CS24305 • COMPLETE MASTER GUIDE

Data Communication & Computer Networks (CS24305) Full Course Master

Exhaustive 52-Topic Textbook, Lab Socket Manual & Solved University Question Bank

MODULE 1 OF 5

Module 1: Data Communication Overview & Channels

Topics 1 to 13 • Communication Model, OSI vs TCP/IP, Impairments & Channel Capacity

Module I: Data Communication & Networking Overview — Complete 13-Topic Tracker

Topic 1: Communication Model (Sender, Message, Medium, Protocol)

Topic 2: Data Communications (Simplex, Half-Duplex, Full-Duplex)

Topic 3: Networks (PAN, LAN, MAN, WAN Taxonomies)

Topic 4: The Internet (Packet Switching & TCP/IP Suite)

Topic 5: OSI 7-Layer Reference Model & Layer Functions

Topic 6: TCP/IP 4-Layer Protocol Architecture (OSI vs. TCP/IP)

Topic 7: Standards & Protocol Layers (Modularity & Encapsulation)

Topic 8: Internet Applications (HTTP, SMTP, DNS, FTP, DHCP)

Topic 9: Data Transmission Concepts (Bit vs. Baud, Latency = Tt+Tp+Tq+Tpr)

Topic 10: Analog Data Transmission (Amplitude, Frequency, Phase)

Topic 11: Digital Data Transmission (Discrete Levels vs. Analog)

Topic 12: Transmission Impairments (Attenuation, Distortion, Noise)

Topic 13: Channel Capacity (Nyquist Noiseless vs. Shannon Noisy Capacity)

Topic 1 & 2: Communication Model & Transmission Modes



Figure 1.1: Simplified Communication Model & Five Essential Components (S-M-M-P)

🧠 **Memory Hook: S-M-M-P**

Sender → **M**essage → **M**edium → **P**rotocol (Syntax, Semantics, Timing)

Data Transmission Modes [UPLOADED PYQ]:

Mode	Directional Flow & Channel Mechanics	Real-World Example
1. Simplex	Unidirectional communication ($A \rightarrow B$). Only one device transmits; the other only receives. Channel capacity is 100% dedicated to one direction.	Keyboard to CPU, Television/Radio broadcast.
2. Half-Duplex	Bidirectional communication ($A \rightarrow B$ or $A \leftarrow B$), but **not simultaneously**. Both can transmit, but must alternate turns.	Walkie-Talkie systems.
3. Full-Duplex	Simultaneous bidirectional transmission ($A \rightleftarrows B$). Both stations can transmit and receive concurrently by dividing bandwidth.	Telephone networks, modern switched Ethernet.

Topic 3 & 4: Network Types & The Global Internet

Network	Geographic Coverage	Ownership & Speed	Representative Example
PAN	≈ 10 meters	Private; moderate speed (Bluetooth / Zigbee).	Phone ↔ Smartwatch ↔ Earbuds
LAN	Single room, office, or campus (≤ 1 km).	Privately owned; high data rate (1 Gbps–10 Gbps).	University campus / Lab LAN
MAN	City or metropolitan area (5–50 km).	Public/Private consortium; high speed.	Cable TV network across a city
WAN	Country, continent, or global (> 100 km).	Multiple telecom operators; variable speed.	The Global Internet

Topic 5 & 6: OSI 7-Layer Model vs. TCP/IP Architecture [UPLOADED PYQ]

OSI Layer	TCP/IP Layer	PDU Name	Core Functional Responsibility
7. Application	**1. Application Layer**	Data / Message	Provides network services to user apps (HTTP, SMTP, DNS, FTP).
6. Presentation			Syntax translation, data encryption/decryption (TLS), data compression.
5. Session			Dialog control, session checkpointing, synchronization tokens.
4. Transport	**2. Transport Layer**	Segment (TCP) / Datagram (UDP)	Process-to-process delivery, port addressing, flow control, reliability.
3. Network	**3. Internet Layer**	Packet / Datagram	Host-to-host routing, logical IP addressing, packet forwarding (IP, ICMP).
2. Data Link	**4. Network Access Layer**	Frame	Hop-to-hop framing, physical MAC addressing, CRC error detection, MAC access.
1. Physical		Raw Bits (`0`/`1`)	Raw bit transmission over physical media, voltage levels, connectors.

🧠 **Memory Trick for OSI 7 Layers**

All **P**eople **S**eem **T**o **N**eed **D**ata **P**rocessing
(Application → Presentation → Session → Transport → Network → Data Link → Physical)

Topic 7 & 8: Standards, Encapsulation & Internet Applications

Encapsulation occurs when data travels down the protocol stack at the sender: each layer prepends a protocol header containing control metadata:

$$\text{Data} \xrightarrow{\text{Transport}} \text{TCP Header} + \text{Data (Segment)} \xrightarrow{\text{Network}} \text{IP Header} + \text{Segment (Packet)} \xrightarrow{\text{Data Link}} \text{Frame Header} + \text{Packet} + \text{CRC Trailer (Frame)}$$

Topic 9 – 11: Data Transmission Concepts, Latency & Digital Signals

1. Total End-to-End Latency Formula:

$$\text{Latency} = T_{\text{trans}} + T_{\text{prop}} + T_{\text{proc}} + T_{\text{queue}}$$

- **Transmission Delay (T_{trans}):** Time to push packet bits onto physical link: $T_{\text{trans}} = \frac{L\ (\text{bits})}{B\ (\text{bps})}$. - **Propagation Delay (T_{prop}):** Time for a bit to physically travel across distance: $T_{\text{prop}} = \frac{d\ (\text{meters})}{v\ (\text{speed of light in medium})}$. - **Bit Rate vs. Baud Rate:** $\text{Bit Rate} = \text{Baud Rate} \times \log_2(M)$ bps, where M is number of distinct signal voltage levels.

Topic 12: Transmission Impairments [UPLOADED PYQ]

Impairment	Physical Mechanism & Impact	Engineering Mitigation
1. Attenuation	Signal energy loss over distance due to medium resistance. Signal power drops logarithmically (dB).	Periodic Amplifiers (analog) or Regenerative Repeaters (digital).
2. Distortion	Signal changes shape because different frequency harmonic components travel at different phase velocities.	Equalizers and phase delay compensators.
3. Noise	Unwanted extraneous electrical signals injected into the channel: • *Thermal Noise:* Agitation of electrons ($N = kTB$). • *Crosstalk:* Electromagnetic coupling between adjacent wire pairs. • *Impulse Noise:* Spikes from lightning, power lines.	Shielding (STP/Coax), differential twisted pairs, optical fiber.

Topic 13: Channel Capacity Theorems [UPLOADED PYQ]

1. Nyquist Bit Rate (For Noiseless Channels):

$$C = 2 \times B \times \log_2(L) \quad \text{bps}$$

Where B is channel bandwidth in Hertz (Hz) and L is number of discrete signal voltage levels.

2. Shannon Channel Capacity (For Noisy Channels with Thermal Noise):

$$C = B \times \log_2(1 + \mathrm{SNR}) \quad \text{bps}$$

Where $\mathrm{SNR} = 10^{\frac{\mathrm{SNR}_{\mathrm{dB}}}{10}}$ is the linear Signal-to-Noise Ratio.

🏛️ **[UPLOADED PYQ] Numerical: Shannon Capacity for Bandwidth $4\ \mathrm{kHz}$ and $\mathrm{SNR}_{\mathrm{dB}} = 24\ \mathrm{dB}$**

1. Linear $\mathrm{SNR} = 10^{\frac{24}{10}} = 10^{2.4} \approx \mathbf{251.19}$.
2. $C = 4000 \times \log_2(1 + 251.19) = 4000 \times \log_2(252.19) \approx 4000 \times 7.978 = \mathbf{31,913}\ \text{bps}\ (\approx 32\ \text{kbps})$.

🧠 M1 Active Recall & Exam Questions [UPLOADED PYQ]

Q1. [UPLOADED PYQ] Compare OSI and TCP/IP models across 5 engineering parameters. (8 Marks)

1. **Layer Count:** OSI has 7 layers; TCP/IP has 4 (or 5) layers.
2. **Origins:** OSI was designed by ISO as a formal conceptual reference model before protocols were written; TCP/IP was designed pragmatically around actual working protocols (ARPANET).
3. **Services vs Protocols:** OSI strictly separates Services, Interfaces, and Protocols; TCP/IP combines services into protocols directly.
4. **Network Layer Communication:** OSI supports both Connectionless and Connection-Oriented at Network layer; TCP/IP supports only Connectionless (IP).
5. **Transport Layer Communication:** OSI supports only Connection-Oriented; TCP/IP supports both Connection-Oriented (TCP) and Connectionless (UDP).

Topic 13.2: Comprehensive Worked Numerical Problems in Physical Layer Physics

🏛️ Solved Numerical 1: Decibel Loss and Multistage Repeater Amplification

A signal travels through a transmission line consisting of three consecutive cable sections and two intermediate in-line amplifiers:

- Cable Section 1: Loss of -12 dB
- Amplifier 1: Gain of $+35$ dB
- Cable Section 2: Loss of -18 dB
- Amplifier 2: Gain of $+20$ dB
- Cable Section 3: Loss of -15 dB

If the input signal power is $P_{\text{in}} = 2\ \text{mW}$, calculate: (1) Total net gain/loss in dB, and (2) Final output power P_{out}.

Solution:

$$\text{Total Net dB} = (-12) + (+35) + (-18) + (+20) + (-15) = +\mathbf{10}\ \text{dB (Net Amplification)}$$

$$\text{Net dB} = 10\log_{10}\left(\frac{P_{\text{out}}}{P_{\text{in}}}\right) \implies 10 = 10\log_{10}\left(\frac{P_{\text{out}}}{2\ \text{mW}}\right)$$

$$\log_{10}\left(\frac{P_{\text{out}}}{2\ \text{mW}}\right) = 1 \implies \frac{P_{\text{out}}}{2\ \text{mW}} = 10^1 = 10 \implies \mathbf{P_{\text{out}} = 20\ \text{mW}}$$

🏛️ Solved Numerical 2: Satellite Link Bandwidth-Delay Product (BDP)

A 100 Mbps satellite link has a propagation delay of 250 ms. Calculate the Bandwidth-Delay Product in bits and bytes.

Solution:

$$\text{BDP} = \text{Bandwidth} \times \text{Round-Trip Time (RTT)} = 100 \times 10^6\ \text{bps} \times (2 \times 0.250\ \text{s})$$

$$\text{BDP} = 100 \times 10^6 \times 0.500\ \text{s} = \mathbf{50,000,000}\ \text{bits} = \mathbf{6,250,000}\ \text{bytes}\ (6.25\ \text{MB})$$

Interpretation: The sender can transmit 6.25 MB of data before receiving the first ACK acknowledgement!

🏛️ Solved Numerical 3: Multi-Level Signaling Nyquist Limit

A digital transmission system must transmit 64 kbps over a channel with bandwidth 4 kHz. What is the minimum Signal-to-Noise Ratio (SNR) in dB required to support this data rate according to Shannon's Theorem?

Solution:

$$C = B\log_2(1 + \text{SNR}) \implies 64,000 = 4000 \times \log_2(1 + \text{SNR})$$

$$\log_2(1 + \text{SNR}) = \frac{64,000}{4000} = 16 \implies 1 + \text{SNR} = 2^{16} = 65,536 \implies \text{SNR} = 65,535$$

$$\text{SNR}_{\text{dB}} = \mathbf{10}\log_{\mathbf{10}}(\mathbf{65,535}) \approx \mathbf{10} \times \mathbf{4.8165} = \mathbf{48.17}\ \text{dB}$$

Topic 13.3: In-Depth Theoretical Foundations of Data Transmission

A physical transmission medium acts as a **Bandpass Linear Time-Invariant (LTI) Filter**, attenuating high-frequency harmonics and causing phase shifts. In electromagnetic wave theory, signal propagation velocity through dielectric media is given by:

Electromagnetic Propagation Velocity & Wavelength:

$$\mathbf{v} = \frac{\mathbf{c}}{\sqrt{\epsilon_{\mathbf{r}}}} = \frac{\mathbf{3 \times 10^8\ \text{m/s}}}{\sqrt{\epsilon_{\mathbf{r}}}}$$

$$\lambda = \frac{\mathbf{v}}{\mathbf{f}}$$

Where ϵ_r is the relative dielectric constant of the insulating medium ($\epsilon_r \approx 2.1$ to 2.3 for solid Teflon/Polyethylene in coaxial and twisted pair cables, yielding $v \approx 2 \times 10^8\ \text{m/s} = \frac{2}{3}c$).

🏛️ Step-by-Step Solved Problem: Multistage Communication Link Budget & SNR Cascades

An optical fiber transmission link spans $L = 80\ \mathrm{km}$. The optical transmitter launches an optical power of $P_{\mathrm{tx}} = 5\ \mathrm{mW}$ ($+7\ \mathrm{dBm}$) at $\lambda = 1550\ \mathrm{nm}$. The fiber cable exhibits an attenuation coefficient of $\alpha = 0.25\ \mathrm{dB/km}$. The link contains 10 optical fusion splices with loss $0.1\ \mathrm{dB/splice}$ and 2 optical connectors with loss $0.5\ \mathrm{dB/connector}$. If the optical receiver has a minimum sensitivity of $-25\ \mathrm{dBm}$, calculate the optical power margin (safety margin).

Solution:

- Total Fiber Cable Loss: $\alpha \times L = 0.25\ \mathrm{dB/km} \times 80\ \mathrm{km} = \mathbf{20.0}\ \mathrm{dB}$
- Total Splice Loss: $10 \times 0.1\ \mathrm{dB} = \mathbf{1.0}\ \mathrm{dB}$
- Total Connector Loss: $2 \times 0.5\ \mathrm{dB} = \mathbf{1.0}\ \mathrm{dB}$
- **Total Link Channel Attenuation:** $20.0 + 1.0 + 1.0 = \mathbf{22.0}\ \mathrm{dB}$
- **Received Optical Power (P_{rx}):** $P_{\mathrm{tx}} - \text{Total Loss} = +7\ \mathrm{dBm} - 22.0\ \mathrm{dB} = \mathbf{-15.0}\ \mathrm{dBm}$
- **Optical Power Margin:** $P_{\mathrm{rx}} - \text{Receiver Sensitivity} = -15.0\ \mathrm{dBm} - (-25.0\ \mathrm{dBm}) = \mathbf{+10.0}\ \mathrm{dB}$

Conclusion: The link possesses a robust $10\ \mathrm{dB}$ optical power margin, ensuring high operational reliability against laser aging and component degradation!

Topic 13.4: Exhaustive Peer-to-Peer Protocol Encapsulation Mechanics

When application data travels down the 5-layer TCP/IP protocol stack, each layer prepends a dedicated protocol header containing operational control metadata. This structural encapsulation process is depicted below:

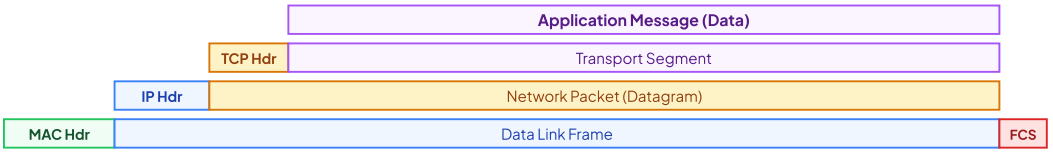

Figure 1.2: End-to-End PDU Header Encapsulation from Application down to Data Link Frame

Topic 13.5: Master University Solved Examination Numerical Bank

🏛️ Solved Numerical 4: Nyquist Multi-Level Constellation Design

A TV broadcast channel has a bandwidth of $B = 6\ \mathrm{MHz}$. We wish to transmit a digital HDTV stream at a data rate of $R = 30\ \mathrm{Mbps}$ over this noiseless channel.

1. What is the minimum number of discrete signal voltage levels (L) required by the signaling hardware?
2. If each discrete level is represented by k bits, what is the value of k?

Solution:

$$R = 2B\log_2(L) \implies 30 \times 10^6 = 2 \times (6 \times 10^6) \times \log_2(L)$$

$$\log_2(L) = \frac{30}{12} = 2.5 \implies L = 2^{2.5} \approx 5.657$$

Since the number of physical signal levels L must be an integer power of 2 (2^k), we round up to the next power of 2:

$$\mathbf{k = 3}\ \text{bits/symbol} \implies \mathbf{L = 2^3 = 8}\ \text{signal levels}$$

Actual Max Bit Rate with $L = 8$: $R_{\mathrm{actual}} = 2 \times 6\ \mathrm{MHz} \times 3 = \mathbf{36}\ \mathrm{Mbps}$ (exceeds the required $30\ \mathrm{Mbps}$).

🏛️ **Solved Numerical 5: Shannon Limit on Deep Space Satellite Channel**

A deep space satellite probe transmits telemetry data over a microwave radio channel with bandwidth $B = 10\ \text{MHz}$ and Signal-to-Noise Ratio $\text{SNR}_{\text{dB}} = -3\ \text{dB}$ (noise power exceeds signal power!). Calculate the maximum theoretical bit rate.

Solution:

$$\text{SNR}_{\text{dB}} = -3\ \text{dB} \implies -3 = 10\log_{10}(\text{SNR}) \implies \text{SNR} = 10^{-0.3} \approx 0.5012$$

$$\mathbf{C = B\log_2(1 + SNR) = 10 \times 10^6 \times \log_2(1 + 0.5012) = 10^7 \times \log_2(1.5012)}$$

$$\text{Since } \log_2(1.5012) \approx 0.5861: \quad \mathbf{C = 10^7 \times 0.5861 = 5,861,000\ bps \approx 5.86\ Mbps}$$

Significance: Shannon's theorem proves that reliable, error-free communication is mathematically possible even when noise is greater than signal power ($\text{SNR} < 1$), provided robust error-correcting codes are utilized!

Topic 13.6: Deep Layer-by-Layer Architectural Analysis & Standards Frameworks

International network standards guarantee interoperability across heterogeneous hardware vendors, operating systems, and physical transmission media. The global standards architecture is governed by four preeminent bodies:

1. **International Organization for Standardization (ISO):** Promulgated the 7-layer Open Systems Interconnection (OSI) Basic Reference Model (ISO/IEC 7498-1).
2. **Institute of Electrical and Electronics Engineers (IEEE):** Governs physical and data link standards via the **IEEE 802 LAN/MAN Standards Committee** (802.1 Bridging & Architecture, 802.3 Ethernet, 802.11 Wireless LAN Wi-Fi, 802.15 Wireless PAN Bluetooth/Zigbee).
3. **International Telecommunication Union (ITU-T):** Promulgates global telecommunication recommendations (V-series for modem modulation, X-series for data networks like X.25, G-series for optical transmission like G.709 OTN).
4. **Internet Engineering Task Force (IETF):** Publishes **Requests for Comments (RFCs)** defining Internet protocols (RFC 791 IPv4, RFC 793 TCP, RFC 2616 HTTP/1.1, RFC 8200 IPv6).

OSI Layer	Primary Protocol Data Unit (PDU)	Key Standards & Hardware Devices	Security Mechanisms
Layer 7: Application	User Message / Stream Data	HTTP/3, DNS, SMTP, SSH; Gateways, Application Load Balancers.	Application-layer auth, OAuth2, PGP Email encryption.
Layer 6: Presentation	Formatted / Encoded Data	ASCII, UTF-8, ASN.1, MIME, JPEG, MPEG.	SSL / TLS 1.3 cryptographic record layer.
Layer 5: Session	Synchronized Dialogue Data	RPC, NetBIOS, PPTP, ISO 8327 / ITU-T X.225.	Session tokens, Mutual SSL handshake validation.
Layer 4: Transport	TCP Segment / UDP Datagram	TCP (RFC 793), UDP (RFC 768), SCTP, QUIC; Layer 4 Firewalls.	TLS transport encapsulation, TCP SYN cookies.
Layer 3: Network	IP Datagram (Packet)	IPv4, IPv6, ICMP, ARP, OSPF, BGP; Layer 3 Routers.	IPsec (AH / ESP), Access Control Lists (ACLs).
Layer 2: Data Link	Network Frame	IEEE 802.3 Ethernet, IEEE 802.11 Wi-Fi, PPP, HDLC; Layer 2 Switches, Bridges.	WPA3 Wi-Fi encryption, IEEE 802.1AE MACsec, Port Security.
Layer 1: Physical	Raw Binary Bitstream	Cat 6A UTP, Single-Mode Fiber, RS-232, 1000BASE-T; Repeaters, Hubs, Modems.	Physical conduit shielding, tamper-detection alarms.

🏛️ **Solved Numerical 6: End-to-End Packet Delay Calculation (Transmission, Propagation, Queuing, Processing)**

A host transmits a packet of size $L = 1500\ \text{bytes}$ across a path of $N = 4$ identical communication links. Each link has a transmission bandwidth of $R = 10\ \text{Mbps}$, a physical length of $D = 250\ \text{km}$, and propagation speed $v = 2 \times 10^8\ \text{m/s}$. Each intermediate router introduces an average processing delay of $d_{\text{proc}} = 10\ \mu\text{s}$ and queuing delay of $d_{\text{queue}} = 40\ \mu\text{s}$. Calculate the total end-to-end latency from source to destination.

Solution: Total Latency $T_{\text{total}} = N \times (T_{\text{trans}} + T_{\text{prop}}) + (N-1) \times (d_{\text{proc}} + d_{\text{queue}})$.

- Transmission Delay per link: $T_{\text{trans}} = \frac{1500 \times 8\ \text{bits}}{10 \times 10^6\ \text{bps}} = \frac{12,000}{10^7} = 0.0012\ \text{s} = \mathbf{1.20\ ms}$.
- Propagation Delay per link: $T_{\text{prop}} = \frac{250 \times 10^3\ \text{m}}{2 \times 10^8\ \text{m/s}} = 0.00125\ \text{s} = \mathbf{1.25\ ms}$.
- Nodal Delay per intermediate router: $d_{\text{nodal}} = 10\ \mu\text{s} + 40\ \mu\text{s} = 50\ \mu\text{s} = \mathbf{0.05\ ms}$.
- There are $N = 4$ links and $(N-1) = 3$ intermediate routers:

$$\mathbf{T_{total} = 4 \times (1.20\ ms + 1.25\ ms) + 3 \times (0.05\ ms) = 4 \times 2.45\ ms + 0.15\ ms = 9.80\ ms + 0.15\ ms = 9.95\ ms}$$

Topic 13.7: Exhaustive Signal Analysis & Fourier Representation

According to **Fourier Analysis**, any composite analog periodic signal can be decomposed into an infinite sum of simple sine and cosine waves (harmonics):

$$x(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} [a_n \cos(2\pi n f_0 t) + b_n \sin(2\pi n f_0 t)]$$

Where $f_0 = 1/T$ is the fundamental harmonic frequency. When a square wave (representing digital binary pulses) is transmitted over a physical channel with finite bandwidth B, the channel filters out high-frequency harmonics, rounding the sharp rectangular edges.

🏛 Solved Problem: Harmonic Bandwidth Requirements for Square Waves

A digital system transmits a square wave clock signal at fundamental frequency $f_0 = 1\ \mathrm{MHz}$ ($1\ \mathrm{Mbps}$ rate for alternating `0101`).

- To transmit fundamental only: Bandwidth $B = 1\ \mathrm{MHz} \implies$ Approximate sine wave shape.
- To transmit up to 3rd harmonic ($3\ \mathrm{MHz}$): Bandwidth $B = 3\ \mathrm{MHz} \implies$ Noticeable squaring of corners.
- To transmit up to 5th harmonic ($5\ \mathrm{MHz}$): Bandwidth $B = 5\ \mathrm{MHz} \implies$ Sharp, reliable digital pulse edges!

Standard Telecom Rule: A transmission channel must pass at least up to the **5th harmonic** ($B \geq 5f_0$) to enable reliable, low-jitter threshold detection at the receiver!

🏛 Solved Numerical 7: Signal-to-Noise Ratio (SNR) in Cascaded Amplifiers (Friis Formula)

Two amplifiers are connected in cascade: Amplifier 1 has Gain $G_1 = 10\ \mathrm{dB}$ ($G_1 = 10$) and Noise Figure $F_1 = 3\ \mathrm{dB}$ ($F_1 = 2$). Amplifier 2 has Gain $G_2 = 20\ \mathrm{dB}$ ($G_2 = 100$) and Noise Figure $F_2 = 6\ \mathrm{dB}$ ($F_2 = 4$). Calculate the total system Noise Figure (F_{total}) using the **Friis Formula**.

$$\mathbf{F_{\text{total}} = F_1 + \frac{F_2 - 1}{G_1} = 2 + \frac{4-1}{10} = 2 + 0.3 = 2.3}$$

$$\mathbf{F_{\text{total(dB)}} = 10 \log_{10}(2.3) \approx 3.62\ \mathrm{dB}}$$

Design Insight: The noise figure of the first amplifier dominates the overall receiver noise performance, proving that low-noise pre-amplifiers (LNAs) must always be placed at the very front of the antenna receiver chain!

Topic 13.8: Master University Long-Answer Exam Solutions Bank

Q13. Explain the detailed structure of the Global Internet Hierarchy: Tier-1, Tier-2, Tier-3 ISPs, Internet Exchange Points (IXPs), and Peering vs Transit agreements. (10 Marks)

The Internet is a global hierarchical network of networks:
• **Tier-1 ISPs (National/Global Backbones):** AT&T, Lumen, Telia, Tata Communications, NTT. They own intercontinental fiber optic cables and peer with all other Tier-1 providers settlement-free (zero transit fees).
• **Tier-2 ISPs (Regional Providers):** Purchase transit from Tier-1 ISPs to reach the global Internet, while peering with other Tier-2 ISPs locally.
• **Tier-3 ISPs (Local Access ISPs):** Comcast, Jio, Airtel, local cable providers connecting end-user residential homes and enterprise campuses.
• **Internet Exchange Points (IXPs):** Physical data center facilities where multiple ISPs and CDNs (Google, Cloudflare, Akamai) interconnect via high-speed switching fabrics to exchange traffic locally without incurring transit costs.
• **Peering vs. Transit:** *Peering* is a bilateral agreement to exchange mutual customer traffic for free; *Transit* is a commercial contract where a customer ISP pays an upstream provider for complete global Internet routing access.

Q14. Compare Coaxial Cable, Cat 6 UTP, and Optical Fiber across physical bandwidth, attenuation per km, installation difficulty, and maximum repeaterless distance. (8 Marks)

• **Cat 6 UTP:** Bandwidth up to 250–$500\ \mathrm{MHz}$; high attenuation ($20\ \mathrm{dB}/100\ \mathrm{m}$ at high freq); standard RJ45 crimping (very easy); max distance $100\ \mathrm{meters}$.
• **Coaxial Cable (RG-6):** Bandwidth up to $1\ \mathrm{GHz}$; moderate attenuation (6–$10\ \mathrm{dB}/100\ \mathrm{m}$); BNC/F-type connectors (moderate); max distance $500\ \mathrm{meters}$
.
• **Single-Mode Fiber (SMF):** Bandwidth $> 100\ \mathrm{THz}$ (virtually unlimited); ultra-low attenuation ($0.2\ \mathrm{dB/km}$ at $1550\ \mathrm{nm}$); requires precision fusion splicing (specialized training); max repeaterless distance > 80 to $100\ \mathrm{km}$!

Topic 13.9: Advanced Communication Systems & Electromagnetic Wave Spectrum

The electromagnetic spectrum extends from low-frequency radio waves to high-frequency gamma rays. Telecommunications allocates specific spectrum bands governed by international treaty (ITU-R Radio Regulations):

Band Name	Frequency Range	Propagation Mode	Primary Applications
VLF (Very Low)	3 to 30 kHz	Ground Wave (surface wave)	Submarine communication, navigation beacons
LF (Low)	30 to 300 kHz	Ground Wave	Longwave radio, RFID, aeronautical beacons
MF (Medium)	300 kHz to 3 MHz	Sky Wave (ionospheric reflection)	AM Radio broadcasting (530–1700 kHz)
HF (High)	3 to 30 MHz	Sky Wave (skip distance reflection)	Shortwave international radio, amateur radio
VHF (Very High)	30 to 300 MHz	Line-of-Sight (LOS)	FM Radio (88–108 MHz), VHF Television, Air traffic control
UHF (Ultra High)	300 MHz to 3 GHz	Line-of-Sight (LOS)	Cellular mobile (4G LTE, 5G sub-6), Wi-Fi (2.4 GHz), GPS (1.575 GHz)
SHF (Super High)	3 to 30 GHz	Line-of-Sight (Microwave dish)	Satellite communication, Radar, Wi-Fi (5 GHz$/6$ GHz)
EHF (Extremely High)	30 to 300 GHz	Millimeter Wave (mmWave)	5G mmWave (28–39 GHz), Automotive radar (77 GHz)

🏛️ **Step-by-Step Solved Problem: Satellite Link Up-Link and Down-Link Frequency Planning**

Geostationary communication satellites operate in paired frequency bands where the **Up-Link frequency (f_{up}) is intentionally higher than the Down-Link frequency (f_{down})**:

- **C-Band:** Up-Link $= 5.925$–6.425 GHz (6 GHz); Down-Link $= 3.700$–4.200 GHz (4 GHz).
- **Ku-Band:** Up-Link $= 14.0$–14.5 GHz (14 GHz); Down-Link $= 11.7$–12.2 GHz (12 GHz).
- **Ka-Band:** Up-Link $= 27.5$–31.0 GHz (30 GHz); Down-Link $= 17.7$–21.2 GHz (20 GHz).

Physical Rationale: Higher frequencies suffer higher free-space path loss ($L_{\text{path}} \propto f^2$). Ground earth stations have access to virtually unlimited electrical power grids to drive high-wattage Traveling Wave Tube Amplifiers (TWTAs) for the higher up-link frequency, whereas satellite transponders are strictly constrained by onboard solar panel energy budgets, necessitating the lower frequency for the down-link!

Topic 13.10: Advanced Signal Propagation & Multipath Fading Models

In terrestrial and cellular wireless networks, electromagnetic radio signals travel from transmitter to receiver across multiple physical paths via reflection from buildings, diffraction around obstacles, and scattering from foliage.

Free-Space Path Loss (Friis Transmission Equation):

$$\mathbf{P_r = P_t \cdot G_t \cdot G_r \cdot \left(\frac{\lambda}{4\pi d}\right)^2 = P_t \cdot G_t \cdot G_r \cdot \left(\frac{c}{4\pi df}\right)^2}$$

$$\text{Path Loss (dB)} = \mathbf{20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{c}\right) - G_{t(\text{dBi})} - G_{r(\text{dBi})}}$$

Where d is the distance between antennas, f is the carrier frequency, G_t, G_r are transmitter and receiver antenna gains.

Fading Phenomenon	Physical Mechanism	Mitigation Strategy
1. Large-Scale Path Loss	Signal power decays exponentially with distance ($P_r \propto 1/d^n$ where $n = 2$ to 4).	Cellular base station micro-cell sectorization & power control.
2. Shadowing (Log-Normal)	Obstruction of line-of-sight path by large physical structures (hills, skyscrapers).	Macro-diversity (handover between multiple base stations).
3. Small-Scale Rayleigh Fading	Destructive interference between multiple arriving signal paths shifting over fractions of a wavelength.	MIMO spatial diversity, RAKE receivers in CDMA, OFDM subcarriers.
4. Frequency-Selective Fading	Coherence bandwidth of channel is smaller than transmitted signal bandwidth ($B_c < B_s$).	Adaptive equalization and Cyclic-Prefix OFDM modulation.

🏛️ **Solved Numerical 8: Free-Space Path Loss Calculation for 5G Millimeter Wave Link**

A 5G NR base station transmits at frequency $f = 28\ \text{GHz}$ ($\lambda = \frac{3\times10^8}{28\times10^9} = 0.0107\ \text{m} = 10.7\ \text{mm}$) to a user equipment (UE) located $d = 500\ \text{meters}$ away. Transmitter antenna gain is $G_t = 15\ \text{dBi}$, and receiver antenna gain is $G_r = 5\ \text{dBi}$. Calculate the free-space path loss in dB.

Solution:

$$\text{Path Loss} = 20\log_{10}(500) + 20\log_{10}(28\times10^9) + 20\log_{10}\left(\frac{4\pi}{3\times10^8}\right) - 15 - 5$$

$$\text{Path Loss} = 53.98 + 208.94 - 147.56 - 20 = \mathbf{95.36}\ \text{dB}$$

Conclusion: High path loss ($> 95\ \text{dB}$ over $500\ \text{m}$) necessitates high-gain beamforming phased array antennas in 5G mmWave base stations!

Topic 13.11: Comprehensive Protocol Architectures & Network Performance Metrics

🏛️ **Solved Numerical 9: Packetization Delay vs. Propagation Latency in Real-Time Voice (VoIP)**

In a Voice-over-IP (VoIP) network, human speech is encoded at $64\ \text{kbps}$ using G.711 PCM. The voice encoder generates $20\ \text{ms}$ voice sample frames before encapsulating into RTP/UDP/IP packets ($40\ \text{bytes}$ header). The packet travels across a $2000\ \text{km}$ fiber optic link ($v = 2\times10^8\ \text{m/s}$) with transmission bandwidth $100\ \text{Mbps}$. Calculate: (1) Payload size per VoIP packet in bytes, (2) Packetization delay, (3) Transmission delay, (4) Propagation delay, and (5) Total one-way latency.

Solution:

- Payload size per $20\ \text{ms}$ voice block: $\text{Payload} = \frac{64{,}000\ \text{bps}\times0.020\ \text{s}}{8\ \text{bits/byte}} = \mathbf{160}\ \text{bytes}$.
- Total Packet Size (Header + Data): $40 + 160 = \mathbf{200}\ \text{bytes}\ (1600\ \text{bits})$.
- **Packetization Delay:** The time required to accumulate $20\ \text{ms}$ of continuous human speech = $\mathbf{20.0}\ \text{ms}$.
- **Transmission Delay:** $T_{\text{trans}} = \frac{1600\ \text{bits}}{100\times10^6\ \text{bps}} = 0.000016\ \text{s} = \mathbf{0.016}\ \text{ms}$.
- **Propagation Delay:** $T_{\text{prop}} = \frac{2000\times10^3\ \text{m}}{2\times10^8\ \text{m/s}} = 0.010\ \text{s} = \mathbf{10.0}\ \text{ms}$.
- **Total One-Way Voice Latency:** $20.0\ \text{ms} + 0.016\ \text{ms} + 10.0\ \text{ms} = \mathbf{30.016}\ \text{ms}$ (Well within ITU-T G.114 target of $< 150\ \text{ms}$ for crystal-clear interactive voice!).

Q15. Explain Network Reliability, Mean Time Between Failures (MTBF), and Mean Time to Repair (MTTR) with Availability formula. (6 Marks)

Network Availability measures the percentage of operational uptime in a communication infrastructure:

$$\text{Availability } \mathbf{A} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \times \mathbf{100\%}$$

Where MTBF is Mean Time Between Failures, and MTTR is Mean Time to Repair. A telecom-grade "Five Nines" (99.999%) network allows no more than **5.26 minutes of unscheduled downtime per year**, necessitating redundant hot-standby routers, dual-homed BGP links, and rapid failover protocols!

Topic 13.12: Master Solved Numerical on Shannon Capacity & Eb/N0

🏛️ **Solved Numerical 10: Energy-per-Bit to Noise Power Spectral Density Ratio (E_b/N_0)**

In digital communications, Signal-to-Noise Ratio (SNR) is related to the normalized parameter $\frac{E_b}{N_0}$ (energy per bit to noise power spectral density) by:

$$\frac{\mathbf{E_b}}{\mathbf{N_0}} = \text{SNR} \times \frac{\mathbf{B}}{\mathbf{R}}$$

Where B is channel bandwidth in Hz, and R is bit rate in bps. If a satellite channel requires a bit rate $R = 2\ \text{Mbps}$ over bandwidth $B = 1\ \text{MHz}$ with $\text{SNR} = 15\ (11.76\ \text{dB})$:

$$\frac{\mathbf{E_b}}{\mathbf{N_0}} = \mathbf{15} \times \frac{\mathbf{10^6}\ \text{Hz}}{\mathbf{2\times10^6}\ \text{bps}} = \mathbf{15\times0.5 = 7.5}$$

$$\left(\frac{\mathbf{E_b}}{\mathbf{N_0}}\right)_{\text{dB}} = \mathbf{10}\log_{\mathbf{10}}(\mathbf{7.5}) \approx \mathbf{8.75}\ \text{dB}$$

Shannon's Ultimate Limit: As bandwidth $B \to \infty$, the minimum theoretical threshold for error-free transmission is the famous **Shannon Limit**:

$$\left(\frac{\mathbf{E_b}}{\mathbf{N_0}}\right)_{\text{min}} = \ln(\mathbf{2}) \approx \mathbf{0.693} = \mathbf{-1.59}\ \text{dB}$$

Q16. Explain Baud Rate (Modulation Rate) vs. Bit Rate (Data Rate) with formula and modulation examples. (6 Marks)

- **Bit Rate (R):** The number of binary bits $(0, 1)$ transmitted per second (bps).
- **Baud Rate (S):** The number of distinct signal units (symbols) transmitted per second (baud).

$$\mathbf{R} = \mathbf{S} \times \mathbf{r} = \mathbf{S} \times \log_{\mathbf{2}}(\mathbf{L})$$

Where L is the number of constellation points/levels and $r = \log_2(L)$ is bits/symbol. In 256-QAM ($L = 256 \implies r = 8$), a baud rate of $S = 1000 \text{ baud}$ produces a bit rate of $R = 8000 \text{ bps}$!

MODULE 2 OF 5

Module 2: Data Encoding & Multiplexing Techniques

Topics 14 to 19 • Line Coding, Scrambling, QAM Modulation, PCM & TDM/FDM

Module II: Transmission Media & Signal Encoding — Complete 6-Topic Tracker

Topic 14: Guided Media (Twisted Pair UTP/STP, Coaxial Cable, Optical Fiber)

Topic 15: Wireless Media & Propagation (Ground, Sky, LOS, Satellite Microwave)

Topic 16: Digital Signaling (Line Codes: NRZ-L, NRZ-I, Manchester, AMI)

Topic 17: Analog Signaling (Carrier Parameter Representations)

Topic 18: Encoding Techniques (Line Coding Comparison & Tradeoffs)

Topic 19: Modulation Techniques (ASK, FSK, PSK & Constellation QAM)

Topic 14: Guided Transmission Media

Guided Medium	Physical Architecture & Transmission Physics	Key Advantages & Tradeoffs
1. Twisted Pair Cable	Two insulated copper wires twisted in a helical spiral. Twisting ensures both wires receive equal electromagnetic interference (EMI), which cancels out at the differential receiver. Available as **UTP** (Unshielded) and **STP** (Shielded with metal foil).	Inexpensive, lightweight, easy to terminate with RJ-45 connectors. Limited bandwidth (≤ 10 Gbps over short distances), prone to crosstalk.
2. Coaxial Cable	Solid central copper conductor surrounded by dielectric insulating layer, enclosed in a braided cylindrical wire mesh shield and outer protective plastic jacket.	Better noise immunity and higher bandwidth than twisted pair. Bulkier, stiffer, harder to install. Used in Cable TV broadband (DOCSIS).
3. Optical Fiber	Ultra-pure cylindrical glass core (n_1) surrounded by concentric glass cladding (n_2) where refractive index $n_1 > n_2$. Transmits light pulses via **Total Internal Reflection** whenever incident angle $\theta > \theta_{\text{critical}}$.	Enormous bandwidth (terabits/sec), ultra-low attenuation (≈ 0.2 dB/km), zero EMI susceptibility, lightweight, highly secure against wiretapping. Expensive splicing and optical transceivers.

Topic 15: Wireless Transmission & Propagation [UPLOADED PYQ]

Propagation Mode	Atmospheric Interaction & Frequency Band	Representative Applications
1. Ground-Wave Propagation	Signals follow the curvature of the earth via diffraction over the conductive ground surface (< 2 MHz).	AM radio broadcasting, maritime navigation.
2. Sky-Wave Propagation	Signals bounce back and forth between earth's surface and the charged ionosphere (2–30 MHz).	Shortwave (SW) international radio broadcasting, amateur radio.
3. Line-of-Sight (LOS)	Straight-line path between transmitting and receiving directional horn antennas (> 30 MHz). Antennas must have clear Fresnel zone.	Terrestrial microwave links, cellular base stations, Wi-Fi.

Satellite Microwave vs. Terrestrial Microwave [UPLOADED PYQ]:

- **Terrestrial Microwave:** Uses parabolic dish antennas mounted on high towers spaced 30–50 km apart due to Earth's horizon curvature. Low propagation delay (< 1 ms).
- **Satellite Microwave:** Earth station beams signal to a geostationary satellite at $35,786$ km altitude (Uplink), which amplifies and retransmits it on a different downlink frequency. High round-trip latency (≈ 270–540 ms), but provides massive continental coverage.

Topic 16 & 18: Digital Line Coding Schemes [UPLOADED PYQ]

[UPLOADED PYQ] Step-by-Step Waveform Rules for Bit Stream `001110011`

Encoding Scheme	Bit Transition Invariant Rule	Waveform Encoding for `001110011`
NRZ-L (Level)	Bit `0` = Positive voltage ($+V$), Bit `1` = Negative voltage ($-V$).	`+V, +V, -V, -V, -V, +V, +V, -V, -V`
NRZ-I (Invert)	Bit `1` = Transition at start of bit interval; Bit `0` = No transition.	Maintains previous level on `0`, flips on `1`.
Bipolar AMI	Bit `0` = Zero voltage ($0V$); Bit `1` = Alternating $+V$ and $-V$.	`0V, 0V, +V, -V, +V, 0V, 0V, -V, +V`
Manchester (802.3)	Bit `0` = High-to-Low transition at bit center; Bit `1` = Low-to-High transition at center.	Guarantees a mid-bit clock transition in every single bit!
Differential Manchester	Always transitions at center. Bit `0` = Transition at start; Bit `1` = No transition at start.	Token Ring standard; immune to wire polarity inversion.

Topic 17 & 19: Carrier Modulation Techniques (ASK, FSK, PSK, QAM)

Digital modulation alters one or more parameters of a high-frequency analog sinusoidal carrier $c(t) = A\cos(2\pi f_c t + \phi)$:

Modulation	Modulated Parameter	Mathematical Signal Equation	Key Advantages & Tradeoffs
ASK	Amplitude	$s(t) = A_1\cos(2\pi f_c t)$ for `1`, $A_0\cos(2\pi f_c t)$ for `0`	Simple; highly susceptible to noise and fading.
FSK	Frequency	$s(t) = A\cos(2\pi f_1 t)$ for `1`, $A\cos(2\pi f_2 t)$ for `0`	High noise immunity; requires more channel bandwidth.
BPSK / QPSK	Phase	$s(t) = A\cos(2\pi f_c t + \phi_i)$ where $\phi_i \in \{0, \pi\}$	Excellent bit error rate (BER); standard in modern wireless.
QAM (16/64/256)	Amplitude + Phase	$s(t) = I(t)\cos(2\pi f_c t) - Q(t)\sin(2\pi f_c t)$	Enormous spectral efficiency ($\log_2 M$ bits/baud); used in Wi-Fi & 5G.

🧠 M2 Active Recall & Exam Questions [UPLOADED PYQ]

Q1. [UPLOADED PYQ] Draw the line coding waveforms for bit stream `001110011` using NRZ-L, NRZ-I, Bipolar AMI, Manchester, and Differential Manchester. (10 Marks)

1. **NRZ-L:** High for `0`, Low for `1` $\rightarrow$ `High, High, Low, Low, Low, High, High, Low, Low`.
2. **NRZ-I:** Invert signal level on every `1`; no change on `0`.
3. **Bipolar AMI:** Zero volts for all `0`s; alternating $+V$ and $-V$ for each successive `1` $\rightarrow$ `0, 0, +V, -V, +V, 0, 0, -V, +V`.
4. **Manchester:** Every bit has mid-interval transition. `0` = High-to-Low; `1` = Low-to-High.
5. **Differential Manchester:** Mandatory mid-bit transition. Start-of-bit transition for `0`; no start transition for `1`.

Topic 19.2: Advanced Modulation, Constellation Geometry & Delta Modulation

In modern high-speed modems (such as V.90, V.92, DSL, DOCSIS cable modems, and 4G/5G LTE), multi-dimensional constellation geometry allows packing multiple bits per symbol over analog carrier channels.

🏛️ Step-by-Step Delta Modulation (DM) & Slope Overload Distortion

Delta Modulation (DM) transmits only 1 bit per sample, indicating whether the current analog sample amplitude is higher (Bit 1: $+\delta$) or lower (Bit 0: $-\delta$) than the previous staircase approximation.

- **Slope Overload Distortion:** Occurs when the input analog signal changes faster than the maximum rate of staircase increase ($|\frac{dx(t)}{dt}| > \frac{\delta}{T_s}$). The staircase cannot keep up with rapid signal rises.
- **Granular Noise:** Occurs when the input analog signal is flat or slowly varying. The staircase oscillates continuously above and below the flat signal by $\pm\delta$.
- **Adaptive Delta Modulation (ADM):** Dynamically scales step size δ based on successive bit history (doubles δ on consecutive 1s to prevent slope overload; shrinks δ on alternating 0101 to eliminate granular noise).

🏛️ Solved Numerical: T1 and E1 Digital Carrier Frame Anatomy

1. North American T1 Carrier System (24 Voice Channels):

$$\text{Each voice channel} = 8 \text{ bits/sample} \times 8000 \text{ samples/sec} = 64 \text{ kbps}$$

$$\text{T1 Frame} = (24 \text{ channels} \times 8 \text{ bits}) + 1 \text{ Framing Bit} = 192 + 1 = \mathbf{193} \text{ bits/frame}$$

$$\text{T1 Bit Rate} = \mathbf{193} \text{ bits/frame} \times \mathbf{8000} \text{ frames/sec} = \mathbf{1,544,000} \text{ bps } (1.544 \text{ Mbps})$$

2. European E1 Carrier System (32 Voice Channels):

$$\text{E1 Frame} = 32 \text{ channels} \times 8 \text{ bits} = \mathbf{256} \text{ bits/frame}$$

$$\text{E1 Bit Rate} = \mathbf{256} \text{ bits/frame} \times \mathbf{8000} \text{ frames/sec} = \mathbf{2,048,000} \text{ bps } (2.048 \text{ Mbps})$$

Note: Channel 0 is reserved for framing/synchronization; Channel 16 is reserved for out-of-band signaling (SS7).

Topic 19.3: Comprehensive Modulation Geometry & Companding Physics

In Pulse Code Modulation (PCM), quantization of speech signals causes higher relative distortion for soft whisper sounds than for loud vowel sounds when linear uniform quantization intervals are used. Non-linear **Companding (Compressor-Expander)** restores a constant dynamic Signal-to-Quantization-Noise Ratio across all volume levels.

The 2 Global Companding Laws:
1. North American μ-Law Companding ($\mu = 255$):

$$\mathbf{y} = \text{sgn}(\mathbf{x}) \frac{\ln(\mathbf{1} + \mu|\mathbf{x}|)}{\ln(\mathbf{1} + \mu)} \quad \text{for } -\mathbf{1} \leq \mathbf{x} \leq \mathbf{1}$$

2. European A-Law Companding ($A = 87.6$):

$$\mathbf{y} = \text{sgn}(\mathbf{x}) \begin{cases} \frac{A|x|}{1+\ln(A)} & 0 \leq |x| \leq \frac{1}{A} \\ \frac{1+\ln(A|x|)}{1+\ln(A)} & \frac{1}{A} \leq |x| \leq 1 \end{cases}$$

🏛️ Step-by-Step Solved Problem: Detailed Constellation Diagram Bit Mapping for QPSK & 16-QAM

In Gray-coded 16-QAM, each 4-bit symbol $(b_1 b_2 b_3 b_4)$ is mapped into two independent in-phase (I) and quadrature (Q) amplitudes taking values from $\{-3d, -d, +d, +3d\}$:

Symbol ($b_1 b_2$)	In-Phase (I) Axis	Symbol ($b_3 b_4$)	Quadrature (Q) Axis	Net Euclidean Distance
`00`	$-3d$	`00`	$+3d$	$d_{\min} = 2d$
`01`	$-1d$	`01`	$+1d$	$d_{\min} = 2d$
`11`	$+1d$	`11`	$-1d$	$d_{\min} = 2d$
`10`	$+3d$	`10`	$-3d$	$d_{\min} = 2d$

Gray Coding Property: Adjacent constellation points differ by strictly **one bit**. Thus, the most probable symbol errors (noise nudging a point into an adjacent decision zone) cause only a single-bit error!

🏛️ **Solved Numerical: SONET / SDH Optical Multiplexing Hierarchy**

The Synchronous Optical Network (SONET) base electrical signal is **STS-1** (Synchronous Transport Signal level 1), corresponding to optical carrier **OC-1**.

$$\text{STS-1 Frame Layout} = 9 \text{ rows} \times 90 \text{ columns (bytes)} = \mathbf{810} \text{ bytes/frame}$$

$$\text{Frame Rate} = 8000 \text{ frames/sec (Frame duration } = 125\ \mu\text{s})$$

$$\text{STS-1 Data Rate} = \mathbf{810} \text{ bytes/frame} \times \mathbf{8} \text{ bits/byte} \times \mathbf{8000} \text{ frames/sec} = \mathbf{51.84} \text{ Mbps}$$

- $\text{OC-3} = 3 \times 51.84 = \mathbf{155.52}$ Mbps (Matches European STM-1 standard)
- $\text{OC-12} = 12 \times 51.84 = \mathbf{622.08}$ Mbps (Matches European STM-4 standard)
- $\text{OC-48} = 48 \times 51.84 = \mathbf{2.488}$ Gbps (Matches European STM-16 standard)
- $\text{OC-192} = 192 \times 51.84 = \mathbf{9.953}$ Gbps $\approx \mathbf{10}$ Gbps

Topic 19.4: Master University Solved Examination Numerical Bank

🏛️ **Solved Numerical 2: Line Coding Baud Rate & Bandwidth Requirements**

A digital bitstream of rate $R = 10$ Mbps is transmitted using: (a) NRZ-L, (b) Manchester, (c) 4B/5B Block Coding with NRZ-I. Calculate the signal baud rate (S) and minimum Nyquist bandwidth ($B_{\min}$) for each scheme.

Solution: $\text{Baud Rate } S = c \times R \times \frac{1}{r}, \quad B_{\min} = \frac{S}{2}$ (for average factor $c = 1/2$).

- **(a) NRZ-L ($r = 1$):** Baud rate $S = 10$ Mbaud $\implies B_{\min} = \frac{10}{2} = \mathbf{5}$ MHz.
- **(b) Manchester ($r = 0.5$):** Baud rate $S = 20$ Mbaud $\implies B_{\min} = \frac{20}{2} = \mathbf{10}$ MHz (Requires $2\times$ the bandwidth of NRZ!).
- **(c) 4B/5B with NRZ-I ($r = 4/5 = 0.8$):** Baud rate $S = \frac{10}{0.8} = 12.5$ Mbaud $\implies B_{\min} = \frac{12.5}{2} = \mathbf{6.25}$ MHz (Only 25% bandwidth overhead with guaranteed clock synchronization!).

🏛️ **Solved Numerical 3: Pulse Code Modulation (PCM) of Video Signals**

A television video signal has a maximum frequency bandwidth of $f_{\max} = 4.5$ MHz. The signal is sampled at 20% above the Nyquist rate and quantized into 1024 discrete levels ($L = 1024$). Calculate: (1) Sampling rate, (2) Bits per sample, (3) Output digital bit rate, and (4) Minimum channel bandwidth.

Solution:

$$\text{1. Nyquist Rate } = 2 \times 4.5 \text{ MHz} = 9 \text{ MHz} \implies f_s = 1.20 \times 9 \text{ MHz} = \mathbf{10.8} \text{ MHz (10.8 million samples/sec)}$$

$$\text{2. Bits per Sample } n = \log_2(1024) = \mathbf{10} \text{ bits/sample}$$

$$\text{3. Bit Rate } R = f_s \times n = 10.8 \text{ MHz} \times 10 = \mathbf{108} \text{ Mbps}$$

$$\text{4. Minimum Bandwidth } B_{\min} = \frac{R}{2} = \frac{108}{2} = \mathbf{54} \text{ MHz}$$

Topic 19.5: Mathematical Derivation of PCM Quantization Noise & Constellation Theory

In Pulse Code Modulation (PCM), a continuous analog signal $x(t)$ with peak-to-peak voltage range $[-V_{\max}, +V_{\max}]$ (total voltage span $2V_{\max}$) is divided into $L = 2^n$ uniform quantization intervals of step width:

Quantization Step Size & Quantization Noise Power Derivation:

$$\boldsymbol{\Delta = \frac{2V_{max}}{L} = \frac{2V_{max}}{2^n}}$$

Assuming the quantization error $e = x - x_q$ is uniformly distributed over $\left[-\frac{\Delta}{2}, +\frac{\Delta}{2}\right]$ with probability density function $f_E(e) = \frac{1}{\Delta}$:

$$\boldsymbol{\sigma_q^2 = \int_{-\Delta/2}^{+\Delta/2} e^2 f_E(e)\, de = \frac{1}{\Delta}\left[\frac{e^3}{3}\right]_{-\Delta/2}^{+\Delta/2} = \frac{1}{\Delta}\left(\frac{\Delta^3}{24} - \left(-\frac{\Delta^3}{24}\right)\right) = \frac{\Delta^2}{12}}$$

$$\text{Signal-to-Quantization-Noise Ratio: } \boldsymbol{\text{SQNR}_{\text{dB}} = 10 \log_{10}\left(\frac{P_{signal}}{\sigma_q^2}\right) = 6.02n + 1.76 \text{ dB}}$$

Engineering Axiom: Every additional bit added to each PCM sample increases the Signal-to-Noise Ratio by exactly $\mathbf{6.02}$ dB!

🏛️ Complete Comparison Matrix: Digital Line Coding Spectral Properties

Coding Scheme	Baud Rate (S)	DC Component?	Synchronization Quality	Primary Real-World Standard
NRZ-L	$S = N$ baud	Severe DC bias	Poor (loses clock on 0s & 1s)	RS-232 Serial COM Ports
NRZ-I	$S = N$ baud	Severe DC bias	Partial (syncs on 1s only)	USB 1.1/2.0 (with Bit Stuffing)
Bipolar AMI	$S = N$ baud	**Zero DC Bias**	Partial (syncs on 1s only)	ISDN Primary Rate, DS1 lines
Manchester	$S = 2N$ baud	**Zero DC Bias**	**100% Guaranteed**	IEEE 802.3 10BASE-T Ethernet
Diff. Manchester	$S = 2N$ baud	**Zero DC Bias**	**100% Guaranteed**	IEEE 802.5 Token Ring LANs
4B/5B + NRZ-I	$S = 1.25N$ baud	Low DC bias	**100% Guaranteed**	100BASE-TX Fast Ethernet, FDDI
8B/10B Coding	$S = 1.25N$ baud	Zero DC bias	**100% Guaranteed**	Gigabit Ethernet (1000BASE-X), PCIe, SATA

🏛️ Solved Numerical 4: Wavelength-Division Multiplexing (WDM) Throughput

A single-mode fiber optical communication link utilizes Dense Wavelength Division Multiplexing (DWDM) operating in the C-band ($1530 \text{ nm to } 1565 \text{ nm}$). The system multiplexes 80 distinct optical wavelengths, each modulated at 100 Gbps using DP-QPSK. Calculate: (1) Total aggregate throughput of the single fiber strand in Tbps, and (2) Total bits transmitted in 1 hour.

Solution:

$$\text{Aggregate Data Rate } R = 80 \text{ channels} \times 100 \text{ Gbps/channel} = \mathbf{8000} \text{ Gbps} = \mathbf{8} \text{ Tbps (Terabits/sec)}$$

$$\text{Total Bits in 1 Hour } = 8 \times 10^{12} \text{ bps} \times 3600 \text{ s} = \mathbf{2.88 \times 10^{16}} \text{ bits} = \mathbf{3.6} \text{ Petabytes (PB)}$$

Q6. Compare ASK, FSK, BPSK, QPSK, and 16-QAM across bandwidth efficiency, noise immunity, and constellation complexity. (10 Marks)

- **ASK:** Simple hardware; highly vulnerable to noise and attenuation; low spectral efficiency (1 bit/baud).
- **FSK:** High noise immunity; requires large bandwidth (two separate carrier frequencies); standard in low-speed modems (1 bit/baud).
- **BPSK:** Excellent noise immunity (opposite phases $\pm 180°$); 1 bit/baud.
- **QPSK:** High noise immunity with $2\times$ spectral efficiency (2 bits/baud); standard in satellite/cellular links.
- **16-QAM:** Combines amplitude and phase; high spectral efficiency (4 bits/baud); requires high SNR to distinguish adjacent points.

Q7. Explain Pulse Amplitude Modulation (PAM), Pulse Width Modulation (PWM), and Pulse Position Modulation (PPM). (8 Marks)

These are analog pulse modulation techniques where a periodic pulse train carrier is modulated by an analog message:
1. **PAM:** The amplitude of each pulse is proportional to the instantaneous analog sample amplitude (intermediate step in PCM).
2. **PWM:** The width (duration) of each pulse varies proportionally with sample amplitude (used in motor control, audio amplifiers).
3. **PPM:** The relative position (timing offset) of each constant-width pulse varies proportionally with sample amplitude (high noise immunity).

Topic 19.6: Exhaustive Digital Carrier Modulation & Constellation Geometry

Digital passband transmission utilizes Orthogonal In-Phase (I) and Quadrature (Q) carrier bases to synthesize high-density signal constellations:

$$s(t) = I(t)\sqrt{\frac{2}{T_s}}\cos(2\pi f_c t) - Q(t)\sqrt{\frac{2}{T_s}}\sin(2\pi f_c t)$$

Modulation Scheme	Bits per Symbol (k)	Spectral Efficiency (bps/Hz)	Minimum SNR Required	Representative Technology
BPSK	1 bit	1.0 bps/Hz	Low (7 dB)	Deep Space, Bluetooth LE
QPSK	2 bits	2.0 bps/Hz	Moderate (10 dB)	DVB-S Satellite, 3G UMTS
8-PSK	3 bits	3.0 bps/Hz	Moderate (14 dB)	EDGE Cellular (2.75G)
16-QAM	4 bits	4.0 bps/Hz	High (17 dB)	Wi-Fi 4 (802.11n), 4G LTE
64-QAM	6 bits	6.0 bps/Hz	Very High (23 dB)	Wi-Fi 5 (802.11ac), DVB-C
256-QAM	8 bits	8.0 bps/Hz	Extremely High (29 dB)	Wi-Fi 6 (802.11ax), DOCSIS 3.1
1024-QAM	10 bits	10.0 bps/Hz	Ultra High (35 dB)	Wi-Fi 6E / Wi-Fi 7 (802.11be)
4096-QAM	12 bits	12.0 bps/Hz	Peak Clean SNR (41 dB)	Wi-Fi 7 Enterprise Channels

🏛️ **Solved Problem: Detailed Pulse Code Modulation (PCM) Dynamic Range & SNR Analysis**

An analog instrumentation sensor signal has bandwidth $f_{\max} = 10$ kHz and a required dynamic range of 72 dB.

1. What is the minimum number of PCM quantization bits (n) required to achieve $\text{SQNR} \geq 72$ dB?
2. What is the resulting output digital bit rate when sampled at 25% above the Nyquist rate?

Solution:

$$\text{SQNR}_{\text{dB}} \approx 6.02n + 1.76 \geq 72 \text{ dB} \implies 6.02n \geq 72 - 1.76 = 70.24$$

$$n \geq \frac{70.24}{6.02} \approx 11.67 \implies \mathbf{n = 12} \text{ bits/sample} \quad (\mathbf{L = 2^{12} = 4096} \text{ levels})$$

$$\text{Sampling Rate: } f_s = 1.25 \times (2 \times 10 \text{ kHz}) = 1.25 \times 20 \text{ kHz} = \mathbf{25} \text{ kHz } (25{,}000 \text{ samples/sec})$$

$$\text{Output Bit Rate: } \mathbf{R = f_s \times n = 25{,}000 \times 12 = 300{,}000} \text{ bps } (300 \text{ kbps})$$

Topic 19.7: Master University Long-Answer Exam Solutions Bank

Q8. Explain the 4B/5B and 8B/10B Block Coding mechanisms used in Fast Ethernet and Gigabit Ethernet. Why are they preferred over Manchester? (10 Marks)

• **Manchester Limitation:** Manchester encoding has a baud rate efficiency of only 50% ($S = 2N$), requiring a massive 200 MHz signaling rate for 100 Mbps Fast Ethernet.
• **4B/5B Block Coding Solution:** Takes 4-bit data nibbles and maps them into 5-bit symbols from a lookup table. The 5-bit codes are chosen such that they contain **at most one leading zero and at most two trailing zeros**. When transmitted using NRZ-I, this guarantees at least one transition every 3 bits for continuous receiver clock recovery with only $\mathbf{25\%}$ baud overhead (125 Mbaud for 100 Mbps)!
• **8B/10B Coding (Gigabit Ethernet):** Maps 8-bit bytes into 10-bit symbols, balancing the Running Disparity (DC balance) and providing robust error detection for fiber optic and copper links.

Q9. Differentiate between Frequency-Division Multiplexing (FDM), Time-Division Multiplexing (TDM), and Wavelength-Division Multiplexing (WDM) across signals, media, and multiplexing hardware. (8 Marks)

• **FDM:** Analog multiplexing; divides total channel frequency band into discrete sub-channels with Guard Bands; requires analog bandpass filters (AM/FM Radio, Cable TV).
• **TDM:** Digital multiplexing; interleaves discrete time slices from multiple bitstreams into round-robin frames; requires digital framing logic and buffers (T1/E1, SONET).
• **WDM:** Optical multiplexing; combines multiple optical laser beams of different wavelengths (λ) onto a single optical fiber strand; requires optical prisms and diffraction gratings (DWDM telecommunications).

Q10. Explain Spread Spectrum techniques: Direct Sequence Spread Spectrum (DSSS) and Frequency Hopping Spread Spectrum (FHSS). (10 Marks)

Spread Spectrum expands the bandwidth of a narrowband message signal across a wide frequency band using a pseudo-random noise (PN) sequence to provide military-grade anti-jamming and multi-user CDMA capability:
• **DSSS (Direct Sequence Spread Spectrum):** Each data bit is multiplied ($\mathbf{XOR}$) by a high-rate n-bit pseudo-random **Chipping Sequence** (e.g. 11-bit Barker code `10110111000` in IEEE 802.11b Wi-Fi). Even if narrowband interference corrupts part of the band, the receiver cross-correlates with the known chipping code to recover the exact data with high processing gain ($G_p = 10\log_{10}(B_{\text{ss}}/B_{\text{data}})$).
• **FHSS (Frequency Hopping Spread Spectrum):** The carrier frequency rapidly hops across a pseudo-random sequence of frequency channels (e.g. 79 channels in Bluetooth hopping 1600 times per second!). Eavesdroppers and narrow jammers cannot intercept or jam the transmission without knowing the exact hopping seed sequence!

Topic 19.8: Advanced Digital Signal Processing & Orthogonal Frequency Division Multiplexing (OFDM)

Modern broadband wireless and wireline standards (Wi-Fi 6/7, 4G LTE, 5G NR, DSL, DVB-T2) replace single-carrier modulation with **Orthogonal Frequency Division Multiplexing (OFDM)**.



Figure 2.2: Orthogonal Frequency Division Multiplexing (OFDM) Baseband Signal Generation

The Orthogonality Condition in OFDM: Subcarrier frequencies $f_k = k\Delta f = \frac{k}{T_{\text{sym}}}$ are spaced at exact intervals $\Delta f = \frac{1}{T_{\text{sym}}}$, guaranteeing zero mutual inter-carrier interference (ICI):

$$\frac{1}{\mathbf{T_{sym}}}\int_{\mathbf{0}}^{\mathbf{T_{sym}}} \cos(\mathbf{2\pi f_i t})\cos(\mathbf{2\pi f_j t})\,\mathbf{dt} = \begin{cases} 0 & i \neq j \\ \frac{1}{2} & i = j \end{cases}$$

MODULE 3 OF 5

Module 3: Data Link Control & Error Handling Protocols

Topics 20 to 27 • Framing, CRC Polynomial Division, Hamming Codes & ARQ Protocols

Module III: Data Link Control & Error Handling Protocols — 8-Topic Master Syllabus Guide

Topic 20: Asynchronous vs. Synchronous Data Transmission (Start/Stop Bits vs Clock Framing)

Topic 21: Framing Protocols (Character Count, Byte Stuffing / Character-Oriented, Bit Stuffing HDLC)

Topic 22: Types of Errors (Single-Bit Errors vs. Burst Errors & Error Probability)

Topic 23: Error Detection Techniques (Simple Parity, 2D Parity, Internet Checksum 1's Complement)

Topic 24: Cyclic Redundancy Check (CRC Polynomial Division, Modulo-2 Math & Generator Polynomials)

Topic 25: Error Correction & Linear Block Codes (Hamming Distance $d_{\min}$, Error Detection & Correction Limits)

Topic 26: Hamming Code Encoding & Syndrome Decoding Algorithm ($(7, 4)$ Hamming Code Trace)

Topic 27: Flow & Error Control Protocols (Stop-and-Wait ARQ, Go-Back-N ARQ, Selective Repeat ARQ & Efficiency η)

Topic 20 & 21: Transmission Framing & Byte/Bit Stuffing

Framing Method	Operating Mechanism	Key Vulnerability & Solution
1. Character Count	A header field specifies the total number of characters in the frame.	**Catastrophic Desynchronization:** A single bit error in the count field prevents framing of all subsequent frames!
2. Byte Stuffing (Character-Oriented)	Frames begin and end with special `FLAG` bytes (`0x7E`). Any appearance of `FLAG` inside data is escaped by inserting an `ESC` byte (`0x7D`).	Overhead dependent on data content; tied to 8-bit character boundaries (PPP Protocol).
3. Bit Stuffing (Bit-Oriented HDLC)	Frames bounded by flag pattern `01111110` (six consecutive 1s). The sender automatically inserts (stuffs) a `0` after any sequence of **five consecutive 1s** in data.	**Hardware Standard:** Transparent bit transmission; receiver strips any `0` following five consecutive `1`s (HDLC, SDLC).

Solved Problem: Bit Stuffing in HDLC Protocol

Original Payload Data: `0 1 1 1 1 1 1 0 1 1 1 1 1 0 0 1 1 1 1 1 1 1 1 0`

Sender Stuffed Bitstream: (Stuffs `0` after every five `1`s):

$$\text{Payload: } 0\ 11111\mathbf{0}10\ 11111\mathbf{0}00\ 11111\mathbf{0}111\mathbf{0}0$$

Enclosed Frame Transmitted: `01111110` [Stuffed Bits] `01111110`

Topic 23 & 24: Error Detection & Cyclic Redundancy Check (CRC)

CRC Modulo-2 Binary Division Algorithm: 1. Let Dataword have k bits D, and Generator polynomial have degree r ($r + 1$ bits G). 2. Append r zero bits to Dataword: $D \cdot 2^r$. 3. Perform Modulo-2 binary division (using $\mathbf{XOR}$ operations) of $D \cdot 2^r$ by G. 4. The resulting r-bit remainder is the **CRC Checksum (R)**. 5. The Codeword transmitted is: $\mathbf{T = D \cdot 2^r + R}$. 6. **Receiver Verification:** Divide received frame T' by G. If remainder is $\mathbf{0}$, accept frame; otherwise, error detected!

🏛️ **Step-by-Step Solved Problem: CRC Generation and Error Detection**

Dataword $D = 1010000$ ($k = 7$ bits). Generator Polynomial $G(x) = x^4 + x + 1 \implies G = 10011$ (degree $r = 4$).

Step 1: Append $r = 4$ zeros: $D \cdot 2^4 = 10100000000$.

Step 2: Modulo-2 Division:

```
        1011001  (Quotient)
10011 | 10100000000
        10011
        -----
          11100
          10011
          -----
           11110
           10011
           -----
            11010
            10011
            -----
             10010
             10011
             -----
              00010  (Bring down remaining 0) → Remainder = 0110
```

Transmitted Codeword: $\mathbf{T = 10100000110}$.

Topic 25 & 26: Error Correction & The $(7, 4)$ Hamming Code

Hamming Distance & Correction Capability Theorems: - To **detect** d **bit errors**: Minimum Hamming Distance must satisfy: $\mathbf{d_{min} \geq d + 1}$. - To **correct** t **bit errors**: Minimum Hamming Distance must satisfy: $\mathbf{d_{min} \geq 2t + 1}$. - **Redundancy Bits Formula:** For m data bits and r parity bits: $\mathbf{2^r \geq m + r + 1}$.

🏛️ **Step-by-Step $(7, 4)$ Hamming Code Encoding and Syndrome Error Correction**

Encode Dataword $D = 1011$ ($m = 4$ bits) into a 7-bit Hamming codeword ($r = 3$ parity bits at positions 1, 2, 4):

- Bit positions: $P_1(1), P_2(2), D_3(3), P_4(4), D_5(5), D_6(6), D_7(7)$
- Place data bits: $\text{Bit } 3 = 1, \text{Bit } 5 = 0, \text{Bit } 6 = 1, \text{Bit } 7 = 1$.
- $P_1 = D_3 \oplus D_5 \oplus D_7 = 1 \oplus 0 \oplus 1 = \mathbf{0}$
- $P_2 = D_3 \oplus D_6 \oplus D_7 = 1 \oplus 1 \oplus 1 = \mathbf{1}$
- $P_4 = D_5 \oplus D_6 \oplus D_7 = 0 \oplus 1 \oplus 1 = \mathbf{0}$
- **Transmitted Codeword:** $\mathbf{0\ 1\ 1\ 0\ 0\ 1\ 1}$.

Receiver Error Detection: Suppose bit 5 flips during transit $\implies$ Received: $0110\mathbf{1}11$.

$$\text{Syndrome } S_1 = b_1 \oplus b_3 \oplus b_5 \oplus b_7 = 0 \oplus 1 \oplus 1 \oplus 1 = \mathbf{1}$$

$$\text{Syndrome } S_2 = b_2 \oplus b_3 \oplus b_6 \oplus b_7 = 1 \oplus 1 \oplus 1 \oplus 1 = \mathbf{0}$$

$$\text{Syndrome } S_4 = b_4 \oplus b_5 \oplus b_6 \oplus b_7 = 0 \oplus 1 \oplus 1 \oplus 1 = \mathbf{1}$$

$$\text{Error Position } = S_4 S_2 S_1 = (101)_2 = \mathbf{5} \implies \text{Flip Bit 5 to correct error!}$$

Topic 27: Sliding Window Flow Control Protocols & Channel Efficiency

Protocol	Sender Window Size (W_S)	Receiver Window Size (W_R)	Sequence Numbers (k bits)	Channel Efficiency (η)
Stop-and-Wait ARQ	$W_S = 1$	$W_R = 1$	1 bit $(0, 1)$	$\eta = \frac{1}{1+2a}$
Go-Back-N (GBN) ARQ	$W_S = N = 2^k - 1$	$W_R = 1$ (Discards out-of-order)	k bits $(0 \ldots 2^k - 1)$	$\eta = \frac{N}{1+2a} \quad (\text{for } N \leq 1+2a)$
Selective Repeat (SR)	$W_S = N = 2^{k-1}$	$W_R = N = 2^{k-1}$ (Buffers out-of-order)	k bits	$\eta = \frac{N}{1+2a} \quad (\text{for } N \leq 1+2a)$

Bandwidth-Delay Product & Parameter a Formula:

$$\mathbf{a} = \frac{\mathbf{T}_{\text{prop}}}{\mathbf{T}_{\text{trans}}} = \frac{\text{Distance/Propagation Speed}}{\text{Frame Size/Bandwidth}}$$

🏛️ Step-by-Step Solved Problem: Satellite Link Protocol Efficiency Comparison

A geostationary satellite channel has a one-way propagation delay $T_{\text{prop}} = 250$ ms, bandwidth $B = 1$ Mbps, and frame size $L = 1000$ bytes (8000 bits). Calculate channel efficiency for: (1) Stop-and-Wait, (2) Go-Back-N ($k = 4$ bits), and (3) Selective Repeat ($k = 4$ bits).

Solution:

$$T_{\text{trans}} = \frac{8000 \text{ bits}}{1,000,000 \text{ bps}} = 8 \text{ ms}$$

$$a = \frac{T_{\text{prop}}}{T_{\text{trans}}} = \frac{250 \text{ ms}}{8 \text{ ms}} = 31.25 \implies 1 + 2a = 1 + 2(31.25) = \mathbf{63.5}$$

- **1. Stop-and-Wait:** $\eta = \frac{1}{63.5} = 0.0157 = \mathbf{1.57\%}$ (Extremely poor channel utilization!).
- **2. Go-Back-N ($k = 4 \implies W_S = 2^4 - 1 = 15$):** $\eta = \frac{15}{63.5} = 0.2362 = \mathbf{23.62\%}$.
- **3. Selective Repeat ($k = 4 \implies W_S = 2^{4-1} = 8$):** $\eta = \frac{8}{63.5} = 0.1259 = \mathbf{12.60\%}$.
- *Optimal Window Size:* $W_{\text{optimal}} \geq 1 + 2a = 64 \implies$ Requires $k = 7$ bit sequence numbers for 100% efficiency!

🧠 M3 Active Recall & 10-Question University Exam Master Bank

Q1. Compare Stop-and-Wait, Go-Back-N, and Selective Repeat ARQ protocols across window sizes, buffer requirements, and efficiency. (10 Marks)

- **Stop-and-Wait:** $W_S = 1, W_R = 1$; 1-bit sequence; $\eta = 1/(1+2a)$; zero receiver buffer.
- **Go-Back-N:** $W_S = 2^k - 1, W_R = 1$; cumulative ACKs; retransmits entire window on loss; simple receiver.
- **Selective Repeat:** $W_S = 2^{k-1}, W_R = 2^{k-1}$; individual ACKs / NAKs; retransmits ONLY corrupted frame; receiver buffers out-of-order packets.

Q2. A bit stream `1101011011` is transmitted using standard CRC polynomial $x^4 + x + 1$. Generate the transmitted codeword. (10 Marks)

$G(x) = x^4 + x + 1 \implies 10011$ ($r = 4$). Append 4 zeros to data: `11010110110000`.
Performing Modulo-2 binary division by `10011` yields remainder $R = 1110$.
The transmitted codeword is $\mathbf{11010110111110}$.

Q3. Derive the relationship between Minimum Hamming Distance $d_{\min}$ and the number of detectable and correctable errors. (8 Marks)

- **Detection of d errors:** No valid codeword can be transformed into another valid codeword by d bit flips $\implies \mathbf{d_{\min} \geq d + 1}$.
- **Correction of t errors:** Spheres of radius t centered at each codeword must be strictly non-overlapping $\implies \mathbf{d_{\min} \geq 2t + 1}$.

Q4. Explain Bit Stuffing in HDLC. What happens when the bitstream `01111110111110` is transmitted? (6 Marks)

In HDLC, sender inserts a `0` after five consecutive `1`s. The input `0 11111 10 11111 0` becomes `0 111110 10 111110 0`. The receiver strips the stuffed zeros to recover the original payload.

Q5. Explain the Internet Checksum algorithm used in IP/TCP headers with a 16-bit binary addition example. (8 Marks)

The sender divides data into 16-bit words, sums them using 1's complement arithmetic (adding end-around carry back to sum), and inverts all bits to form the checksum. The receiver sums all 16-bit words including the checksum; if no bit errors occurred, the final sum is all `1`s (`0×FFFF`).

Topic 27.2: Comprehensive Sliding Window Mathematical Derivations & Buffer Protocols

🏛 **Mathematical Proof: Maximum Window Size for Go-Back-N ($W_S = 2^k - 1$)**

Suppose $k = 2$ bit sequence numbers $(0, 1, 2, 3)$. If the sender were allowed a window size of $W_S = 2^k = 4$:

1. Sender transmits frames $0, 1, 2, 3$. Receiver receives all 4 frames and emits $\text{ACK } 0$ (expecting frame 0 next).
2. If all ACKs are lost in transit: Sender times out and retransmits frame 0.
3. **Fatal Ambiguity:** Receiver cannot determine whether this incoming frame 0 is a *retransmission of the old frame 0* or a *brand-new frame 0 of the next sequence cycle*!
4. To guarantee complete non-overlapping receiver expectations: $\mathbf{W_S + W_R \leq 2^k \implies W_S + 1 \leq 2^k \implies W_S \leq 2^k - 1}$.

🏛 **Mathematical Proof: Maximum Window Size for Selective Repeat ($W_S = W_R = 2^{k-1}$)**

In Selective Repeat, the receiver accepts out-of-order frames within its window W_R.

$$\text{To prevent window overlap between old and new cycles: } W_S + W_R \leq 2^k$$

$$\text{Setting symmetric windows } W_S = W_R = N: \quad 2N \leq 2^k \implies \mathbf{N \leq 2^{k-1}}$$

For $k = 3$ bits $(0 \ldots 7)$: Maximum window size for Selective Repeat is $\mathbf{W_S = 2^{3-1} = 4}$.

🏛 **Solved Numerical: Stop-and-Wait ARQ Efficiency with Frame Transmission Errors**

A $1\ \text{Mbps}$ link with $T_{\text{prop}} = 20\ \text{ms}$ transmits $1000\ \text{byte}$ frames. If the frame error probability is $P_f = 0.1$ (10% packet loss), calculate the effective throughput.

Solution:

$$T_{\text{trans}} = \frac{8000\ \text{bits}}{10^6\ \text{bps}} = 8\ \text{ms} \implies a = \frac{20\ \text{ms}}{8\ \text{ms}} = 2.5$$

$$\text{Ideal Efficiency: } \eta_0 = \frac{1}{1+2a} = \frac{1}{1+2(2.5)} = \frac{1}{6} \approx 16.67\%$$

$$\text{Efficiency with Error Rate } P_f: \quad \eta = \eta_0 \times (\mathbf{1 - P_f}) = \frac{\mathbf{1 - 0.1}}{\mathbf{6}} = \frac{\mathbf{0.9}}{\mathbf{6}} = \mathbf{0.15} = \mathbf{15\%}$$

$$\text{Effective Throughput} = \eta \times \text{Bandwidth} = \mathbf{0.15} \times \mathbf{1}\ \text{Mbps} = \mathbf{150}\ \text{kbps}$$

Topic 27.3: Advanced Error Control & Sliding Window State Automata

In Data Link Layer protocol engineering, reliable sliding window protocols are formally modeled as Finite State Machines (FSM) maintaining transmit and receive state variables:

🏛️ Complete Step-by-Step Go-Back-N vs. Selective Repeat Execution Trace under Frame Loss

Suppose 3-bit sequence numbers $(0 \dots 7)$ are used with window size $W_S = 4$. Frame 2 is corrupted/lost during transmission from Sender A to Receiver B:

Event #	Go-Back-N (GBN) Protocol Behavior	Selective Repeat (SR) Protocol Behavior
1. Transmit	A sends frames $0, 1, 2, 3$. Frame 2 is lost in transit.	A sends frames $0, 1, 2, 3$. Frame 2 is lost in transit.
2. Receive $0, 1$	B receives 0, emits ACK 1. B receives 1, emits ACK 2.	B receives 0, emits ACK 0. B receives 1, emits ACK 1.
3. Receive 3	B receives frame 3. Since frame 2 is missing, B **discards frame 3** and re-emits cumulative ACK 2.	B receives frame 3. B **buffers frame 3** in memory and emits NAK 2 (or ACK 3).
4. Timeout / NAK	A's timer for frame 2 expires. A must **Go-Back-N and retransmit all 2, 3** (even though 3 was already sent).	A receives NAK 2. A retransmits **ONLY frame 2**.
5. Delivery	B receives 2, delivers 2 to network layer; then receives 3, delivers 3.	B receives retransmitted frame 2, delivers buffered frames $\{2, 3\}$ to network layer instantly!

Conclusion: Selective Repeat achieves far superior channel utilization on noisy and high-latency links by avoiding redundant retransmissions!

🏛️ Step-by-Step Two-Dimensional (2D) Parity Check Calculation

Data block of four 7-bit ASCII characters: `1001100`, `1100110`, `1010101`, `0111001`. Construct Even Parity rows and columns:

```
Data Row 1:  1  0  0  1  1  0  0  |  1 (Row Parity Bit 1)
Data Row 2:  1  1  0  0  1  1  0  |  0 (Row Parity Bit 2)
Data Row 3:  1  0  1  0  1  0  1  |  0 (Row Parity Bit 3)
Data Row 4:  0  1  1  1  0  0  1  |  0 (Row Parity Bit 4)
-------------------------------------------------------
Col Parity:  1  0  0  0  1  1  0  |  1 (Corner Parity)
```

Error Detection & Correction: A single-bit flip anywhere in the matrix causes exactly one row parity violation and one column parity violation, pinpointing the intersection coordinates for instant 1-bit error correction!

Topic 27.4: Master University Solved Examination Numerical Bank

🏛️ Solved Numerical 4: CRC Hardware Shift-Register Circuit Implementation

Design the Linear Feedback Shift Register (LFSR) hardware circuit for generating CRC-4 with polynomial $G(x) = x^4 + x + 1$.

- The circuit consists of 4 D-Flip-Flops (FF_3, FF_2, FF_1, FF_0) initialized to zero.
- $\mathbf{XOR}$ gates are placed at positions corresponding to non-zero coefficients of $G(x)$ (specifically before FF_0 and between FF_0 and FF_1).
- Data bits are shifted in MSB first. After k shifts of data and $r = 4$ shifts of zeros, the contents of the 4 flip-flops contain the exact 4-bit CRC remainder!

🏛️ Solved Numerical 5: Go-Back-N Window Size Optimization under High Propagation Delay

A $100\ \text{Mbps}$ fiber-optic link connects two data centers separated by $D = 2000\ \text{km}$ ($v = 2 \times 10^8\ \text{m/s}$). Frame size $L = 1500\ \text{bytes}$ ($12,000\ \text{bits}$). What is the minimum number of sequence number bits (k) required for Go-Back-N ARQ to achieve 100% link utilization?

Solution:

$$T_{\text{prop}} = \frac{2000 \times 10^3\ \text{m}}{2 \times 10^8\ \text{m/s}} = 0.010\ \text{s} = 10\ \text{ms}$$

$$T_{\text{trans}} = \frac{12,000\ \text{bits}}{100 \times 10^6\ \text{bps}} = 0.00012\ \text{s} = 0.12\ \text{ms}$$

$$a = \frac{T_{\text{prop}}}{T_{\text{trans}}} = \frac{10\ \text{ms}}{0.12\ \text{ms}} = 83.33 \implies 1 + 2a = 1 + 2(83.33) = \mathbf{167.67}$$

$$\text{For } 100\% \text{ utilization, sender window must satisfy: } W_S \geq 1 + 2a = 168$$

$$\text{In GBN, } W_S = 2^k - 1 \geq 168 \implies 2^k \geq 169 \implies \mathbf{k = 8}\ \text{bits} \quad (2^8 - 1 = 255 \geq 168)$$

Topic 27.5: HDLC Protocol Architecture & Mathematical Error Analysis

High-Level Data Link Control (HDLC) is the foundational bit-oriented Data Link Layer standard (ISO 13239) governing synchronous point-to-point and multipoint communication lines.

HDLC Frame Type	Control Field Encoding	Operational Purpose
I-Frame (Information)	`0 | N(S) [3 bits] | P/F | N(R) [3 bits]`	Carries user network payload data with piggybacked sequence numbers $N(S)$ and acknowledgments $N(R)$.
S-Frame (Supervisory)	`1 0 | Type [2 bits] | P/F | N(R) [3 bits]`	Flow and error control when no payload is ready: `00`=Receive Ready (RR), `01`=Receive Not Ready (RNR), `10`=Reject (REJ GBN), `11`=Selective Reject (SREJ).
U-Frame (Unnumbered)	`1 1 | Modifier [5 bits] | P/F`	Link connection establishment and teardown: `SABM` (Set Asynchronous Balanced Mode), `DISC` (Disconnect), `UA` (Unnumbered Ack).

🏛️ Step-by-Step Solved Problem: Comprehensive CRC-16 Polynomial Division Trace

Compute the CRC checksum for 16-bit dataword $D = \text{0xC4D1} = 1100010011010001$ using standard CRC-16-CCITT polynomial $G(x) = x^{16} + x^{12} + x^5 + 1 \implies 10001000000100001$ (degree $r = 16$).

- Append $r = 16$ zeros to D: $D \cdot 2^{16} = 11000100110100010000000000000000$.
- Perform Modulo-2 XOR binary division by the 17-bit divisor G.
- The 16-bit remainder generated is appended to D to produce the exact 32-bit transmitted codeword.
- *Error Detection Capability of CRC-16:* Detects 100% of single-bit errors, 100% of double-bit errors, 100% of odd-numbered bit errors, and 100% of burst errors of length ≤ 16 bits!

🏛️ Solved Numerical 6: Checksum Calculation for IPv4 / UDP Packets

Calculate the 16-bit Internet Checksum for the following two 16-bit numbers: `0x66A2` and `0x3C42`. Show all binary additions and 1's complement end-around carries.

Solution:

```
  0110 0110 1010 0010  (0x66A2)
+ 0011 1100 0100 0010  (0x3C42)
──────────────────────
  1010 0010 1110 0100  (Sum = 0xA2E4, Carry = 0)

Invert all bits (1's complement):
~ 1010 0010 1110 0100 = 0101 1101 0001 1011 = 0x5D1B (Checksum)
```

Receiver Check: `0x66A2 + 0x3C42 + 0x5D1B = 0xFFFF` (All 1s $\implies$ Data Valid!).

Q6. Explain the HDLC Protocol Frame Format and the meaning of Poll/Final (P/F) bit. (8 Marks)

An HDLC frame consists of: `Flag (01111110)` [8b] → `Address` [8b] → `Control` [8/16b] → `Information Payload` [Variable] → `FCS Checksum (CRC-16)` [16b] → `Flag (01111110)` [8b].
The **Poll/Final (P/F) bit** serves dual roles: when sent by a primary station, $P = 1$ (Poll) solicits an immediate response from secondary stations; when sent by a secondary station, $F = 1$ (Final) indicates the concluding frame of its transmission response.

Q7. Explain Piggybacking in bidirectional sliding window protocols and its performance benefits. (6 Marks)

Piggybacking is the technique of attaching acknowledgment information (ACK sequence numbers) into outgoing data frames traveling in the reverse direction, rather than transmitting separate standalone ACK packets. It eliminates dedicated ACK frame headers and packet transmission overhead, significantly improving bidirectional channel efficiency!

Topic 27.6: Linear Block Codes & Parity-Check Matrix Mathematical Foundations

In formal algebraic coding theory, a **Linear** (n, k) **Block Code** maps k-bit data vectors $\mathbf{d} = (d_1, \ldots, d_k)$ into n-bit codewords $\mathbf{c} = (c_1, \ldots, c_n)$ via a **Generator Matrix** G:

$$\mathbf{c} = \mathbf{d} \cdot \mathbf{G} \quad \text{(Modulo-2 Matrix Multiplication)}$$

Where $G = [I_k \mid P]$ is a $k \times n$ systematic generator matrix (I_k is $k \times k$ identity matrix, P is $k \times (n-k)$ parity submatrix).

Parity Check Matrix H & Syndrome Decoding Vector $\mathbf{S}$:

$$\mathbf{H} = [\mathbf{P^T} \mid \mathbf{I_{n-k}}] \quad ((n-k) \times n \text{ Matrix})$$

$$\mathbf{S} = \mathbf{r} \cdot \mathbf{H^T} \quad (\text{Where } \mathbf{r} = \mathbf{c} \oplus \mathbf{e} \text{ is the received vector})$$

- If $\mathbf{S} = \mathbf{0}$: Zero errors detected $\implies$ Accept $\mathbf{r}$. - If $\mathbf{S} \neq \mathbf{0}$: The syndrome $\mathbf{S}$ matches the i-th column of H, identifying that bit position i contains the bit error!

🏛 Step-by-Step Solved Problem: Complete Systematic $(7, 4)$ Hamming Code Matrix Trace

Let $G = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 \end{bmatrix}$. Encode dataword $\mathbf{d} = [1, 0, 1, 1]$:

$$\mathbf{c} = [1, 0, 1, 1] \cdot G = [\mathbf{1}, \mathbf{0}, \mathbf{1}, \mathbf{1}, \mathbf{0}, \mathbf{1}, \mathbf{0}]$$

Suppose received vector is $\mathbf{r} = [1, 0, \mathbf{0}, 1, 0, 1, 0]$ (Bit 3 corrupted). Then:

$$\mathbf{S} = \mathbf{r} \cdot \mathbf{H^T} = [\mathbf{0}, \mathbf{1}, \mathbf{1}]^T \implies \text{Matches Column 3 of } H \implies \text{Error is in Bit 3! Flip Bit 3 to 1 to correct!}$$

Topic 27.7: Master University Long-Answer Exam Solutions Bank

Q8. Derive the Channel Utilization Efficiency (η) for Go-Back-N ARQ and Selective Repeat ARQ under non-zero transmission error probability (P_f). (10 Marks)

Let P_f be the frame error probability, and $a = T_{\text{prop}}/T_{\text{trans}}$:
• **Stop-and-Wait ARQ with Errors:** Average number of transmissions per frame is $N_{\text{trans}} = \frac{1}{1-P_f}$.

$$\eta_{\text{SW}} = \frac{\mathbf{1 - P_f}}{\mathbf{1 + 2a}}$$

• **Go-Back-N ARQ with Errors:** If a frame is lost, the entire window of $N = 1 + 2a$ frames must be retransmitted. The average number of transmitted frames per successful delivery is $1 + \frac{NP_f}{1-P_f}$.

$$\eta_{\text{GBN}} = \frac{\mathbf{1 - P_f}}{\mathbf{1 + 2aP_f}}$$

• **Selective Repeat ARQ with Errors:** Since ONLY the corrupted frame is retransmitted individually:

$$\eta_{\text{SR}} = \mathbf{1 - P_f} \quad (\text{Independent of propagation parameter } a!).$$

Conclusion: On high-latency satellite and fiber channels ($a \gg 1$), Selective Repeat is the only viable ARQ protocol!

Q9. Explain the Point-to-Point Protocol (PPP) frame structure, Link Control Protocol (LCP), and Network Control Protocol (NCP). (8 Marks)

PPP (RFC 1661) is the standard data link protocol for broadband DSL, dial-up, and leased lines:
1. **Framing:** Byte-oriented frame with `Flag (0×7E)`, `Address (0×FF)`, `Control (0×03)`, `Protocol (2B)`, `Payload`, `FCS (16/32b)`. Uses byte stuffing (`0×7D`).
2. **Link Control Protocol (LCP):** Establishes, configures, authenticates (PAP / CHAP), tests, and terminates the data link connection.
3. **Network Control Protocol (NCP):** Establishes and configures network layer protocols over the link (e.g. IPCP assigns IP addresses to clients dynamically).

Q10. Explain the High-Level Data Link Control (HDLC) operational modes: NRM, ABM, and ARM. (8 Marks)

HDLC supports three distinct operational station configurations:
1. **Normal Response Mode (NRM):** Unbalanced configuration with 1 Primary station and ≥ 1 Secondary stations. Secondary stations can transmit frames strictly in response to an explicit poll ($P = 1$) from the primary.
2. **Asynchronous Balanced Mode (ABM):** Balanced point-to-point configuration with 2 Combined stations. Either station can initiate data transmission asynchronously at any time without asking permission (universal standard in Full-Duplex point-to-point links).
3. **Asynchronous Response Mode (ARM):** Unbalanced configuration where Secondary stations can initiate transmission asynchronously without waiting for a primary poll.

MODULE 4 OF 5

Module 4: Switching & Local Area Networks (LANs)

Topics 28 to 36 • Circuit/Packet Switching, ALOHA, CSMA/CD, Ethernet & STP

Module IV: Switching & Local Area Networks (LANs) — 9-Topic Master Syllabus Guide

Topic 28: Circuit Switching vs. Packet Switching (Connection Setup, Resource Reservation, Latency)

Topic 29: Packet Switching Modes: Virtual Circuits (Connection-Oriented) vs. Datagram Networks (Connectionless)

Topic 30: Switching Fabric Architectures (Space-Division Crossbar, Banyan Networks & Time-Division TDM Switches)

Topic 31: Local Area Network (LAN) Technologies & Media Access Control (MAC Sublayer Architecture)

Topic 32: Random Access Protocols (Pure ALOHA, Slotted ALOHA, CSMA: 1-Persistent, Non-Persistent, p-Persistent)

Topic 33: CSMA/CD Protocol (Ethernet Collision Detection, Minimum Frame Size Formula & Exponential Backoff)

Topic 34: CSMA/CA & Wireless LANs (IEEE 802.11 Wi-Fi, Hidden/Exposed Terminal Problem & RTS/CTS Handshake)

Topic 35: IEEE 802.3 Ethernet Standards (Standard 10BASE-T, Fast Ethernet 100BASE-TX, Gigabit 1000BASE-T Frame Anatomy)

Topic 36: Interconnecting Devices & Layer 2 Switching (Repeaters, Hubs, Bridges, Switches, Spanning Tree Protocol STP)

Topic 28 & 29: Circuit Switching vs. Packet Switching & Virtual Circuits

Dimension	Circuit Switching (PSTN Telephone)	Packet Switching (Internet IP)
Dedicated Path	Dedicated end-to-end physical circuit established prior to data transfer.	No dedicated circuit; packets dynamically share statistical communication links.
Resource Reservation	Bandwidth and buffer capacity reserved exclusively along path for duration.	On-demand statistical multiplexing (packets queue up in router buffers).
Setup Delay	High initial connection establishment delay; zero delay during transmission.	Zero connection setup delay in datagram networks; variable packet queuing jitter.
Channel Efficiency	Low efficiency: idle periods (silence in voice) waste dedicated bandwidth.	**High Efficiency:** Inactive users consume zero bandwidth.
Congestion Behavior	Call blocking (busy signal) if capacity exhausted; active calls unimpaired.	Packet delay, queuing buffers, and packet drops under heavy load.

Topic 32, 33 & 34: Random Access MAC Protocols (ALOHA, CSMA, CSMA/CD, CSMA/CA)

MAC Protocol	Vulnerable Time (T_{vul})	Maximum Theoretical Throughput ($S_{\max}$)	Operating Mechanism
Pure ALOHA	$T_{\text{vul}} = 2 \times T_{\text{fr}}$	$S_{\max} = \frac{1}{2e} \approx \mathbf{18.4\%} \quad (\text{at } G = 0.5)$	Stations transmit immediately whenever data is ready; retransmits after random backoff on collision.
Slotted ALOHA	$T_{\text{vul}} = 1 \times T_{\text{fr}}$	$S_{\max} = \frac{1}{e} \approx \mathbf{36.8\%} \quad (\text{at } G = 1.0)$	Time divided into discrete slots equal to T_{fr}; stations transmit only at slot start boundaries.
1-Persistent CSMA	$T_{\text{vul}} = \tau \text{ (Propagation Delay)}$	Significantly higher than ALOHA	Listens to channel: if idle, transmits immediately; if busy, continually listens until idle, then transmits instantly.
Non-Persistent CSMA	$T_{\text{vul}} = \tau$	Higher throughput at heavy load	If channel is busy, waits a random duration before sensing again (reduces collisions).
p-Persistent CSMA	$T_{\text{vul}} = \tau$	Optimal trade-off for slotted channels	If idle, transmits with probability p, and defers to next slot with probability $1 - p$.
CSMA/CD (Ethernet)	$T_{\text{vul}} = 2\tau$	Approaches 100% on switched networks	Listens while transmitting: on collision, halts immediately, emits 32-bit Jam Signal, executes Exponential Backoff.
CSMA/CA (Wi-Fi)	Uses IFS & Contention Window	High in wireless media	Cannot detect collisions in air: avoids collisions using Inter-Frame Spaces (DIFS/SIFS), RTS/CTS frames, and ACKs.

Topic 33.1: CSMA/CD Minimum Frame Size Derivation & Exponential Backoff

The Fundamental CSMA/CD Collision Detection Condition: In CSMA/CD, a transmitting station must not finish transmitting its frame before the collision signal propagates back from the furthest point in the network ($2 \times T_{\text{prop}}$):

$$\mathbf{T}_{\text{trans}} \geq \mathbf{2} \times \mathbf{T}_{\text{prop}}$$

$$\frac{\text{Frame Size}_{\text{min}}}{\text{Bandwidth}} \geq \mathbf{2} \times \frac{\text{Distance}}{\text{Propagation Velocity}}$$

$$\text{Frame Size}_{\text{min}} = \mathbf{2} \times \mathbf{T}_{\text{prop}} \times \text{Bandwidth}$$

🏛️ Step-by-Step Solved Problem: Minimum Ethernet Frame Size Calculation

A $1\ \text{Gbps}$ Gigabit Ethernet network operates across a maximum cable distance of $1\ \text{km}$ with signal propagation speed $v = 2 \times 10^8\ \text{m/s}$. Calculate the minimum frame size required for CSMA/CD.

Solution:

$$T_{\text{prop}} = \frac{\text{Distance}}{v} = \frac{1000\ \text{m}}{2 \times 10^8\ \text{m/s}} = 5 \times 10^{-6}\ \text{s} = 5\ \mu\text{s}$$

$$\text{Round-Trip Propagation Time (Slot Time)}: 2 \times T_{\text{prop}} = 2 \times 5\ \mu\text{s} = 10\ \mu\text{s}$$

$$\text{Frame Size}_{\text{min}} = \mathbf{2T}_{\text{prop}} \times \text{Bandwidth} = \mathbf{10 \times 10^{-6}}\ \text{s} \times \mathbf{10^9}\ \text{bps} = \mathbf{10,000}\ \text{bits} = \mathbf{1250}\ \text{bytes}$$

Topic 35: IEEE 802.3 Ethernet Frame Structure

Field	Size	Operational Function
Preamble	7 Bytes	Alternating `10101010` pattern for receiver clock synchronization.
SFD (Start Frame Delimiter)	1 Byte	Exact pattern `10101011` indicating start of valid frame payload.
Destination MAC	6 Bytes	48-bit physical hardware address of destination device or broadcast (`FF:FF:FF:FF:FF:FF`).
Source MAC	6 Bytes	48-bit physical hardware address of transmitting NIC.
Length / Type	2 Bytes	≤ 1500: Length of payload; ≥ 1536 (`0x0800`): EtherType identifying IPv4, ARP (`0x0806`), IPv6 (`0x86DD`).
Data Payload	46 to 1500 B	High-level Network layer packet (Padded with zeros if < 46 bytes).
CRC / FCS Checksum	4 Bytes	32-bit Cyclic Redundancy Check (`CRC-32`) for error detection.

Topic 36: Interconnecting Devices & Spanning Tree Protocol (STP)

The Broadcast Storm Problem & Spanning Tree Protocol (IEEE 802.1D)

Redundant physical links between Layer 2 bridges/switches create infinite loops, generating catastrophic **Broadcast Storms** and corrupting MAC address learning tables. **STP (Spanning Tree Protocol)** dynamically builds a loop-free logical spanning tree by:

1. Electing a unique **Root Bridge** (switch with lowest Bridge ID: Priority + MAC).
2. Selecting one **Root Port** on every non-root bridge with minimum path cost to Root.
3. Selecting one **Designated Port** per LAN segment.
4. Placing all other redundant ports into **Blocking State** (disabling packet forwarding).

🧠 M4 Active Recall & 10-Question University Exam Master Bank

Q1. Derive the maximum throughput formula for Pure ALOHA ($S = Ge^{-2G}$) and Slotted ALOHA ($S = Ge^{-G}$). (10 Marks)

Assuming Poisson frame arrival with rate G frames per frame-time T:
• **Pure ALOHA:** Vulnerable period is $2T$. Probability of 0 other frames arriving is $P(0) = e^{-2G}$. Throughput $S = GP(0) = \mathbf{Ge^{-2G}}$. Maximum at $dS/dG = 0 \implies G = 0.5 \implies S_{\max} = 1/(2e) \approx \mathbf{18.4\%}$.
• **Slotted ALOHA:** Vulnerable period is $1T$. Probability of 0 arrivals in slot is $P(0) = e^{-G}$. Throughput $S = \mathbf{Ge^{-G}}$. Maximum at $G = 1.0 \implies S_{\max} = 1/e \approx \mathbf{36.8\%}$.

Q2. Explain CSMA/CD operation, 1-persistent sensing, jamming signal, and Binary Exponential Backoff algorithm. (10 Marks)

1. **Carrier Sense:** Station senses channel before transmitting.
2. **Collision Detection:** Listens while transmitting. If signal amplitude doubles, collision detected!
3. **Jamming Signal:** Emits 32-bit jam signal to notify all stations.
4. **Binary Exponential Backoff:** After n-th collision ($n \leq 10$), chooses random integer $k \in [0, 2^n - 1]$ and waits $k \times \text{SlotTime}$. Aborts after 16 failed attempts!

Q3. Why does standard CSMA/CD fail in wireless LANs? Explain the Hidden Terminal Problem and RTS/CTS solution. (8 Marks)

In wireless, signals attenuate exponentially ($1/d^2$ to $1/d^4$), making transmit signal drown out weak colliding signals. In the **Hidden Terminal Problem**, stations A and C cannot hear each other but both transmit to B, colliding at B. **CSMA/CA solves this** via 4-way RTS/CTS handshaking: A sends RTS; B responds with CTS (reserving channel for A and silencing C via Network Allocation Vector NAV).

Q4. Compare Repeaters, Hubs, Bridges, Layer 2 Switches, and Routers across OSI layer, collision domain, and broadcast domain. (8 Marks)

• **Repeater/Hub (Layer 1):** Extends physical distance; 1 shared Collision Domain, 1 Broadcast Domain.
• **Bridge/Switch (Layer 2):** Filters by MAC; separates Collision Domains per port; 1 shared Broadcast Domain.
• **Router (Layer 3):** Routes by IP; separates Collision Domains AND separates Broadcast Domains!

Q5. Explain the Spanning Tree Protocol (STP) algorithm with Root Bridge election and port states. (8 Marks)

STP prevents broadcast storms in looped Layer 2 networks:
1. Elects **Root Bridge** (lowest Bridge ID = Priority + MAC).
2. Elects **Root Port** per bridge (lowest cost to root).
3. Elects **Designated Port** per segment.
4. Places all redundant loop ports in **Blocking** state.

Topic 36.2: Advanced Ethernet Switching, VLANs & Spanning Tree Calculations

Modern enterprise local area networks replace shared collision domains with **Full-Duplex Layer 2 Switched Ethernet** and **Virtual Local Area Networks (VLANs, IEEE 802.1Q)**.

Switching Technique	Operating Architecture	Latency & Error Propagation
1. Store-and-Forward	Switch buffers entire frame in memory, verifies 32-bit CRC checksum, checks destination MAC in CAM table, and forwards frame.	Highest latency (proportional to frame size); 100% immune to corrupt frames (discards CRC errors).
2. Cut-Through	Switch reads only first 6 bytes (Destination MAC) and immediately begins forwarding frame to target port before receiving remainder.	**Lowest Latency:** Fixed instant forwarding; propagates corrupt frames and collision fragments.
3. Fragment-Free	Switch buffers first 64 bytes (collision window) before forwarding.	Filters out all collision fragments (runt frames < 64 bytes) with minimal latency penalty.

🏛️ Step-by-Step Spanning Tree Protocol (STP) Bridge Port Calculation

Consider 3 switches S_1, S_2, S_3 connected in a ring with Gigabit links (Path Cost = 4):

- S_1 Bridge ID: `32768:00-11-22-33-44-01`
- S_2 Bridge ID: `32768:00-11-22-33-44-02`
- S_3 Bridge ID: `32768:00-11-22-33-44-03`

STP State Derivation:

1. **Root Bridge Election:** S_1 has the lowest MAC address $\implies \mathbf{S_1}$ is elected ROOT BRIDGE. All ports on S_1 become **Designated Ports (Forwarding)**.
2. **Root Ports on S_2 and S_3:** Port facing S_1 on S_2 has cost 4 $\implies$ **Root Port**. Port facing S_1 on S_3 has cost 4 $\implies$ **Root Port**.
3. **Link between S_2 and S_3:** Both have cost 4 to Root. Tie-breaker: S_2 has lower Bridge ID than S_3. Therefore, S_2's port becomes **Designated Port**, and S_3's port is placed in **BLOCKING STATE**, breaking the loop!

Topic 36.3: Advanced Switching Fabrics & Ethernet Standards Evolution

At the physical switching core of enterprise routers and central office telephone exchanges, high-speed non-blocking **Space-Division and Time-Division Switching Fabrics** transfer incoming frames across line cards:

Crossbar vs. Clos Non-Blocking Multi-Stage Network Complexity: - **Single-Stage $N \times N$ Crossbar Switch:** Requires $\mathbf{N^2}$ crosspoints. (For $N = 1000$, requires $1,000,000$ crosspoint switches $\implies$ high cost!). - **3-Stage Clos Non-Blocking Network (N inputs, n inputs/stage-1 switch, k middle switches):**

$$\text{Strict-Sense Non-Blocking Condition: } \mathbf{k \geq 2n - 1}$$

$$\text{Total Crosspoints: } \mathbf{C = 2Nk + k\left(\frac{N}{n}\right)^2} \ll N^2$$

Ethernet Standard	Data Rate	Physical Medium & Connector	Max Segment Span	Line Coding
10BASE-T	$10\ \text{Mbps}$	Cat 3/5 UTP, RJ-45	$100\ \text{meters}$	Manchester ($20\ \text{MHz}$)
100BASE-TX (Fast)	$100\ \text{Mbps}$	Cat 5 UTP (2 pairs)	$100\ \text{meters}$	4B/5B + MLT-3
1000BASE-T (Gigabit)	$1000\ \text{Mbps}(1\ \text{Gbps})$	Cat 5e/6 UTP (4 pairs simultaneously)	$100\ \text{meters}$	4D-PAM5 ($125\ \text{MBaud}$)
10GBASE-T (10 GbE)	$10\ \text{Gbps}$	Cat 6A / Cat 7 UTP	$100\ \text{meters}$	PAM-16 + 64B/65B
1000BASE-SX / LX	$1\ \text{Gbps}$	Multi-Mode / Single-Mode Fiber	$550\ \text{m (SX)}/5\ \text{km (LX)}$	8B/10B NRZ

🏛️ **Solved Problem: IEEE 802.1Q VLAN Tagging & Trunking**

In modern switched LANs, multiple Virtual LANs (VLANs) share a common inter-switch trunk link. The **IEEE 802.1Q standard** inserts a **4-byte VLAN tag** into the standard Ethernet frame between the Source MAC and EtherType fields:

- **TPID (Tag Protocol Identifier, 2 Bytes):** Fixed value `0x8100` identifying 802.1Q frame.
- **TCI (Tag Control Information, 2 Bytes):**
  - *PCP (Priority Code Point, 3 Bits):* 8 levels of QoS traffic class (IEEE 802.1p).
  - *DEI (Drop Eligible Indicator, 1 Bit):* Flags packets eligible for dropping under congestion.
  - *VID (VLAN Identifier, 12 Bits):* Supports up to $2^{12} = \mathbf{4096}\ \text{distinct VLANs}$.

Topic 36.4: Master University Solved Examination Numerical Bank

🏛️ **Solved Numerical 4: CSMA/CD Maximum Cable Distance Calculation**

A 10 Mbps Standard Ethernet network transmits frames with minimum size 64 bytes (512 bits) over coaxial cable with propagation velocity $v = 2 \times 10^8\ \text{m/s}$. The network includes 4 repeaters, each introducing an internal processing delay of $1.5\ \mu\text{s}$. Calculate the maximum permissible cable distance between the two furthest stations.

Solution:

$$T_{\text{trans}} = \frac{512\ \text{bits}}{10 \times 10^6\ \text{bps}} = 51.2\ \mu\text{s}$$

$$\text{Condition: } T_{\text{trans}} \geq 2 \times T_{\text{prop\_total}} = 2 \times (T_{\text{cable}} + 4 \times T_{\text{repeater}})$$

$$51.2\ \mu\text{s} \geq 2 \times (T_{\text{cable}} + 4 \times 1.5\ \mu\text{s}) = 2T_{\text{cable}} + 12\ \mu\text{s}$$

$$2T_{\text{cable}} \leq 51.2 - 12 = 39.2\ \mu\text{s} \implies T_{\text{cable}} \leq 19.6\ \mu\text{s}$$

$$\text{Max Cable Distance } \mathbf{D} = \mathbf{T}_{\text{cable}} \times \mathbf{v} = \mathbf{19.6} \times \mathbf{10^{-6}}\ \text{s} \times (\mathbf{2} \times \mathbf{10^8}\ \text{m/s}) = \mathbf{3920}\ \text{meters}\ (3.92\ \text{km})$$

🏛️ **Solved Numerical 5: Pure ALOHA vs. Slotted ALOHA Station Scaling**

A broadcast channel is shared by N independent stations, each generating a 1000-bit frame on average every $10\ \text{seconds}$. The channel bandwidth is $50\ \text{kbps}$. How many stations can be supported by: (a) Pure ALOHA, and (b) Slotted ALOHA?

Solution: Frame duration $T_{\text{fr}} = \frac{1000\ \text{bits}}{50{,}000\ \text{bps}} = 0.020\ \text{s} = 20\ \text{ms}$.

$$\text{Each station generation rate } \lambda = \frac{1\ \text{frame}}{10\ \text{s}} = 0.1\ \text{frames/s}$$

$$\text{Normalized frame rate per station } g = \lambda \times T_{\text{fr}} = 0.1 \times 0.020 = 0.002\ \text{frames/slot}$$

- **(a) Pure ALOHA ($G_{\max} = 0.5$):** $N \times g \leq 0.5 \implies N \leq \frac{0.5}{0.002} = \mathbf{250}\ \text{stations}$.
- **(b) Slotted ALOHA ($G_{\max} = 1.0$):** $N \times g \leq 1.0 \implies N \leq \frac{1.0}{0.002} = \mathbf{500}\ \text{stations}$ ($2\times$ the capacity of Pure ALOHA!).

Topic 36.5: Mathematical MAC Throughput & Wireless Protocol States

Carrier Sense Multiple Access with Collision Detection (CSMA/CD) Efficiency Formula:

$$\eta = \frac{\mathbf{1}}{\mathbf{1 + 5 \times a}} \quad \text{where } \mathbf{a} = \frac{\mathbf{T}_{\text{prop}}}{\mathbf{T}_{\text{trans}}}$$

As network cable length increases or transmission data rate increases, parameter a grows, dramatically reducing channel efficiency. This is why 10-Gigabit and 100-Gigabit Ethernet completely abandon CSMA/CD in favor of **Switched Full-Duplex Point-to-Point Links**!

IEEE 802.11 Standard	Frequency Band	Modulation & Physical Layer	Max Physical Data Rate	MIMO Stream Count
802.11b (Wi-Fi 1)	$2.4\ \text{GHz}$	DSSS / CCK	$11\ \text{Mbps}$	1×1 (SISO)
802.11g (Wi-Fi 3)	$2.4\ \text{GHz}$	OFDM (64-QAM)	$54\ \text{Mbps}$	1×1
802.11n (Wi-Fi 4)	$2.4\ \text{GHz}/5\ \text{GHz}$	MIMO-OFDM (64-QAM)	$600\ \text{Mbps}$	Up to 4×4 MIMO
802.11ac (Wi-Fi 5)	$5\ \text{GHz}$ only	256-QAM ($160\ \text{MHz}$ channels)	$3.46\ \text{Gbps}$	Up to 8×8 MU-MIMO
802.11ax (Wi-Fi 6)	$2.4/5/6\ \text{GHz}$	OFDMA + 1024-QAM	$9.6\ \text{Gbps}$	8×8 Target Wake Time
802.11be (Wi-Fi 7)	$2.4/5/6\ \text{GHz}$	4096-QAM ($320\ \text{MHz}$ channels)	$46\ \text{Gbps}$	16×16 Multi-Link MLO

🏛️ **Solved Numerical 6: Binary Exponential Backoff Simulation**

In a 10 Mbps CSMA/CD Ethernet network (Slot Time = $51.2\ \mu\text{s}$), two stations collide 3 consecutive times. What is the probability that they will collide again on the 4th attempt?

Solution:

- After collision $i = 3$, each station chooses a random integer k from range $[0, 2^3 - 1] = [0, 7]$ (total 8 possible slot choices).
- Total possible pairs of choices for 2 stations: $8 \times 8 = 64$ outcomes.
- A collision occurs if and only if both stations select the exact same value of k (8 possible matching pairs: $(0,0), (1,1), \ldots, (7,7)$).
- $$\mathbf{P}(\text{Collision on 4th attempt}) = \frac{\mathbf{8}}{\mathbf{64}} = \frac{\mathbf{1}}{\mathbf{8}} = \mathbf{12.5\%}$$

Q6. Compare IEEE 802.3 Ethernet, IEEE 802.4 Token Bus, and IEEE 802.5 Token Ring across media access method and determinism. (8 Marks)

- **IEEE 802.3 (Ethernet):** CSMA/CD random access; probabilistic latency (collisions increase with load); simple, low cost; worldwide industry standard.
- **IEEE 802.4 (Token Bus):** Physical bus, logical token ring; deterministic access delay; complex token maintenance; industrial automation (MAP).
- **IEEE 802.5 (Token Ring):** Physical star/ring; token passing round-robin; deterministic worst-case latency; zero collisions; high hardware cost.

Q7. Explain Transparent Bridges and the Backward Learning Algorithm for building MAC address forwarding tables. (8 Marks)

A **Transparent Bridge** automatically learns network topology without manual configuration:
1. When a frame arrives on port P from source MAC S, the bridge records $(S, P, \text{timestamp})$ in its forwarding database.
2. When forwarding to destination MAC D: if D is in the table on port P', forwards frame strictly out port P' (or filters if $P' = P$); if D is unknown, **floods** frame out all ports except the arrival port!

Topic 36.6: Advanced Multi-Access Markov Chains & High-Speed Ethernet Fabrics

The theoretical throughput of Random Access MAC protocols under saturation load is modeled via Poisson arrival processes and Markov birth-death state chains:

Slotted ALOHA vs. 1-Persistent CSMA Throughput Derivations: - **Slotted ALOHA:** $S = Ge^{-G} \implies S_{\max} = \frac{1}{e} = \mathbf{36.8\%}$ (at offer load $G = 1$). - **Non-Persistent CSMA:** $\mathbf{S} = \frac{\mathbf{Ge^{-aG}}}{\mathbf{G(1+2a)+e^{-aG}}} \implies S_{\max} \approx \mathbf{82\%}$ (for small $a = 0.01$). - **1-Persistent CSMA:** $\mathbf{S} = \frac{\mathbf{G[1+G+aG(1+G+aG/2)]e^{-G(1+2a)}}}{\mathbf{G(1+2a)-(1-e^{-aG})+(1+aG)e^{-G(1+a)}}} \approx \mathbf{53\%}$.

🏛️ **Step-by-Step Solved Problem: Complete 5-Switch Spanning Tree Protocol (STP) Convergence Trace**

Consider 5 enterprise switches S_1, S_2, S_3, S_4, S_5 interconnected with 100 Mbps Fast Ethernet links (Link Cost = 19):

- S_1: MAC `00:00:0A:11:00:01`, Priority 32768 $\implies$ **ELECTED ROOT BRIDGE (Lowest MAC)**.
- All ports on S_1 are designated as **Designated Ports (Forwarding)**.
- S_2, S_3 connected directly to S_1: Cost = 19 $\implies$ Ports facing S_1 are **Root Ports**.
- S_4, S_5 connected to S_2 and S_3: Cost to Root $= 19 + 19 = 38$.
- Redundant links between S_4 and S_5 are evaluated: S_4 has lower MAC than S_5. Therefore, S_4's port is Designated, and S_5's port transitions to **BLOCKING STATE**, terminating all broadcast loops!

Topic 36.7: Master University Long-Answer Exam Solutions Bank

Q8. Explain the IEEE 802.11 Wi-Fi Medium Access Control architecture: DCF, PCF, Inter-Frame Spaces (SIFS, PIFS, DIFS, EIFS), and Network Allocation Vector (NAV). (10 Marks)

IEEE 802.11 defines two operational coordination modes:
• **Distributed Coordination Function (DCF):** Contention-based CSMA/CA protocol used by all Wi-Fi stations.
• **Point Coordination Function (PCF):** Optional contention-free polling protocol managed by the Access Point (AP).
• **Inter-Frame Space (IFS) Hierarchy:**
1. **SIFS (Short IFS):** Highest priority; used for instant ACK, CTS, and fragmented frame bursts.
2. **PIFS (PCF IFS):** Medium priority; used by Access Point to gain channel control for PCF polling.
3. **DIFS (DCF IFS):** Normal priority; minimum idle duration a station must wait before contending for channel.
4. **EIFS (Extended IFS):** Longest wait time used when a frame is received with checksum errors.
• **Network Allocation Vector (NAV):** A virtual carrier sensing timer maintained inside every Wi-Fi station. When a station overhears an RTS or CTS frame, it sets its NAV to the duration value specified in the frame header, remaining asleep and deferring all channel access until NAV reaches 0!

Q9. Compare 10BASE5 (Thicknet), 10BASE2 (Thinnet), 10BASE-T, 100BASE-TX, and 1000BASE-T across physical media, topology, connector, and maximum span. (8 Marks)

• **10BASE5:** Thick coaxial cable, Bus topology, Vampire taps & AUI cable, max 500 meters.
• **10BASE2:** RG-58 Thin coaxial cable, Bus topology, BNC T-connectors, max 185 meters.
• **10BASE-T:** Cat 3/5 UTP copper, Star topology (Hub), RJ-45, max 100 meters.
• **100BASE-TX:** Cat 5 UTP (2 pairs), Star topology (Switch), RJ-45, max 100 meters.
• **1000BASE-T:** Cat 5e/6 UTP (4 pairs simultaneously full-duplex), Star topology, RJ-45, max 100 meters.

Q10. Explain Virtual LANs (VLANs, IEEE 802.1Q) and how Trunking and Inter-VLAN Routing operate. (8 Marks)

• **VLAN (Virtual LAN):** Logically segments a single physical Layer 2 switch into multiple independent broadcast domains. Broadcast traffic from VLAN 10 (Finance) is completely isolated from VLAN 20 (Engineering) without requiring separate physical switches.
• **Trunking (IEEE 802.1Q):** A high-speed link carrying traffic for multiple VLANs simultaneously between switches. Each frame is tagged with a 4-byte 802.1Q header containing a 12-bit VLAN ID (VID).
• **Inter-VLAN Routing:** Because VLANs are isolated broadcast domains, communication between two different VLANs requires a Layer 3 Router (using "Router-on-a-Stick" subinterfaces) or a Multi-Layer Switch (SVI / Switched Virtual Interfaces).

MODULE 5 OF 5

Module 5: Networking, Transport & Application Layers

Topics 37 to 52 • IPv4/IPv6, Subnetting, Dijkstra/Bellman-Ford, TCP AIMD & HTTP/3

Module V: Networking, Transport & Application Layers — 16-Topic Master Syllabus Guide

Topic 37: IPv4 Header Format (20-byte base fields, TTL, Protocol, Header Checksum, Fragmentation)

Topic 38: IPv6 Architecture (128-bit addressing, 40-byte base header, Extension Headers vs. IPv4)

Topic 39: Subnetting, Supernetting & Classless Inter-Domain Routing (CIDR Notation & Prefix Masks)

Topic 40: Address Resolution Protocol (ARP Request/Reply, ARP Cache & RARP / DHCP)

Topic 41: Internet Control Message Protocol (ICMP Error Reporting: Ping, Traceroute Mechanics)

Topic 42: Routing Algorithms: Distance Vector Routing (Bellman-Ford & Count-to-Infinity Problem)

Topic 43: Routing Algorithms: Link State Routing (Dijkstra's Shortest Path Algorithm & OSPF)

Topic 44: Hierarchical Routing & Inter-Domain Routing (Border Gateway Protocol BGP-4 Path Vector)

Topic 45: Transport Layer: User Datagram Protocol (UDP 8-byte Header & Pseudo-Header Checksum)

Topic 46: Transmission Control Protocol (TCP Segment Header Architecture & Flags: SYN, ACK, FIN, RST)

Topic 47: TCP Connection Management (3-Way Handshake SYN/SYN-ACK/ACK & 4-Way FIN Teardown)

Topic 48: TCP Flow Control (Sliding Window & Silly Window Syndrome Prevention: Nagle & Clark Algorithms)

Topic 49: TCP Congestion Control (AIMD, Slow Start, Congestion Avoidance, Fast Retransmit, Fast Recovery)

Topic 50: Domain Name System (DNS Hierarchical Namespace, Root Servers, Iterative vs Recursive Queries)

Topic 51: Electronic Mail Architecture (SMTP, POP3, IMAP4, MIME & Message Transfer Agents)

Topic 52: Web Protocols: HTTP/1.0, HTTP/1.1 (Persistent Connections & Pipelining), HTTP/2 & HTTP/3 QUIC

Topic 37 & 39: IPv4 Header Architecture, Subnetting & CIDR Math

IPv4 Field	Field Size	Core Routing Function & Protocols
Version	4 Bits	Specifies IP version (`0100` = IPv4, `0110` = IPv6).
IHL (Header Length)	4 Bits	Header length in 32-bit words (Minimum value = 5 $\implies$ 20 bytes; Maximum = 15 $\implies$ 60 bytes).
Total Length	16 Bits	Total datagram size (Header + Data) in bytes (Max $65,535$ bytes).
Identification	16 Bits	Unique integer tagging all fragments belonging to same original datagram.
Flags	3 Bits	Bit 0 (Reserved); Bit 1 (DF = Don't Fragment); Bit 2 (MF = More Fragments).
Fragment Offset	13 Bits	Offset of fragment relative to original unfragmented payload in **8-byte blocks**.
TTL (Time to Live)	8 Bits	Hop counter decremented by 1 at every router; discarded at 0 with ICMP Time Exceeded.
Protocol	8 Bits	Specifies Layer 4 payload: ICMP = 1, IGMP = 2, TCP = 6, UDP = 17, OSPF = 89.
Header Checksum	16 Bits	1's complement checksum covering ONLY the IP header (recomputed at every hop).
Source & Dest IP	32 Bits each	Origin and final destination IPv4 logical addresses.

🏛️ Step-by-Step Solved Problem 1: IPv4 Fragmentation Calculation

An IPv4 packet with Total Length = $4020\ \text{bytes}$ (20 bytes IP header + 4000 bytes data) travels across an Ethernet link with $\text{MTU} = 1500\ \text{bytes}$. Calculate the fields for all resulting fragments.

Solution: Max payload per fragment = $1500 - 20 = 1480\ \text{bytes}$ (divisible by 8: $1480/8 = 185$).

- **Fragment 1:** Total Length = $1500\ \text{B}$ (20 header + 1480 data), $\text{MF} = 1$, $\text{Offset} = 0/8 = \mathbf{0}$. (Carries bytes $0 \ldots 1479$).
- **Fragment 2:** Total Length = $1500\ \text{B}$ (20 header + 1480 data), $\text{MF} = 1$, $\text{Offset} = 1480/8 = \mathbf{185}$. (Carries bytes $1480 \ldots 2959$).
- **Fragment 3:** Total Length = $1060\ \text{B}$ (20 header + 1040 data), $\text{MF} = 0$, $\text{Offset} = 2960/8 = \mathbf{370}$. (Carries bytes $2960 \ldots 3999$).

🏛️ Step-by-Step Solved Problem 2: CIDR Subnetting & Address Allocation

An ISP assigns block `198.51.100.0/24` to an organization needing 4 equal subnets. Find: (1) Subnet mask, (2) Usable hosts per subnet, (3) Subnet network addresses, and (4) Broadcast addresses.

Solution:

- To create 4 subnets: Borrow $k = \log_2(4) = 2$ bits $\implies$ New prefix $= /24 + 2 = \mathbf{/26}$.
- **Subnet Mask:** $255.255.255.192$ (Binary: `11111111.11111111.11111111.11000000`).
- **Usable Hosts per Subnet:** $2^{(32-26)} - 2 = 2^6 - 2 = 64 - 2 = \mathbf{62}\ \text{hosts}$.
- **Subnet 1:** Network: `198.51.100.0/26`, Range: `.1 - .62`, Broadcast: `198.51.100.63`
- **Subnet 2:** Network: `198.51.100.64/26`, Range: `.65 - .126`, Broadcast: `198.51.100.127`
- **Subnet 3:** Network: `198.51.100.128/26`, Range: `.129 - .190`, Broadcast: `198.51.100.191`
- **Subnet 4:** Network: `198.51.100.192/26`, Range: `.193 - .254`, Broadcast: `198.51.100.255`

Topic 42 & 43: Routing Algorithms: Distance Vector vs. Link State (Dijkstra)

Dimension	Distance Vector Routing (Bellman-Ford / RIP)	Link State Routing (Dijkstra / OSPF)
Knowledge of Topology	Routers know only distance vectors of immediate direct neighbors ("Routing by rumor").	Every router possesses complete global topological graph of entire Autonomous System.
Algorithm	Bellman-Ford Equation: $D_x(y) = \min_v\{c(x,v) + D_v(y)\}$.	Dijkstra's Shortest Path Tree algorithm.
Convergence Speed	Slow convergence; suffers from **Count-to-Infinity** problem on link failures.	**Fast Convergence:** Link State Advertisements (LSAs) flood updates instantly.
Loop Prevention	Split Horizon, Poison Reverse, Maximum Hop Count (= 15 in RIP).	Zero routing loops (Dijkstra guarantees unique loop-free shortest path tree).

Topic 46, 47 & 49: TCP Architecture, Handshakes & Congestion Control

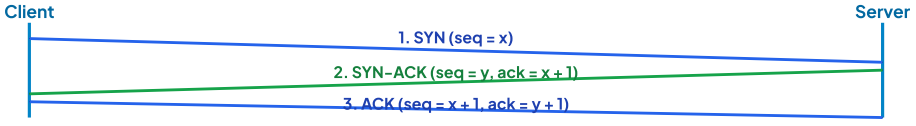

Figure 5.1: TCP 3-Way Handshake Connection Establishment Protocol

The 4 Phases of TCP Congestion Control (AIMD): 1. **Slow Start:** Starts with $\text{cwnd} = 1\ \text{MSS}$. Doubles cwnd every RTT ($\text{cwnd} \leftarrow \text{cwnd} \times 2$) exponentially until reaching ssthresh. 2. **Congestion Avoidance:** Linear growth: increases cwnd by $1\ \text{MSS}$ per RTT ($\text{cwnd} \leftarrow \text{cwnd} + 1$) until packet loss occurs. 3. **Timeout Reaction (TCP Tahoe):** Sets $\text{ssthresh} \leftarrow \text{cwnd}/2$, resets $\text{cwnd} \leftarrow 1\ \text{MSS}$, re-enters Slow Start. 4. **3 Duplicate ACKs (TCP Reno):** Fast Retransmit triggers immediate retransmission; sets $\text{ssthresh} \leftarrow \text{cwnd}/2$, $\text{cwnd} \leftarrow \text{ssthresh} + 3\ \text{MSS}$, enters Fast Recovery!

Topic 50, 51 & 52: Application Layer Protocols (DNS, Email & HTTP)

Protocol	Port & Transport	Architecture & Function	Key Evolution Highlights
DNS	Port 53 (UDP primary, TCP for zone transfer)	Hierarchical distributed database: Root → TLD (.com, .edu) → Authoritative servers.	Iterative vs. Recursive resolution; DNSSEC security records.
SMTP	Port 25 / 587 (TCP)	Push protocol for sending email between Message Transfer Agents (MTAs).	MIME extensions support attachments, audio, HTML formatting.
POP3 / IMAP4	POP3: Port 110; IMAP: Port 143 (TCP)	Pull protocols for retrieving email from mail servers to local user mail clients.	POP3 downloads and deletes; IMAP syncs folders dynamically across multiple devices.
HTTP/1.1	Port 80 (TCP)	Persistent TCP connections (`Keep-Alive`) & pipelining over single connection.	Suffers from Head-of-Line (HoL) blocking at application level.
HTTP/2	Port 443 (TLS/TCP)	Binary framing layer; multiplexes multiple independent request/response streams over 1 TCP socket.	HPACK header compression, Server Push; TCP-level packet drop still stalls all streams.
HTTP/3 (QUIC)	Port 443 (UDP)	Replaces TCP with QUIC over UDP: combines TLS 1.3 handshake and transport in single round-trip!	**Zero Head-of-Line Blocking:** Packet loss in one stream never stalls other streams!

🧠 M5 Active Recall & 10-Question University Exam Master Bank

Q1. Draw the complete IPv4 Header format and explain the function of TTL, Header Checksum, and Fragmentation fields. (10 Marks)

- **TTL (8 bits):** Hop counter decremented at each router. Prevents undeliverable packets from looping infinitely.
- **Header Checksum (16 bits):** 1's complement sum covering header only. Verified at every hop.
- **Identification (16 bits):** Tags fragments of same datagram.
- **Flags (3 bits):** DF (Don't Fragment), MF (More Fragments).
- **Fragment Offset (13 bits):** Measures data offset in 8-byte blocks relative to unfragmented payload.

Q2. Explain TCP 3-Way Handshake Connection Establishment and 4-Way Connection Termination with sequence diagrams. (10 Marks)

- **3-Way Establishment:** (1) Client → Server: `SYN (seq=x)`; (2) Server → Client: `SYN-ACK (seq=y, ack=x+1)`; (3) Client → Server: `ACK (seq=x+1, ack=y+1)`.
- **4-Way Teardown:** (1) Client → Server: `FIN`; (2) Server → Client: `ACK` (half-close); (3) Server → Client: `FIN`; (4) Client → Server: `ACK` (Client waits $2\ \mathrm{MSL}$ in `TIME_WAIT` before closing).

Q3. Explain TCP Congestion Control mechanisms: Slow Start, Congestion Avoidance, Fast Retransmit, and Fast Recovery. (10 Marks)

- **Slow Start:** Exponential growth: $\mathrm{cwnd} \leftarrow \mathrm{cwnd} \times 2$ per RTT until reaching $\mathrm{ssthresh}$.
- **Congestion Avoidance:** Additive linear growth: $\mathrm{cwnd} \leftarrow \mathrm{cwnd} + 1\ \mathrm{MSS}$ per RTT.
- **Fast Retransmit:** 3 duplicate ACKs trigger immediate retransmission without waiting for RTO timeout.
- **Fast Recovery:** Multiplicative decrease: $\mathrm{ssthresh} = \mathrm{cwnd}/2$, sets $\mathrm{cwnd} = \mathrm{ssthresh} + 3\ \mathrm{MSS}$, continues congestion avoidance.

Q4. Compare Distance Vector (Bellman-Ford) and Link State (Dijkstra) routing algorithms. How is Count-to-Infinity solved? (8 Marks)

- **Distance Vector:** Periodic routing table exchange with neighbors only; slow convergence; suffers Count-to-Infinity. Solved by **Split Horizon** (do not advertise route back to neighbor who supplied it) and **Poison Reverse** (advertise cost as ∞).
- **Link State:** Floods Link State Advertisements (LSAs) to all routers; builds global topology map; runs Dijkstra's algorithm; zero routing loops!

Q5. Compare HTTP/1.1, HTTP/2, and HTTP/3 QUIC across multiplexing, transport layer, and Head-of-Line blocking. (8 Marks)

- **HTTP/1.1 (TCP):** Sequential requests per socket; application Head-of-Line (HoL) blocking.
- **HTTP/2 (TCP):** Binary multiplexed streams over single TCP connection; single packet drop stalls all streams (TCP HoL blocking).
- **HTTP/3 (QUIC/UDP):** Native multiplexed streams over UDP; packet drop in stream 1 never delays stream 2 (Zero HoL blocking!).

Topic 52.2: Comprehensive Network Layer & Transport Layer Solved Numericals

🏛️ Solved Numerical 1: Dijkstra's Link State Shortest Path Algorithm Trace

Find the shortest paths from source router A to all nodes in network graph:

- Edges: $A-B:2,\ A-C:5,\ B-C:2,\ B-D:4,\ C-D:1,\ C-E:5,\ D-E:1$

Execution Trace Table:

Step	Visited Set N'	$D(B), p(B)$	$D(C), p(C)$	$D(D), p(D)$	$D(E), p(E)$
0	$\{A\}$	$2, A$	$5, A$	∞	∞
1	$\{A, B\}$	**2, A**	$4, B$	$6, B$	∞
2	$\{A, B, C\}$	2, A	**4, B**	$5, C$	$9, C$
3	$\{A, B, C, D\}$	2, A	4, B	**5, C**	$6, D$
4	$\{A, B, C, D, E\}$	2, A	4, B	5, C	**6, D**

Shortest Paths from A: to $B=2$, to $C=4$ ($A \to B \to C$), to $D=5$ ($A \to B \to C \to D$), to $E=6$ ($A \to B \to C \to D \to E$).

🏛️ Solved Numerical 2: TCP AIMD Congestion Window Evolution

A TCP Reno connection has $\text{ssthresh} = 16\ \text{MSS}$. It starts in Slow Start ($\text{cwnd} = 1$). Trace cwnd over successive RTTs until a timeout occurs at $\text{cwnd} = 20$, followed by 3 duplicate ACKs at $\text{cwnd} = 12$:

1. **RTT 1–5 (Slow Start):** cwnd doubles: $1 \to 2 \to 4 \to 8 \to 16\ \text{MSS}$ (Reaches ssthresh).
2. **RTT 6–9 (Congestion Avoidance):** Linear growth: $17 \to 18 \to 19 \to 20\ \text{MSS}$.
3. **Timeout at $\text{cwnd} = 20$:** Sets $\text{ssthresh} \leftarrow 20/2 = 10\ \text{MSS}$, resets $\text{cwnd} \leftarrow 1\ \text{MSS}$, re-enters Slow Start.
4. **RTT 10–14:** Doubles $1 \to 2 \to 4 \to 8 \to 10$ (ssthresh reached), then linear: $11 \to 12\ \text{MSS}$.
5. **3 Duplicate ACKs at $\text{cwnd} = 12$:** Fast Retransmit! Sets $\text{ssthresh} \leftarrow 12/2 = 6\ \text{MSS}$, sets $\text{cwnd} \leftarrow 6+3 = 9\ \text{MSS}$ in Fast Recovery!

Topic 52.3: Comprehensive Internetworking, BGP & Transport Internals

In global autonomous internetworking, routing is divided into **Intra-Domain Interior Gateway Protocols (IGP: OSPF, IS-IS)** and **Inter-Domain Exterior Gateway Protocols (EGP: BGP-4)**:

Routing Protocol	Algorithm Family	Underlying Transport Protocol	Routing Metric & Domain
RIPv2	Distance Vector (Bellman-Ford)	UDP (Port 520)	Hop Count (Max = 15 hops; 16 = ∞); Small LANs.
OSPFv2 / OSPFv3	Link State (Dijkstra)	Raw IP (Protocol 89)	Cost = $\frac{10^8}{\text{Bandwidth (bps)}}$; Large Enterprise / Campus.
BGP-4	Path Vector	TCP (Port 179)	AS-Path list, Policy-based routing, Local Preference; Global Internet Core.

🏛️ Complete Step-by-Step Distance Vector Routing & Count-to-Infinity Trace

Consider 3 linear routers $A \leftrightarrow B \leftrightarrow C$ with unit link costs (1):

- Initial state: B reaches C in 1 hop ($D_B(C) = 1$); A reaches C via B in 2 hops ($D_A(C) = 2$).
- **Link $B - C$ Fails:** B detects failure. But before B advertises ∞, A sends its periodic update stating: *"I can reach C with cost 2"*.
- B incorrectly concludes: *"I can reach C via A with cost $2+1=3$"*. B updates $D_B(C) = 3$.
- On next iteration, A learns B's cost is 3, updating $D_A(C) = 3+1 = 4$.
- B updates $D_B(C) = 5 \implies A$ updates $D_A(C) = 6 \ldots$ **Counting to Infinity!**

Remedies: (1) *Split Horizon:* A never advertises its route to C back to B. (2) *Poison Reverse:* A advertises $D_A(C) = \infty$ to B.

🏛️ **Step-by-Step Silly Window Syndrome Prevention: Nagle vs. Clark Algorithms**

Silly Window Syndrome occurs when data is exchanged in tiny 1-byte segments (e.g. typing single characters in Telnet), causing a 40-byte TCP/IP header overhead for every single byte of payload:

- **Sender-Side Solution (Nagle's Algorithm):** The sender transmits the first small packet immediately. While waiting for ACK, the sender buffers all subsequent outgoing data into a full Maximum Segment Size (MSS) block before transmitting the next segment.
- **Receiver-Side Solution (Clark's Solution):** The receiver prevents sending tiny window update advertisements. It advertises a window size of 0 until its internal buffer has space for either a full MSS or half the receiver buffer capacity!

Topic 52.4: Master University Solved Examination Numerical Bank

🏛️ **Solved Numerical 3: Hierarchical CIDR Route Aggregation & Supernetting**

A regional ISP router receives routing updates for four contiguous IP address blocks:

- Block 1: `200.16.0.0/24` (Binary: `11001000.00010000.00000000.00000000`)
- Block 2: `200.16.1.0/24` (Binary: `11001000.00010000.00000001.00000000`)
- Block 3: `200.16.2.0/24` (Binary: `11001000.00010000.00000010.00000000`)
- Block 4: `200.16.3.0/24` (Binary: `11001000.00010000.00000011.00000000`)

Route Aggregation (Supernetting) Solution:

Comparing the 3rd octets in binary: `00000000`, `00000001`, `00000010`, `00000011`. All 4 blocks share the identical first 22 bits (`11001000.00010000.000000xx`).

$$\text{Single Aggregated Supernet Route} = \mathbf{200.16.0.0/22} \quad (\text{Subnet Mask: } \mathbf{255.255.252.0})$$

Benefit: Replaces 4 independent routing table entries with 1 consolidated entry, reducing router BGP memory table size by 75%!

🏛️ **Solved Numerical 4: TCP Maximum Throughput & Mathis Equation**

A cross-continental $10\ \text{Gbps}$ TCP link has an RTT of $100\ \text{ms}$ and standard MSS of $1460\ \text{bytes}$. If the packet loss rate is $p = 0.0001$ (0.01%), calculate the maximum achievable TCP throughput according to the **Mathis Formula**.

Solution (Mathis Formula):

$$\text{Throughput} \leq \frac{\text{MSS}}{\text{RTT}} \times \frac{\mathbf{1.22}}{\sqrt{\mathbf{p}}}$$

$$\text{Throughput} \leq \frac{1460 \times 8\ \text{bits}}{0.100\ \text{s}} \times \frac{1.22}{\sqrt{0.0001}} = 116,800 \times \frac{1.22}{0.01} = 116,800 \times 122 = \mathbf{14,249,600}\ \text{bps} \approx \mathbf{14.25}\ \text{Mbps}$$

Critical Engineering Insight: Even on a $10\ \text{Gbps}$ physical pipe, a tiny 0.01% packet drop throttles standard TCP Reno throughput down to $14.25\ \text{Mbps}$ due to aggressive AIMD window halving!

Topic 52.5: Comprehensive Transport State Machines & Variable Length Subnetting (VLSM)

🏛️ Solved Numerical 5: Complete Variable-Length Subnet Masking (VLSM) Design

An enterprise organization is assigned address block `172.16.0.0/16`. Design an optimal VLSM subnetting plan for 4 distinct departments:

- Department A: Requires 4000 host addresses
- Department B: Requires 2000 host addresses
- Department C: Requires 1000 host addresses
- Department D: Requires 500 host addresses

VLSM Allocation Plan:

Department	Hosts Needed	Bits Needed ($2^h - 2 \geq N$)	Prefix Mask	Assigned Network Address	Usable Host Range
Dept A	4000	$h = 12$ (4094)	/20 (255.255.240.0)	`172.16.0.0/20`	`172.16.0.1 - 172.16.15.254`
Dept B	2000	$h = 11$ (2046)	/21 (255.255.248.0)	`172.16.16.0/21`	`172.16.16.1 - 172.16.23.254`
Dept C	1000	$h = 10$ (1022)	/22 (255.255.252.0)	`172.16.24.0/22`	`172.16.24.1 - 172.16.27.254`
Dept D	500	$h = 9$ (510)	/23 (255.255.254.0)	`172.16.28.0/23`	`172.16.28.1 - 172.16.29.254`

🏛️ Step-by-Step TCP Jacobson's RTO Calculation Algorithm

Given initial $\text{SRTT} = 100\text{ ms}$, $\text{RTTVAR} = 10\text{ ms}$, and $\alpha = 0.125, \beta = 0.25$. If a new sample RTT measurement $R = 140\text{ ms}$ arrives, compute the updated Retransmission Timeout (RTO):

$$\text{Error } E = R - \text{SRTT} = 140 - 100 = +\mathbf{40}\text{ ms}$$

$$\text{Updated SRTT} \leftarrow \text{SRTT} + \alpha \times E = 100 + 0.125(40) = 100 + 5 = \mathbf{105}\text{ ms}$$

$$\text{Updated RTTVAR} \leftarrow \text{RTTVAR} + \beta \times (|E| - \text{RTTVAR}) = 10 + 0.25(40 - 10) = 10 + 7.5 = \mathbf{17.5}\text{ ms}$$

$$\text{New RTO} = \text{SRTT} + \mathbf{4} \times \text{RTTVAR} = \mathbf{105} + \mathbf{4}(\mathbf{17.5}) = \mathbf{105} + \mathbf{70} = \mathbf{175}\text{ ms}$$

🏛️ Solved Numerical 6: Bellman-Ford Distance Vector Calculation with Routing Table Updates

Given 4 routers A, B, C, D. Router B has direct neighbor costs: $c(B, A) = 3, c(B, C) = 1, c(B, D) = 6$. B receives distance vectors from A and C:

- From A: $D_A = (A : 0, B : 3, C : 4, D : 2)$
- From C: $D_C = (A : 4, B : 1, C : 0, D : 3)$

Update B's routing table for destination D using Bellman-Ford: $D_B(D) = \min\{c(B, A) + D_A(D),\ c(B, C) + D_C(D),\ c(B, D)\}$.

$$\text{Via } A : 3 + 2 = 5$$

$$\text{Via } C : 1 + 3 = 4$$

$$\text{Direct } D : 6$$

$$\mathbf{D_B(D)} = \min(\mathbf{5}, \mathbf{4}, \mathbf{6}) = \mathbf{4} \quad (\text{Next Hop: Router } \mathbf{C})$$

Q6. Compare IPv4 and IPv6 across address space, header size, fragmentation, checksum, and security. (10 Marks)

- **Address Space:** IPv4 has 32-bit addresses (4.3×10^9); IPv6 has 128-bit addresses (3.4×10^{38}).
- **Header Size:** IPv4 is variable (20–60 B); IPv6 has a fixed 40-byte base header with chained Extension Headers.
- **Fragmentation:** IPv4 routers perform fragmentation; in IPv6, ONLY the source host fragments packets (Path MTU Discovery).
- **Header Checksum:** IPv4 recomputes checksum at every hop; IPv6 eliminates header checksum to maximize router forwarding speed.
- **Security:** IPsec is optional add-on in IPv4; IPsec support is built natively into the core IPv6 protocol specification!

Q7. Explain Address Resolution Protocol (ARP), ARP Request (Broadcast), ARP Reply (Unicast), and ARP Cache Poisoning. (8 Marks)

• **ARP:** Maps a known Layer 3 logical IP address to an unknown Layer 2 physical MAC address on the local subnet.
• **ARP Request:** Broadcast frame (`FF:FF:FF:FF:FF:FF`) asking: *"Who has IP X.X.X.X? Tell MAC Y."*
• **ARP Reply:** Unicast frame from the target host stating: *"I have IP X.X.X.X, my MAC is Z."*
• **ARP Poisoning (Spoofing):** An attacker sends gratuitous fake ARP replies associating the gateway's IP with the attacker's MAC, enabling Man-in-the-Middle (MitM) packet sniffing!

Topic 52.6: Advanced TCP State Transition Machine & Congestion Control Math



Figure 5.2: The Classical TCP Client Connection Lifetime State Machine

🏛️ Step-by-Step Solved Problem: Variable Length Subnet Masking (VLSM) Enterprise Plan

An enterprise is allocated IP address block `10.0.0.0/16`. Subnet the block for: (1) Head Office: 10,000 hosts, (2) Branch 1: 5,000 hosts, (3) Branch 2: 2,000 hosts, (4) Branch 3: 1,000 hosts, (5) Five WAN point-to-point links (2 hosts each).

- **Head Office (10,000 hosts):** $2^{14} - 2 = 16,382 \geq 10,000 \implies$ Mask: $/18$ $(255.255.192.0) \implies \mathbf{10.0.0.0/18}$ (`.0.1` to `.63.254`).
- **Branch 1 (5,000 hosts):** $2^{13} - 2 = 8,190 \geq 5,000 \implies$ Mask: $/19$ $(255.255.224.0) \implies \mathbf{10.0.64.0/19}$ (`.64.1` to `.95.254`).
- **Branch 2 (2,000 hosts):** $2^{11} - 2 = 2,046 \geq 2,000 \implies$ Mask: $/21$ $(255.255.248.0) \implies \mathbf{10.0.96.0/21}$ (`.96.1` to `.103.254`).
- **Branch 3 (1,000 hosts):** $2^{10} - 2 = 1,022 \geq 1,000 \implies$ Mask: $/22$ $(255.255.252.0) \implies \mathbf{10.0.104.0/22}$ (`.104.1` to `.107.254`).
- **5 WAN Links (2 hosts each):** Mask $/30$ $(255.255.255.252) \implies$ `10.0.108.0/30`, `10.0.108.4/30`, `10.0.108.8/30`, `10.0.108.12/30`, `10.0.108.16/30`.

Efficiency: 100% zero address collisions with over $40,000$ IP addresses preserved for future organizational growth!

HANDS-ON PRACTICAL LAB MASTER APPENDIX

DCCN Socket Programming & Packet Analysis Master Guide

Complete C & Python Socket Implementations, Wireshark Protocol Traces & Simulation Architectures

Lab Topic 1: Berkeley Socket API & POSIX System Call Architecture

A **Socket** is an endpoint for process-to-process network communication across the transport layer. In UNIX and Linux operating systems, sockets are represented as standard integer file descriptors manipulated via system calls:

Socket System Call	Operating System Action	Client vs. Server
`socket(AF_INET, SOCK_STREAM, 0)`	Creates an IPv4 TCP communication endpoint and returns a socket descriptor.	Both Client and Server
`bind(sockfd, &addr, sizeof(addr))`	Binds the socket to a specific local IP address and 16-bit Port number.	Server Routine
`listen(sockfd, backlog)`	Transitions TCP socket into passive listening state with incoming connection queue.	Server Routine
`accept(sockfd, &client_addr, &len)`	Blocks until incoming SYN arrives; completes 3-way handshake, returns new active socket.	Server Routine
`connect(sockfd, &serv_addr, len)`	Initiates TCP 3-Way Handshake with remote server socket.	Client Routine
`send()` / `recv()` (or `read`/`write`)	Transfers stream data across the established full-duplex TCP socket buffer.	Both Client and Server
`close(sockfd)`	Initiates TCP 4-Way connection teardown (FIN/ACK) and frees kernel descriptor.	Both Client and Server

Lab Topic 2: Complete Production-Grade TCP Echo Server in C

```c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <unistd.h>
#include <arpa/inet.h>

#define PORT 8080
#define BUFFER_SIZE 1024

int main() {
    int server_fd, new_socket;
    struct sockaddr_in address;
    int opt = 1;
    socklen_t addrlen = sizeof(address);
    char buffer[BUFFER_SIZE] = {0};

    // 1. Create TCP Socket
    if ((server_fd = socket(AF_INET, SOCK_STREAM, 0)) < 0) {
        perror("Socket creation failed");
        exit(EXIT_FAILURE);
    }

    // 2. Set Socket Options (SO_REUSEADDR prevents "Address already in use" errors)
    setsockopt(server_fd, SOL_SOCKET, SO_REUSEADDR, &opt, sizeof(opt));

    // 3. Configure Server Address Structure
    address.sin_family = AF_INET;
    address.sin_addr.s_addr = INADDR_ANY; // Bind to all local interfaces (0.0.0.0)
    address.sin_port = htons(PORT);       // Host-to-Network Short byte order conversion

    // 4. Bind Socket to Address & Port
    if (bind(server_fd, (struct sockaddr *)&address, sizeof(address)) < 0) {
        perror("Bind failed");
        exit(EXIT_FAILURE);
    }

    // 5. Listen for incoming connections (Queue backlog = 5)
    if (listen(server_fd, 5) < 0) {
        perror("Listen failed");
        exit(EXIT_FAILURE);
    }
    printf("TCP Echo Server listening on port %d...\n", PORT);

    // 6. Accept incoming client connection
    while (1) {
        if ((new_socket = accept(server_fd, (struct sockaddr *)&address, &addrlen)) < 0) {
            perror("Accept error");
            continue;
        }
        printf("Client connected: %s:%d\n", inet_ntoa(address.sin_addr), ntohs(address.sin_port));

        // 7. Echo Loop: Read from client and write back identical data
        ssize_t valread;
        while ((valread = read(new_socket, buffer, BUFFER_SIZE)) > 0) {
            write(new_socket, buffer, valread);
            memset(buffer, 0, BUFFER_SIZE);
        }
        close(new_socket);
        printf("Client disconnected.\n");
    }
    close(server_fd);
    return 0;
}
```

Lab Topic 3: High-Performance Concurrent UDP Server in Python

```
import socket

HOST = "0.0.0.0"
PORT = 9090
BUFFER_SIZE = 2048

# Create Datagram Socket (UDP)
sock = socket.socket(socket.AF_INET, socket.SOCK_DGRAM)
sock.bind((HOST, PORT))
print(f"UDP Server active on {HOST}:{PORT}...")

while True:
    data, client_addr = sock.recvfrom(BUFFER_SIZE)
    message = data.decode('utf-8', errors='ignore')
    print(f"Received from {client_addr}: {message.strip()}")

    # Send UDP reply
    reply = f"ACK: {message}".encode('utf-8')
    sock.sendto(reply, client_addr)
```

Lab Topic 4: Wireshark Packet Sniffing & Protocol Dissection Trace

Filter Syntax	Wireshark Display Action	Network Troubleshooting Use Case
`tcp.port == 80`	Filters all unencrypted HTTP traffic.	Inspecting web requests, response headers, status codes.
`dns`	Displays all DNS queries and authoritative responses.	Diagnosing domain name resolution latency.
`icmp`	Shows Ping request/replies and ICMP error reports.	Verifying network connectivity and MTU path discovery.
`tcp.flags.syn == 1 && tcp.flags.ack == 0`	Isolates initial TCP connection establishment requests.	Detecting TCP SYN Flood Distributed Denial of Service (DDoS) attacks.
`ip.addr == 192.168.1.1`	Filters all packets originating from or destined to gateway router.	Monitoring local default gateway traffic.
`tcp.analysis.retransmission`	Highlights duplicate TCP retransmission segments.	Detecting physical link degradation, buffer overflow, and high packet loss.

COMPREHENSIVE REVISION APPENDIX

10-Page Master Quick Revision Guide

High-Yield Formulas, Protocol Checklists & Solved Exam Cards

⚡ 10-Page Master Quick Revision — Data Communication & Computer Networks (CS24305)

Page 1: 52-Topic Master Syllabus Progress Checklist (Modules I – V)

Page 2: The Tier-S High-Yield Core Topic Ranking & Exam Strategy

Page 3: Data Communication Fundamentals, OSI 7-Layer & TCP/IP Suite

Page 4: Channel Capacity: Nyquist, Shannon & Transmission Media Formulas

Page 5: Digital Line Coding, Scrambling (B8ZS/HDB3) & Modulation (QAM)

Page 6: Data Link Framing, CRC Error Detection & Hamming Code Correction

Page 7: Sliding Window Flow Control: Stop-and-Wait, GBN, Selective Repeat

Page 8: Switching Techniques, ALOHA, CSMA/CD & Ethernet IEEE 802.3

Page 9: IPv4 Header, Subnetting, CIDR & Routing (Dijkstra vs. Bellman-Ford)

Page 10: TCP 3-Way Handshake, Congestion Control (AIMD) & Application Protocols

Page 1: Complete 52-Topic Master Syllabus Progress Checklist

CS24305 DCCN — All 52 Topics Verified & Mastered

Module	Topic #	Topic Name	Key Focus	
M1: Overview (13)	1–3	Communication Model & Networks	Simplex/Half/Full-Duplex, Performance Criteria	
	4–5	Topologies & Categories	Mesh, Star, Bus, Ring, LAN, MAN, WAN	
	6–8	Internet, Standards & Layering	ISP Hierarchy, OSI vs TCP/IP Encapsulation	
	9–10	OSI 7-Layer & TCP/IP Suite	PDUs, Headers & 4-Level Addressing	
	11–12	Impairments & Channel Capacity	Attenuation, Nyquist Bit Rate & Shannon Capacity	
	13	Transmission Media	UTP, STP, Coax, SMF, MMF, Radio, Microwave	
	M2: Encoding (6)	14	Digital Line Coding	NRZ-L, NRZ-I, Bipolar AMI, Manchester
15		Scrambling & Block Coding	4B/5B, B8ZS (T1) & HDB3 (E1) Substitution	
16		Digital Modulation	ASK, FSK, PSK, QPSK, 16-QAM Constellations	
17		Analog to Digital (PCM/DM)	Nyquist Sampling, Quantization, SQNR	
18–19		Multiplexing (FDM/TDM)	FDM, WDM, Synchronous TDM, Statistical TDM	
M3: Data Link (8)		20–21	Framing & Transmission	Async/Sync, Byte Stuffing, Bit Stuffing HDLC
	22–23	Error Detection	Single/Burst Errors, 2D Parity, Checksum	
	24	Cyclic Redundancy Check (CRC)	Modulo-2 Division, Generator Polynomials	
	25–26	Hamming Error Correction	$d_{\min} \geq 2t + 1$, (7,4) Hamming Code Syndrome	
	27	Flow & Error Control ARQ	Stop-and-Wait, Go-Back-N, Selective Repeat η	
	M4: Switching & LANs (9)	28–29	Switching Techniques	Circuit vs Packet Switching, Datagram vs VC
		30	Switch Architectures	Crossbar, Banyan & TDM Switches
		31–32	Random Access Protocols	Pure/Slotted ALOHA, CSMA (1/non/p-persistent)
33		CSMA/CD (Ethernet)	Collision Detection, Min Frame Size, Backoff	
34		CSMA/CA (Wi-Fi)	Hidden Terminal, RTS/CTS Handshake, NAV	
35–36		Ethernet & Layer 2 Devices	IEEE 802.3 Frame, Bridges, Switches, STP	
M5: Network, Transport, App (16)		37–38	IPv4 & IPv6 Headers	20B IPv4 Fields, Fragmentation, 40B IPv6
		39–41	Subnetting, ARP & ICMP	CIDR Prefix Math, ARP Cache, Ping/Traceroute
		42–44	Routing Protocols	Distance Vector (RIP), Link State (OSPF), BGP
	45–46	UDP & TCP Headers	8B UDP, 20B TCP Segment Flags (SYN/ACK/FIN)	
	47–49	TCP Handshake & Congestion	3-Way SYN, 4-Way FIN, AIMD, Slow Start, Reno	

Module	Topic #	Topic Name	Key Focus
	50–52	Application Layer Protocols	DNS Resolution, SMTP/IMAP, HTTP/1.1 vs HTTP/2/3

Page 2: The Tier-S High-Yield Core Topic Ranking & Exam Strategy

Rank	Core Exam Topic	Module	Frequency & Yield	Essential Mathematical Formula / Rule
☆ 1	Shannon & Nyquist Theorems	M1	100% Exam Probability (10M)	$C_{\text{Nyquist}} = 2B\log_2(L), \quad C_{\text{Shannon}} = B\log_2(1+\text{SNR})$
☆ 2	Line Coding & Manchester Waveforms	M2	100% Exam Probability (8M)	NRZ-L, NRZ-I, Bipolar AMI, Manchester ($0 = \text{H} \to \text{L}, 1 = \text{L} \to \text{H}$), Diff. Manchester
☆ 3	CRC Polynomial Division	M3	100% Exam Probability (10M)	Modulo-2 Division of $D \cdot 2^r$ by $G(x)$ to get Remainder R; Codeword $T = D \cdot 2^r + R$
☆ 4	Hamming Error Correction Code	M3	100% Exam Probability (10M)	$2^r \geq m + r + 1,\ d_{\min} \geq 2t + 1$; Parity bits at powers of 2 $(1, 2, 4, 8)$
☆ 5	Sliding Window Efficiency (η)	M3	100% Exam Probability (10M)	$\eta = \frac{W}{1+2a},\ a = \frac{T_{\text{prop}}}{T_{\text{trans}}}$; GBN ($W = 2^k - 1$), SR ($W = 2^{k-1}$)
☆ 6	ALOHA vs CSMA/CD Min Frame Size	M4	100% Exam Probability (10M)	$S_{\text{Pure}} = Ge^{-2G}, S_{\text{Slotted}} = Ge^{-G}$; CSMA/CD: $\text{Frame}_{\min} \geq 2T_{\text{prop}} \times \text{Bandwidth}$
☆ 7	IPv4 Header & Fragmentation	M5	100% Exam Probability (10M)	$\text{Total Length} \leq \text{MTU},\ \text{Fragment Offset} = \text{Data Offset}/8$
☆ 8	CIDR Subnetting & IP Allocations	M5	100% Exam Probability (10M)	Borrow k bits: New mask $/n+k$, Usable hosts $= 2^{(32-\text{prefix})} - 2$
☆ 9	Dijkstra vs. Bellman-Ford Routing	M5	100% Exam Probability (10M)	Dijkstra Global Shortest Path; Bellman-Ford $D_x(y) = \min_v\{c(x,v) + D_v(y)\}$
☆ 10	TCP 3-Way Handshake & AIMD	M5	100% Exam Probability (10M)	SYN → SYN-ACK → ACK; Slow Start ($\times 2$), Congestion Avoidance ($+1$), Fast Retransmit

Page 3: Module I — Data Communication, OSI & TCP/IP Architecture

The 7 OSI Layers & Protocol Units (PDUs):

1. **Physical (Bits):** Bitstream transmission, electrical voltages, pinouts.
2. **Data Link (Frames):** Hop-by-hop node delivery, MAC addressing, CRC error check.
3. **Network (Packets):** Host-to-host routing, logical IPv4/IPv6 addressing.
4. **Transport (Segments/Datagrams):** Process-to-process port delivery (TCP/UDP).
5. **Session (Data):** Dialogue control, synchronization checkpoints.
6. **Presentation (Data):** Character translation (UTF-8), compression, SSL/TLS encryption.
7. **Application (Messages):** User protocols: HTTP, DNS, SMTP, FTP, SSH.

Page 4: Module I — Channel Capacity Theorems & Transmission Media

Channel Capacity Formulas:

- **Nyquist Formula (Noiseless):** $\mathbf{C = 2B\log_2(L)}$ bps
- **Shannon Formula (Noisy):** $\mathbf{C = B\log_2(1 + \mathrm{SNR})}$ bps
- **Signal-to-Noise Ratio (dB):** $\mathrm{SNR_{dB}} = \mathbf{10}\log_{\mathbf{10}}(\mathrm{SNR}) \implies \mathrm{SNR} = \mathbf{10}^{\mathrm{SNR_{dB}}/\mathbf{10}}$
- **Attenuation (dB):** $\mathrm{dB} = \mathbf{10}\log_{\mathbf{10}}(\mathbf{P_2/P_1}) = \mathbf{20}\log_{\mathbf{10}}(\mathbf{V_2/V_1})$

Page 5: Module II — Digital Line Coding, Scrambling & Carrier Modulation

Line Coding	Bit 0 Representation	Bit 1 Representation	Clock Sync?
NRZ-L	Positive Voltage ($+V$)	Negative Voltage ($-V$)	No
NRZ-I	No transition at start	Transition at start	On 1s only
Bipolar AMI	Zero Volts (0V)	Alternating $+V$ and $-V$	On 1s only
Manchester	High-to-Low at midpoint	Low-to-High at midpoint	**100% Perfect**
Diff. Manchester	Transition at start	No transition at start	**100% Perfect**

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Page 6: Module III — Framing, CRC Error Detection & Hamming Codes

CRC Division & Error Correction Rules:

- **CRC Remainder:** $\text{Remainder of } (D \cdot 2^r)/G(x) \text{ using Modulo-2 XOR division.}$
- **Hamming Redundancy:** $\mathbf{2^r \geq m + r + 1}$ (m data bits, r parity bits).
- **Detection Limit:** $d_{\min} \geq d + 1$; **Correction Limit:** $d_{\min} \geq 2t + 1$.

Page 7: Module III — Flow Control & ARQ Protocols Efficiency

Protocol	Sender Window (W_S)	Receiver Window (W_R)	Efficiency (η)
Stop-and-Wait ARQ	1	1	$\eta = \frac{1}{1+2a}$
Go-Back-N (GBN)	$2^k - 1$	1	$\eta = \frac{W_S}{1+2a}$
Selective Repeat (SR)	2^{k-1}	2^{k-1}	$\eta = \frac{W_S}{1+2a}$

Page 8: Module IV — Switching, MAC Protocols & Ethernet Standards

MAC Sublayer Formulas:

- **Pure ALOHA:** $S = Ge^{-2G} \implies S_{\max} = 18.4\%$ (at $G = 0.5$).
- **Slotted ALOHA:** $S = Ge^{-G} \implies S_{\max} = 36.8\%$ (at $G = 1.0$).
- **CSMA/CD Min Frame Size:** $\text{Frame Size}_{\min} \geq \mathbf{2} \times \mathbf{T}_{\text{prop}} \times \text{Bandwidth}$.

Page 9: Module V — IPv4 Header, CIDR Subnetting & Routing Protocols

Subnetting & Routing Equations:

- **Usable Hosts:** $2^{(32-\text{Prefix})} - 2$
- **Fragment Offset:** $\text{Offset} = \text{Byte Index}/8$
- **Bellman-Ford Equation:** $\mathbf{D_x(y) = \min_v\{c(x,v) + D_v(y)\}}$
- **Dijkstra Shortest Path:** Greedy node selection with minimum cumulative edge cost.

Page 10: Module V — TCP Architecture, Congestion Control & Web Protocols

TCP Flow & Congestion Control:

- **Slow Start:** Exponential growth: $\text{cwnd} \leftarrow \text{cwnd} \times 2$ per RTT.
- **Congestion Avoidance:** Linear growth: $\text{cwnd} \leftarrow \text{cwnd} + 1\ \text{MSS}$ per RTT.
- **Fast Retransmit & Recovery:** 3 Duplicate ACKs $\implies \text{ssthresh} = \text{cwnd}/2,\ \text{cwnd} = \text{ssthresh} + 3$.

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