Data Communication & Networks

Instructor: Ouldooz Baghban Karimi

CMPT 371 - Summer 2019
About Me

Ouldooz Baghban Karimi

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Education
PhD, Computer Science, Simon Fraser University
MSc, Computer Engineering, Iran University of Science and Technology
BSc, Computer Engineering, University of Tehran

Interests
Networks and Systems
Virtualization
Data, Security, and Privacy
Teaching Assistants

Kamila Bekshentayeva
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Education: M.Sc. Simon Fraser University ENSC Department
Interests: Network anomaly detection using machine learning algorithms, Virtual Network Embedding for Data Center Networks

Hossein Asghari
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Education: M.Sc. Simon Fraser University
Interests: bioinformatics
Course Goals

• Understand principles of computer networks

• Understand the current state, architectures, and protocols used in computer networks

• Build a foundation to start learning advanced computer networks
Overview

• Introduction
  • Basic principles and architecture
  • Reference models

• Network Applications

• Transport Layer

• Network Layer

• Data Link Layer

• Advanced Topics & Review
Grading

- **Assignments (4 homework assignments, 2 mini-projects): 20%**
  - -25% each late day
- **Quizzes (5): 10%**
- **Midterm (June 25, 2019): 20%**
- **Final (August 6, 2019): 50%**
- **Bonus Points: Up to 2%**
Office Hours

• Ouldooz
  • Tuesdays & Thursdays: 8-10 am BBY TASC1 9215, By appointment
  • Wednesdays 12-2 pm SRY 4142, By appointment

• Kamila
  • Tuesdays 1-3pm BBY, Drop in

• Hossein
  • Tuesdays 3-5pm BBY, Drop-in
  • Mondays 3:30-5:30pm (By appointment)
Course Resources

• Course Web Page
  • https://coursys.sfu.ca/2019su-cmpt-371-e1/

• Discussion Board, Assignments, Additional Learning Materials: Canvas

• Course mailing lists
  • cmpt-371-teaching (Teaching Team)
  • cmpt-371: Announcements (registered automatically)

• Email policy (cmpt-371-teaching)
  • Teaching Team Mailing list
    • [Urgent] Brief Description
    • [Office Appointment Request] Brief Description
    • [Request] Brief Description

• Anonymous feedback form
  • https://forms.gle/pwbZpn6BcECDXapE8
Textbooks & References

- **Computer Networking: A Top-Down Approach**
  7th Edition
  James Kurose, Keith Ross
  Pearson
  2016

- **Computer Networks: A Systems Approach**
  5th Edition
  Larry Peterson, Bruce Davie
  Morgan Kaufmann
  2011

  Online: https://book.systemsapproach.org

- **Data & Computer Communications**
  10th Edition
  William Stallings
  Prentice Hall
  2014

- **TCP/IP Illustrated** (Volume I: The Protocols)
  First Edition
  W. Richard Stevens
  Pearson
  1993

- **Unix Network Programming**
  Volume I: The Sockets Networking API
  Third Edition
  Richard Stevens, Bill Fenner, Andrew Rudoff
  Addison Wesley
  2003
Introduction


Reference: Computer Networks: A Systems Approach. Larry Peterson, Bruce Davie, Morgan Kaufmann
Introduction

✓ The Internet

• Basics
  • Network Edge and Core and Internet Structure
  • Resources & Sharing

• Network Performance
  • Loss, Bandwidth, Throughput, Latency, Delay, Jitter, ...

• Protocols and Reference Models
• Network Security: Networks Under Attack
• History of Networking
The Internet

• Nuts and Bolts
  • Hosts
    • End systems running network applications

• Communication Links
  • Fiber, Copper, Radio, Satellite

• Packet Switches and Routers
  • Find routers and forward packets and data
The Internet

• Network of networks: Interconnected ISPs
  • Infrastructure providing service to applications
  • Infrastructure providing programming interfaces to applications

• Protocols
  • Protocols define format, order of messages sent and received among network entities, and actions taken on message transmission, receipt
  • Examples: TCP, IP, HTTP, Skype, 802.11

• Internet Standards
  • RFCs: Request For Comments
  • IETF: Internet Engineering Task Force
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Network Edge

• Edge: End systems

• Connecting End systems to Edge Routers
  • Home Access
    • DSL
    • Cable
    • FTTH
    • Dial-up
    • Satellite

• Enterprise Access
  • WiFi
  • Ethernet

• Mobile & Wide-Area Wireless Access
  • 3G
  • LTE
  • 5G
# Access Networks: DSL

- **Digital Subscriber Line (DSL)**
  - Uses **pre-existing** telephone line to central office DSLAM
    - Data over DSL phone line goes to Internet
    - Voice over DSL phone line goes to telephone net
  - < 2.5 Mbps upstream transmission rate (typically < 1 Mbps)
  - < 24 Mbps downstream transmission rate (typically < 10 Mbps)
Access Networks: Cable Network

• **FDM (Frequency Division Multiplexing):** different channels transmitted in different frequency bands

• **HFC (Hybrid Fiber Coax):** Asymmetric: up to 30Mbps downstream transmission rate, 2Mbps upstream transmission rate

• **Network** of cables and fibers attaches homes to ISP router
  • Homes share access network to cable headend
  • Unlike DSL, which has dedicated access to central office
Access Networks: Home Networks

- wireless devices
- often combined in single box
- wireless access point (54 Mbps)
- to/from headend or central office
- cable or DSL modem
- router, firewall, NAT
- wired Ethernet (1 Gbps)
Access Networks: Enterprise Access Networks

- Ethernet
  - Typically used in companies, universities, etc.
  - 10Mbps, 100Mbps, 1Gbps, 10Gbps transmission rates
  - Today, end systems typically connect into Ethernet switch
Wireless Access Networks

• Wireless Local Access Networks (LANs)
  • Shared wireless access network connects end system to router (through access point)
  • Within building (100 ft.)
  • 802.11b/g/n (WiFi): 11, 54, 450 Mbps transmission rate

• Wide-Area Wireless Access (WANs)
  • Provided by telco (cellular) operator, 10’s KM
  • Between 1 and 10 Mbps
  • 3G, 4G: LTE, 5G
Access Media

• Physical Media
  • Guided Media
    • Twisted-Pair Copper Wire
      Two insulated copper wires,
      Category 5: 100Mbps, 1Gbps Ethernet
      Category 6: 10Gbps
    • Coaxial Cable
      Two concentric copper conductors
      Bidirectional
      Broadband (multiple channels on cable, HFC)
    • Fiber Optics
      Glass fiber carrying light pulses, each pulse a bit
      High-speed point-to-point transmission (e.g., 10’s-100’s Gbps transmission rate),
      Low error rate: repeaters spaced far apart, immune to electromagnetic noise

• Unguided Media
Access Media

• Physical Media
  • Guided Media
  • Unguided Media
    • Radio (No wire, Bidirectional)
      • Propagation Environment Effects
        • Reflection
        • Obstruction by objects
        • Interference

• Radio Link Types
  • Terrestrial Microwave (e.g. Up to 45Mbps Channels)
  • LAN (e.g. WiFi: 54Mbps)
  • Wide Area (e.g. LTE Cellular: ~10Mbps)
  • Satellite Radio Channels
    • Kbps to 45Mbps Channel: or multiple smaller channels
    • 270 mSec end-to-end delay
    • Geosynchronous versus low altitude
Network Core

• Connect the access networks
  • Mesh of interconnected routers
  • Providing a path between source and destination through shared network resources
    • Packet Switching
    • Circuit Switching
Internet Structure

• How to connect ISPs together?

• Connect each access ISP to every other access ISP?

connecting each access ISP to each other directly doesn’t scale: $O(N^2)$ connections.
Connect each access ISP to one global transit ISP? Customer & provider ISPs have economic agreement. If one global ISP is viable business, there will be competitors! Need for interconnection? Internet Exchange Points
Internet Structure

- If one global ISP is viable business, there will be competitors which must be interconnected.
- Regional networks may arise to connect access nets to ISPs.
- Content provider networks (e.g., Google, Microsoft, Akamai) may run their own network, to bring services and content close to end users.
Internet Structure

Solution
- At center: small number of well-connected large networks
  - Tier-1 commercial ISPs
    - E.g. Level 3, Sprint, AT&T, NTT
    - National & international coverage
  - Content provider network
    - E.g. Google
    - Private network that connects its data centers to Internet,
    - Often bypassing tier-1, regional ISPs
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Packet Switching & Circuit Switching

Packet Switching

**routing:** determines source-destination route taken by packets
- routing algorithms

**forwarding:** move packets from router's input to appropriate router output

Circuit Switching
Resources & Sharing

- **Packet Switching**
  - Hosts break messages into packets
  - Packets go from one router to the next across links on path from source to destination
  - Each packet transmitted at full link capacity
  - Two key network-core functions
    - **Routing**: Determines source-destination route taken by packets
    - **Forwarding**: Moves packets from router’s input to appropriate router output

- **Circuit Switching**
  - End to end resources reserved and allocated between source and destination
    - TDM: Time-Division Multiplexing
    - FDM: Frequency-Division Multiplexing
Resources & Sharing

• **Circuit Switching:** FDM versus TDM

Example:
4 users

![Diagram showing FDM and TDM](image-url)
Resources & Sharing

• **Packet Switching**: Store-and-forward

Entire packet must arrive at router before it can be transmitted on the next link.

Packet switching allows more users to use network!
Resources & Sharing

• **Example**
  - 1 M bps link
  - Each user 100 k bps when “active” and Active 10% of time

• **Circuit-switching:** 10 users (1 Mbps / 100 Kbps = 10)

• **Packet switching:**
  - Probability of single user active at any given time: 0.1
  - With 35 users probability that at any given time exactly 10 users are transmitting simultaneously: \( \binom{35}{10} \times 0.1^{10} (1 - 0.1)^{35-10} \)
  - Probability that when we have 35 users, more than 10 users are transmitting simultaneously? Less than 0.0004
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Network Performance

• Network Performance
  • Throughput (Bandwidth)
  • Delay (Latency)
  • Loss
  • Jitter
  • Delay x Bandwidth Product
Throughput (Bandwidth)

- **Throughput**: Rate (bits/time unit) at which bits transferred between sender and receiver
  - **Instantaneous**: rate at given point in time
  - **Average**: rate over longer period of time

- **Bottleneck link**: link on end-end path that constrains end-end throughput
Delay (Latency)

• Packet Switching
  • Four sources of delay
    • Transmission Delay
  • Nodal Procession Delay
  • Queueing Delay
  • Propagation Delay

\[
d_{\text{nodal}} = d_{\text{proc}} + d_{\text{queue}} + d_{\text{trans}} + d_{\text{prop}}
\]
Queueing Delay

- $R$: link bandwidth (bps)
- $L$: packet length (bits)
- $a$: average packet arrival rate

\[
\frac{La}{R} \sim 0 : \text{avg. queueing delay small}
\]

\[
\frac{La}{R} \rightarrow 1 : \text{avg. queueing delay large}
\]

\[
\frac{La}{R} > 1 : \text{more “work” arriving}
\]
Loss

- Queue (aka buffer) preceding link in buffer has finite capacity
  - Packet arriving to full queue dropped (aka lost)
  - Lost packet may be retransmitted by previous node, by source end system, or not at all
Delay

- **Packet Switching: Four sources of delay**
  - **Transmission Delay**
    \[ d_{\text{trans}}: \text{transmission delay:} \]
    - \( L: \) packet length (bits)
    - \( R: \) link bandwidth (bps)
    - \( d_{\text{trans}} = \frac{L}{R} \)
  - **Propagation Delay**
    \[ d_{\text{prop}}: \text{propagation delay:} \]
    - \( d: \) length of physical link
    - \( s: \) propagation speed in medium (~2 \( \times \) \( 10^8 \) m/sec)
    - \( d_{\text{prop}} = \frac{d}{s} \)
  - **Nodal Procession Delay**
    \[ d_{\text{proc}}: \text{nodal processing} \]
    - check bit errors
    - determine output link
    - typically < msec
  - **Queueing Delay**
    \[ d_{\text{queue}}: \text{queuing delay} \]
    - time waiting at output link for transmission
    - depends on congestion level of router
Jitter & Delay × Bandwidth Product

• Jitter
  • Packet delay variations
    • Packet delay difference between for different packets
  • Important in multimedia applications
  • Mitigation by buffers at the receiver side

• Delay × Throughput
  • If you consider network as a pipe, the delay bandwidth product provides the volume of the pipe

E.g one-way latency of 50ms and bandwidth of 45Mbps:

\[50 \times 10^{-3} \text{sec} \times 45 \times 10^6 \text{bits/sec} = 2.25 \times 10^6 \text{bits} \]
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✓ Protocols and Reference Models

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Dealing with complex systems
  • Explicit structure allows identification, relationship of complex system’s pieces
    • Layered **reference model** for discussion
  • Modularization eases maintenance, updating of system
    • Change of implementation of layer’s service transparent to rest of system
    • E.g., change in gate procedure doesn’t affect rest of system

**Could layering be harmful?**

**Layers:** Each layer implements a service
  • Via its own internal-layer actions
  • Relying on services provided by layer below
Internet Protocol Stack

• **Application**: supporting network applications
  - FTP, SMTP, HTTP

• **Transport**: process-process data transfer
  - TCP, UDP

• **Network**: routing of datagrams from source to destination
  - IP, routing protocols

• **Link**: data transfer between neighboring network elements
  - Ethernet, 802.111 (WiFi), PPP

• **Physical**: bits “on the wire”
OSI/ISO Reference Model

Additional layers to Internet Protocol Stack

- **Presentation**: Allow applications to interpret meaning of data
  - Encryption
  - Compression
  - Machine-specific conventions

- **Session**: Synchronization, checkpointing, recovery of data exchange

Internet stack missing these layers. These services, **if needed**, must be implemented in application.
Encapsulation
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Network Security

- Internet not originally designed with (much) security in mind
  - Original vision: A group of mutually trusting users attached to a transparent network

- Important
  - How networks could be attacked
  - How we can defend networks against attacks
  - How to design architectures that are immune to attacks
Networks Under Attack

- Malware for hosts spread through the network
  - Virus: self-replicating infection by receiving/executing object (e.g. e-mail attachment)
  - Worm: self-replicating infection by passively receiving object that gets itself executed

- Spyware: can record keystrokes, web sites visited, upload info to collection site

- Network & Server Attacks
  - Infected host enrolled on Botnets used for spam or DoS attacks
    - DoS Attacks
    - DDoS

- Sniffer

- IP Spoofing
Denial of Service

- **Denial of Service (DoS):** attackers make resources (server, bandwidth) unavailable to legitimate traffic by overwhelming resource with bogus traffic

  - Select target
  
  - Break into hosts around the network (see botnet)

  - Send packets to target from compromised hosts
    - Vulnerability Attack
    - Bandwidth Flooding
    - Connection Flooding
Packet Sniffing

Packet Sniffing:

- Broadcast media (shared Ethernet, wireless)
- Promiscuous network interface reads/records all packets passing by (e.g. including passwords)
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✓ History of Networking
History of Computer Networks

• **1961-1972: Early packet-switching principles**
  • **1961:** Kleinrock - queueing theory shows effectiveness of packet-switching
  • **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
History of Computer Networks

• 1972-1980: Internetworking, new and proprietary nets
  • 1970: ALOHAnet satellite network in Hawaii
  • 1974: Cerf and Kahn - architecture for interconnecting networks
  • Late 70’s: Proprietary architectures
  • Late 70’s: Switching fixed length packets (ATM precursor)
  • 1979: ARPAnet has 200 nodes

Cerf and Kahn’s internetworking principles:
  • Minimalism, autonomy - no internal changes required to interconnect networks
  • Best effort service model
  • Stateless routers
  • Decentralized control

define today’s Internet architecture
History of Computer Networks

1980-1990: new protocols, a proliferation of networks

- **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
- **1988**: 100,000 hosts connected to confederation of networks
History of Computer Networks

• 1990, 2000’s: commercialization, the Web, new apps
  • Early 1990’s: ARPAnet decommissioned
  • 1991: NSF lifts restrictions on commercial use of NSFnet (Decommissioned, 1995)
  • Early 1990s: Web
    • Hypertext [Bush 1945, Nelson 1960’s]
    • HTML, HTTP: Berners-Lee
    • 1994: Mosaic, later Netscape
    • Late 1990’s: commercialization of the Web

• Late 1990’s – 2000’s
  • More killer apps: instant messaging, P2P file sharing
  • Network security to forefront
  • Estimated 50 million hosts and 100 million+ users
  • Backbone links running at Gbps
History of Computer Networks

• 2005-present
  • ~5B devices (including smartphones and tablets) attached to Internet (2016)
  • Aggressive deployment of broadband access
  • Increasing ubiquity of high-speed wireless access
  • Emergence of online social networks: (Facebook: ~1B users)
  • Service providers (Google, Microsoft) create their own networks
    • bypass Internet, providing instantaneous access to search, video content, email, etc.
  • E-commerce, universities, enterprises running their services in cloud (e.g., Amazon E C2)
Acknowledgements

• The following materials have been used in preparation of this slide set:

    7th Edition
    James Kurose, Keith Ross
    Pearson
    2016

    5th Edition
    Larry Peterson, Bruce Davie
    Morgan Kaufmann
    2011