Computer Networks and Communication

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Abstract

This chapter explores the protocols, architectures, security mechanisms, and performance considerations that underpin modern computer networks. It begins with foundational protocols such as TCP/IP and HTTP/HTTPS, highlighting their roles in reliable data transmission and secure web communication. The discussion extends to both wired and wireless network topologies, including the evolution of Ethernet, Wi-Fi, and emerging 5G technologies, reflecting the growing complexity and ubiquity of networked systems [1]. Security mechanisms are examined in depth, covering firewalls, AES encryption, and VPNs, with an emphasis on best practices for safeguarding data in transit and at rest. Quality of Service (QoS) techniques are introduced to illustrate how networks prioritize and manage traffic for critical applications such as streaming and real-time analytics. The chapter culminates in a detailed case study of the 2017 WannaCry ransomware attack, demonstrating how protocol vulnerabilities and inadequate patch management can lead to global-scale disruptions. Through this integrated approach, readers gain both theoretical insights and practical strategies for designing, securing, and optimizing resilient communication networks [2].

Keywords: TCP/IP, HTTP/HTTPS, Firewalls, AES Encryption, VPN, QoS, WannaCry.

1 Introduction

1.1 Computer Networks in Modern Society

Computer networks form the critical infrastructure enabling global communication, commerce, and social interaction. From streaming services to financial transactions, networks facilitate real-time data exchange between billions of devices worldwide. Their importance extends to:

- **Daily Life**: Social media, smart home devices, and telemedicine
- **Business**: Cloud computing, supply chain management, and remote collaboration
- **Society**: Critical infrastructure (power grids, transportation) and democratic processes [3]

1.2 Historical Evolution

The network revolution began with **ARPANET** (1969), which pioneered:

- Packet switching (vs. circuit-switched networks)
- Decentralized architecture resistant to nuclear attacks
- TCP/IP protocol standardization (1983) [4]

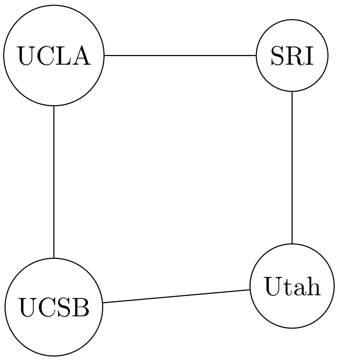

Fig. 1: ARPANET's initial 4-node topology (1969)

The 1990s saw the **World Wide Web** democratize information access, while modern developments include:

- Wireless networks (Wi-Fi 6, 5G NR with 1ms latency)
- IoT ecosystems (30B+ connected devices by 2025)
- Edge computing architectures [5]

1.3 Chapter Structure & Significance

This chapter analyzes four pillars of modern networking:

- **Protocols**: TCP/IP handshake mechanics, HTTPS encryption
- **Topologies**: From star configurations to decentralized mesh networks
- **Security**: Firewalls, VPNs, and quantum-resistant cryptography
- **Performance**: QoS implementations for latency-sensitive applications

A case study of the **2017 WannaCry ransomware attack** demonstrates how protocol vulnerabilities (SMBv1) enabled $4B+ in global damages, emphasizing the need for defense-in-depth strategies.

2 Network Protocols

Modern computer networks rely on a suite of protocols to ensure reliable, secure, and efficient communication. This section examines the TCP/IP three-way handshake, contrasts HTTP and HTTPS, and discusses the role of ports and sockets, highlighting vulnerabilities such as those exploited by ransomware attacks.

2.1 TCP/IP Three-Way Handshake

The Transmission Control Protocol (TCP) establishes a reliable connection between two hosts using a three-way handshake, which prevents data loss and ensures both parties are synchronized [6]. The process involves:

1. **SYN**: The client sends a synchronization (SYN) packet with its initial sequence number (e.g., 100) to the server.
2. **SYN-ACK**: The server replies with a SYN-ACK packet, including its own sequence number (e.g., 300) and an acknowledgment number (client's sequence + 1).
3. **ACK**: The client responds with an ACK, acknowledging the server's sequence number + 1 (301), completing the handshake.

This handshake ensures both endpoints agree on initial sequence numbers, enabling reliable, ordered data transfer and loss recovery. It is foundational for secure and robust Internet communication [7].

2.2 HTTP and HTTPS

HTTP (Hypertext Transfer Protocol) is the standard protocol for web communication, but it transmits data in plaintext, making it vulnerable to eavesdropping and man-in-the-middle attacks. HTTPS (HTTP Secure) adds a layer of encryption using TLS/SSL, protecting data integrity and confidentiality [8]. The TLS handshake involves negotiating encryption algorithms, exchanging certificates, and establishing session keys (often using ECDHE for forward secrecy).

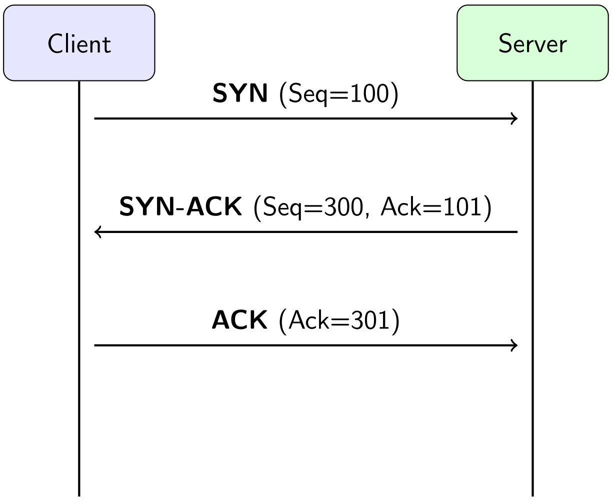

Fig. 2: TCP three-way handshake process.

Table 1: Comparison of HTTP and HTTPS

Feature	**HTTP**	**HTTPS**
Encryption	None	TLS (AES-256, ChaCha20)
Port	80	443
Authentication	None	X.509 Certificate
Vulnerabilities	Eavesdropping, MITM	CA compromise, protocol downgrade

HTTPS is now the de facto standard for all sensitive web traffic, and modern browsers flag non-HTTPS sites as insecure [9].

2.3 Ports and Sockets

Ports are logical endpoints for network communication, with well-known ports assigned to common protocols (e.g., 80 for HTTP, 443 for HTTPS, 445 for SMB). Sockets combine an IP address and port number, uniquely identifying each connection. Misconfigured or open ports can expose systems to attacks; for example, SMB on port 445 was exploited in the WannaCry ransomware outbreak [10].

> *Best practice: Block unused ports at the firewall and monitor for unusual traffic patterns to reduce the attack surface.*

These protocols and mechanisms form the backbone of secure, reliable, and scalable networked systems.

3 Network Topologies

Network topology defines the arrangement of devices and connections in a network, significantly impacting performance, reliability, and management. This section examines two fundamental topologies and their practical applications.

3.1 Star Topology

Star topology connects all devices to a central hub or switch, creating a centralized architecture that dominates enterprise Ethernet LANs [11].

Advantages:

- **Reliability through isolation:** A single cable failure affects only one device
- **Simplified management:** Centralized monitoring makes troubleshooting straightforward
- **Scalability:** Adding devices requires only connecting to available switch ports
- **Enhanced performance:** Dedicated paths reduce collision domains
- **Security features:** Support for VLANs, ACLs, and port security

Disadvantages:

- **Single point of failure:** If the central switch fails, the entire network goes down
- **Higher cabling costs:** Requires more wiring (e.g., 10 nodes at 50m each needs 500m of cable)
- **Performance bottlenecks:** Limited by central device capacity (e.g., switch backplane)
- **Infrastructure demands:** Requires rack space, cooling, and power protection

3.2 Mesh Topology

Mesh topology creates multiple direct connections between devices, forming a decentralized network particularly suited for IoT deployments.

Advantages:

- **High reliability:** Multiple redundant paths ensure continued operation
- **Fault tolerance:** Network remains functional despite node failures
- **No central dependency:** Eliminates single points of failure
- **Flexible routing:** Data can take multiple paths to destination
- **Organic scalability:** Networks can expand without central constraints

Disadvantages:

- **Complexity:** Challenging to implement and manage with increasing node count
- **Expensive deployment:** Requires $n(n-1)/2$ links for n devices in full mesh
- **Higher power consumption:** Each node must maintain multiple connections
- **Configuration overhead:** More complex setup and maintenance procedures

3.3 Case Example: Smart Home Mesh vs. Office Star LAN

A modern smart home typically employs mesh networks through protocols like Zigbee, Z-Wave, or Thread. These networks connect devices such as smart speakers, thermostats, and security sensors with multiple communication paths. If a smart lock cannot reach the hub directly, it can route through a nearby light switch, enhancing reliability despite signal-blocking walls or interference.

Recent research demonstrates that integrating deep reinforcement learning with mesh-based IoT networks enables real-time, autonomous optimization of both communication paths and energy demand in smart grids and smart home environments, significantly improving reliability and efficiency[12].

In contrast, office environments typically implement star topology with managed switches connecting workstations, printers, and servers. This architecture facilitates centralized IT management (e.g., port security, VLANs), optimizes bandwidth for data-intensive applications, and simplifies troubleshooting. The central switches often connect to redundant core switches to mitigate the single point of failure risk.

The choice between these topologies reflects different priorities: mesh networks emphasize reliability and flexibility for distributed IoT devices, while star networks optimize management and performance for data-intensive business operations.

4 Wireless and Mobile Networks

Wireless and mobile networks have transformed connectivity for both personal and industrial applications. This section reviews key standards, security features, and challenges of Wi-Fi and cellular networks, as well as the role of Bluetooth/BLE in the Internet of Things (IoT).

4.1 Wi-Fi Standards: 802.11ac (Wi-Fi 5) and 802.11ax (Wi-Fi 6)

Wi-Fi 5 (802.11ac) operates exclusively in the 5 GHz band, offering theoretical speeds up to 3.5 Gbps and lower interference compared to 2.4 GHz. It supports technologies such as multi-user MIMO and beamforming, enabling higher capacity and more stable connections for home and office environments [13]. Wi-Fi 6 (802.11ax) extends coverage to 2.4, 5, and 6 GHz (Wi-Fi 6E), boosting maximum speed to 9.6 Gbps and reducing latency to as low as 1 ms. Features like OFDMA and BSS coloring enhance efficiency in dense environments, making Wi-Fi 6 ideal for IoT and enterprise deployments.

Security: WPA3 is the latest Wi-Fi Protected Access standard, required for Wi-Fi 6E and recommended for all new deployments. It introduces Simultaneous Authentication of Equals (SAE), forward secrecy, and improved protection against brute-force attacks. WPA3 is backward compatible with WPA2 but offers stronger encryption and handshake security [**?**].

4.2 Cellular Networks: 4G LTE vs. 5G

4G LTE networks typically deliver speeds up to 1 Gbps with latency between 30 and 70 ms, sufficient for most mobile apps. 5G, however, operates in sub-6 GHz and mmWave bands, offering up to 20 Gbps and latency as low as 1 ms. This enables real-time applications such as autonomous vehicles, remote surgery, and massive IoT deployments, where millions of devices can connect per square kilometer [14].

4.3 Bluetooth/BLE for IoT

Bluetooth Low Energy (BLE) is designed for short-range, low-power communication, making it ideal for wearables, smart sensors, and asset tracking. BLE supports mesh networking, allowing devices to relay data and extend coverage. Recent advances in Ambient IoT leverage BLE for energy harvesting and maintenance-free deployments, further expanding its industrial and consumer applications [15].

4.4 Challenges: Roaming, Interference, and Security

Wireless networks face challenges such as seamless roaming between access points, interference from overlapping channels, and security in public hotspots. Wi-Fi 6 and 5G address these issues with improved handoff protocols, spectrum management, and mandatory encryption for sensitive data. WPA3 and 5G authentication protocols provide robust defenses, but users should remain vigilant against rogue access points and unencrypted networks.

4.5 Comparison Table: Wi-Fi and 5G Technologies

Table 2: Comparison of Wi-Fi and 5G Technologies

	Frequency Bands	**Max Speed**	**Latency**	**Range**	**Security**	**Use Cases**
Wi-Fi 5 (802.11ac)	5 GHz	Up to 3.5 Gbps	10–20 ms	30–50 m	WPA2/WPA3	Home, Office
Wi-Fi 6 (802.11ax)	2.4/5/6 GHz	Up to 9.6 Gbps	1–5 ms	30–50 m	WPA3	Dense environments, IoT
5G	Sub-6 GHz, mmWave	Up to 20 Gbps	1 ms	Up to 1 km	AES, 5G Auth.	Mobile, IoT, Smart Cities

In summary, Wi-Fi 6 and 5G represent the cutting edge of wireless networking, delivering high speed, low latency, and robust security for a wide range of applications, from home internet to industrial automation and smart cities [13, 14].

5 Network Performance and Quality of Service (QoS)

Computer networks face increasingly diverse traffic demands, from delay-sensitive VoIP calls to bandwidth-intensive video streams. This section examines key performance metrics, QoS techniques, monitoring tools, and their application in real-world scenarios.

5.1 Performance Metrics

- **Bandwidth**: Maximum data transfer rate, typically measured in bits per second (bps). Modern networks range from 100 Mbps (Fast Ethernet) to 400 Gbps (data center backbones).
- **Latency**: End-to-end delay for data transmission, critical for interactive applications. Components include:
  - Propagation delay (distance)
  - Serialization delay (packet size/link speed)
  - Processing delay (router/switch operations)
  - Queuing delay (network congestion)
- **Jitter**: Variation in packet arrival times, especially detrimental to real-time applications. As noted by CBT Nuggets, "High jitter leads to packet loss, degraded audio/video quality, and inconsistent application performance" [16].
- **Packet Loss**: Percentage of packets that fail to reach their destination, causing retransmissions and degraded quality. Acceptable thresholds vary by application (e.g., $<1\%$ for VoIP, $<0.1\%$ for financial transactions).

5.2 QoS Techniques

Network administrators employ several mechanisms to ensure appropriate service levels:

- **Traffic Prioritization (DiffServ)**: Differentiates traffic by marking packets with Differentiated Services Code Points (DSCP), allowing routers to implement Per-Hop Behaviors (PHBs). Common classes include:
  - Expedited Forwarding (EF): Low latency, jitter, and loss (VoIP)
  - Assured Forwarding (AF): Four classes with three drop precedences each
  - Best Effort (BE): Default with no guarantees
- **Resource Reservation (RSVP)**: Reserves network resources for specific flows. "With traditional RSVP, if just one network node says 'no' to a reservation, then no path is set up at all" [17]. Particularly useful for video conferencing and telepresence applications.
- **Queue Management (WFQ)**: Weighted Fair Queuing allocates bandwidth according to traffic priority. "WFQ allocates bandwidth according to IP Precedence using weightings and the number of WFQ queues depend on the number of flows" [17].

5.3 Monitoring Tools

- **Wireshark**: Industry-standard protocol analyzer providing "deep protocol inspection" and "display filters" for packet identification. Essential for troubleshooting QoS implementation issues and verifying DSCP markings.
- **Load Balancing**: Distributes traffic across multiple links or servers. Techniques include round-robin, weighted distribution, and dynamic allocation based on real-time performance metrics.

5.4 Case Example: Streaming Video with QoS

Streaming video presents particular challenges due to its bandwidth intensity and susceptibility to jitter. Goel and Sarkar demonstrated a QoS scheme that "prioritize[s] packets within a given video stream" by associating "highest priority to those particular video packets that are crucial in the video decoding process" [16].

Their implementation achieved:

- 3.75% increase in video data throughput
- 40% reduction in average delay
- 7% decrease in packet loss

The system prioritized I-frames (reference frames) over P-frames (predictive frames) and B-frames (bidirectional frames). While this increased jitter by 18.75%, the overall visual quality improved significantly. Importantly, this approach maintained acceptable QoS for concurrent audio streams, with only a 0.5% reduction in audio throughput-"practically unperceivable by the human ear" [16].

This balanced approach demonstrates that effective QoS implementation can significantly enhance user experience for bandwidth-intensive applications while maintaining reasonable service levels for other traffic types.

6 Network Security

6.1 Firewalls

Firewalls act as gatekeepers between trusted internal networks and untrusted external networks (e.g., the Internet). Modern implementations use three primary techniques:

- **Packet Filtering**: Examines headers (IP addresses, ports, protocols) using predefined rules

  ```
  iptables -A INPUT -p tcp --dport 80 -j ACCEPT
  ```

- **Stateful Inspection**: Tracks active connections and context
  - Maintains connection state table
  - Allows return traffic for established sessions
- **Application Gateways (Proxy Firewalls)**:

  - Terminates and inspects application-layer traffic
  - Provides deep packet inspection (DPI)
  - Mitigates SQLi and XSS attacks

Next-generation firewalls (NGFWs) integrate intrusion prevention (IPS) and threat intelligence feeds [18].

6.2 AES Encryption

The Advanced Encryption Standard (AES) is a symmetric block cipher adopted worldwide for securing sensitive data:

- **Key Sizes**: 128, 192, or 256 bits (AES-256 recommended)
- **Block Size**: 128 bits
- **Modes**:
  - GCM (Authenticated Encryption)
  - CBC (With HMAC for integrity)
- **Performance**:
  - 1.5 cycles/byte on AES-NI enabled CPUs
  - 10x faster than RSA for bulk encryption

AES forms the backbone of TLS 1.3, VPNs, and disk encryption systems [19].

6.3 Virtual Private Networks (VPNs)

VPNs create secure tunnels over public networks using:

- **IPsec (Internet Protocol Security)**:
  - Operates at Layer 3
  - Uses ESP (Encapsulating Security Payload)
  - Supports transport/tunnel modes
- **OpenVPN**:
  - User-space implementation
  - Uses TLS for key exchange
  - Bypasses restrictive firewalls via TCP/443

Modern VPNs implement perfect forward secrecy (PFS) using ECDHE key exchange and AES-GCM encryption [20].

6.4 Exercise: Block SMB Port 445

To prevent WannaCry-style attacks, create a firewall rule blocking SMB:

```
# Linux (iptables)
iptables -A INPUT -p tcp --dport 445 -j DROP
iptables -A INPUT -p udp --dport 445 -j DROP
```

```
# Windows (PowerShell)
New-NetFirewallRule -DisplayName "Block SMB" `
                    -Direction Inbound `
                    -Protocol TCP,UDP `
                    -LocalPort 445 `
                    -Action Block
```

6.5 Firewall and VPN Architecture

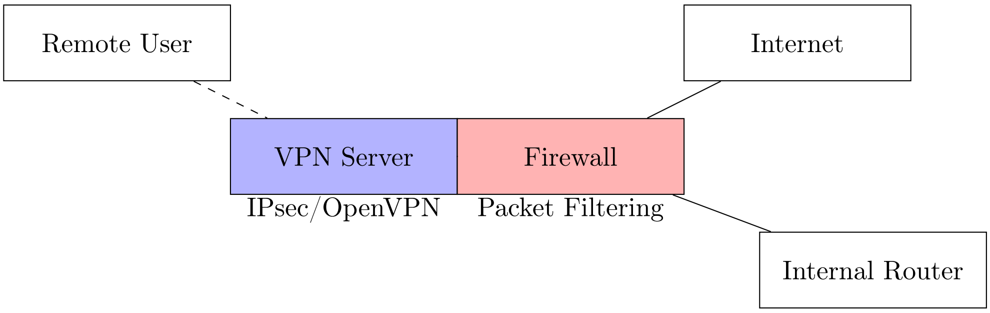

Fig. 3: Network security architecture with firewall and VPN integration

7 Case Study: 2017 WannaCry Ransomware Attack

7.1 Attack Vector

The WannaCry ransomware exploited **EternalBlue**, a vulnerability in Microsoft's Server Message Block (SMBv1) protocol. This exploit, originally developed by the NSA, allowed remote code execution via TCP port 445. Despite Microsoft releasing patch MS17-010 in March 2017, unpatched systems remained vulnerable, enabling WannaCry to propagate globally [21].

7.2 Propagation Mechanics

- **Worm-like Spread**: After initial infection, WannaCry scanned local networks and the internet for vulnerable SMBv1 hosts.
- **Encryption**: Used AES-128 to encrypt 176 file types, demanding $300–$600 in Bitcoin for decryption.
- **Global Impact**: Infected 300,000+ systems across 150 countries, disrupting healthcare (NHS UK), logistics (FedEx), and telecoms (Telefónica) [22].

7.3 Kill Switch Discovery

Security researcher Marcus Hutchins identified a hardcoded domain in WannaCry's code (`iuqerfsodp9ifjaposdfjhgosurijfaewrwergwea.com`). Registering this domain activated a "kill switch," halting further propagation. However, already encrypted systems remained locked.

7.4 Lessons Learned

- **Patch Management**: Organizations using outdated Windows versions (e.g., Windows XP) suffered most. Regular updates could have prevented 99% of infections.
- **Network Segmentation**: Isolating critical systems limits lateral movement during breaches.
- **Protocol Hardening**: Disabling obsolete protocols (e.g., SMBv1) reduces attack surfaces.

7.5 Attack Workflow

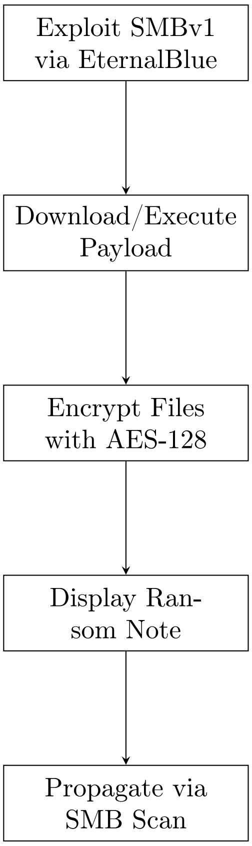

Fig. 4: WannaCry attack workflow

7.6 Global Impact Analysis

The WannaCry ransomware attack had a swift and devastating effect on organizations worldwide. Its rapid propagation via the SMBv1 protocol led to widespread system infections across multiple continents within just a few days. Critical infrastructure, healthcare, and business services were disrupted, resulting in significant operational and financial losses. Europe experienced the highest number of infections, particularly in the public health and transportation sectors. Asia and the Americas were also heavily impacted, highlighting the global nature of cyber threats in an interconnected world. The table below summarizes the estimated number of affected systems by region and the overall economic losses attributed to the attack.

Table 3: WannaCry Global Impact (2017)

Region	**Affected Systems**
Europe	130,000
Asia	100,000
Americas	70,000
Total Losses	$4 billion (estimated)

8 Exercises

8.1 Simulate TCP Three-Way Handshake in Python

```
import socket

# Create client and server sockets
client = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
server = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
server.bind(('localhost', 8080))
server.listen(1)

# Client sends SYN
client.connect(('localhost', 8080))  # Triggers SYN

# Server responds with SYN-ACK
conn, addr = server.accept()         # Sends SYN-ACK

# Client sends ACK
client.send(b'ACK')                  # Final handshake step
```

8.2 Configure Mesh Wi-Fi and Measure Latency

- Use OpenWrt routers with 802.11s mesh protocol
- Measure latency between nodes using `ping` and `iperf3`
- Compare results with star topology:

```
iperf3 -c 192.168.1.100 -t 60 -J > mesh_results.json
```

8.3 Block Ransomware Propagation via Firewall

Prevent SMB-based attacks like WannaCry:

```
# Linux iptables rules
iptables -A INPUT -p tcp --dport 445 -j DROP
iptables -A INPUT -p udp --dport 445 -j DROP

# Windows PowerShell
New-NetFirewallRule -DisplayName "BlockSMB" `
                    -Direction Inbound `
                    -Protocol TCP,UDP `
                    -LocalPort 445 `
                    -Action Block
```

8.4 Analyze QoS Impact on Video Streaming

1. Set up traffic shaping with `tc` (Linux):

   ```
   tc qdisc add dev eth0 root handle 1: htb
   tc class add dev eth0 parent 1: classid 1:1 htb rate 10mbps
   ```

2. Capture traffic with Wireshark filter: `dscp == 34`
3. Compare MOS scores with/without QoS prioritization

8.5 WannaCry Mitigation Report Guidelines

Investigate the 2017 attack and recommend defenses:

- Patch management strategies for legacy systems
- Network segmentation best practices
- SMB protocol hardening techniques
- Incident response plan requirements

Reference NCSC's post-incident analysis for mitigation patterns [23].

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