Fundamentals of Networks

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- What is a Network?
  - A collection of devices (aka nodes) interconnected by different types of links, which allow devices to communicate at a distance in order to support diverse applications
  - Devices:
    * End systems or terminal nodes: computer (desktop, laptop), cell-phone, tablet, car, sensor, and virtually almost anything
    * Intermediate nodes: modem, repeater, hub, switch, router, base station, etc.
  - Links:
    * Wired links: fiber, copper, etc.
    * Wireless links: electromagnetic waves (radio, microwave, terahertz band, infra-red, etc.), acoustic waves (ultra-sounds), etc.
  - Applications:
    * E-mail, instant messaging, web browsing, multimedia streaming, etc.
- A wireless sensor network
  - Many applications:
    * Military applications: battlefield surveillance, nuclear, biological, and chemical attack prevention, etc.
    * Environmental applications: tracking birds, smart irrigation, earth monitoring, etc.
    * Health applications: health telemonitoring, drug administration tracking, etc.
- Network Types (classified by size):
  - PAN (Personal Area Networks) — Bluetooth, USB, etc.

    - Range of a person
  - LAN (Local Area Networks) — WiFi, Ethernet, etc.
    - Range of a single building: a home, office, or factory
  - MAN (Metropolitan Area Networks) — WiMax, cable, etc.
    - Range of a city
  - WAN (Wide Area Networks) — Cellular, landline telephone, etc.
    - Range of an entire country or continent
  - Satellite

- Thus, the internet is a "network of networks"
  - Billions of connected computing devices:
    - Hosts = end systems
    - Running network applications at Internet's "edge"
  - Packet switches: forward packets (chunks of data)
    - Routers, switches, etc.
  - Communication links
    - Fiber, copper, radio, satellite
    - Transmission rate: link capacity (bps)
  - Networks
    - Managed by organization
  - Interconnected ISPs (Internet Service Providers)

- Protocols are everywhere
  - Control sending, receiving of messages
  - Examples: HTTP (Web), streaming video, Skype, TCP, IP, WiFi, 4G, 5G, Ethernet

- Internet Standardization
  - IETF: Internet Engineering Task Force
    - RFC: Request for Comments
  - IEEE: Institute of Electrical and Electronics Engineers
    - IEEE 802.3, IEEE 802.11

- Infrastructure that provides services to applications:

- Web, streaming video, multimedia teleconferencing, e-mail, games, e-commerce, social media, interconnected appliances

- Provides programming interface to distributed applications:
  - “Hooks” allowing sending/receiving applications “connect” to, use Internet transport service
  - Provides service options, analogous to postal service

- Protocols
  - For humans, an example is language (we have phonetics, grammar, etc.)
  - All communication activity in Internet governed by protocols
  - Sample definition: Protocols define the format, order of messages sent and received among network entities, and actions taken on message transmission and receipt.

- A closer look at internet structure:
  - Edge of the network:
    * Hosts: clients and servers
    * Servers often in data centers
  - Access networks:
    * Wired, wireless communication links
  - Network core:
    * Interconnected routers
    * Network of networks

- Physical Media
  - Bit: unit of information that is carried by the signal that propagates between transmitter and receiver
  - Physical link: what lies between transmitter and receiver
  - Types of media:
    * Guided media: signals propagate solid media (e.g. copper, fiber, coaxial)
      · Twisted pair (TP) — Two insulated copper wires twisted together in a helical form (The signals are usually carried as the difference in voltage between the two wires in the pair to increase robustness against noise).
      · Coaxial cable — Two concentric cooper conductors, with bidirectional capabilities. Longer distances at higher data transmission rates than twisted pairs. A broadband system; that is, multiple frequency channels on cable.

        - Fiber optic cable — Glass fiber carrying light pulses, each pulse a bit. High-speed operation, with point-to-point transmissions ranging from 10's-100's Gbps. Very low error rate because it is immune to electromagnetic noise, with repeaters spaced far apart. Downside: expensive and fragile
    - Unguided media: signals propagate freely (no physical wire, like a radio)
        - Signal can be carried in different ways — electromagnetic waves (most commonly used), acoustic waves (typically underwater), magnetic-induction (e.g. Near Field Communications)
        - Propagation environment effects — reflection, obstruction by objects, interference

- Network types classified by switching technology — there are two fundamental approaches to moving data through a network of links
  - Circuit Switching
    - Resources needed along a path (e.g. link transmission rate) to provide for communication between hosts are reserved before the transmission starts
    - This reservation defines the path followed by data and guarantees the communication
    - The resources are reserved for the duration of the communication session between the hosts
  - Packet Switching
    - A message is divided into smaller data units or packets, which are transmitted over the network using the resources demanded
    - No reservation of resources
    - Different packets in the same "information stream" may traverse different paths and suffer different delays

- The Network Core
  - The network core of the Internet is a meash of interconnected packet switches
  - Thus, the Internet is a packet-switched network
  - Packet switching: hosts break host messages into packets
    - Packets are forwarded from one router to the next across links on path from source to destination
    - Each packet is transmitted at full link capacity in each link
    - No reservation → A packet may have to wait (that is, queue on a router)
  - Host sending function
    1. Takes application message
    2. Breaks into smaller chunks or packets, of length L bits

3. Transmits packet into access network at transmission rate R (bits/sec)
   * Full link transmission rate: link capacity (aka link bandwidth)
4. Packet transmission delay = Time needed to transmit L-bit packet into link $= \frac{L}{R}$

- Router Function
  * Store and forward — entire packet must arrive at input link of router before it can be forwarded to output link and then transmitted on next link
  * Transmission delay — takes L/R seconds to transmit (push out) L-bit packet into output link at R bps
  * End-to-end transmission delay — $2L/R$, ignoring other types of delays (more on delay shortly)

- Circuit Switching
  - End-to-end resources reserved for, and allocated to communication between source and destination
  - Commonly used in traditional telephone networks
  - Usually, the communication is referred to as a "call"
  - Before the sender can send the information, the network must establish a connection between the sender and the receiver (resource reservation)
    * Switches on the path between the sender and receiver maintain connection state

- Internet Structure
  - Hosts connect to Internet via access to Internet Service Provider (ISPs)
    * Residential, enterprise (company, university, commercial) ISPs
  - Access ISPs in turn must be interconnected
    * So that any two hosts can send packets to each other
  - Resulting network of networks is very complex
    * Evolution was driven by economics and national policies

- Nodal Delay
  - Four types — Nodal processing, transmission, queueing, and propagation
  - $d_{nodal} = d_{proc} + d_{queue} + d_{trans} + d_{prop}$
  - Nodal Processing (d_{proc})
    * Check bit errors, determine output link, ...
    * Typically < 1[µs] or less

- Queuing Delay (d_{queue})
  * Time waiting at output link for transmission
  * Depends on congestion level of router
  * Can vary from packet to packet
  * Each output link has its own buffer (aka queue)
  * Buffers have finite memory space
  * Arrival rate (bps) to output link in router exceeds transmission rate, R bps, of this link temporarily
- Transmission Delay (d_{trans})
  * L packet length (bits)
  * R link transmission rate (bps)
  * $d_{trans} = L/R$
- Propagation Delay (d_{prop})
  * d length of physical link
  * s propagation speed ($2 \cdot 10^8$ to $3 \cdot 10^8$ meters per second)
  * $d_{prop} = d/s$

- Packet Queuing Delay
  - R link capacity (bps)
  - L packet length (bits per packet)
  - a average packet arrival rate (packets per second)
  - The traffic intensity is $(La)/R$
    * When $(La)/R \approx 0$, average queueing delay small
    * When $(La)/R = 1$, average queueing delay large
    * When $(La)/R > 1$, "work" arriving is more than can be serviced — average delay is infinite

- End-to-end Delay
  - Total delay from source to destination
  - Nodal delays in the source to destination path accumulate to give the end-to-end delay
  - There can also be additional delays in the end system, *e.g.*:
    * Delays when transmitting a packet in shared links (more later)
    * Packetization delay: typically present in real-time applications
      · Time that it takes to fill a packet with encoded real-time data before sending the packet

- Throughput
  - Throughput: rate (bits/time unit) at which the receiver receives the data from the sender (aka end-to-end throughput)
    * Instantaneous — rate at given point in time
    * Average — Rate over longer period of time
- Protocol Layers and Service Models
  - Example — Think about the organization of air travel
    * Ticket purchase, baggage check, gates (loading), runway takeoff, airplane routing, and then the steps repeat in the reverse order
  - Layers — Each layer implements a service
    * Via its own internal-layer actions
    * Using the services provided by the layer directly below
- Why Layering?
  - Explicit structure allows identification, relationship of complex system's pieces
    * Layered reference model for discussion: conceptual framework for building components of the network
      · TCP/IP reference model (Internet reference model)
      · OSI model
    * Modularization eases maintenance, updating of system
      · Change of implementation of layer's service transparent to rest of system
      · For example, change in gate procedure doesn't affect rest of system
  - Protocol Layering
    * Network designers organize protocols in layers to provide structure to the design of network protocols
      · Each protocol belongs to one of the layers
      · A layer protocol can be implemented in software or hardware or in a combination of the two
    * Service model of a layer — services that a layer offers to the layer above
      · Each layer provides its service by:
      · Performing certain actions within the layer
      · Using the services of the layer directly below
    * Network architecture — A set of layers and protocol
      · Provide the network developer with specific set of services to implement the layer
      · Does not provide details of implementation

        * Protocol stack — the protocols of various layers

- Internet Protocol Stack

  1. Application — Supporting network applications
     - Protocols: IMAP, SMTP, HTTP
  2. Transport — Process-process data transfer; adds a transport header to message bits to form segment
     - Protocols: TCP, UDP
  3. Network — Routing of packets from source to destination; adds another header to form packet
     - Protocols: IP, routing protocols
  4. Link — Data transfer between neighboring network elements; adds another header to form frame
     - IEEE 802.3 (Ethernet), IEEE 802.11 (WiFi), PPP, ...
  5. Physical — Bits "on the wire"

Application
Transport
Network
Link
Physical

- ISO OSI Reference Model

  - Has two layers not found in the Internet protocol stack
    * Presentation — allow applications to interpret meaning of data, e.g., encryption, compression, machine-specific conventions
    * Session — Syncrhonization checkpointing, recovery of data exchange
    * Internet stack "missing" these layers
      · These services, if needed, must be implemented in application

Application
Presentation
Session
Transport
Network
Link
Physical

- Internet History

- 1961: Kleinrock — queueing theory shows effectiveness of packet-swtiching
- 1964: Baran — packet-switching in military nets
- 1967: ARPAnet conceived by Advanced Research Projects Agency
- 1969: First ARPAnet node operational
- 1972:
  - ARPAnet public demo
  - NCP (Network Control Protocol) first host-host protocol
  - First e-mail program
  - ARPAnet has 15 nodes
- 1970: ALOHAnet satellite network in Hawaii
- 1974: Cerf and Kahn — architecture for interconnecting networks
  - Minimalism, autonomy — no internal changes required to interconnect networks
  - Best-effort service model
  - Stateless routing
  - Decentralized control
  - This defined today's internet structure
- 1976: Ethernet at Xerox PARC
- Late 70's: Proprietary architectures: DECnet, SNA, XNA
- Late 70's: Switching fixed length packets (ATM precursor)
- 1979: ARPAnet has 200 nodes
- 1983: Deployment of TCP/IP
- 1982: SMTP e-mail protocol defined
- 1983: DNS defined for name-to-IP-address translation
- 1985: FTP protocol defined
- 1988: TCP congestion control
- New national networks: CSnet, BITnet, NSFnet, Minitel
- 100,000 hosts connected to confederation of networks
- Early 1990s: ARPAnet decommissioned
- 1991: NSF lifts restrictions on commercial use of NSFnet (decommissioned, 1995)
- Early 1990s: Web
  - Hypertext [Bush 1945, Nelson 1960s]
  - HTML, HTTP: Berners-Lee
  - 1994: Mosaic, later Netscape
- Late 1990s: Commercialization of the Web