Washington University in St. Louis

Engineering

1. Introduction to Computer Networks

- Overview of packet switching and the Internet
- Structure of the Internet
- Network Performance
- Internet Protocol Layers
- Internet Security

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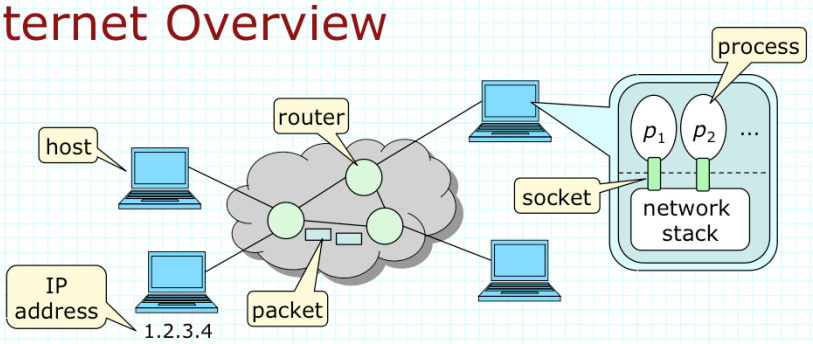
Internet Overview



- *Routers* forward *packets* among *hosts*
- *Internet Protocol* (IP) provides *best-effort delivery* of *datagram* packets based on *addresses* in packet *headers*
- Communication occurs between running programs
- Host operating systems implement *network stack*
- *Sockets* provide interface between programs and the network stack

What is the Internet?

- A set of interconnected components
  - » hosts (including cell phones, tablets, laptops, servers)
  - » packet switches (routers, wireless access points)
  - » connecting links (fiber, copper cable, wireless)
- Protocols used to enable communication
  - » IP, TCP, HTTP, Ethernet, Skype,...
  - » agreed upon message formats and procedures that enable communication among various components
  - » standards created by various organizations – IETF, IEEE, ITU,...
- Services provided by components and protocols
  - » reliable data delivery
  - » remote access to information
  - » electronic commerce
  - » telephony, online games, file sharing,...

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What is Packet Switching?

- Information carried in discrete chunks called packets
- Packets include a *header* that determines how packet is handled as it moves through the network
  - » in Internet, headers contain address of the destination allowing each packet to be handled independently
  - » alternative approach: headers contain local routing "tags" that are updated as packets pass through network
    - requires configuration of tag tables before communication
- As opposed to what?
  - » telephone networks have traditionally used *circuit switching*
  - » involves dedicated communications channel, not packets
  - » requires initial end-to-end configuration, but then data flows through as continuous stream of bits
  - » relatively simple technology – first developed >100 years ago

Packet Switching vs Circuit Switching

- Ability to send data at different rates
  - » packets can be sent at any rate, constrained only by the capacity limits of the underlying links
  - » circuit networks typically built around single data rate
    - 64 Kb/s in telephone networks
- Dynamic sharing for variable rate traffic
  - » in circuit networks, network capacity is *reserved* for each end-to-end channel – cannot be shared with others
  - » in packet network, capacity is typically not reserved, so packet networks can carry more traffic, when traffic is variable
  - » makes it is more difficult for packet nets to deliver consistent performance for applications like voice, real-time video
- Technological complexity/cost
  - » circuit nets originally built around simple analog technology
  - » packet nets require digital technology – but, now very cheap

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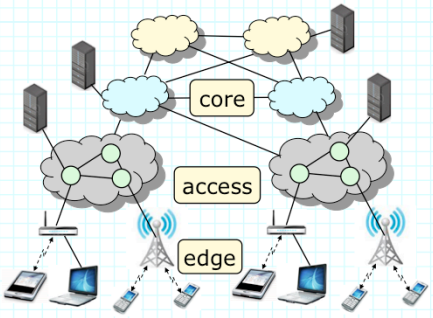
The Structure of the Network

- Network edge
  - » hosts and applications
  - » application architectures
    - client/server, peer-to-peer
- Access network
  - » physical media
    - wired Ethernet, wireless, DSL, cable networks, ...
  - » access network components
    - DSL modems, firewalls, network address translators, ...
- Network core
  - » interconnected routers and related services
    - Domain Name Service (DNS), routing protocols
  - » enable communication among a "network of networks"



Access Networks

- First-hop – from end systems to access routers
- Common types
  - » residential access – dial-up, DSL, cable modems, fiber-to-home
  - » institutional access – universities, businesses, governments
  - » mobile access – for cell phone, tablets
- Key attributes
  - » network data rates
    - 50 Kb/s for dialup to 1 Gb/s for wired Ethernet in institutional nets
  - » dedicated or shared
    - in shared access, must compete for access bandwidth with other users, making service more variable
  - » susceptibility to interference and eavesdropping
    - service quality in wireless nets can be highly variable
    - encryption essential for privacy

Network Core

- Rough hierarchy of Internet Service Providers
  - » Tier 1 ISPs operate at national/international scale
    - large routers (Tb/s capacities) and growing
    - connected by high speed links (2.4 to 40 Gb/s)
  - » Tier 2 ISPs operate on regional scale
  - » Tier 3 ISPs operate on local scale, provide access
  - » Large content providers (Google, Akamai, ...) operate partly like Tier 1 ISPs
- Internet is a "network of networks"
  - » packets pass through many networks on their way from source to destination
  - » requires cooperation among providers and mechanisms to share cost and revenue
  - » ownership and management highly distributed
  - » over 15,000 ISPs today

Exercises

1. Which of the following are *not* valid IP addresses?
   a) 12.34.5.57 *b*) 134.25.321.44 *c*) 0x23fed97c
   d) 0.0.0.0 *e*) 0x35c984b *f*) 235.31.48.21
2. Suppose that 100 packets arrive at a router at the same time, and all must be sent out on the same output link. If it takes 5 μs to send one packet, what is the maximum delay experienced by the arriving packets? What is the minimum delay? What is the average?

Packet Network Performance

- Three main metrics
  - » throughput – rate at which we can move data across a network
  - » delay – time required for packet to go from end-to-end
  - » data loss – fraction of data that is corrupted or discarded by network
- What constrains network performance?
  - » physical infrastructure – data rate of network links, propagation delay of signals (speed-of-light delay), interference/noise
  - » competing traffic – creates queuing delays, packet loss due to queue overflow
- Providing performance guarantees
  - » requires reserving network capacity for specific traffic streams
  - » can be done in packet networks and is done within many private networks – no support for this in public internet

Delays in Networks

- Speed-of-light delay
  - » in fiber, about 130,000 miles/s (or about 210,000 km/s)
  - » NY to LA is about 5,000 km, so 23 ms
    - but network links add distance, making 30 ms a better estimate
- Transmission delay – determined by data rate of links
  - » on 1 Mb/s link, takes 10 ms to send a 10,000 bit packet
    - on 10 Gb/s link, takes 1 μs, on 50 Kb/s link takes 200 ms
- Queueing delays
  - » each link in a network is preceded by a *queue*
    - implemented using memory
    - packets must wait for those ahead of them in the queue
  - » depends on number/length of packets in queue and link speed
  - » for lightly loaded links, rarely more than 10 packets in queue
  - » on overloaded links, queueing delays may exceed 100 ms

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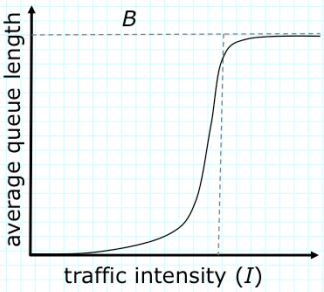
Approximating Queueing Delay



- Key variables
  - *a*: average packet arrival rate (in packets per second)
  - *L*: average packet length (in bits)
  - *R*: link rate (in bits per second)
  - *I*: traffic intensity=*aL*/*R*
  - *B*: queue capacity (in packets)
  - for "random" packet arrivals, "random" packet lengths, $I<1-2/B$

    average queue length$\approx I/(1-I)$
  - » to get average delay, multiply this by *L*/*R*
  - » at 80% traffic intensity (I=0.8), queue contains average of 4 packets – so if *L*=2,000, *R*=1 Mb/s, avg delay≈8 ms
  - » if I=1.2 and *B*=200, avg delay≈400 ms

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Other Sources of Delay

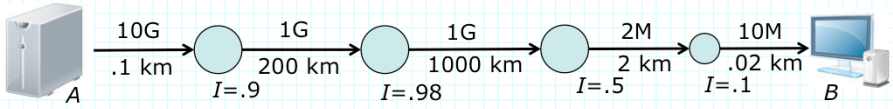
- Packetization delay - time to acquire data to be sent
  - » voice typically encoded at 32 Kb/s (4 bytes per millisecond)
    - so, if we limit packetization delay to 20 ms, each packet carries 80 bytes of voice data
    - an internet packet has about 50 bytes of "overhead" (40% of total)
    - can reduce overhead percentage by increasing delay
    - for telephony, need to limit delay for good user experience
- Component processing delays
  - » components like routers, wireless access points and hosts consume some time processing packets
    - for routers this includes checking packets for errors and determining where they should go next
  - » added to other delays (like queueing, transmission)
  - » typically fairly small: 1-10 μs for routers, 10-50 μs for hosts

Packet Loss

- Bits corrupted on links
  - » very rare in fiber – typically, less than 1 bit in 10^{12} have errors
  - » far more frequent in wireless – one in 10^3 to one in 10^5
    - also highly variable: interference, distance from access point
    - can reduce using variety of coding techniques
  - » electrical signals over wire – intermediate error rates
  - » errors detected by routers, which discard corrupted packets
- Losses due to lack of space in packet queues
  - » can be kept close to zero if traffic flows are regulated to avoid overloads
  - » but very common in internet
    - packet loss rates of 2-20% are not unusual
- Components like routers may corrupt packet data
  - » extremely rare in correctly functioning components

Exercises

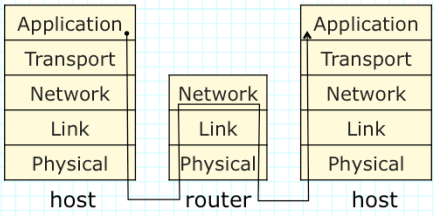
1. Consider the network path shown below. What is the total end-to-end delay for a packet sent from *A* to *B*? The labels above the links denote the line rates (so the middle link has a rate of 1 Gb/s). The labels below the links are their lengths in km. Traffic intensities are shown at the left end of each link. Assume that the average packet length is 250 bytes.



2. Suppose the traffic intensity at the 2 Mb/s link increased to 1.5. If the average queueing delay at this link is 200 ms, what is the capacity of the queue at the left end of the link?

Internet Protocol Layers

- Application layer
  - » implements user applications
    - email, web browsing
- Transport layer
  - » concerned with moving data between processes on hosts
  - » UDP and TCP
- Network layer
  - » concerned with moving packets from host to host through network of routers – IP
- Link layer
  - » concerned with moving packets across local network – Ethernet
- Physical Layer
  - » transferring bits across physical medium



Layers and Encapsulation

- Layers make network design more modular
  - » separate functions allowing different parts of a network to be changed without affecting other parts
  - » "layer violations" inhibit the ability to make changes
  - » layer violations have become common in modern internet
    - firewalls, cross-layer optimizations for better wireless performance
- As packets go "down the stack", each layer adds its own packet header (encapsulation)
  - » UDP (alternatively TCP) adds 8 bytes (20) at transport layer
  - » IPv4 (alternatively IPv6) adds 20 bytes (40) at network layer
  - » Ethernet typically adds 26 bytes at link layer
- As packets go back "up the stack", headers are removed (decapsulation)

Internet Security (or Insecurity)

- Internet designed with little thought for security
  - » designed for well-intentioned and cooperative users
    - in the modern internet, reality is very different
- Variety of tools at disposal of "bad guys"
  - » insert malware on hosts via virus, worm, Trojan horse,...
  - » use malware to spy on users, steal passwords
  - » use subverted hosts to send spam, launch DDOS attacks
  - » evade detection using source-address spoofing
  - » eavesdrop on other users as packets pass through shared nets
  - » record and playback encrypted passwords
- Defenses
  - » keep up with security patches
  - » virus/malware detection and removal
  - » use strong encryption for all sensitive information