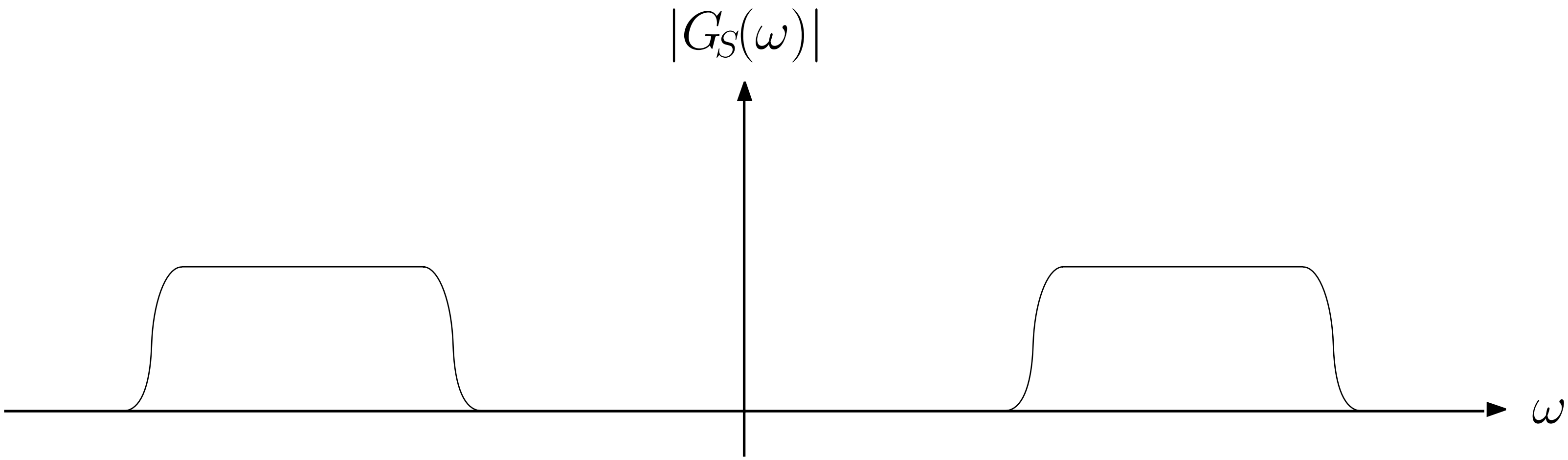
BANDWIDTH USAGE OF COMMUNICATION LINKS (2)

- Broadband (analog), passband (digital)
  - ▷ Multiple channels share the bandwidth of the link
  - ▷ Useful when

$$\text{spectral width of one channel} \ll \text{spectral width of link}$$

  - ▷ Examples:
    - ◦ Long-haul, OC-12c or OC-48c data transmission over repeatered single-mode optical fiber
      - ◇ A digital waveform is used to modulate an optical-frequency carrier
    - ◦ Wavelength division multiplexing (WDM) ($\equiv$ optical FDMA)
      - ◇ Each channel has its own wavelength and bandwidth
    - ◦ Time division multiple access (TDMA)
      - ◇ Each channel is broadened to use the bandwidth of the link
      - ◇ Sharing of the channel occurs in signal space, not frequency space

PASSBAND SPECTRUM (ONE CHANNEL)

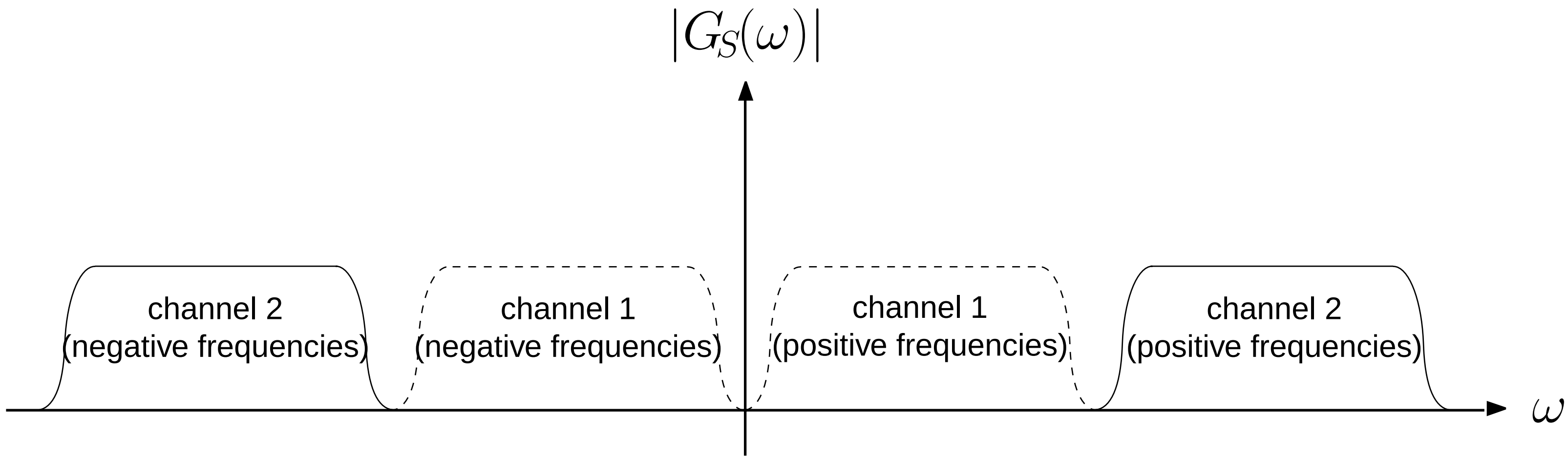


- A real signal that is generated by modulating a carrier is a linear combination of positive and negative frequencies:

$$v(t) = |v_0(t)| \cos\big(\omega t + \phi(t)\big) = v_0(t)e^{j\omega t} + v_0(t)^* e^{-j\omega t}$$

  ▷ $v_0(t)$ is the complex envelope of the wave
    ◦ Only $|v_0(t)|$ varies ⇒ amplitude modulation
    ◦ Only $\phi(t)$ varies ⇒ phase (or frequency) modulation

PASSBAND SPECTRUM (TWO CHANNELS)



- Two modulated cosine signals:

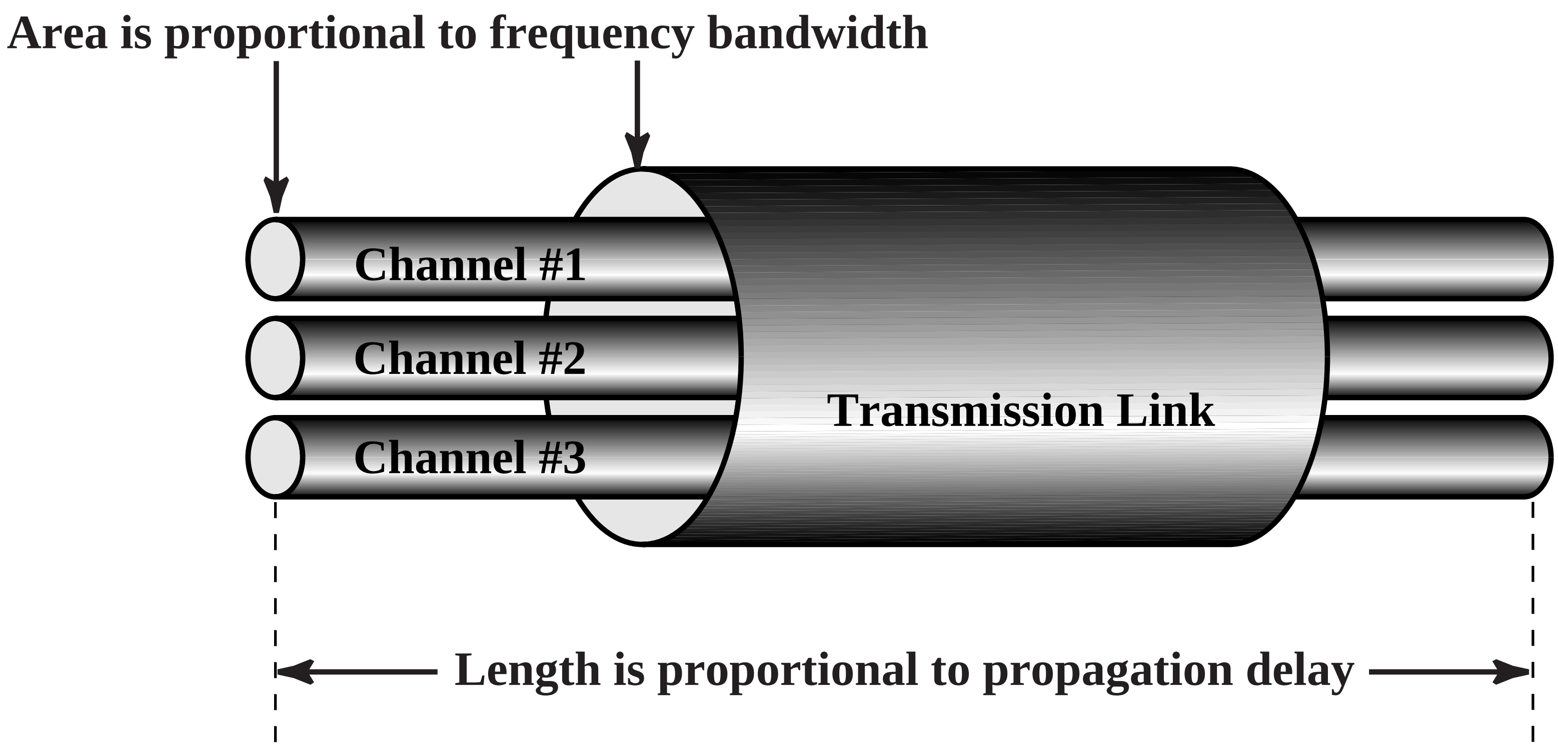
$$v(t) = |v_1(t)| \cos\big(\omega_1 t + \phi_1(t)\big) + |v_2(t)| \cos\big(\omega_2 t + \phi_2(t)\big)$$

EXAMPLES OF BROADBAND TECHNOLOGIES

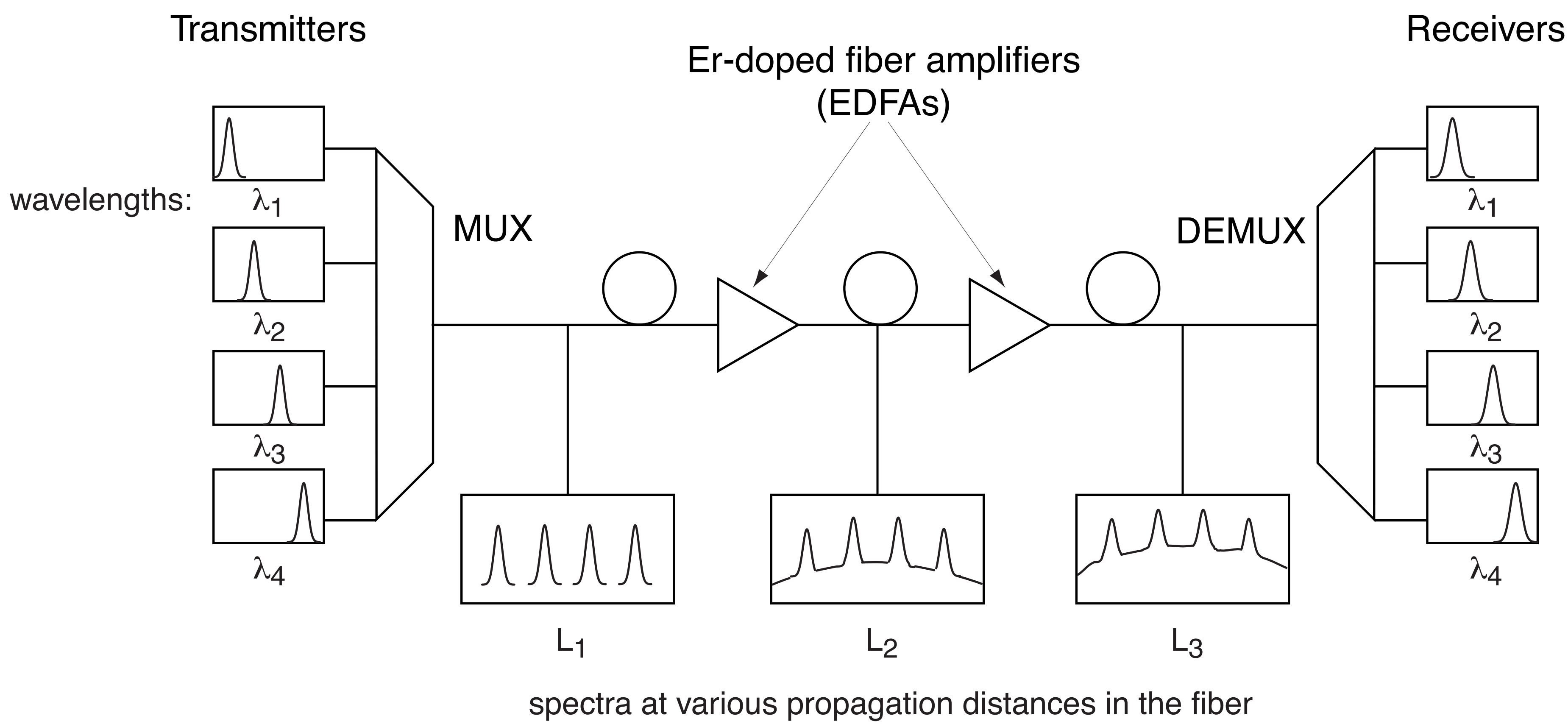
- Frequency division multiple access (FDMA) (RF)
  - ▷ Each channel has its own carrier frequency and bandwidth
  - ▷ Example 1: Broadcast cable TV network
    - ◦ Each broadcast channel has its own carrier frequency
      Bandwidth is 6 MHz/channel

    Example 2: Data/broadcast cable network
    - ◦ Each downlink data or broadcast channel has its own carrier frequency in the range from 65 to 750 MHz; bandwidth is 6 MHz/channel
    - ◦ Each uplink data channel has a 768 kHz band in the range 5–42 MHz
- Wavelength division multiplexing (WDM) ($\equiv$ optical FDMA)
  - ▷ Each channel has its own wavelength and bandwidth
- Time division multiple access (TDMA)
  - ▷ Each channel is broadened to use the bandwidth of the link
  - ▷ Sharing of the channel occurs in signal space, not frequency space

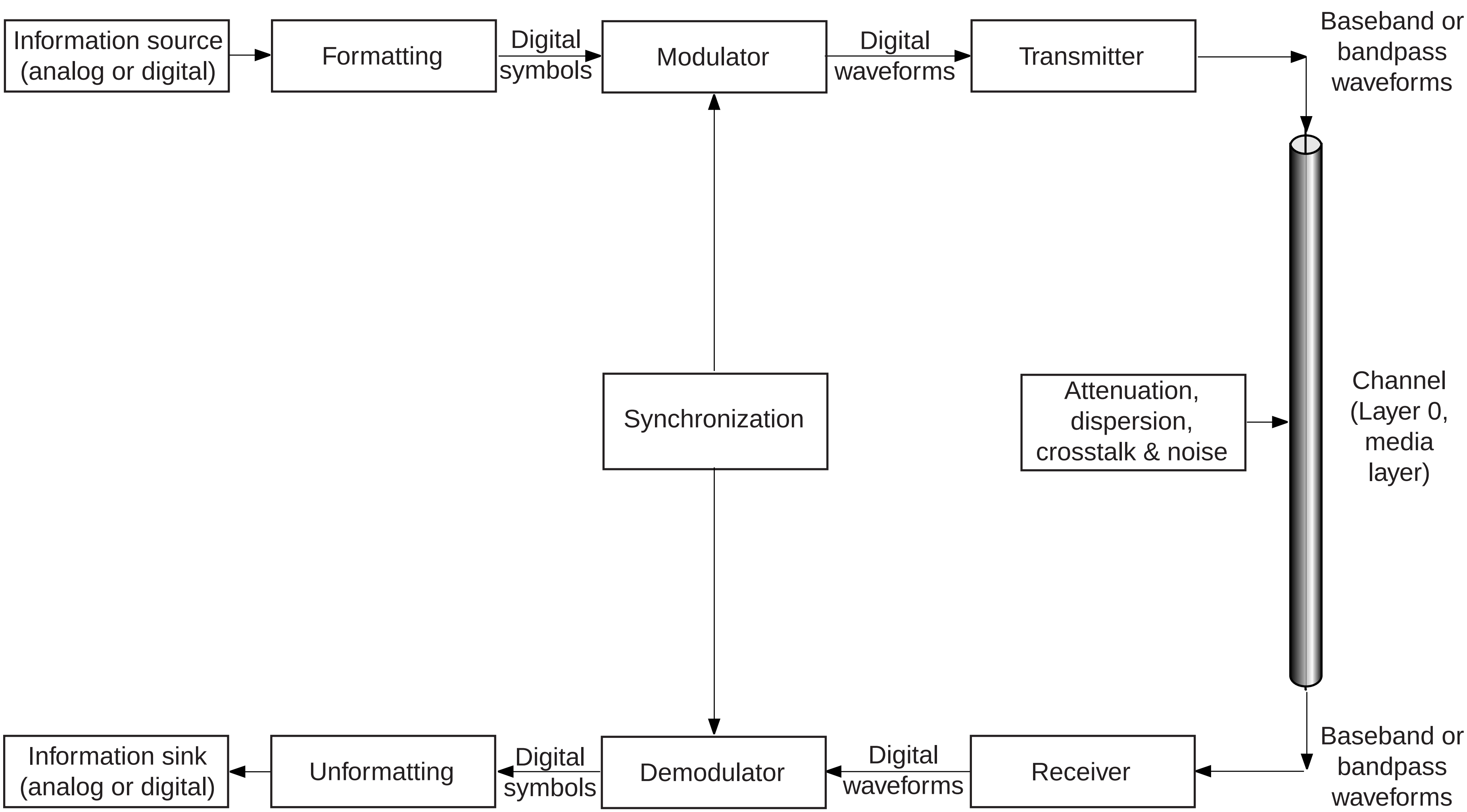
Concept of Frequency Division Multiplexing



Wavelength Division Multiplexing (WDM)

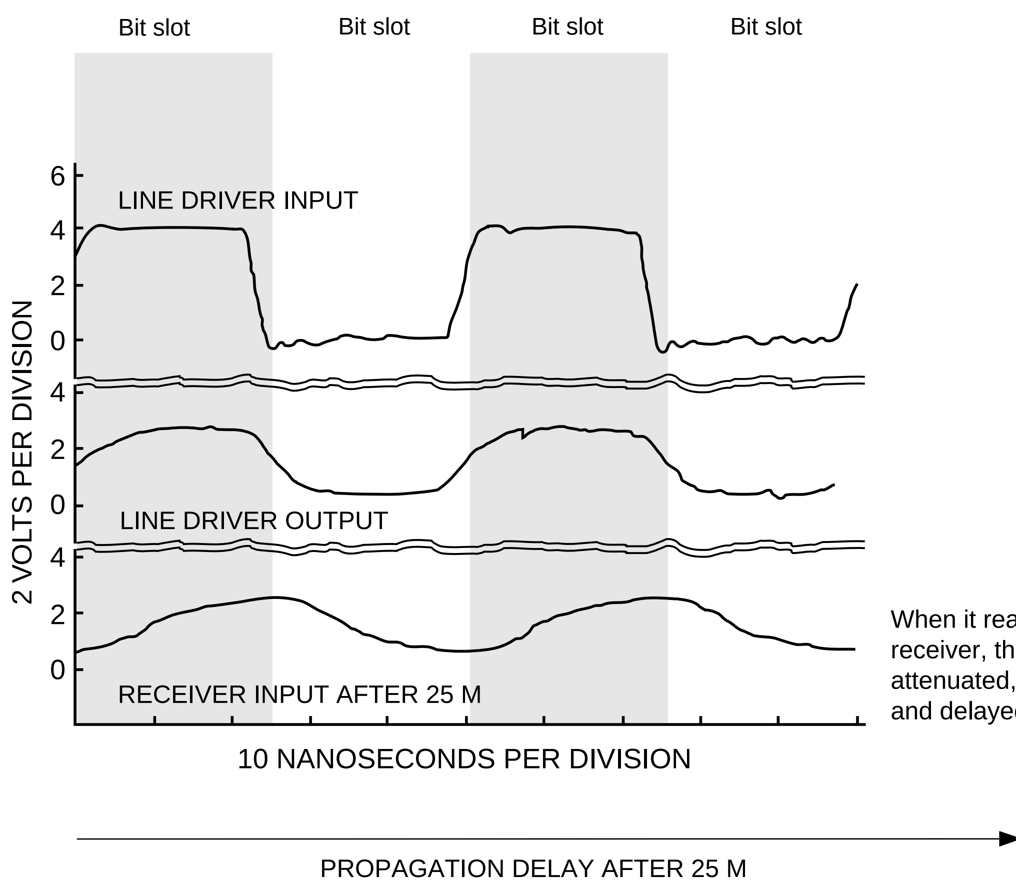


A SINGLE-DUPLEX DIGITAL COMMUNICATION LINK



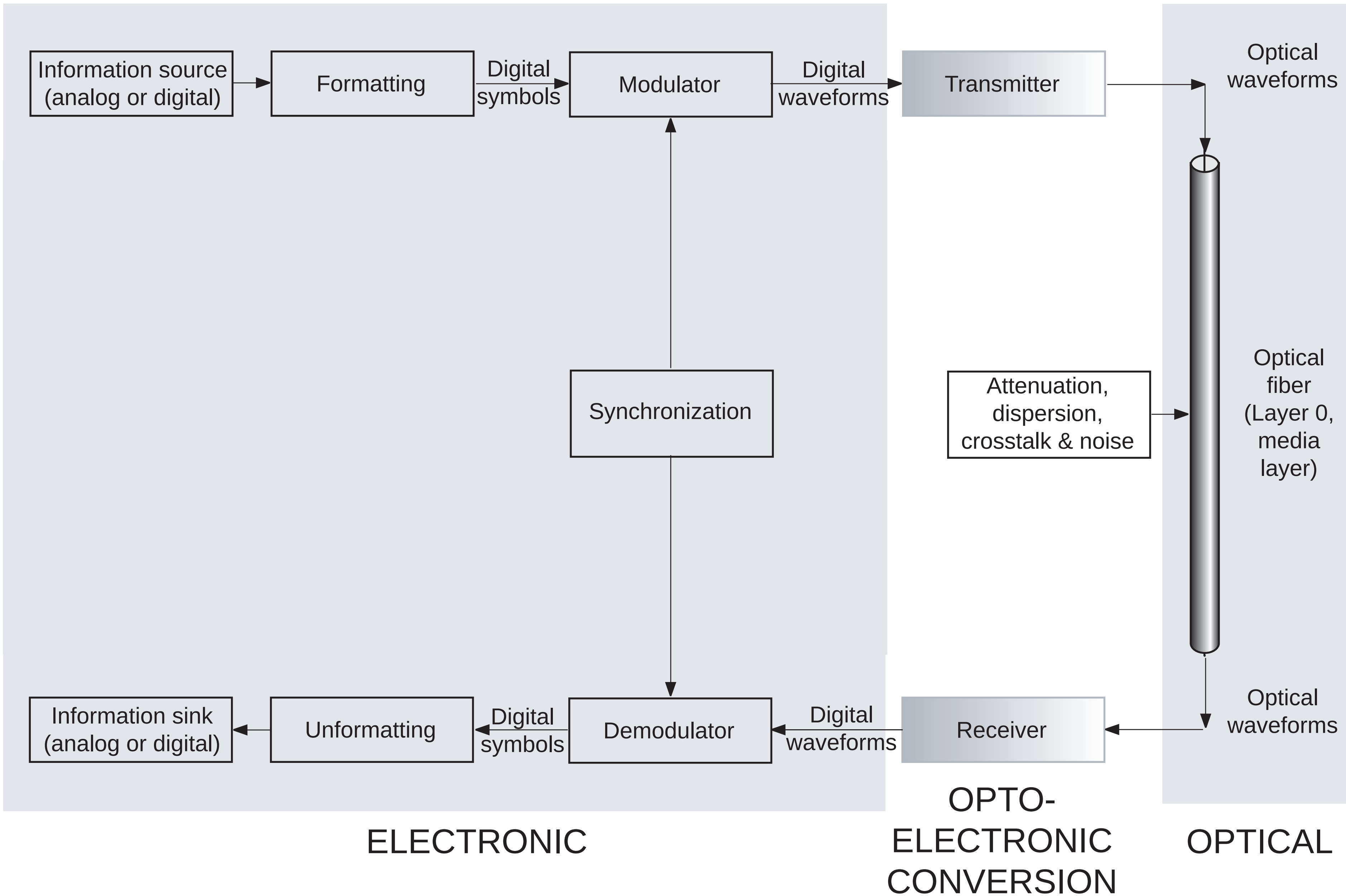
PHYSICAL EFFECTS ON DIGITAL WAVEFORMS

WAVEFORMS THAT REPRESENT THE BIT STREAM 101010...
AT THE BEGINNING AND END OF A SHORT CHANNEL



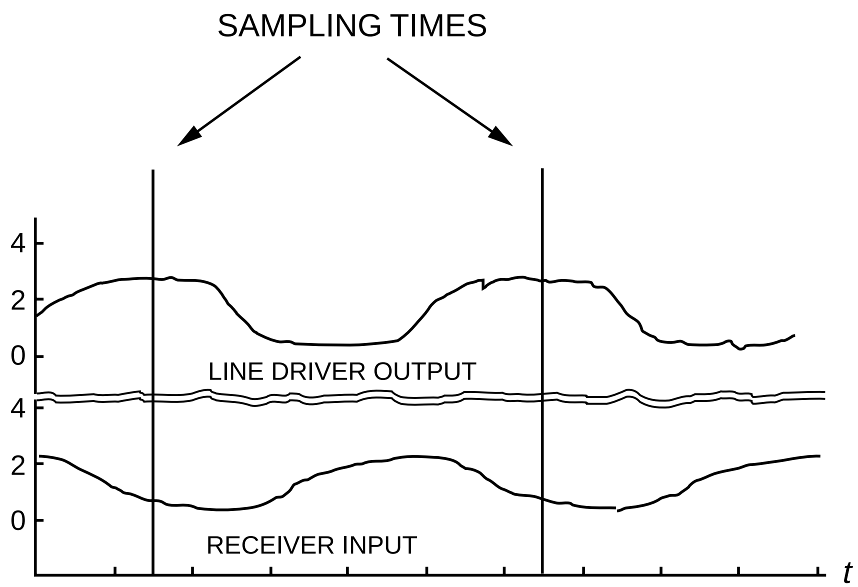
When it reaches the receiver, the signal is attenuated, distorted and delayed

OPTICAL COMMUNICATION SYSTEM

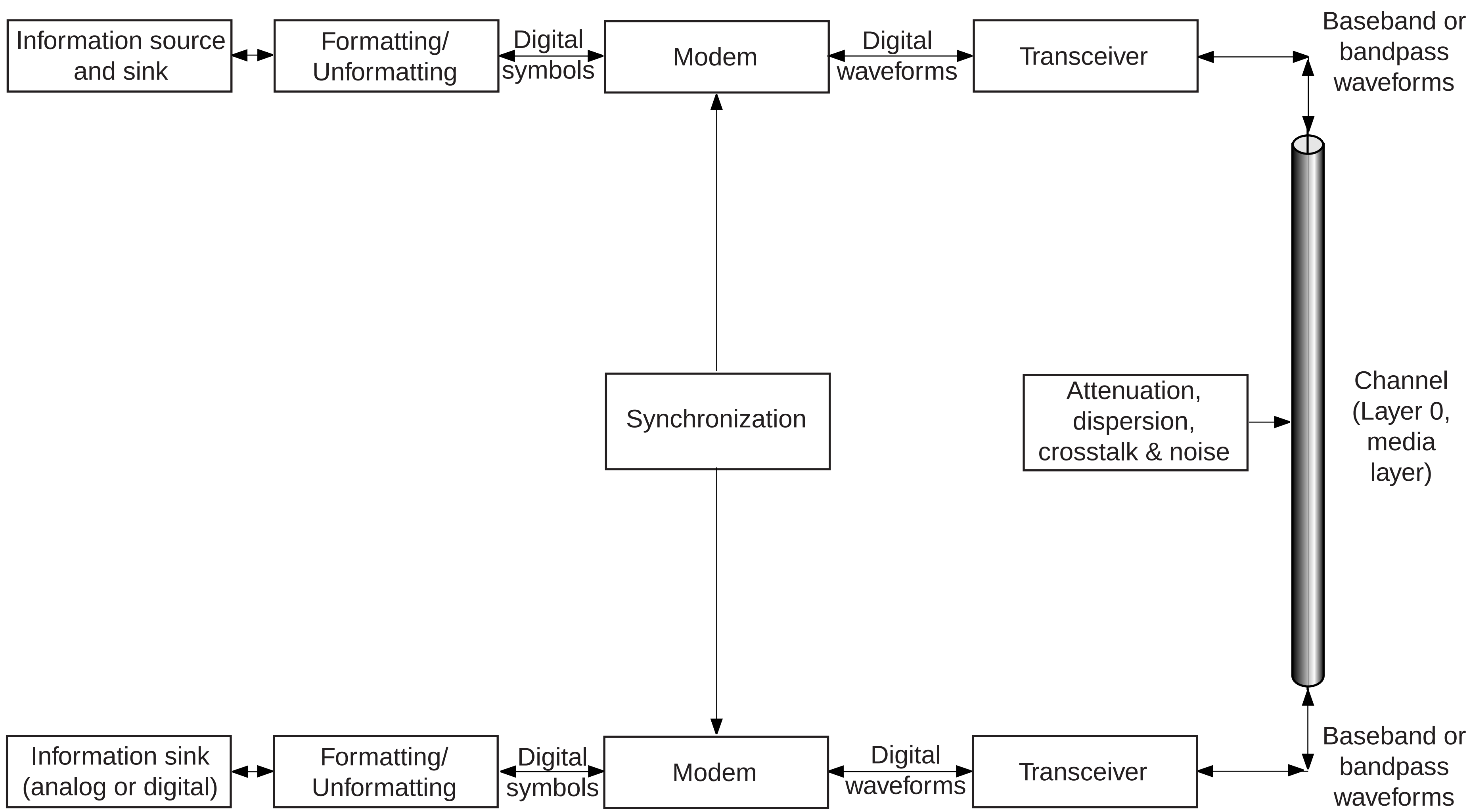


SYNCHRONIZATION IN DIGITAL COMMUNICATIONS

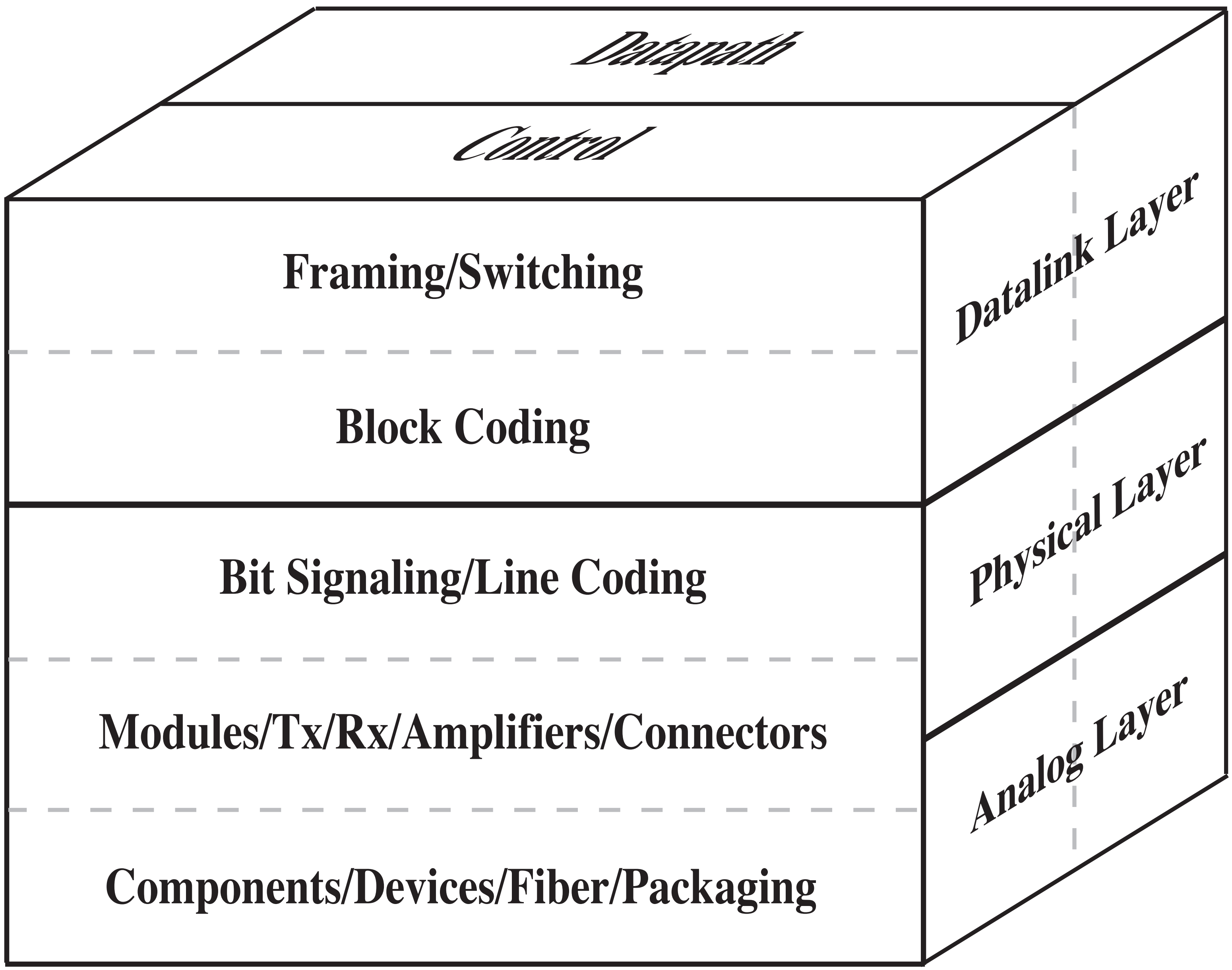
- The receiver needs to be able to identify each digital waveform that arrives, even in the presence of noise and distortion
  - ▷ If high voltage signals a "1" and low voltage signals a "0", then one can identify the 1's and 0's by sampling at discrete times
  - ▷ If the sampling interval or phase are not correct, it is not possible to identify the received waveforms correctly
    - ◦ This leads to a **clock synchronization problem** $\Rightarrow$ framing



A FULL-DUPLEX DIGITAL COMMUNICATION LINK

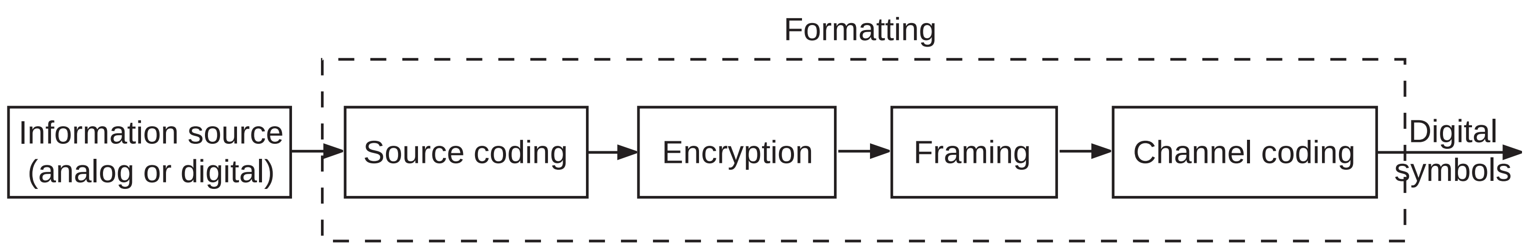


Optical Communication Protocol Stack



DIGITAL FORMATTING

- Comprises the following functions:
  - ▷ In the application layer:
    - ∘ Source coding
      - ◇ Compression of digital data
      - ◇ Quantization of analog data
    - ∘ Encryption
  - ▷ In the socket, network and datalink layers:
    - ∘ Encapsulation and framing (socket, network and datalink layers)
    - ∘ Channel coding (datalink layer)
      - ◇ Mapping of bit groups to codewords (*e.g.*, using a block code)

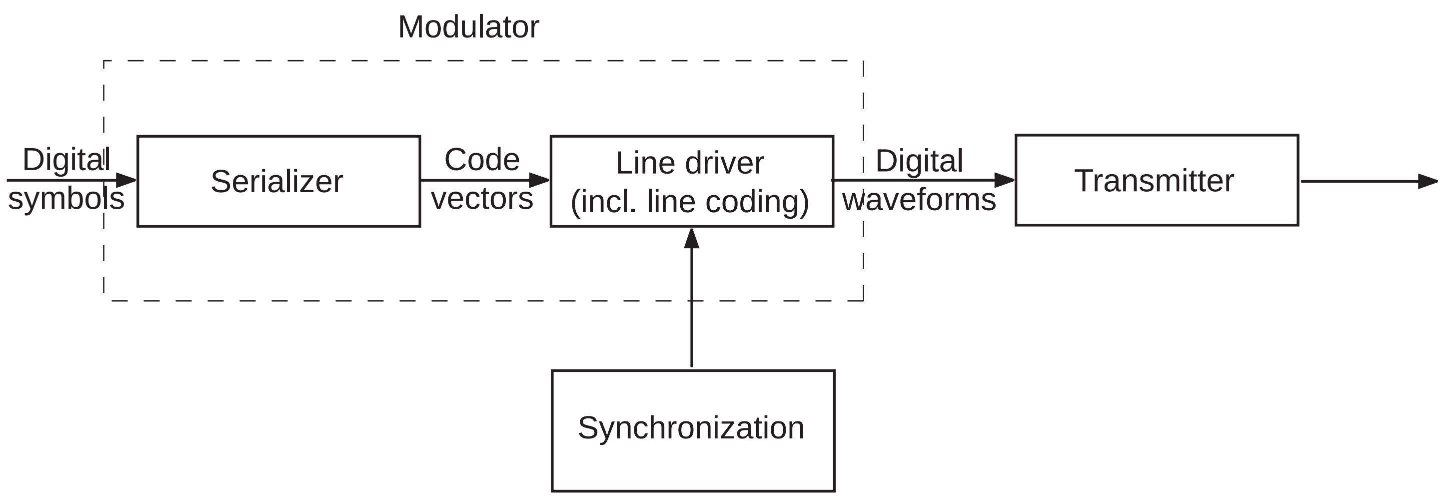


BLOCK CODES AND THEIR APPLICATIONS TO ETHERNET

- A block code takes groups of n bits each and maps them to **codewords**
  - ▷ Each codeword consists of N digits (symbols) in base β, where $\beta^N > 2^n$
  - ▷ A block code is denoted as nBNX, where X stands for β
  - ▷ Bases used in Ethernet are $\beta = 2$ (B), $\beta = 3$ (T) and $\beta = 5$ (Q)
- Goals for block codes in general:
  - ▷ Error detection and **forward error correction**
  - ▷ Reduction of symbol transition rate (baud rate) below bit rate
  - ▷ Provision of non-data codewords to encode control information
- Block codes used in Ethernet:
  - ▷ 4B/5B (100BASE-TX, 100BASE-FX)
  - ▷ 8B/6T (100BASE-T4)
  - ▷ 4B2Q (100BASE-T2)
  - ▷ 8B/10B (1000BASE-CX, 1000BASE-LX, 1000BASE-SX)
  - ▷ 8B/4Q (1000BASE-T)

MODULATION

- Comprises 2 functions:
  - ▷ Conversion from base-β codewords to code vectors, such as
    - ∘ Serialization of 10-bit codewords into code vectors of 1 bit each
    - ∘ Serialization of 6T codewords into code vectors of 3 T symbols each
  - ▷ Line coding
    - ∘ Mapping of base-β symbols to analog signals



ELECTRICAL LINE CODES USED IN ETHERNET

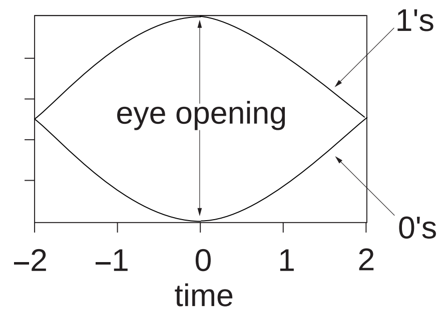
- A line code maps logic levels (symbols) in code space to waveforms
- Goals:
  - ▷ Spectral utilization and shaping
    - ∘ Transmission of signals on media with limited bandwidth
    - ∘ Reduction of RF radiation
  - ▷ Provision of enough transitions for clock recovery
  - ▷ Preservation of DC balance
- Line codes used in Ethernet:
  - ▷ Manchester (10BASE5, 10BASE2, 10BASE-T)
  - ▷ NRZ (10BASE-F, 1000BASE-SX, 1000BASE-LX)
  - ▷ NRZI (100BASE-FX)
  - ▷ MLT-3 (100BASE-TX)
  - ▷ PAM5×5 (100BASE-T2)
  - ▷ 4D-PAM5 (1000BASE-T)

OPTICAL LINE CODES

- Goals:
  - ▷ Spectral utilization and shaping
    - ∘ Transmission of signals with minimal bandwidth in order to minimize the effects of dispersion
  - ▷ Provision of enough transitions for clock recovery
- Common optical line codes:
  - ▷ NRZ
  - ▷ RZ
  - ▷ CRZ

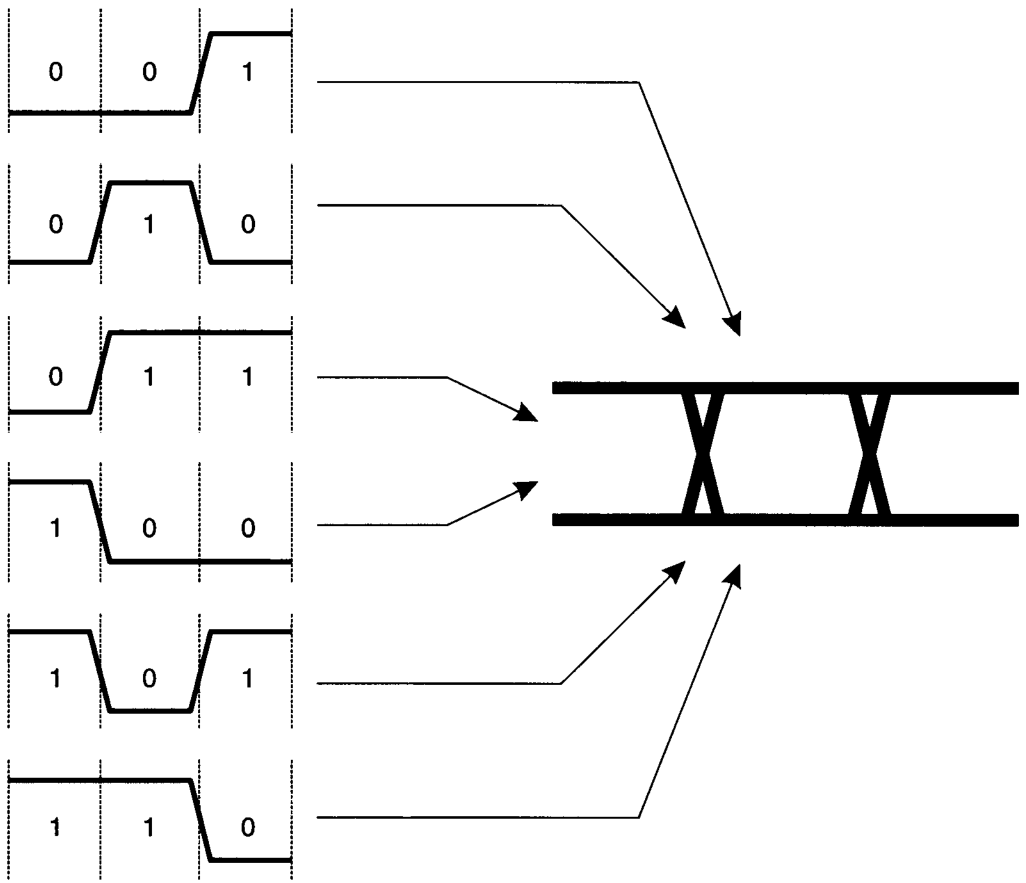
EYE PATTERNS (1)

- An **eye pattern** is obtained by superimposing the actual waveforms for large numbers of transmitted or received symbols
  - ▷ Perfect eye pattern for noise-free, bandwidth-limited transmission of an alphabet of two digital waveforms encoding a binary signal (1's and 0's):



  - ▷ Actual eye patterns are used to estimate the bit error rate and the signal-to-noise ratio

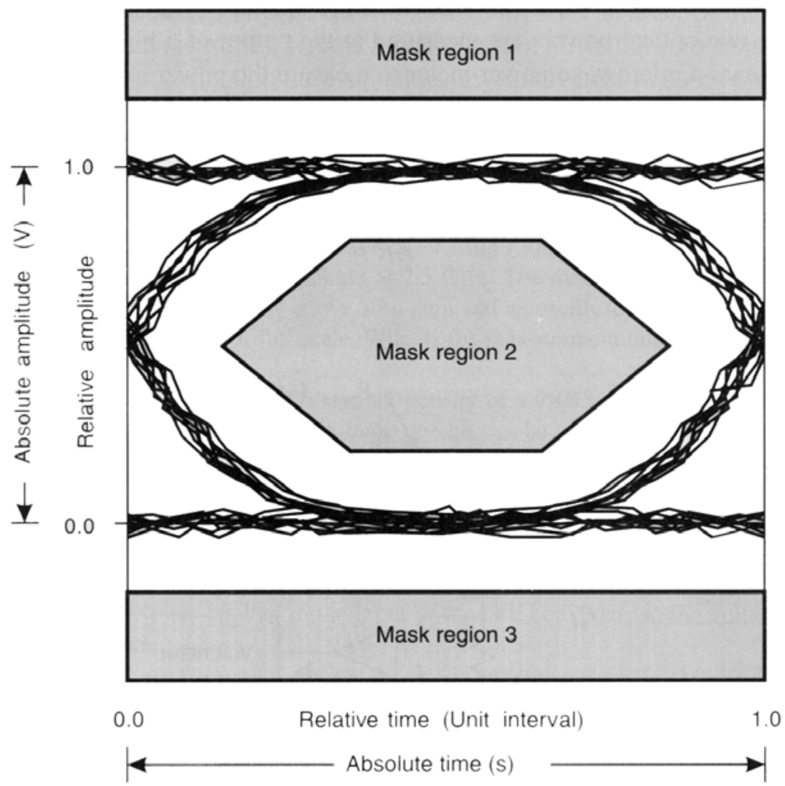
EYE-PATTERN FORMATION



Dennis Derickson, Ed., *Optical Fiber Test and Measurement*, Fig. 8.14

EYE MASK

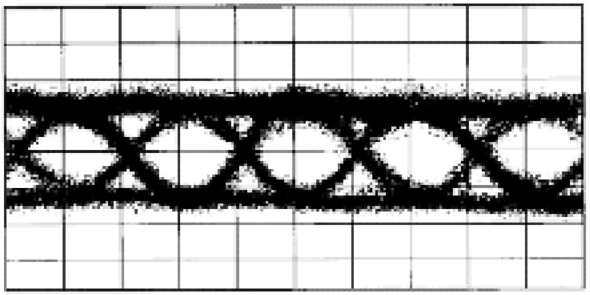
- The signal must not intrude into the shaded areas

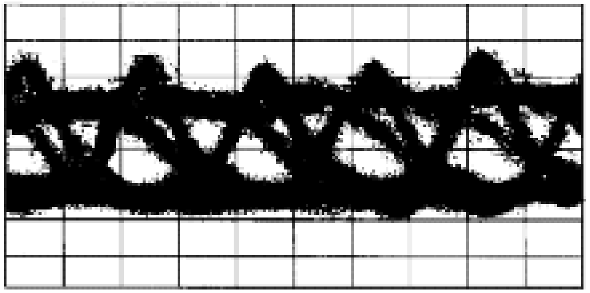


Dennis Derickson, Ed., *Optical Fiber Test and Measurement*, Fig. 8.35

EYE PATTERNS (2)

- Observed eye patterns for fiberoptic transmission of a binary (two-level) NRZ signal at 1.55 μm and 2.5 Gb/s. Horizontal scale: 200 ps/division. Top: $L = 0$ km; bottom: $L = 120$ km.[1] Observed partial eye closing is due to self-phase modulation and group-velocity dispersion.

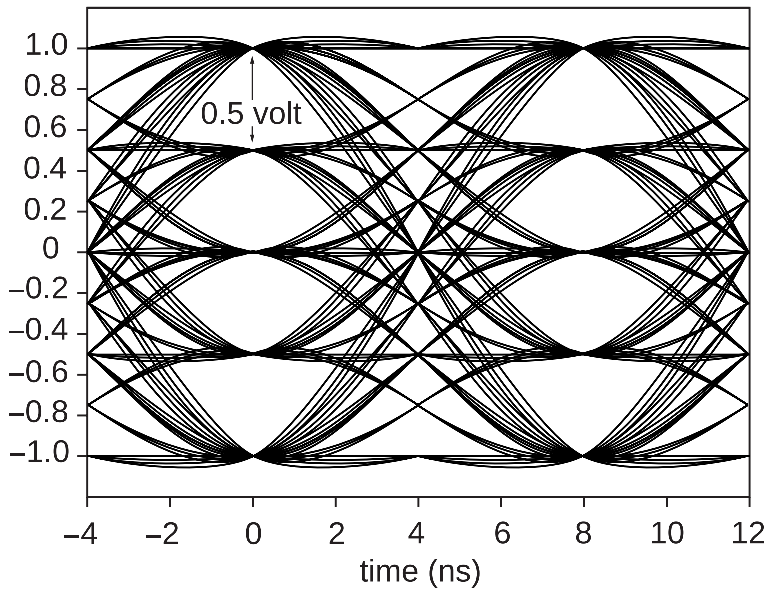




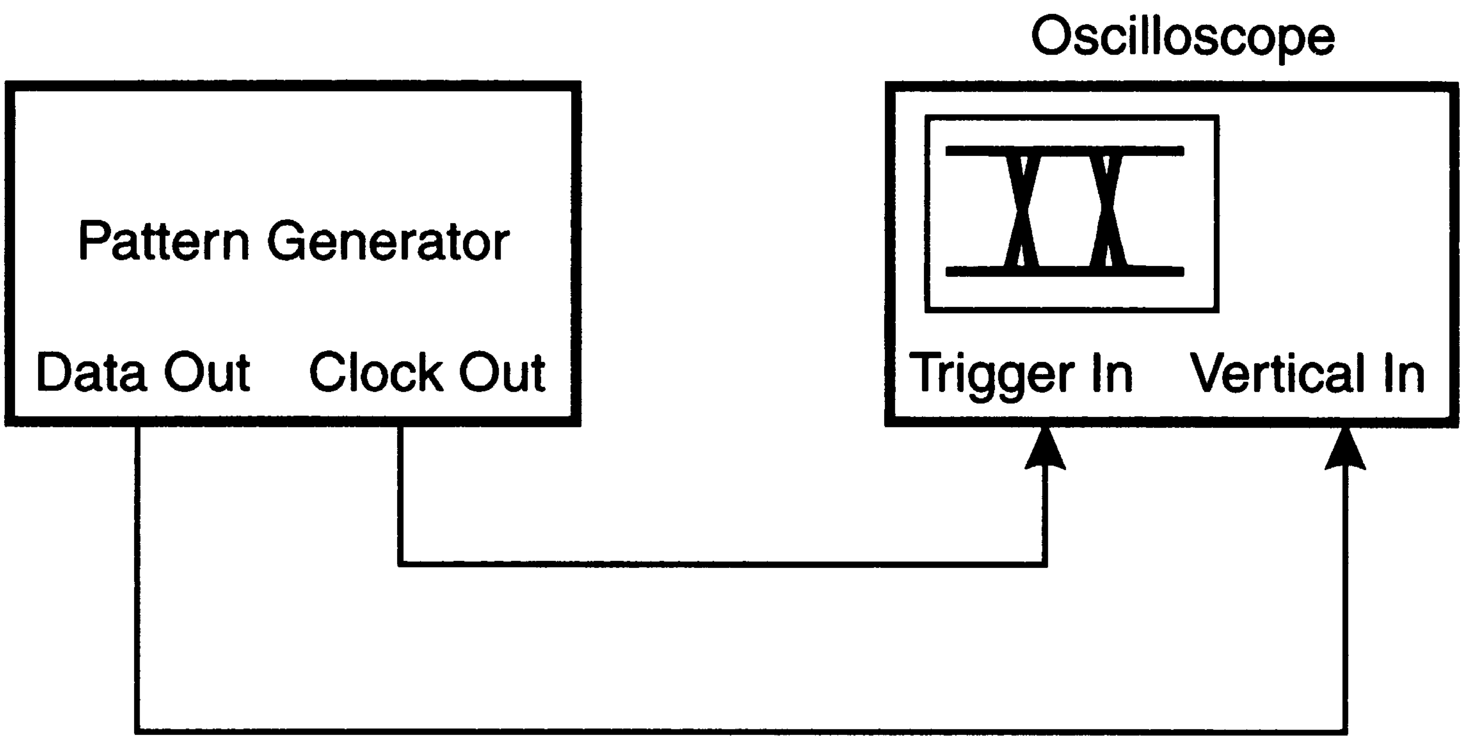
[1] C. Y. Kuo et al., IEEE Photonics Technology Letters **2**, 911–913 (1990)

EYE PATTERNS (3)

- Eye pattern for 5-level PAM (PAM-5), as used to operate gigabit Ethernet over 4 unshielded twisted pairs:



MEASUREMENT OF EYE PATTERNS (1)



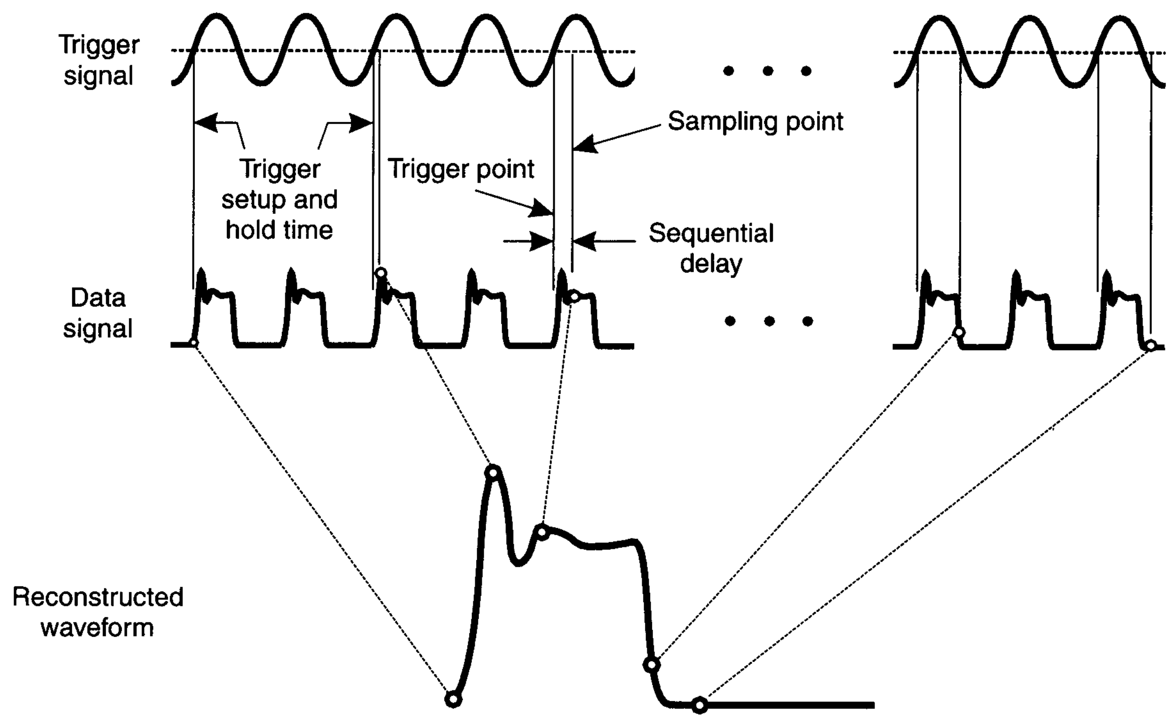
- The pattern generator produces a pseudorandom bit stream

Dennis Derickson, Ed., *Optical Fiber Test and Measurement*, Fig. 8.15

MEASUREMENT OF EYE PATTERNS (2)

- Anritsu MP1763B 12.5 Gb/s pulse pattern generator

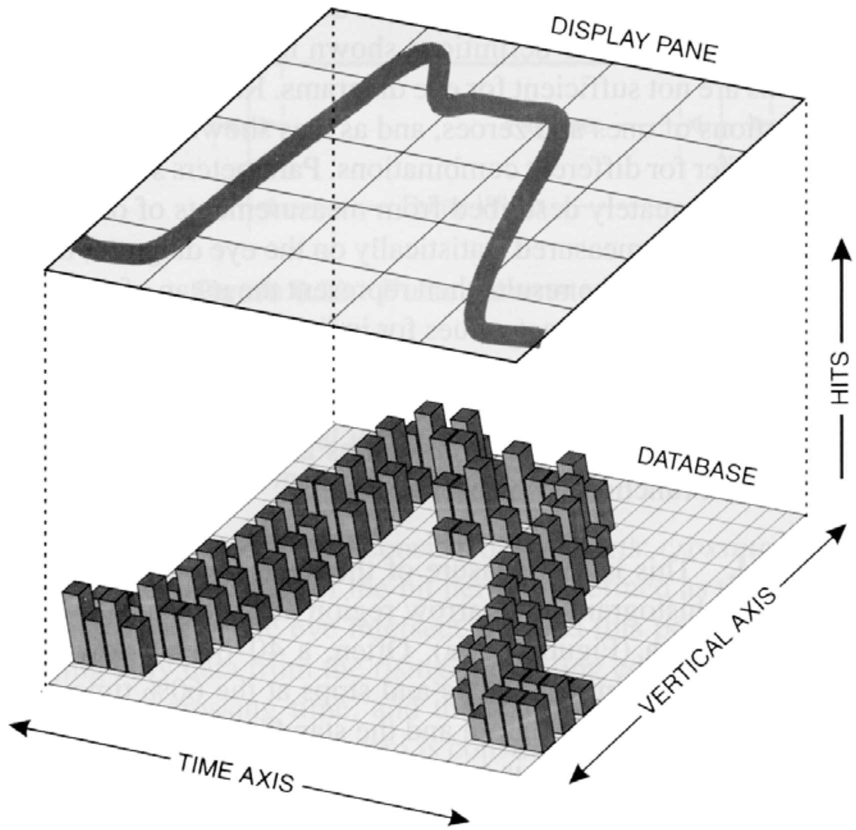
MEASUREMENT OF EYE PATTERNS (3)



- Sequential sampling is used when the data rate exceeds a feasible sampling rate

Dennis Derickson, Ed., *Optical Fiber Test and Measurement*, Fig. 8.18

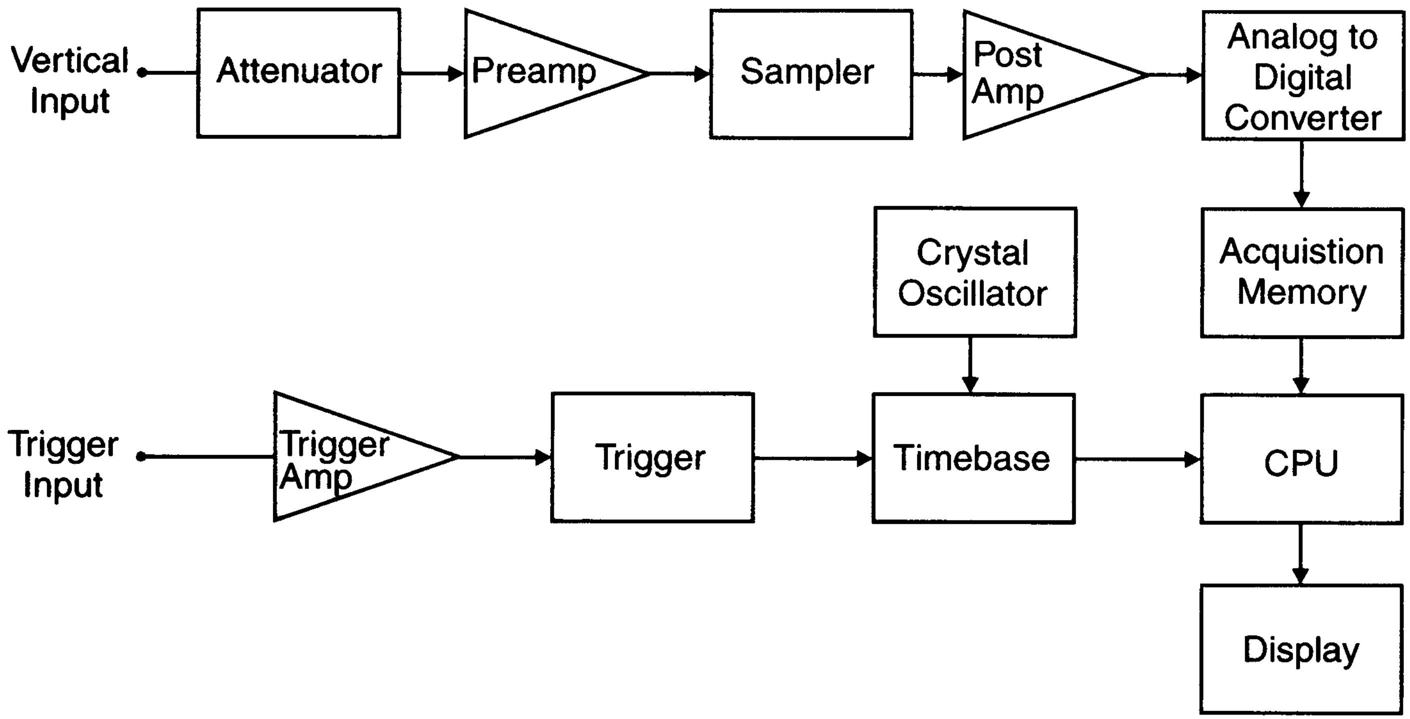
MEASUREMENT OF EYE PATTERNS (4)



- Histograms in a digital oscilloscope

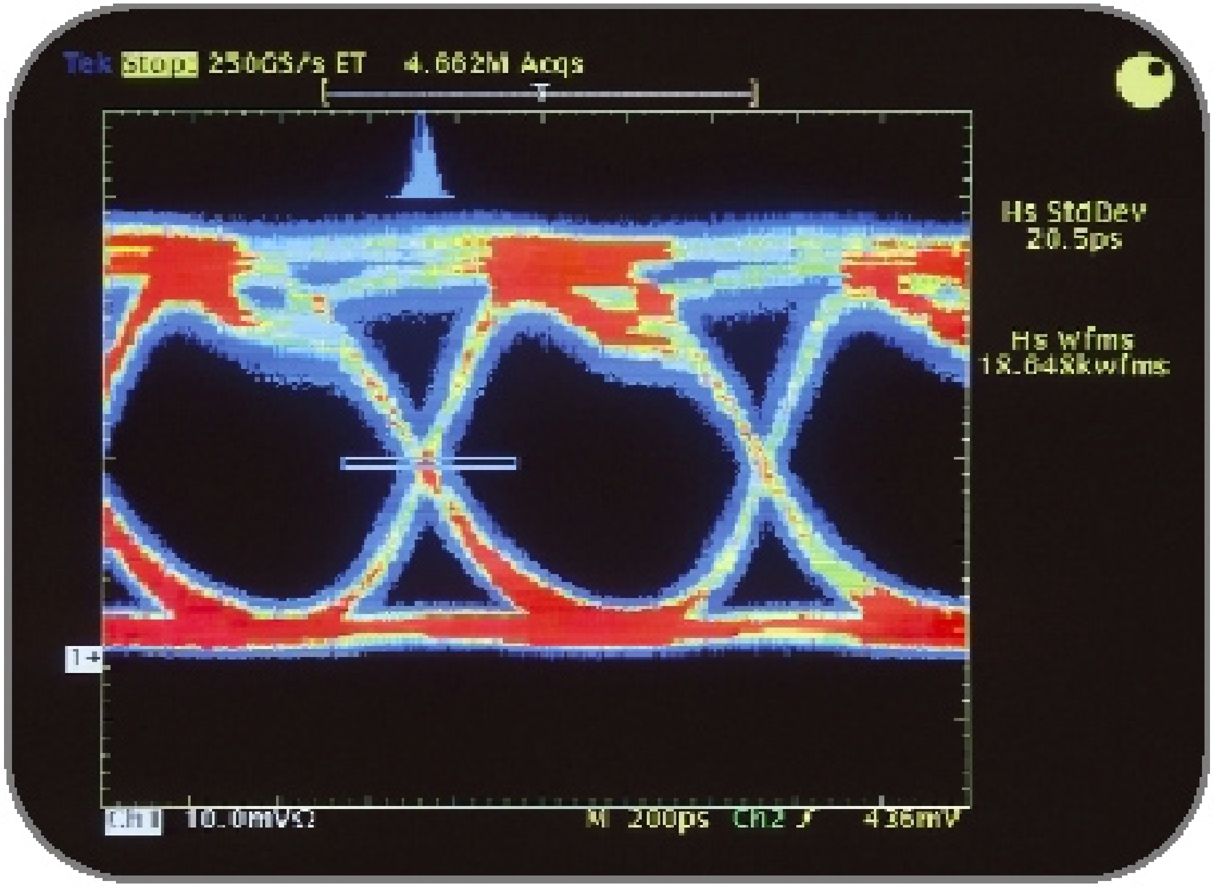
Dennis Derickson, Ed., *Optical Fiber Test and Measurement*, Fig. 8.22

DIGITAL OSCILLOSCOPE ARCHITECTURE



Dennis Derickson, Ed., *Optical Fiber Test and Measurement*, Fig. 8.16

TEKTRONIX DIGITAL PHOSPHOR OSCILLOSCOPE



SOURCE CODING

- Code length:
  - ▷ Let X be a discrete, memoryless source
    - ∘ Alphabet is $\{x_1, \ldots, x_m\}$; (probability of symbol x_i) $= p_i$
    - ∘ Average information content per symbol:

$$H(X) = -\sum_{i=1}^{m} p_i \log_2 p_i \quad \text{bits}$$

    - ∘ Beware! The bits used to represent numerical data are logically distinct from the bits used to represent information content
  - ▷ Assign each symbol x_i a unique binary codeword of length n_i bits
    - ∘ Average codeword length: $L = \sum_{i=1}^{m} p_i n_i$ bits
- **Source coding theorem:**
  - ▷ Greatest lower bound on the average codeword length: $L \geq H(X)$
  - ▷ L can be made arbitrarily close to $H(X)$ by choice of codewords

CHANNEL CAPACITY

- Discrete, noise-free channel:
  - ▷ Alphabet is $\{x_1, \ldots, x_m\}$
    - ∘ Assume that (probability of symbol x_i) $= 1/m$ ($\Rightarrow$ maximum entropy)
    - ∘ Maximum channel capacity:

$$C = \frac{1}{T} \log_2 m \quad \text{bits/second}$$

    - ∘ T = time to transmit one symbol (assumed to be the same for all)
- **Hartley-Shannon theorem** for a noisy channel:
  - ▷ Assume white, band-limited, Gaussian noise
  - ▷ Maximum channel capacity:

$$C = B \log_2 \left(1 + \frac{S}{N}\right) \quad \text{bits/second}$$

  - ▷ B = channel bandwidth, S = signal power, N = noise power

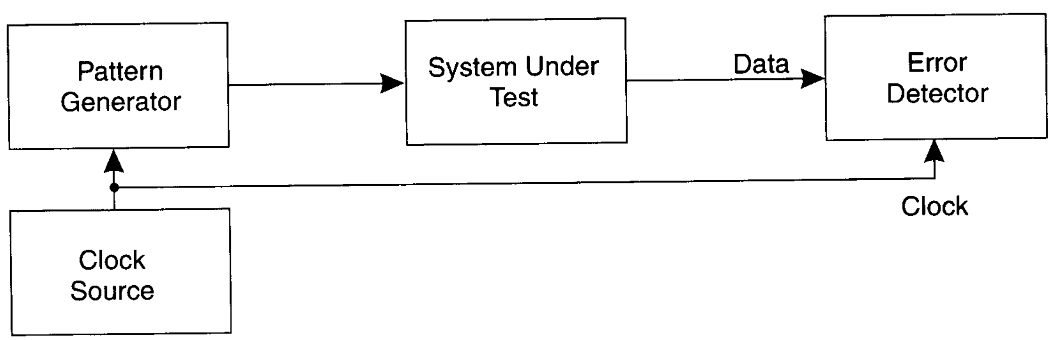
BIT ERROR RATE (1)

- The **bit error rate** or **bit error ratio** is the probability of detecting a bit incorrectly in signaling single bits
  - ▷ An experimental estimate of the probability of error is the ratio

$$\mathrm{BER}(T) = \frac{E(T)}{N(T)}$$

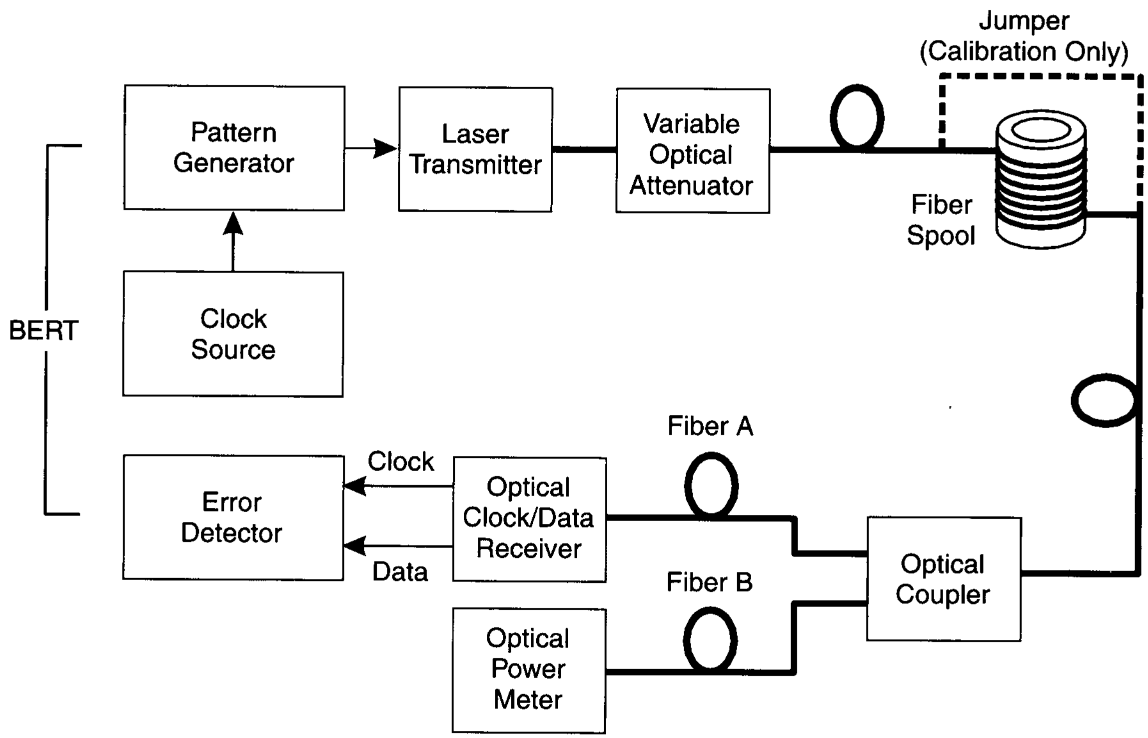
where $E(T)$ is the number of errored bits in the **gating period** T, and $N(T)$ is the total number of bits

  - ▷ Basic bit-error-rate test (BERT) arrangement:



BIT ERROR RATE (2)

- Setup for laboratory measurement of the bit error rate:

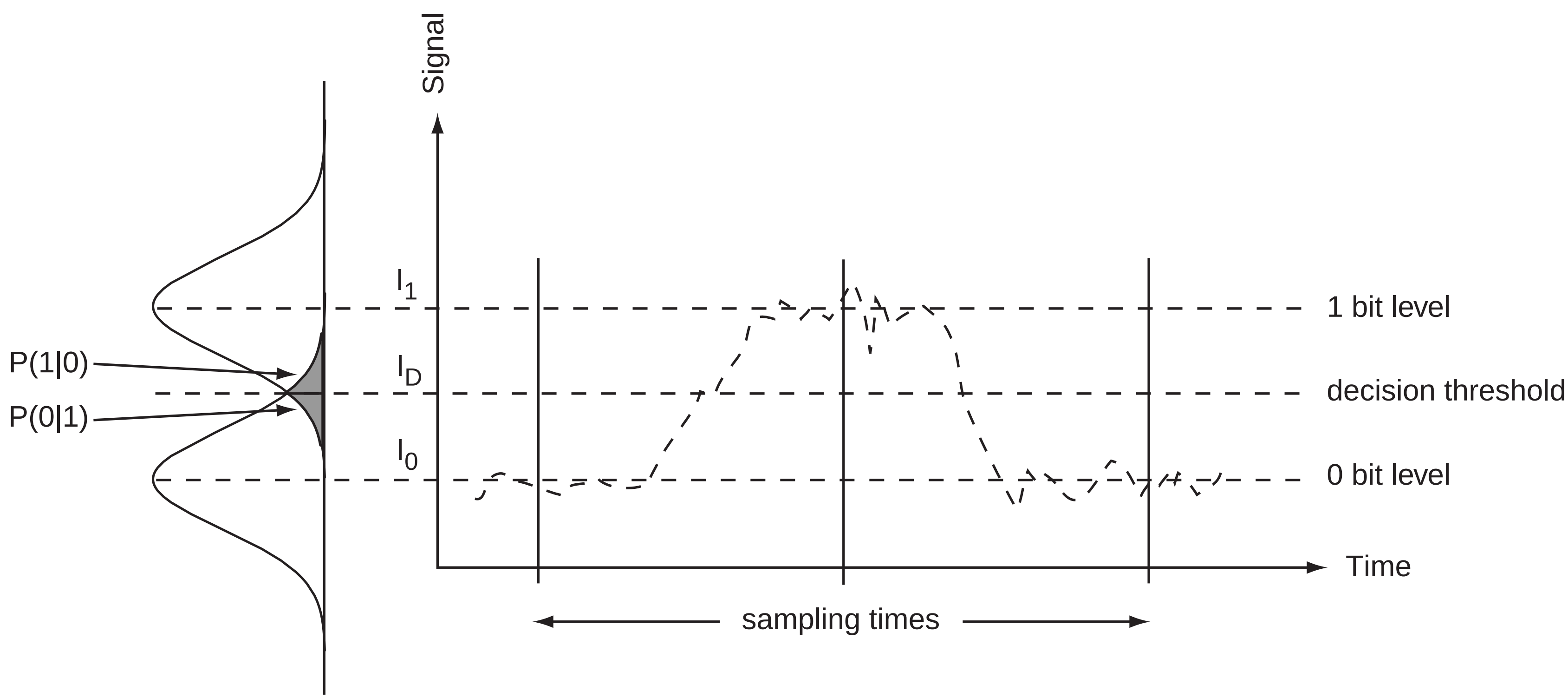


Dennis Derickson, Ed., *Optical Fiber Test and Measurement*, Fig. 8.9

BIT ERROR RATE (3)

- The **bit error rate** is the probability of detecting a bit incorrectly in signaling single bits:

$$\mathrm{BER} = p(1)P(0|1) + p(0)P(1|0)$$



BIT ERROR RATE (4)

- Conditional probability:

$$P(0|1) = \frac{1}{\sigma_1\sqrt{2\pi}} \int_{-\infty}^{I_D} \exp\left(-\frac{(I_1 - I)^2}{2\sigma_1^2}\right) dI = \tfrac{1}{2}\mathrm{erfc}\left(-\frac{I_1 - I_D}{\sigma_1\sqrt{2}}\right)$$

$$\mathrm{erfc}(x) = \text{complementary error function} = \frac{2}{\sqrt{\pi}} \int_{-\infty}^{x} e^{-u^2} du$$

  ▷ Minimum BER occurs when the decision threshold is chosen such that

$$\frac{I_1 - I_D}{\sigma_1} = \frac{I_D - I_0}{\sigma_0}$$

  ▷ Define

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0}$$

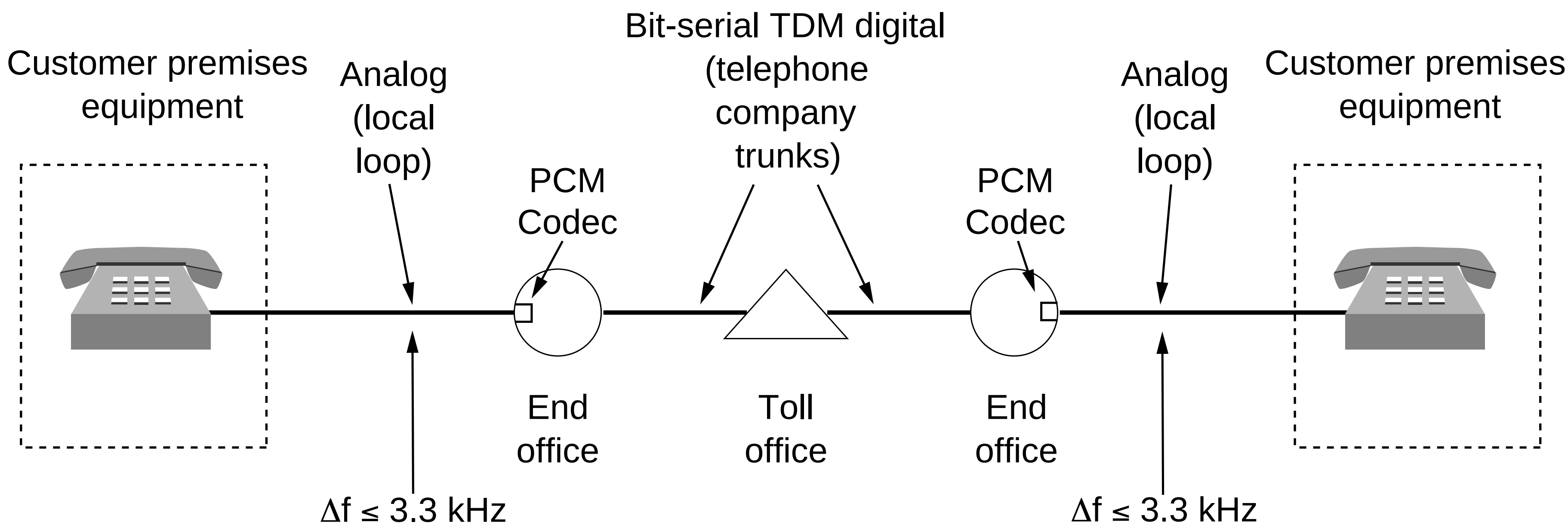
  ▷ At the optimum setting of I_D,

$$\mathrm{BER} = \tfrac{1}{2}\mathrm{erfc}\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{e^{-Q^2/2}}{Q\sqrt{2\pi}}$$

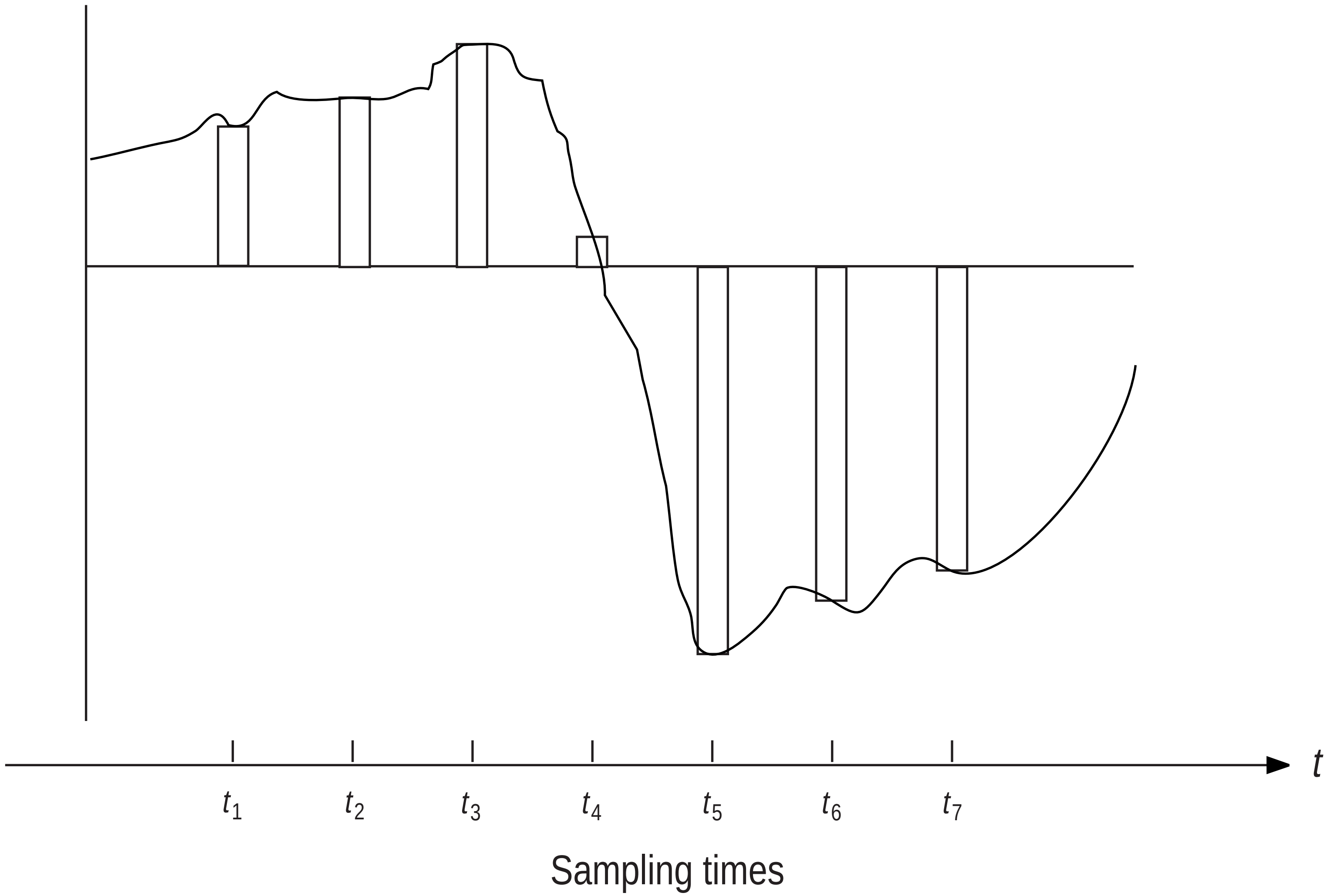
DIGITAL TRANSMISSION OF ANALOG SIGNALS

- Example: North American PSTN
- The analog time-varying voltage produced by sound waves impinging on a microphone travels over a twisted pair of copper wires to an end office
  - ▷ The time-varying voltage is sampled at intervals of 125 μs (8000 s^{-1})
    - ◦ The result is a **pulse amplitude modulation** signal
    - ◦ Original baseband signal can be reconstructed from PAM sequence
    - ◦ Could transmit the PAM sequence on trunk lines, but then we'd have distortion and noise again...
  - ▷ The PAM signal is quantized and encoded digitally using 8 bits/sample
    - ◦ The result is a **pulse code modulation** signal
    - ◦ Quantization noise is an unavoidable side effect of digitization
- The octets from 24 different logical channels are inserted into a DS-1 frame and transmitted over a trunk line at a rate of 8000 frames/second

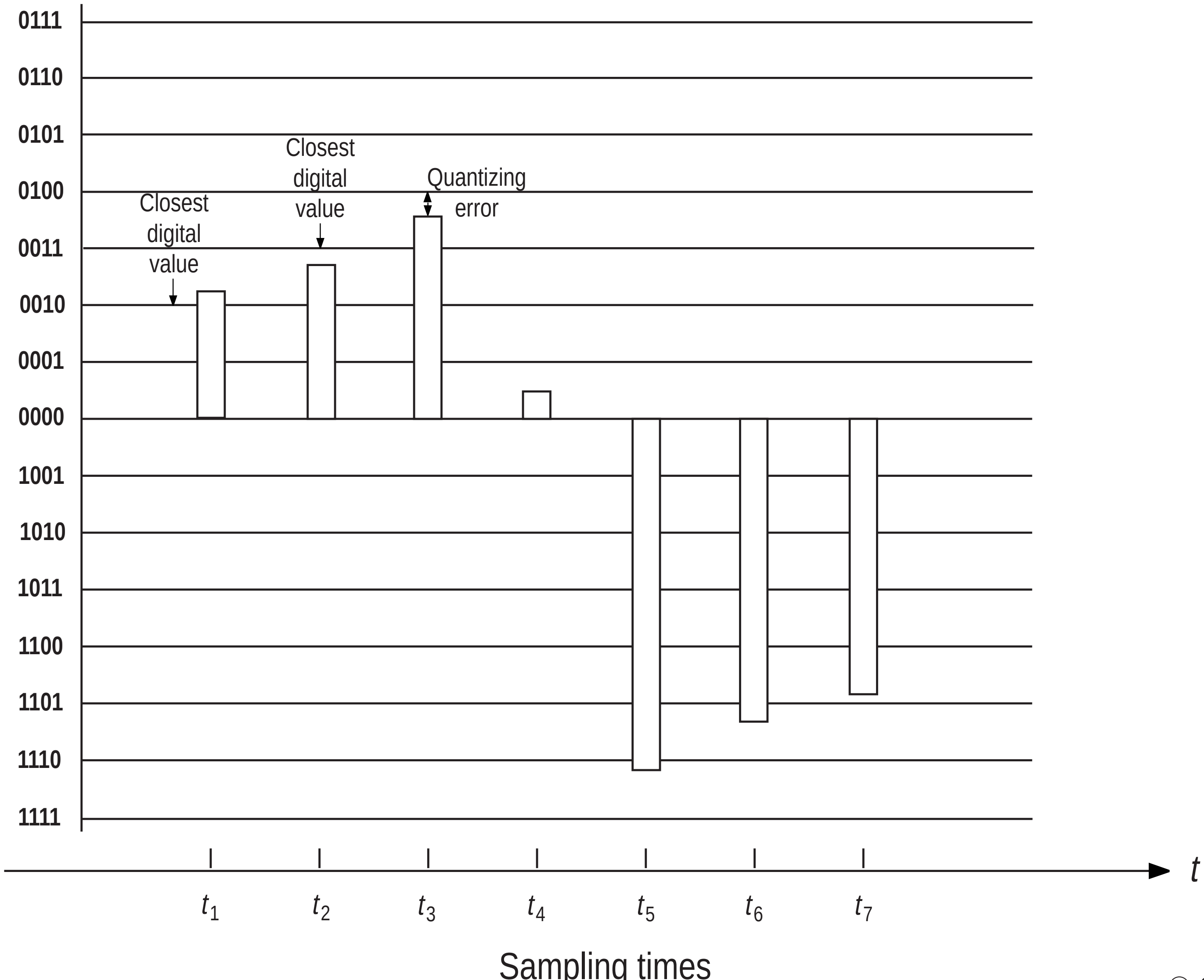
Datapath for a telephone call via the PSTN (U.S.)



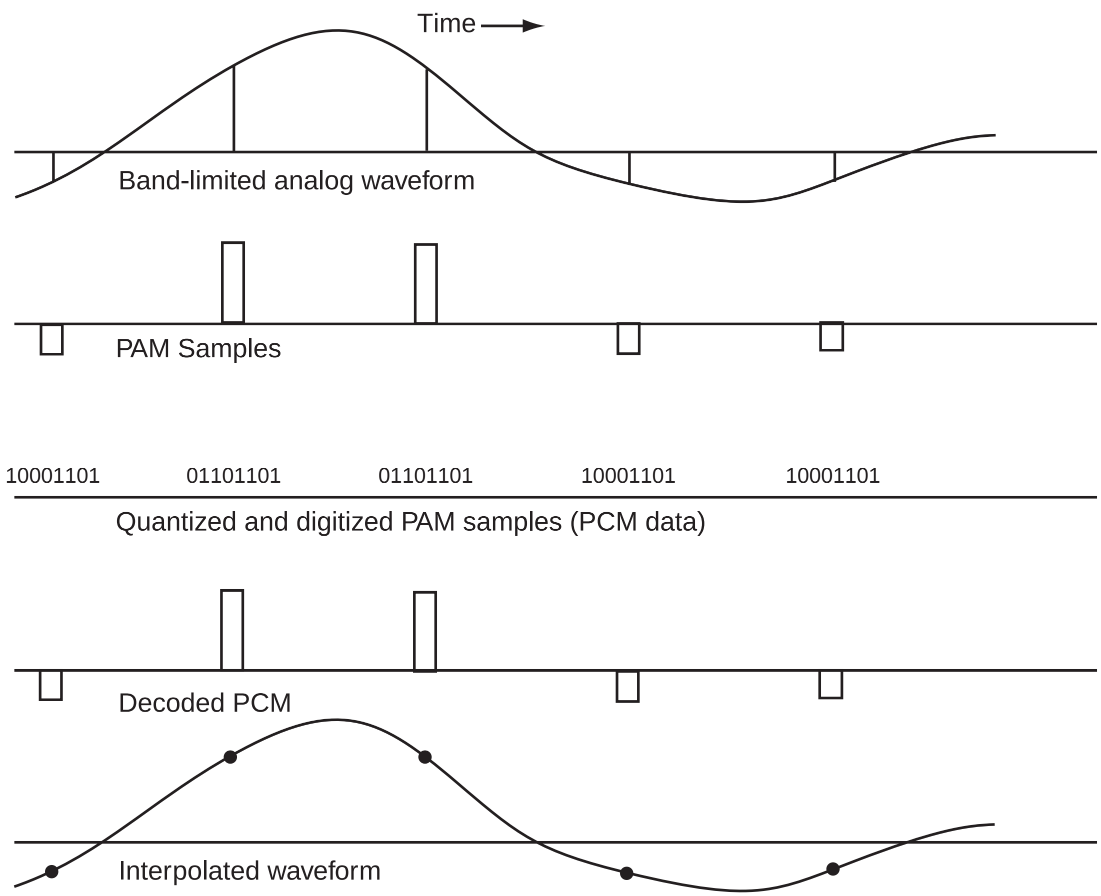
PULSE AMPLITUDE MODULATION (PAM)



ANALOG TO DIGITAL CONVERSION



PULSE CODE MODULATION (PCM) CODING

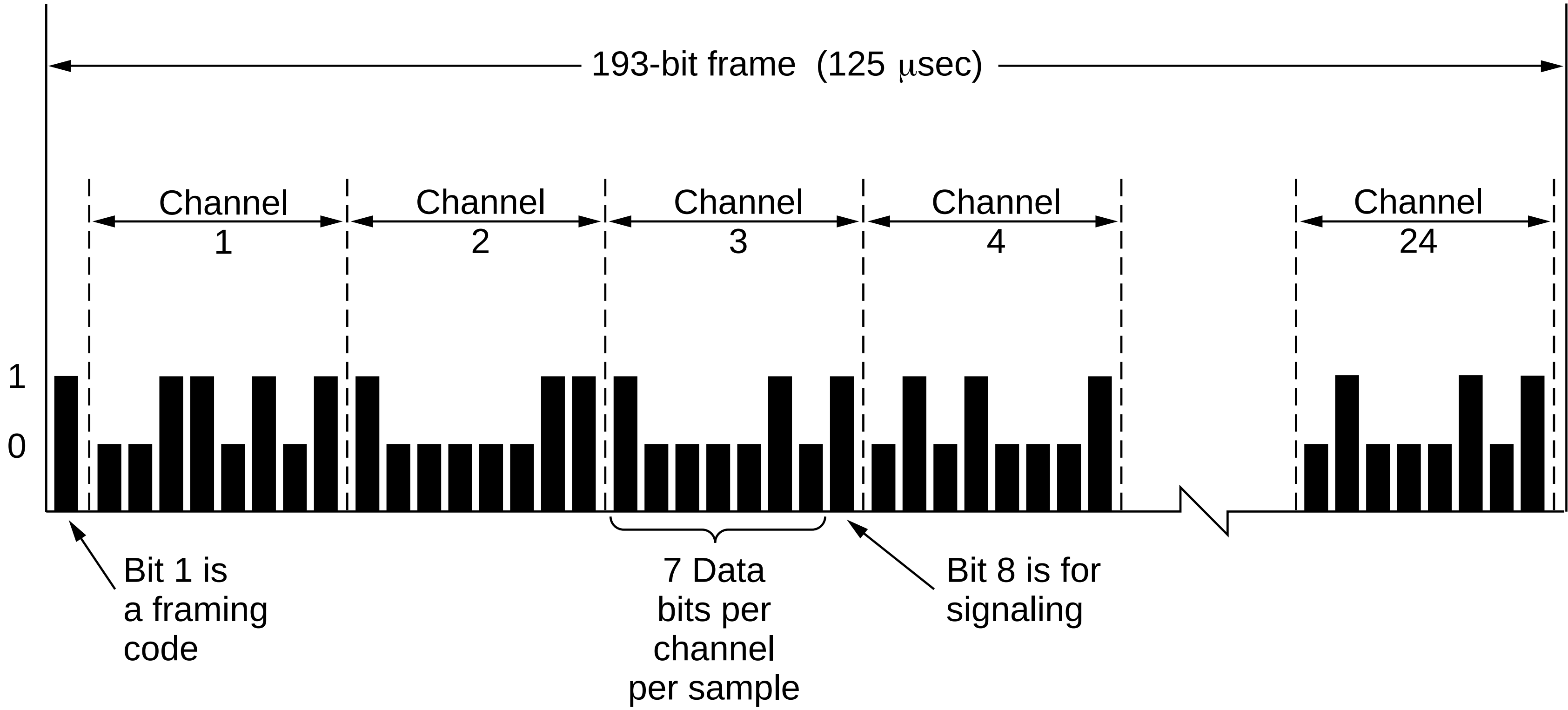


MU-LAW ENCODING

- Purpose: Map the (theoretically infinite) range of sound volumes onto a finite interval, after sampling the signal
  - ▷ Rationale: There are more low-amplitude than high-amplitude sounds in speech
  - ▷ There should be more quantization levels at low amplitudes than at high amplitudes
  - ▷ Quantization noise is an unavoidable side effect of digitization
- Mu-law equation:

$$v(f) = V \operatorname{sgn}(f) \frac{\ln\left[1 + \frac{\mu|f|}{V}\right]}{\ln(1+\mu)}$$

  - ▷ In North America, $\mu = 255$



Time Division Multiplexing (TDM): DS-1 frame (1.544 Mb/s)

TDMA TECHNOLOGIES (1)

- Switching can be accomplished by interchanging time slots (**time-division switching**)
- Bit multiplexing
  - ▷ Each time slot contains 1 bit from each channel for that time slot
  - ▷ Requires synchronization
  - ▷ Switch fabric must be reconfigurable in 1 bit time
- Block multiplexing
  - ▷ Each time slot contains the block transmitted by one channel in one frame time
  - ▷ Requires synchronization
  - ▷ Switch fabric must be reconfigurable between frames

TDM SIGNAL HIERARCHY (NORTH AMERICA, JAPAN, KOREA)

Designation	Channels	Data Rate (Mb/s)	Comments
DS-0	1	0.064	8 kHz × 8 bits PCM voice channel
DS-1	24	1.544	T-1 1 timing bit/frame
DS-1c	48	3.152	T-1c
DS-2	96	6.312	T-2
DS-3	672	44.736	T-3
DS-4	4032	274.176	T-4

TDM SIGNAL HIERARCHY (EUROPE — ITU)

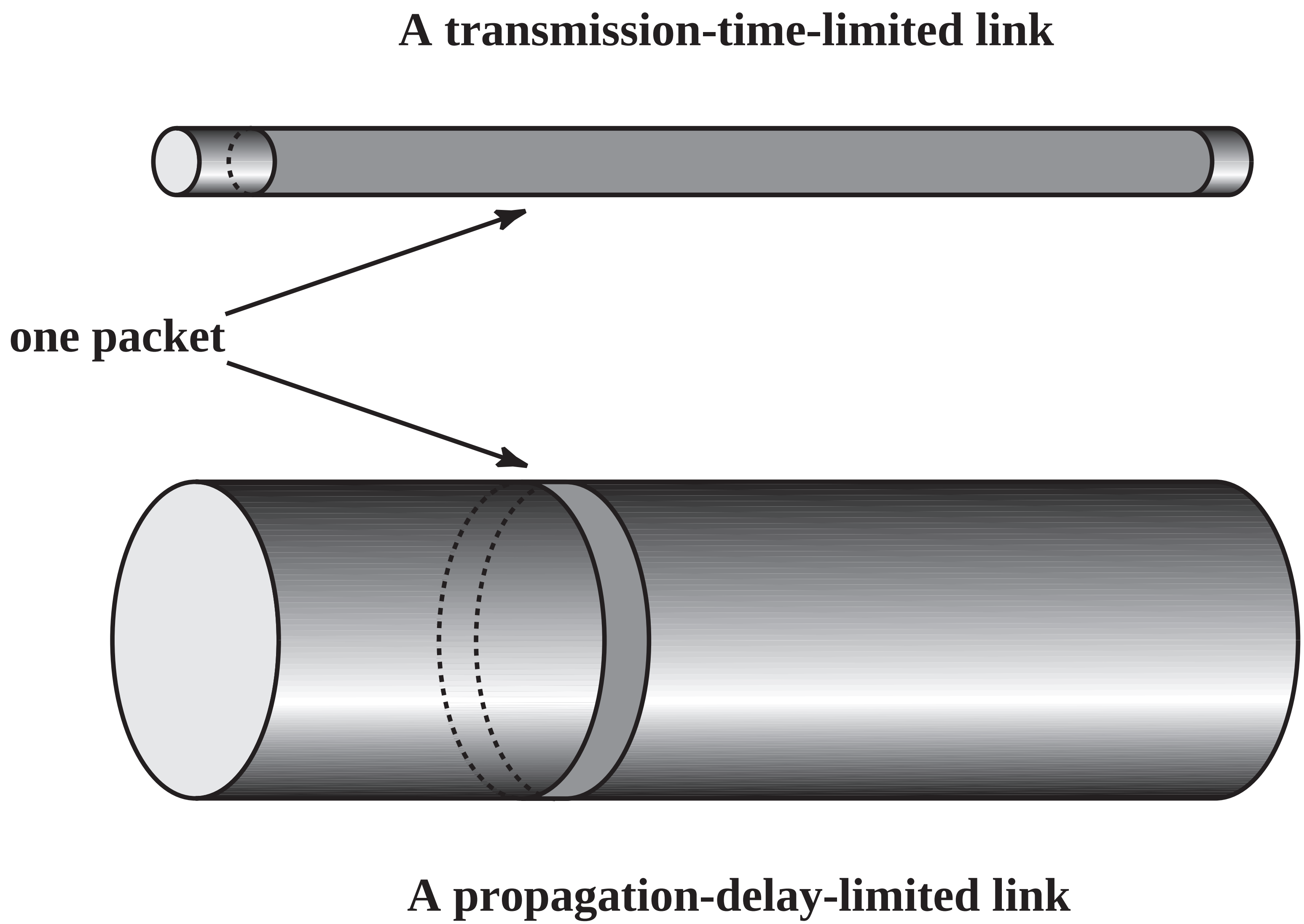
Designation	Channels	Data Rate (Mb/s)
E1	30	2.048
E2	120	8.448
E3	480	34.368
E4	1920	139.264
E5	7680	565.148

SONET/SDH SIGNAL HIERARCHY

SONET Designation	ITU-T Designation	Data Rate (Mb/s)	Payload Rate (Mb/s)
STS-1/OC-1		51.84	50.112
STS-3/OC-3	STM-1	155.52	150.336
STS-9/OC-9	STM-3	466.56	451.008
STS-12/OC-12	STM-4	622.08	601.344
STS-18/OC-18	STM-6	933.12	902.016
STS-24/OC-24	STM-8	1244.16	1202.688
STS-36/OC-36	STM-12	1866.24	1804.032
STS-48/OC-48	STM-16	2488.32	2405.376
STS-192/OC-192	STM-64	9953.28	9621.504

TDMA TECHNOLOGIES (2)

- Code division multiple access (CDMA)
  - ▷ Each channel transmits bits using a unique code
    - ◦ The code is a sequence of short pulses (chips)
    - ◦ Must be orthogonal to the codes of all other channels
  - ▷ Extensively used in wireless communications
- Packet switching
  - ▷ Bit rate for each channel is set at the link's maximum value
  - ▷ Each channel transmits when the link becomes available
  - ▷ Each channel transmits information in "chunks", or **packets**
  - ▷ Addressing information is carried in a **header** in each packet
  - ▷ Switch fabric (if used) must be reconfigurable in the time of a minimum-length packet
  - ▷ Contrast a bandwidth-limited link with a transmission-time-limited link (see next slide)



delivery time = transmission time + propagation delay
transmission time = packet size/bandwidth
propagation delay = distance/group velocity

HOW PROPERTIES OF PHYSICAL LINKS AFFECT NETWORK ARCHITECTURE (1)

- Important properties of physical links include:
  - ▷ How adequate bandwidth is achieved
  - ▷ Delay
  - ▷ Bit error rate
  - ▷ Need for synchronization
  - ▷ Whether physical channels are optical or electrical
  - ▷ Power budget

HOW PROPERTIES OF PHYSICAL LINKS AFFECT NETWORK ARCHITECTURE (2)

- How is **adequate bandwidth** achieved?
  - ▷ Bit-parallel transmission (as in a bus) is usually not an option
    - ∘ Bus skew
      - ⋄ Because pulses traveling on different wires in a multiwire cable experience slightly different electromagnetic environments, the pulses on different wires don't all arrive at the same time
      - ⋄ Makes long-distance, bit-parallel communications *very* difficult
  - ▷ Usable bandwidth depends on distance
    - ∘ Copper cable: Attenuation depends on transmission distance (skin effect)
    - ∘ Optical fiber: Excessive values of (group velocity dispersion) × distance × (bandwidth of pulse in wavelength) lead to intersymbol interference
  - ▷ The usual solution for limited bandwidth is multiple channels (synchronized: TDM; non-synchronized: FDM, WDM)

HOW PROPERTIES OF PHYSICAL LINKS AFFECT NETWORK ARCHITECTURE (3)

- **Delay**
  - ▷ Subject to an upper bound for real-time applications (especially voice)
  - ▷ Electromagnetic propagation delay = distance/v_g
    - ∘ For optical fiber, $v_g \approx \frac{2}{3}c = 2 \times 10^8$ m/s
      - ⋄ 200 meters: propagation delay ≈ 1 μs (LANs)
      - ⋄ 200 kilometers: propagation delay ≈ 1 ms (MANs, small WANs)
      - ⋄ 20,000 kilometers: propagation delay ≈ 0.1 s (planetary WAN)
  - ▷ Buffer delay = (no. of bits buffered)/(bit rate)
  - ▷ Routing, switching or regeneration delay
  - ▷ Software or firmware delay (codecs, etc.)
  - ▷ Measurements of delay:
    - ∘ Propagation delay: Time-domain reflectometry
    - ∘ Total delay: Software (e.g., `ping`, `traceroute`)

HOW PROPERTIES OF PHYSICAL LINKS AFFECT NETWORK ARCHITECTURE (4)

- **Bandwidth-delay product** (BWD) and **bit error rate**
  - ▷ BWD = volume of the pipe that represents a physical channel
    - ∘ BWD = no. of bits or bytes "in flight"
      - ◇ "In flight" means sent, but not yet received or acknowledged
      - ◇ BWD should be $\ll 1/\text{BER}$ (otherwise, too many retransmissions)
      - ◇ Fiberoptic transmission: 10 Gb/s $\times$ 1 s $= 10^{10} \ll 10^{12} = 1/\text{BER}$
  - ▷ BWD is an extremely important parameter for TCP

HOW PROPERTIES OF PHYSICAL LINKS AFFECT NETWORK ARCHITECTURE (5)

- **Synchronization** is necessary for bit-serial operation
  - ▷ Bit-serial digital signals can be decoded correctly only if the receiver uses a properly synchronized local clock
  - ▷ Synchronous communications: All clocks are hierarchically locked to a master clock (as in SONET)
  - ▷ Asynchronous communications: Clocking information is derived from the data transmitted (as in Ethernet or ATM)
  - ▷ Nearly all digital communication links longer than a few meters use **framed** blocks of bits or bit groups
    - ◦ Connection-oriented datalink layer: T-1 frame (24 8-bit samples)
    - ◦ Connectionless datalink layer: Ethernet frame

HOW PROPERTIES OF PHYSICAL LINKS AFFECT NETWORK ARCHITECTURE (6)

- **Electrical vs. optical channels**
  - ▷ Electrons interact strongly with one another
    - ◦ They are good for switching, but not so good for transmission
    - ◦ Examples: The transistor, lossy transmission lines
  - ▷ Photons interact very weakly with one another
    - ◦ They are good for transmission, but not for switching
    - ◦ Transmission example: Optical fiber
    - ◦ There's no optical transistor; therefore, most optical switching systems are optoelectronic (electrical control, optical datapath)
    - ◦ It's hard to make a fast WDM switch (incoming interface to outgoing interface *and* λ_1 to λ_2)
      - ◇ This "technical detail" influences the practicality of switched optical networks

SCALE vs. TYPE OF INTERCONNECTION

Interprocessor distance	Processors are located in the same	Interconnection topology	Examples (non-exclusive)
0.01 m	Die	bit-parallel bus	IC with CPU + FPU
0.1 m	PC board	bit-parallel bus	Processor daughtercard
1 m	System	bit-parallel bus	Multi-headed computer
10 m	Room or small building	bit-serial bus or ring; multiwire bit-group signaling	LAN
100 m	Large building	interconnected buses/rings	
1 km	Small campus	interconnected buses/rings	
10 km	Extended campus	bit-serial bus or point-to-point	VLAN or MAN
100 km	Metropolitan area	bit-serial bus or point-to-point	MAN
1,000 km	State, region or nation	point-to-point	WAN
10,000 km	Continent or planet	point-to-point	The Internet

- LAN = Local Area Network, VLAN = Virtual LAN, MAN = Metropolitan Area Network, WAN = Wide Area Network

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