

## 1. Introduction

The collection of hardware and software that provides the communication facilities for a distributed system is called the communication subsystem. The Internet is a single communication subsystem for all connected hosts.

### Performance

**Latency:** delay after a send before data starts arriving. **Data transfer rate:** speed once transmission begins (bits per second). Message transmission time = latency + (length ÷ data transfer rate). Internet round-trip latencies range from 5 to 500 ms.

#### IP packet layout

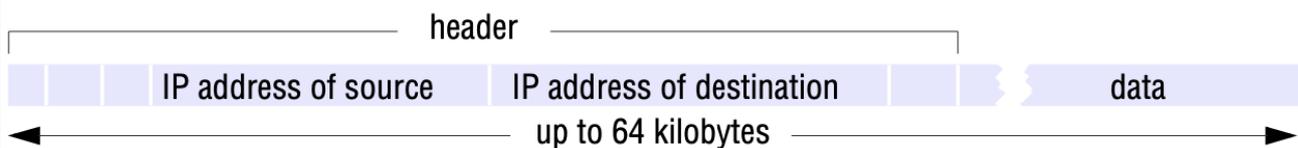


Figure 1.1 Message transmission time formula and its components.

### Other Issues

- **Scalability:** IPv4 to IPv6 transition for addressing growth.
- **Reliability:** most errors are software failures (buffer overflow), not physical media.
- **Security:** firewalls filter all messages per security policy; VPN and cryptography for remote access.
- **Quality of Service:** ability to meet deadlines for real-time multimedia; requires guaranteed bandwidth and bounded latency.

## 2. Types of Network

Type	Description	Technology	Scope
PAN	Personal Area Network; connects personal devices.	Bluetooth	~10 m
LAN	High-speed, single medium; segments interconnected by switches.	Ethernet	Building/campus

WAN	Lower speed; large distances; dedicated router computers.	Leased lines	National/global
MAN	High-bandwidth copper/fibre; up to 50 km.	Ethernet, ATM	City-wide
WLAN	Replaces or supplements wired LAN.	IEEE 802.11 (WiFi)	10-100 Mbps, 1.5 km
WMAN	Alternative to wired building connections.	IEEE 802.16 (WiMAX)	Broadband
WWAN	Mobile phone networks.	GSM, 3G, LTE, 5G	Nationwide

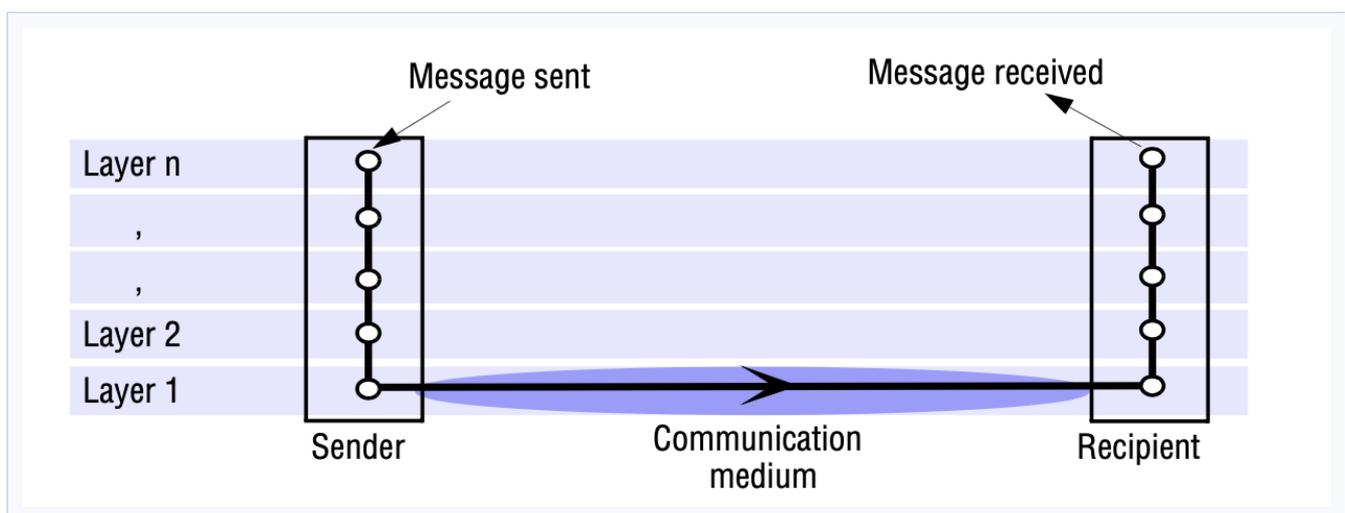


Figure 2.1 Network types by geographic scope: PAN, LAN, WAN, MAN, and wireless variants.

### 3. Network Principles

#### Packet Switching

The basis of all computer networks since the 1960s. Packets are queued at each node and transmitted when the link is available. Communication is asynchronous. Restricted packet lengths allow adequate buffer allocation and prevent undue delays.

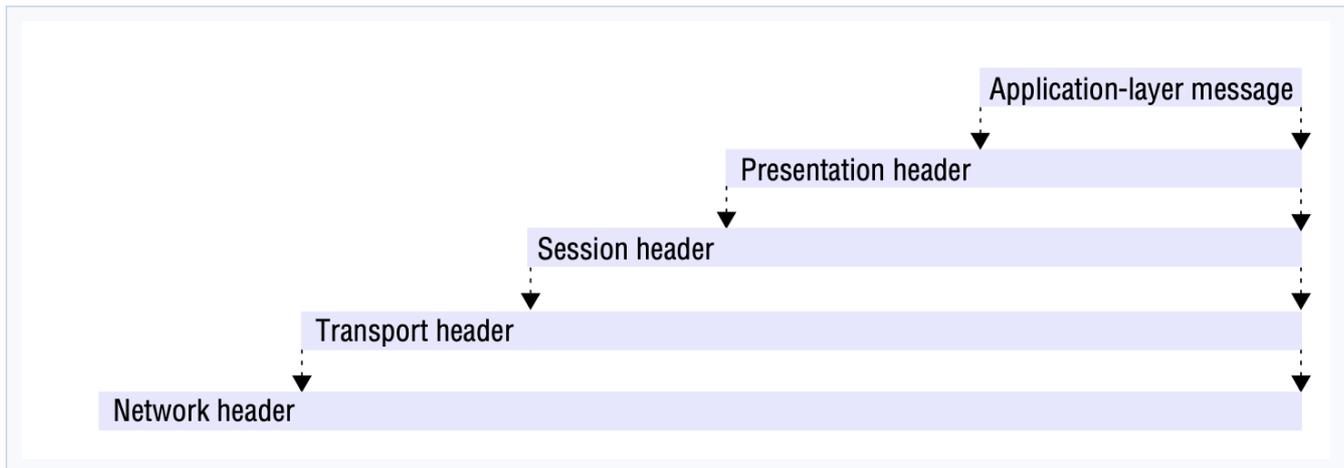


Figure 3.1 Packet switching: store-and-forward operation at each node.

## Switching Schemes

- **Broadcast:** everything transmitted to every node; receivers detect messages addressed to them (Ethernet, wireless).
- **Circuit switching:** dedicated connection for the duration of a call (telephone network).
- **Packet switching:** store-and-forward; no circuit setup.
- **Frame relay:** switches small frames on the fly by examining their first few bits.

## Data Streaming

Real-time audio/video requires  $\sim 1.5$  Mbps (compressed video). The play time of a multimedia element is the time at which it must be displayed or converted to sound. Elements arriving after their play time are dropped. Example: at 24 fps, frame  $N$  has play time  $N/24$  seconds after stream start.

## 4. Protocols

A protocol is a well-known set of rules and formats for communication between processes. Network software is arranged in a hierarchy of layers; each layer provides a service to the layer above.

	<i>Example</i>	<i>Range</i>	<i>Bandwidth (Mbps)</i>	<i>Latency (ms)</i>
<i>Wired:</i>				
LAN	Ethernet	1–2 kms	10–10,000	1–10
WAN	IP routing	worldwide	0.010–600	100–500
MAN	ATM	2–50 kms	1–600	10
Internetwork	Internet	worldwide	0.5–600	100–500
<i>Wireless:</i>				
WPAN	Bluetooth (IEEE 802.15.1)	10–30m	0.5–2	5–20
WLAN	WiFi (IEEE 802.11)	0.15–1.5 km	11–108	5–20
WMAN	WiMAX (IEEE 802.16)	5–50 km	1.5–20	5–20
WWAN	3G phone	cell: 1–5 km	348–14.4	100–500

Figure 4.1 OSI protocol model: seven-layer stack from Physical to Application.

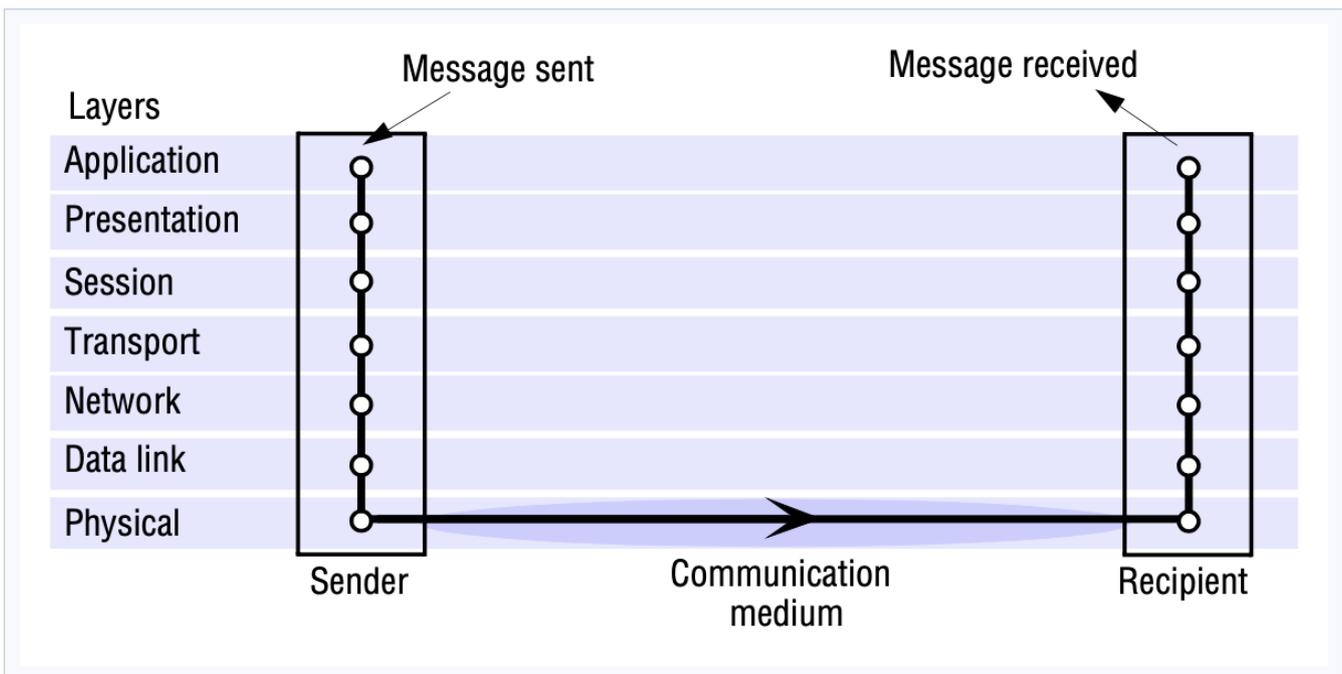


Figure 4.2 Protocol stack: encapsulation at the sender and decapsulation at the receiver.

### Ports and Addressing

- Ports are software-defined destination points attached to processes.
- Well-known ports (0-1023): HTTP:80, FTP:21, Telnet:23, SMTP:25, DNS:53.
- Registered ports (1024-49151); Private ports (49152-65535).

### Packet Delivery

- **Datagram:** one-shot delivery; no setup; packets may arrive out of order.
- **Virtual circuit:** route set up before transmission; packets contain only circuit number.

★ Do not confuse datagram/virtual-circuit (network layer) with UDP/TCP (transport layer).

## IP Packet

Routings from A			Routings from B			Routings from C		
To	Link	Cost	To	Link	Cost	To	Link	Cost
A	local	0	A	1	1	A	2	2
B	1	1	B	local	0	B	2	1
C	1	2	C	2	1	C	local	0
D	3	1	D	1	2	D	5	2
E	1	2	E	4	1	E	5	1

Routings from D			Routings from E		
To	Link	Cost	To	Link	Cost
A	3	1	A	4	2
B	3	2	B	4	1
C	6	2	C	5	1
D	local	0	D	6	1
E	6	1	E	local	0

Figure 4.3 IPv4 packet header structure: version, TTL, protocol, source/destination addresses.

## Routing

Adaptive routing: the best route is re-evaluated periodically, taking into account current traffic and faults. A routing algorithm: (1) determines the route for each packet; (2) dynamically updates its knowledge of the network.

### Pseudo-code for RIP routing algorithm

*Send:* Each  $t$  seconds or when  $Tl$  changes, send  $Tl$  on each non-faulty outgoing link.

*Receive:* Whenever a routing table  $Tr$  is received on link  $n$ :

```

for all rows  $Rr$  in  $Tr$  {
    if ( $Rr.link \neq n$ ) {
         $Rr.cost = Rr.cost + 1$ ;
         $Rr.link = n$ ;
        if ( $Rr.destination$  is not in  $Tl$ ) add  $Rr$  to  $Tl$ ; // add new destination to  $Tl$ 
        else for all rows  $Rl$  in  $Tl$  {
            if ( $Rr.destination = Rl.destination$  and
                ( $Rr.cost < Rl.cost$  or  $Rl.link = n$ ))  $Rl = Rr$ ;
            //  $Rr.cost < Rl.cost$  : remote node has better route
            //  $Rl.link = n$  : remote node is more authoritative
        }
    }
}
    
```

Figure 4.4 Example network topology with routing tables at each node.

Layer	Description	Examples
Application	Protocols at this level are designed to meet the communication requirements of specific applications, often defining the interface to a service.	HTTP, FTP, SMTP, CORBA IIOF
Presentation	Protocols at this level transmit data in a network representation that is independent of the representations used in individual computers, which may differ. Encryption is also performed in this layer, if required.	TLS security, CORBA data representation
Session	At this level reliability and adaptation measures are performed, such as detection of failures and automatic recovery.	SIP
Transport	This is the lowest level at which messages (rather than packets) are handled. Messages are addressed to communication ports attached to processes. Protocols in this layer may be connection-oriented or connectionless.	TCP, UDP
Network	Transfers data packets between computers in a specific network. In a WAN or an internetwork this involves the generation of a route passing through routers. In a single LAN no routing is required.	IP, ATM virtual circuits
Data link	Responsible for transmission of packets between nodes that are directly connected by a physical link. In a WAN transmission is between pairs of routers or between routers and hosts. In a LAN it is between any pair of hosts.	Ethernet MAC, ATM cell transfer, PPP
Physical	The circuits and hardware that drive the network. It transmits sequences of binary data by analogue signalling, using amplitude or frequency modulation of electrical signals (on cable circuits), light signals (on fibre optic circuits) or other electromagnetic signals (on radio and microwave circuits).	Ethernet base-band signalling, ISDN

Figure 4.5 Routing algorithm in action: path selection across a multi-hop network.

## 5. IP Multicast

Available only via UDP at application level. Applications join multicast groups via sockets. Class D addresses (224.0.0.0–239.255.255.255) managed by IANA. Uses: fault tolerance via replicated services; service discovery; replicated data propagation; event notifications.

## 6. Overlay Networks

A virtual network of nodes and virtual links on top of an underlying network. Provides tailored services (multicast, security, content distribution). Disadvantages: extra indirection (performance penalty) and added complexity.

### Exercises

- 1. Estimate transmission time for a 200-byte request / 5000-byte response using UDP, TCP, and same machine. [Latency: 5 ms; rate: 10 Mbps; MTU: 1000 bytes; server processing: 2 ms]
- 2. How does Internet routing handle routing tables that are too large?
- 3. Compare UDP and TCP for Telnet, FTP, rwho/finger, HTTP, and RPC.