Network Evolution, Standards, and Layered Architectures

Outline

Network Evolution
- What makes communication systems work?
- How the network evolved?
- How network provided more services for less cost?
- Predict where technology is going.

Standards
- Organization Objectives
- Standards Organizations

Layered Architectures
- OSI reference (layered) model
- TCP/IP network architecture (layered) model
- Goal: Understand how networks are described
Elements of Current Communication Paradigm
Session Initiation Protocol (SIP) for Voice over IP (VoIP)

INVITE sip: tom@startup.com
c= IN IPv4 192.168.12.5
m=audio 35092 RTP/AVP 0

INVITE sip: tom@192.168.15.17
c= IN IPv4 192.168.12.5
m=audio 35092 RTP/AVP 0

SIP/2.0 200 OK
SIP/2.0 200 OK

ACK

Media flow

Elements of a Communications System
Transmission
Switching/Routing
Signaling
Transmission Network Resources

Time
- When and how long a user gets to talk

Frequency
- What part of the spectrum (channel) is used
- What “code” is used.

TDM
Time Division Multiplexing

FDM
Frequency Division Multiplexing*

Typically, fixed allocation of time slot or channel spectrum

TDM Example

Frame time = 1/8000 = 125 µs
Number of slots/frame = 24
Number of bits/slot = 8
Number of bits/frame = 24*8 = 192
Slot time = 125 µs/24 = 5.2 µs
Bit rate = (number of bits transmitted)/(time to transmit those bits) = 24*8/125 µs = 1.536 Mb/s
Bit time = slot time/(number bits/slot) = frame time/(number bits/frame)
= 1/bit rate = 0.651 µs
Add one bit/frame for synchronization → bit rate = (193/ 125 µs) = 1.544 Mb/s
FDMA and TDMA:

Multiple Access (MA) is a channel access method; allowing several users to share the resource in time or frequency. The users transmit in "order", each using his own frequency channel(s)/time slot(s).

FDMA = Frequency Division Multiple Access

Example:

4 users

TDMA = Time Division Multiple Access

Normally, in MA networks there is dynamic allocation of resource allocation.


Evolution, Organization and Standards

Downlink Physical Channel for Long Term Evolution (LTE/5G)
Orthogonal Frequency Division Multiplexing (OFDM)

Evolution, Organization and Standards
Transmission Network Resources

Downlink/Downstream, e.g., base station → smartphone
Uplink/Upstream, e.g., smartphone → base station

Frequency-division duplexing (FDD)
- Downlink on frequency carrier 1, \( f_1 \)
- Uplink on frequency carrier 2, \( f_2 \)

Time-division Duplexing (TDD)
- Downlink is time slots 1, \( k \)
- Uplink in time slots \( k+1 \), \( M \)
### LTE Operating Bands: 15 bands use FDD and 8 bands use TDD

<table>
<thead>
<tr>
<th>LTE definitions</th>
<th>Example: T-Mobile</th>
</tr>
</thead>
<tbody>
<tr>
<td>UE = User Equipment, e.g., smartphone</td>
<td>Band 2 (1900 MHz)</td>
</tr>
<tr>
<td>eNB = Evolved NodeB</td>
<td>Band 5 (850 MHz)</td>
</tr>
<tr>
<td>= Base station</td>
<td>Band 4 (1700/2100 MHz)</td>
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<td>Band 66</td>
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<td></td>
<td>(Extension of band 4 on 1700/2100 MHz).</td>
</tr>
<tr>
<td></td>
<td>From: <a href="https://www.t-mobile.com/support/coverage/t-mobile-network">https://www.t-mobile.com/support/coverage/t-mobile-network</a></td>
</tr>
<tr>
<td></td>
<td>Allocated LTE frequency bands in USA are found at: <a href="http://anisimoff.org/eng/lte_bands/usa.html">http://anisimoff.org/eng/lte_bands/usa.html</a></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LTE operating bands: (3GPP TS 36.101 [1] Table 5.5.1)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>E-UTRA operating band</strong></td>
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<tr>
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</tbody>
</table>

From: Agilent, 3GPP Long Term Evolution: System Overview, Product Development, and Test Challenges, Application Note
Transmission Network Resources

Code Division Multiple Access (CDMA)

Assume three users share the same medium in time and frequency. Users are synchronized and use different 4-bit orthogonal codes:

\{-1, -1, -1, -1\}, \{-1, +1, -1, +1\}, \{-1, -1, +1, +1\}, \{-1, +1, +1, -1\}

Evolution of Transmission

- Access Technology
  - Twisted pair copper
  - Coax
  - Fiber
  - Wireless
  - Others
    - Powerline
    - Satellite

Evolution over time
• Access Transmission Technology
  Ethernet

POTS=Plain Old Telephone Service
PSTN=Public switched Telephone Network
PBX=Private Branch Exchange
VPN=Virtual Private Network

Switching

- Information in on “Port” $i$
- Information out on “Port” $j$
  - Manual
  - Step-by-step
  - Crossbar with stored program control
  - Digital Switching
  - Packet Switching
  - Optical Switching
  - Quantum Internet?

Physicists transmit data via Earth-to-space quantum entanglement
Phys.org, July 11, 2017
World’s first link layer protocol brings quantum internet closer to a reality, Phys.org, August 20, 2019
Step-by-Step Switch

Crossbar Switch
Evolution, Organization and Standards

Stored Program Control System

Developed in 1950's

Stored Program Control

From: Engineering Operations in the Bell System

Digital Switching Using TDM

A/D in smartphones and Voice over IP (VoIP) Phones
Packet Switching (Statistical Multiplexing)

Packet switching provides flexibility and the dynamic allocation of bandwidth. The Internet is a packet switched network. Packet switching has lead to the integration of all services on one infrastructure.

Optical Switching

Most current switches are electronic. Current switches require photon-to-electron and electron-to-photon conversions—optical to electronic (O/E) and (E/O) interfaces. All optical switching will eliminate these interfaces:

- Faster
- Cheaper
- Lower power required
- Still “slow”
Signaling

Signaling/Control: Governs network elements, e.g., telephone switches or packet switches (routers)
- Sets-up a communications capability, request for resources
- Maintains a communications capability
- Ends (tears down) a communications capability

The signaling network carries the messages that controls the network elements
- Pulses & Tones $\rightarrow$ In the same transmission path as voice signal
- Computer Messages $\rightarrow$ Outside of the transmission path.
  - Common Channel interoffice signaling (CCIS)
  - Signaling System #7, (SS7)
  - Session Initiation Protocol (SIP) for VoIP
  - H.323
  - Others…..
- IP routing protocol signaling messages, packets sent between processors in routers that set up forwarding tables
- TCP signaling messages set up end-to-end connections

Signaling Example

Why are lines sloping?
Survivability \rightarrow Resilience

**FIBER CUT**
- Jan., 4, 1991 - New York metro area
  - 6 million homes without long-distance service
  - New York Mercantile Exchange and New York Commodity Exchange shut down
  - Fiber cuts are common

**Survivability - SS7 FAILURE**
- June, 10, 1991 - California 2 million homes without phone service
- June, 26, 1991 - Baltimore-10 million homes in 4 states without service & U.S. government phones affected

**Survivability-SWITCH and POWER FAILURE**
- September, 17, 1991 - New York metro area
  - 2 million homes without long-distance service
  - 3 major New York airports close for 6 hours
Physical Architecture of the Internet

What’s the Internet: “nuts and bolts” view: how do packet flow over the internet

- billions of connected computing devices: hosts, end-systems
  - Supercomputers, PCs, servers, cloud providers
  - Smartphones,
  - IoT (M2M), running network apps

- communication links
  - fiber, copper, radio, satellite
  - transmission rate = bits/sec
  - Sometimes called *bandwidth*

- routers: forward packets (chunks of data)
Internet structure: network of networks

"Tier-2" ISPs: smaller (often regional) ISPs
- Tier-2 networks connect to one or more tier-1 ISPs, possibly other tier-2 ISPs

Tier-2 ISP pays tier-1 ISP for connectivity to rest of Internet
- tier-2 ISP is customer of tier-1 provider

Internet structure: network of networks

"Tier-3" ISPs and local ISPs
- last hop ("access") network (closest to end systems)
Internet structure: network of networks

A packet passes through many networks!

The Internet is a network of networks

How do you make it all work given:

- Hardware from different vendors
- Software from different vendors
- Different computer operating systems
- Rapid change in enabling technologies, more:
  - CPU power
  - Memory
  - Link Capacity
  - New radios
- Rapid introduction of new applications
- Multiple owners
Network Standards and Open Systems: Need for Standards

Enable interoperability of equipment/software from different vendors
Facilitate the building of a large market to reduce prices
Standards lead to “Open Systems”
With open systems customers are not locked into one vendor’s solution
Open systems lead to a “seamless” user environment, e.g., www

Network Standards and Open Systems: Objectives for Standards

Standards process:
- Development
- Establishment
- Promulgation
Co-ordinate activity
Assure consensus
Information focal point
Mechanism for management
- Why do standards need to be managed?
Network Standards and Open Systems: Standards Organizations

<table>
<thead>
<tr>
<th>Organization</th>
<th>Members</th>
</tr>
</thead>
<tbody>
<tr>
<td>American National Standards Institute ( ANSI)</td>
<td>Manufacturers, Organizations, Government, Users</td>
</tr>
<tr>
<td>Internet Engineering Task Force (IETF)</td>
<td>Request for Comment (RFC)</td>
</tr>
<tr>
<td>Electronic Industries Association (EIA)</td>
<td>Electronic manufacturers</td>
</tr>
<tr>
<td>International Telecommunications Union (ITU)</td>
<td>National PTT’s, Scientific organizations</td>
</tr>
<tr>
<td></td>
<td><strong>IEEE</strong>, e.g. IEEE 802.11</td>
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</tbody>
</table>

Network Standards and Open Systems: Problems with Standards

- Freezes technology
- Multiple standards evolve for same system
- Standards take a long time to be established
- Difficult to evolve to meet rapidly changing needs
- Often standards are complex
- De-facto standards often emerge
Network Architectures and Reference Models

Standards require description and organization of network functionality.
Open systems are build upon a **Layered Architecture** of the network.
Layered Architecture is the "structuring" of network functions.
Note that network protocols are real-time distributed processing.

Reference models provide:

- A conceptual framework to characterize networks
- A mechanism to control/describe the complexity of networks
- Required for open systems
Layered Architectures must have

- Structure
- Symmetry
- Peer protocols

Structure is the collection of related processing functions into layers
Symmetry requires compatible functions exist in source/destination systems
Peer Protocols are the set of rules that govern the processing between peer entities, i.e., the source/destination

Network architectures:
Underlying Principles

Minimize the number of layers thus simplifying the tasks of describing and integrating different layers.
Establish boundaries at points where the description of services is small and the number of interactions is minimum.
Create layers that include different functions.
Network architectures: 
Underlying Principles

Establish boundaries where history demonstrates that the implementation can be partitioned.
Engineer layers so that they can be redesigned to take advantage of new technology without changing the services and interfaces of adjacent layers.
Allow for the bypassing of sublayers.
Each layer should add value.
PDUs and SDUs

- Protocol Data Units (PDU) = packets between Peer entities
- Service Data Units (SDU) = packets between layers

Layered Architecture: International Organization for Standardization (ISO)
Open Systems Interconnection Model (OSI)

OSI reference (layered) model

<table>
<thead>
<tr>
<th>Layer</th>
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</thead>
<tbody>
<tr>
<td>Application Layer</td>
</tr>
<tr>
<td>Presentation Layer</td>
</tr>
<tr>
<td>Session Layer</td>
</tr>
<tr>
<td>Transport Layer</td>
</tr>
<tr>
<td>Network Layer</td>
</tr>
<tr>
<td>Data Link Layer</td>
</tr>
<tr>
<td>Physical Layer</td>
</tr>
</tbody>
</table>

- Each layer adds “information” e.g., a header, to support processing packets at that layer.
- Protocols are partially described by defining the header information, e.g., the meaning of specific bits in the header.
Physical Layer (PHY)

- DTE/DCE interface
  - Data Terminal Equipment (PC)
  - Data Communications Equipment (Modem)
- Electrical/optical/radio connections-modulation formats
- Mechanical connections

Functional Requirements

- Procedural protocol
- Bit transmission

How many PHY interfaces are on your smartphone?

Data Link Layer (DLL)
aka Data Link Control (DLC) layer

- Point-to-point
- Manage the link connection
- Supervise data interchange
- Synchronize and delimit
- Frame (block) sequencing
- Link flow control
- Link error control
- Abnormal condition recovery
- Identification and parameter exchange
Network Layer

Routing, switching, forwarding
Network connections
Logical channel control
Segmenting and blocking
Error recovery
Sequencing and flow control

Network Layer may provide:
- Guaranteed delivery
- Delivery with delay bound
- In-order delivery
- Guaranteed minimal data rate (e.g. in b/s)
- Guaranteed minimal jitter
- Security

Packet Arrival at dest. jitter

Evolution, Organization and Standards
Network Layer

Network Layer: the most complex layer

- Requires the coordinated actions of multiple, geographically distributed network elements (switches & routers)
- Owned by different entities
- Must be able to deal with very large scales
  - Billions of users (people & communicating devices)

Big Challenges

- Addressing: where should information be directed to?
- Routing: what path should be used to get information there?

Transport Layer

End-to-end

Multiplexing

- Multiple sessions on one transport pipe

End-to-end error control

*May* provide for flow regulation

*May* provide for congestion control
Session Layer

Administrative services
- Binding connections
- Unbinding connections

Dialog Services
- Control data exchange
- Interaction and synchronization
- Exception reporting

Presentation Layer

Interpretation of data
Data transformation
Data formatting
Syntax selection
Structuring of data
Application Layer

Highest layer
Serves as window to OSI
Functions to provide all services
Comprehensible to the user e.g.
- Identification
- Availability of resources
- Authority
- Authentication
- Agreement on syntax
Layer management function

Layered Architecture: End-to-End Perspective & Encapsulation

THE OSI LAYERED ARCHITECTURE

\[ zPI = z \text{ layer Protocol Information} \]
Protocol layering and data

Each layer takes data from above
adds header information to create new data unit
passes new data unit to layer below

Example of Encapsulation

TCP Header contains
source & destination
port numbers

IP Header contains
source and destination
IP addresses;
transport protocol type

Ethernet Header contains
source & destination MAC
addresses;
network protocol type

FCS=
Frame Check Sequence
Another Example of Encapsulation: IP over SONET

HTTP Request

- TCP Header
  - Header contains source and destination port numbers

IP Header
  - Header contains source and destination IP addresses; transport protocol type

HDLC framing of PPP-encapsulated packets
  - HDLC = High-Level Data Link Control
  - PPP = Point-to-Point Protocol
  - SONET = Synchronous Optical Network

Putting it all together

- Division of Labor
  - End host
  - Network

- Physical layer entity
  - Data link layer entity
  - Network layer entity
  - Transport layer entity

Modified from: Leon-Garcia & Widjaja: Communication Networks
Overlay Network

An application in end systems 1-5 can run their own routing algorithm.

Idea behind “onion routing”
Onion routing enables anonymous communication over a computer network.
The Onion Router=Tor
https://www.torproject.org/

Putting it all together
Layering: \textit{logical} communication

E.g.: transport

take data from app
add addressing, reliability check info to form packet
send datagram to peer
wait for peer to ack receipt
analogy: post office


Layering: \textit{physical} communication

## Layered Architecture:

| Presentation: What does the peer look like? |
| Sessions: Who is the Peer? |
| Transport: Where is the Peer? |
| Network: What is the route to the peer? |
| Link: How is each step along the route taken? |
| Physical: How is the transmission medium used? |

### Layered Architecture: TCP/IP

TCP/IP network architecture (layered) model

<table>
<thead>
<tr>
<th>Layer</th>
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<tbody>
<tr>
<td>Application Layer</td>
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<tr>
<td>Transport Layer</td>
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<tr>
<td>(host-to-host)</td>
</tr>
<tr>
<td>Internet Layer</td>
</tr>
<tr>
<td><strong>Network Access</strong>  Layer</td>
</tr>
<tr>
<td>Physical</td>
</tr>
</tbody>
</table>
Layered Architecture: TCP/IP

Physical layer is same as in OSI

Network Access Layer:
- Interaction between end-systems and network
- Source provides destination address through network layer
- Makes higher layer software “independent” of underlying networking technology

Layered Architecture: TCP/IP:

Internet Layer
- Routing between networks
- Implemented in end systems
- Implemented in routers
- Internet Protocol (IP)
Layered Architecture: TCP/IP:

Transport Layer
- Reliable end-to-end transport
  - Transport Control Protocol (TCP)
- User datagram protocol (UDP)
- Others, e.g., Real Time Protocol (RTP)

Layered Architecture: TCP/IP:

Application Layer
- ftp
- telnet
- Mail
- www
Common Protocol Functions

Encapsulation
Fragmentation and reassembly
Connection control
Ordered delivery
Flow control
Error control
Addressing
Multiplexing
Transmission services

Encapsulation → adding control information, e.g.,
- Address
- Error detection/correction bits
- Protocol control

Fragmentation and reassembly
- Max packet size
## Common Protocol Functions

### Connection control
- Connection oriented
- Signaling
- Graceful set-up and tear-down

### Ordered delivery
- Deal with reordering
- Lost packets

### Flow control
- Match transmit and receiving rates
- Prevent over running buffers

### Error control
- Error detection
- Error correction
- Adds bits to packets
- Detected errors sometimes causes retransmissions
Common Protocol Functions

Addressing

- Different layers contain different addressed, e.g., Link Layer (Medium Access Control (MAC)) address, Network Address (IP address), and Transport address (socket)

<table>
<thead>
<tr>
<th>Application Interface (TCP/UDP)</th>
<th>Socket Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internetwork Interface</td>
<td>IP address</td>
</tr>
<tr>
<td>Physical Interface</td>
<td>MAC address</td>
</tr>
</tbody>
</table>

Multiplexing

- Enables multiple customers to use one “pipe”
  - MAC address allows sharing on LAN
  - In TDM address is the time slot
  - In the internet host id is the IP address
  - Socket addresses allow multiple applications to use the same IP address

Transmission services,

- QoS, CoS
- Security
- Other “layer” specific services, e.g., framing
Example: LTE Protocol Stack

- Protocol Data Units (PDU) = packets between Peer entities
- Service Data Units (SDU) = packets between layers


Implementation of Layered Architecture: OSI and TCP/IP

Summary

Elements of a Communications System
- Signaling
- Transmission (Time, Frequency, and Code)
- Switching/Routing

Internet Architecture
- Standards
  - Who makes them?
  - Why? (Advantages/disadvantages)

Layered Architecture
- OSI reference (layered) model
- TCP/IP network architecture (layered) model
- Encapsulation

Common Protocol Functions