Intro

Circuit Switching (same circuit for all packets): $T = Te + Tprop + Td$. Te estabelecer ligação, Td envio ($Length/Bitrate$).
Packet Switching (path is defined for each packet during travel): $Tpac = Sum(Ti)$ | $Ti = Tpi + Tdi$. Ti envio packet in conn i ($Length/Bitrate$), Tpi propagação in conn i.

Physical Layer (Real comm channels used by the network. Appears as unreliable virt bit pipe.)

Conversão de sinal digital s(t) num sinal analógico r(t) (convolução de s(t) com h(t))

Quantos mais harmónicos no sinal analógico, mais próximo do digital. Signal de M níveis pode ser reconstruído, $C = 2B * log2(M)$. C, bitrate/channel's capacity. $2B$, baudrate, samples/s, débito de símbolos.

Baseband Transmission (Frequencies from zero up to a maximum Bh. Common for wires)

NRZ-L - 2 levels representing 0 and 1. **NRZ-I** - Change of level represents a 1. **Manchester** - Transition in the middle of the bit. 1: positive - negative. 0: negative - positive. Used in Ethernet.
Clock Recovery - Signals need sufficient transitions. Bad muitos 0's ou 1's seguidos. Solved by **Manchester**.

Passband (Band of frequencies around the frequency of the carrier, fc. Common for wireless and optical channels)

Uses modulation techniques: amplitude, frequency, and phase.

Shannon's Law (Noise high ⇒ low M. high SNR ⇒ high M.)

Noise limits number of levels, M (bit/symbol). Maximum theorectical capacity of a channel (bit/s): $C = B \times log(1 + SNR)$. **B** - bandwidth of the channel (Hz). **N** - White noise (W/Hz). **NB** - noise power seen by receiver (W). **P** - signal power seen by receiver (W).
SNR - Signal Noise Ratio = $P/(N * B)$. **Free Space Loss**: $\frac{P_t}{P_r} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi fd)^2}{c^2}$

Data Link Layer (Service network layer. Errors. Regulate data flow)

Services: Unacknowledged connectionless service, Acknowledged connectionless service, and Acknowledged connection-oriented service. **Framing**: Character count, flag bytes with byte stuffing, or Start and ending flags with bit stuffing.
Types of Errors: Simple Error (random and independent from previous error), Errors in burst (affects neighbour bits. Burst length defined by the first and last bits in error).

Counting Errors (Independent errors)

BER (Bit Error Ratio), bit error probability. **n**, frame length. **FER** (Frame Error Ration), $1 - (1 - BER)^n$.
P[i bits received in error], $nCi * p^i * (1 - p)^{n-i}$ | $\frac{n!}{i! \times (n-i)!}$

Effectiveness of Error Detection Techiniques

Minimum distance of code, d, is the minimum number of bit errors undetected in a block of n bits. If fewer than d errors occur, errors are detected. **Burst detecting ability**, B, is the max burst length of errors detected.

ARQ

Stop and Wait ARQ (Module 2 numbers. No NACK required.)

$Tf = \frac{L}{R}$ | $Tprop = \frac{d}{V}$ | $a = Tprop/Tf$ | $S = \frac{Tf}{2Tprop+Tf} = \frac{1}{1+2a}$ | $Serr = \frac{1-p_e}{1+2a}$ | $R_{max} = R * S_{max}$

Go-back-N ARQ (goes back to ask for missing frame)

Sequence numbers are represented module M, k bits are used for the sequence numbers. $p_e = FER$ | $W = M - 1 = 2^k - 1$

Eficiencia (S) without errors $\begin{cases} 1, W \geq 1 + 2a \\ W/(1 + 2a), W < 1 + 2a \end{cases}$ | Eficiencia (S) with errors $\begin{cases} \frac{1-p_e}{1+2a \times p_e}, W \geq 1 + 2a \\ \frac{W \times (1-p_e)}{(1+2a)(1-p_e+W \times p_e)}, W < 1 + 2a \end{cases}$

Selective-repeat ARQ (asks for the missing frame and saves others)

Adequate if W (a) is very large. $W = \frac{M}{2} = 2^{k-1}$ | $S = \begin{cases} 1 - p_e, W \geq 1 + 2a \\ \frac{W \times (1-p_e)}{1+2a}, W < 1 + 2a \end{cases}$

Delay models

Little's Theorem

The (mean) time a client has to wait before being served, Tw, depends on the number of clients waiting, Nw, and on the arrival rate of the clients, λ. N - average number of clients in a system. T_w - time a client waits in queue. N_w number of clients waiting in queue. T_s - service time. N_s number of clients being served. $N = \lambda T$ | $T = T_w + T_s$ | $N = N_w + N_s$ | $N_w = \lambda T_w$

M/M/1 Queue

$N = \frac{\rho}{1-\rho} = \frac{\lambda}{\mu-\lambda}$ | $T = N/\lambda = \frac{1}{\mu-\lambda}$ | $T_w = \frac{\rho}{\mu(1-\rho)}$ | $N_w = T_w\lambda = N - \rho$ | $\mu = Cap/MedianLen$ | $\rho = \lambda/\mu$ | $T = N/\lambda$

M/M/1/B Queue Packets can be lost ($P(B)$ probability). $\rho(B) = \frac{1}{B+1}, \rho = 1$ | $\rho(B) \approx \frac{\rho-1}{\rho} = \frac{\lambda-\mu}{\lambda}, \rho >> 1$ | $\rho(B) = \frac{(1-\rho)\times\rho^B}{1-\rho^{B+1}}$

M/G/1 Poison arrivals at rate λ. $T = T_w + 1/\mu$ | $N = N_w + \rho$

M/D/1 (constant packet length) Deterministic, constant service time, **Ts**, $1/\mu$. $T_w = \frac{\rho}{2\mu\times(1-\rho)}$.

D/D/1 vs M/M/1 Check Little's theorem. For the same ρ, D/D/1 has less clients, N, waiting because they don't arrive in bursts.

MAC (48 bit) - Medium Access Control

ALOHA

- **Pure ALOHA (unslotted)** - No slot concept. Station transmits when it has a frame to transmit.
- **Slotted ALOHA** - Time divided into time slots. $T_{slot} = T_{frame}$. (Re)transmissions only at the beginning of a slot.

CSMA (Carrier Sense Multiple Access)

Listen before transmission (if channel is busy, defer transmission). Collisions can still occur (propagation delay). If collision, entire packet is lost. Collision probability: $a = T_{prop}/T_{frame} << 1$.

- persistent - if busy, wait until free to transmit.
- non-persistent - if busy, wait a random time and repeat algorithm.
- p-persistent - if free, transmit with **p** probablity (otherwise defer). if busy, if transmission defered from previous time slot, collision, else wait until free and repeat algorithm.

CSMA/CD (full-duplex ethernet => no collisions => method not used)

Collision Detection - stations listens to medium while transmitting. If collision is detected: transmission is aborted, retransmission is delayed using a Binary Exponential Back-off algorithm (after the ith consecutive collision wait a random number of slots in $[0, 2^i - 1]$). Minimum frame size is required for collision detection.

CSMA/CA (Tframe » Tprop)

Monitors channel activity until a certain idle period is detected. Transmit when free. If busy, random backoff interval is selected. This interval is only decremented if the sensed idle. Transmits when the backoff. Needs ACK by destination station. **Station waits** random backoff time between two consecutive frames, even if detected idle.

Switch - frame forwarding/flooding

If entry in table: if destination is on segment from which frame arrived => drop frame; else forward the frame on indicated interface. Else, forward on all but the interface on which the frame arrived (**flood**).

Network Layer (routing + switching. Addressing and congestion control.)

IP addresses mantêm-se. Mac address é os locais: source de onde veio na LAN e dest para onde vai na LAN.

Transport Layer (Transparent transfer data between hosts. E2E error recovery + flow control.)

Network congestion decreases ⇒ CongestionWin increases (and vice-versa).
$MaxWin = MIN(CongestionWin, AdvertisedWin)$ | $EffWin = MaxWin - (LastByteSent - LastByteAcked)$ | $Bitrate = CongestionWin/RTT$