Review

- ✦ Describe each of the following in terms of network layers
  - – Repeater
  - – Hub/Switch
  - – Bridge
  - – Router

Computer Networks

Network Layer

Topics

- ✦ Introduction (5 - 5.1) ¬
- ✦ Routing (5.2)
- ✦ Congestion Control (5.3)
- ✦ Internetworking (5.4) ✗
- ✦ Misc (5.5 - 5.6)
  - – the Internet, ATM

Introduction to Network Layer

- ✦ Service to transport layer
- ✦ Getting packets from source to destination
  - – may require many hops
  - – data link layer from one end of wire to another
- ✦ Must know topology of subnet
- ✦ Avoid overloading routes
- ✦ Deal with different networks

Network Layer Services

- ✦ Depend upon services to Transport Layer
- ✦ Often *network carrier* to *network customer*
  - – very well defined
- ✦ Goals
  - – services independent of subnet technology
  - – shield transport layer from topology
  - – uniform number of network addresses, across LANs or WANS
- ✦ Lots of freedom, but two factions
  - – *connection-oriented* and *connectionless*

Connectionless

- ✦ Internet camp
  - – 30 years of experience with real networks
  - – subnet is unreliable, no matter how well designed
  - – hosts should accept this and do error control and flow control
  - – SEND_PACKET and RECV_PACKET
  - – each packet full information on source, dest
  - – no ordering or flow control since will be redundant with transport layer

Connection-Oriented

- ✦ Telephone company camp
  - – 100 years of international experience
  - – set up connection between end hosts
  - – negotiate about parameters, quality and cost
  - – communicate in both directions
  - – all packets delivered in sequence
    - ◆ some might still be lost
  - – flow control to help slow senders

Connected Vs Connectionless

- ✦ Really, where to put the complexity
  - – transport layer (connectionless)
    - ◆ computers cheap
    - ◆ don't clutter network layer since relied upon for years
    - ◆ some applications don't want all those services
  - – subnet (connected)
    - ◆ most users don't want complex protocols on their machines
      - – embedded systems don't
    - ◆ real-time services much better on connected
- ✦ (Un) Connected, (Un) Reliable
  - – 4 classes, but two are the most popular

Internal Organization

- ✦ *Virtual Circuit*
  - – do not choose new route per packet
  - – establish route and re-use
  - – terminate route when terminate connection
- ✦ *Datagrams*
  - – no advance routes
  - – each packet routed independently
  - – more work but more robust

Summary Comparison

Issue	Datagram subnet	VC subnet
Circuit setup	Not needed	Required
Addressing	Each packet contains the full source and destination address	Each packet contains a short VC number
State information	Subnet does not hold state information	Each VC requires subnet table space
Routing	Each packet is routed independently	Route chosen when VC is set up; all packets follow this route
Effect of router failures	None, except for packets lost during the crash	All VCs that passed through the failed router are terminated
Congestion control	Difficult	Easy if enough buffers can be allocated in advance for each VC

Examples of Services

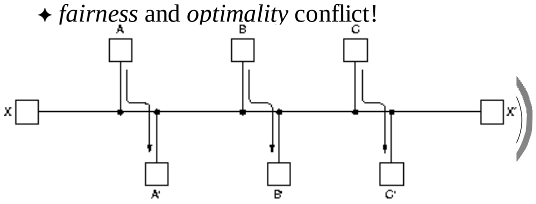
Upper layer	Type of subnet Datagram	 Virtual circuit
Connectionless	UDP over IP	UDP over IP over ATM
Connection-oriented	TCP over IP	ATM AAL1 over ATM

Topics

- ✦ Introduction (5 - 5.1) ✓
- ✦ Routing (5.2) ¬
- ✦ Congestion Control (5.3)
- ✦ Misc (5.5 - 5.6)
  - – the Internet, ATM

Routing Algorithms

- *correctness* and *simplicity* (obviously)
- *robustness*
  - parts can fail, but system should not
  - topology can change
- *stability*
- *fairness* and *optimality* conflict!



Optimality vs. Fairness

- What to optimize?
  - Minimize delay
  - Maximize network throughput
  - But basic queuing theory says if system near capacity then long delays!
- Compromise: minimize hops (common metric)
  - Improves delay
  - Reduces bandwidth, so usually increases throughput

Two Classes of Routing Algorithms

- *Non-Adaptive algorithms*
  - decisions not based on measurements
  - routes computed offline in advance
  - also called *Static Routing*
- *Adaptive algorithms*
  - change routes based on topology and traffic
  - info: locally, adjacent routers, all routers
  - freq: every ΔT seconds, load change, topology change
- Metric?
  - distance, <u>number of hops</u>, transit time

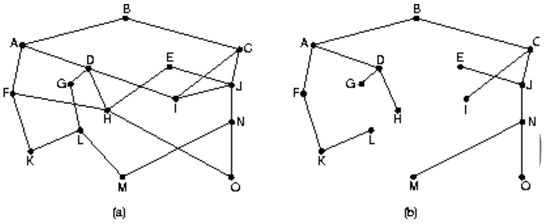
Optimality Principal

"If *J* is on optimal path from *I* to *K*, then optimal path from *J* to *K* is also on that path"

- Explanation by contradiction:
  - Call *I* to *J*, r_1 and *J* to *K*, r_2
  - Assume *J* to *K* has a route better than r_2, say r_3
  - Then $r_1 r_3$ is shorter than $r_1 r_2$
    - contradiction!
- Useful when analyzing specific algorithms

Sink Tree

- Set of optimal nodes to a given destination
- Not necessarily unique
- Routing algorithms want sink trees



Sink Trees

- No loops
  - each packet delivered in finite time
  - well, routers go up and down and have different notions of sink trees
- How is sink tree information collected?
  - we'll talk about this later
- Next up: *static routing algorithms*
- On deck: *adaptive algorithms*

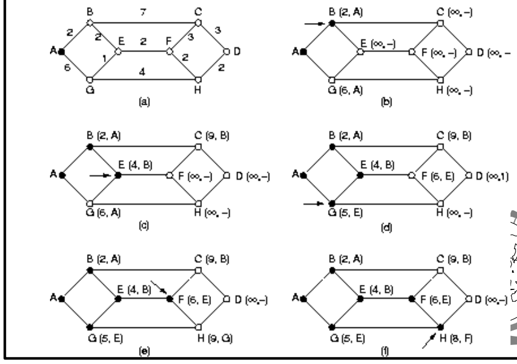
Static Routing - Start Simple

- *Shortest path routing*
- How do we measure shortest?
- Number of hops
- Geographic distance
- Mean queuing and transmission delay
- Combination of above

Computing the Shortest Path

- Dijkstra's Algorithm (1959)
- Label each node with distance from source
  - if unknown, then ∞
- As algorithm proceeds, labels change
  - tentative at first
  - permanent when "added" to tree

Dijkstra's Algorithm: A to D



Flooding

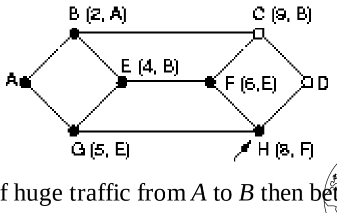
- Send every incoming packet on every outgoing link
  - problems?
- Vast numbers of duplicate packets
  - infinite, actually, unless we stop. How?
- Hop count: decrease each hop
- Sequence number: don't flood twice
- *Selective flooding*: send only in about the right direction

Uses of Flooding

- Military applications
  - redundancy is nice
  - routers can be blown to bits
- Distributed databases
  - multiple sources
  - update all at once
- Baseline
  - flooding always chooses shortest path
  - compare other algorithm to flooding

Flow Based Routing

- Above algorithms only consider topology
  - Do not consider load



- Ex: if huge traffic from *A* to *B* then better path would be *AGEFC*
- Min average delay for the entire subnet

Topics

- ✦ Introduction ✓
- ✦ Routing (5.2)
  - – static ✓
  - – adaptive ¬
- ✦ Congestion Control (5.3)
- ✦ The Internet (5.4, brief)

Modern Routing

- ✦ Most of today’s computer networks use dynamic routing
- ✦ Distance vector routing
  - – Original Internet routing algorithm
- ✦ Link state routing
  - – Modern Internet routing algorithm

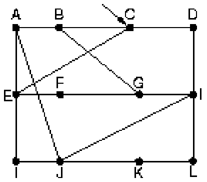
Distance Vector Routing

- ✦ Each router has table
  - – preferred outgoing line
  - – estimate of “distance” to get there
- ✦ Assume knows “distance” to each neighbor
  - – if hops, just 1 hop
  - – if queue length, measure the queues
  - – if delay, can send PING packet
- ✦ Exchange tables with neighbors periodically

Distance Vector Routing Computation

- ✦ Just got *Routing Table* from *X*
  - – X_i is estimate of time from *X* to *i*
- ✦ Delay to *X* is *m* msec
- ✦ Know distance to X (say, from ECHO’s)
  - – Can reach router *i* via *X* in $X_i + m$ msec
- ✦ Do for all neighbors
- ✦ Closest to *i* as “preferred outgoing line”
- ✦ Can then make new routing table

Distance Vector Example

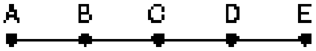


New estimated delay from J

To	A	I	H	K	↓	Line
A	0	24	20	21	8	A
B	12	36	31	28	20	A
C	25	18	19	36	28	I
D	40	27	8	24	20	H
E	14	7	30	22	17	I
F	23	20	19	40	30	I
G	18	31	6	31	18	H
H	17	20	0	19	12	H
I	21	0	14	22	10	I
J	9	11	7	10	0	–
K	24	22	22	0	6	K
L	29	33	9	9	15	K
	JA delay is 8	JI delay is 10	JH delay is 12	JK delay is 6	New routing table for J	

Vectors received from

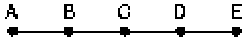
Good News Travels Fast



∞	∞	∞	∞	Initially
1	∞	∞	∞	After 1 exchange
1	2	∞	∞	After 2 exchanges
1	2	3	∞	After 3 exchanges
1	2	3	4	After 4 exchanges

- ✦ A is initially down
- ✦ Path to A updated every exchange
- ✦ Stable in 4 exchanges

Bad News Travels Slowly

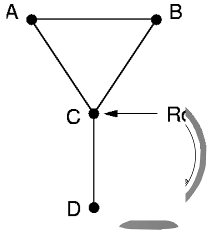


B	C	D	E	
1	2	3	4	Initially
3	2	3	4	After 1 exchange
3	4	3	4	After 2 exchanges
5	4	5	4	After 3 exchanges
5	6	5	6	After 4 exchanges
7	6	7	6	After 5 exchanges
7	8	7	8	After 6 exchanges
	⋮			
∞	∞	∞	∞	

- ✦ Sloooowly converges to ∞ (*count to infinity*)
- ✦ Better to set infinity to max + 1

The Split Horizon Hack

- ✦ Report ∞ to router along path
  - – ex: C says ∞ to reach A when talking to B
- ✦ Widely used … but sometimes fails!
- ✦ If D goes down
  - – C can say ∞ to D quickly
- ✦ A and B have route through other
  - – A and B count to ∞ as slowly as before!
- ✦ Other Ad Hoc also fail

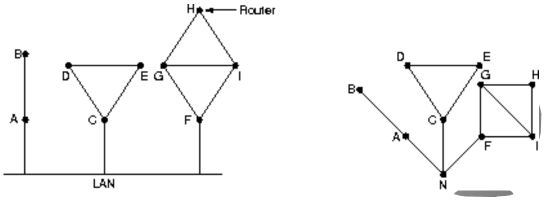


Link State Routing

- ✦ Used (w/variations) on Internet since 1979
- ✦ Basically
  - – Experimentally measure distance
  - – Use Dijkstra's shortest path
- ✦ Steps
  - – Discover neighbors
  - – Measure delay to each
  - – Construct a packet telling what learned
  - – Send to all other routers
  - – Compute shortest path

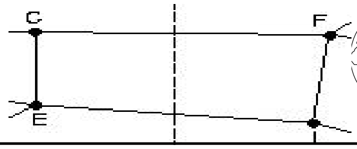
Learning Neighbors

- ✦ Upon boot, send *HELLO* packet along point-to-point line
  - – names must be unique
- ✦ Routers attached to LAN?



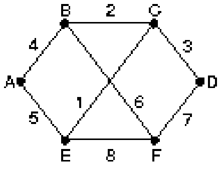
Measuring Line "Cost"

- ✦ Send ECHO packet, other router returns
  - – delay
- ✦ Factor in load (queue length)?
  - – Yes, if other distance equal, will improve perf
  - – No, oscillating routing tables
  - – Ex: Back and forth between C-F and E-I



Building Link State Packets

- ✦ Identity of sender, sequence number, age, list of (neighbors + distance)



Link State

A		B		C		D	
Seq.		Seq.		Seq.		Seq.	
Age		Age		Age		Age	
B	4	A	4	B	2	C	3
E	5	C	2	D	3	F	7
		F	6	E	1		

- ✦ *When* to send them?

Distributing Link State Packets

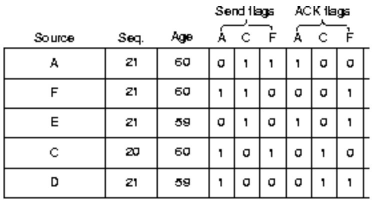
- ✦ Tricky if topology changes as packets travel
  - – routes will change “mid-air” based on new topology
- ✦ Basically, use *flooding* with checks
  - – increment sequence each time new packet sent
- ✦ Forward all new packets
- ✦ Discard all duplicates
- ✦ If sequence number lower than max for sending station
  - – then packet is obsolete and discard

Distribution Problems

- ✦ Sequence numbers wrap around
  - – use 32 bits and will take 137 years
- ✦ Router crashes … start sequence number at 0?
  - – next packet it sends will be ignored
- ✦ Corrupted packet (65540)
  - – packets 5 - 65540 will be ignored
- ✦ Use *age* field
  - – decrement every second
  - – if 0, then discard info for that router
- ✦ Hold for a bit before processing

Keeping Track of Packets

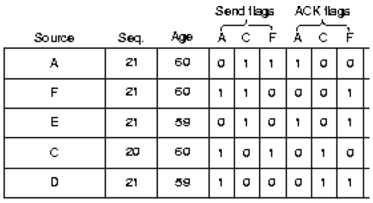
Station B



			Send flags			ACK flags		
Source	Seq.	Age	A	C	F	A	C	F
A	21	60	0	1	1	1	0	0
F	21	60	1	1	0	0	0	1
E	21	59	0	1	0	1	0	1
C	20	60	1	0	1	0	1	0
D	21	59	1	0	0	0	1	1

- ✦ A arrived
  - – ack A
  - – forward C and F
- ✦ F arrived
  - – ack F
  - – forward A and C

Keeping Track of Packets



			Send flags			ACK flags		
Source	Seq.	Age	A	C	F	A	C	F
A	21	60	0	1	1	1	0	0
F	21	60	1	1	0	0	0	1
E	21	59	0	1	0	1	0	1
C	20	60	1	0	1	0	1	0
D	21	59	1	0	0	0	1	1

- ✦ E arrived via EAB and via EFB
  - – send only to C
- ✦ If C arrives via F before forwarded, updated bits and don’t send to F

Computing New Routes

- ✦ Router has all link state packets
  - – build subnet graph
- ✦ *N* routers degree *K*, O(*KN*) space
- ✦ Problems
  - – router lies: forgets link, claims low distance
  - – router fails to forward, or corrupts packets
  - – router runs out of memory, calculates wrong
  - – with large subnets, becomes probable
- ✦ Limit damage from above when happens

Link State Routing Today

- ✦ Open Shortest Path First (OSPF) (5.5.5)
  - – used in Internet today
- ✦ Intermediate Sys Intermediate Sys (IS-IS)
  - – used in Internet backbones
  - – variant used for IPX in Novell networks
  - – carry multiple network layer protocols

A Slight Change in Plans

- The Network Layer
  - Introduction ✓
  - Routing (5.2) ✓
  - The Internet (5.5) ¬
    - ARP (5.5.4)
    - OSPF (5.5.5)
    - BGP (5.5.6)
  - Congestion Control (5.3)

Network to Data Link Adress Translation

- Internet hosts use IP
- Data link layer does not understand IP
  - Ethernet uses 48-bit address
  - ex: ifconfig gives `00:10:4B:9E:B3:E6`
- Q: How do IP addresses get mapped onto data link layer addresses, such as Ethernet?
- A: The Address Resolution Protocol (ARP)

Example 1

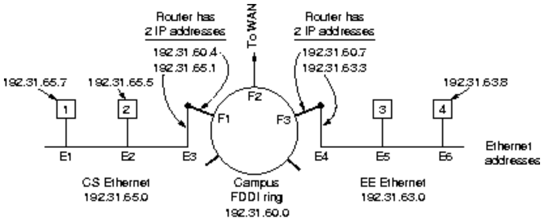


Fig. 5-51. Three interconnected class C networks: two Ethernets and an FDDI ring.

Host 1 sends message to Host 2, say "*mary@eagle.cs.uni.edu*"

Address Resolution

- Lookup IP of *eagle.cs.uni.edu*
  - DNS (chapter 7)
  - returns `192.31.65.5`
- Host 1 builds packet to `192.31.65.5`
  - now, how does data link layer know where to send it?
  - need Ethernet address of Host 2
- Could have config file to map IP to Ethernet
  - hard to maintain for thousands of machines

Address Resolutioning

- Host 1 broadcasts packet asking "Who owns IP address `192.31.65.5`?"
- Each machien checks its IP address.
- Host 2 responds w/Ethernet address (E2)
  - *Address Resolution Protocol* (ARP)
- Host 1 data-link can then encapsulate IP packet in frame addressed to E2 and dump
- Enet board on Host 2 recognizes, strips frame header and sends up to IP layer

ARP Optimizations

- Send to H2 again?
  - cache requests (time out in case of new card)
- Many times, H1 requires ack from H2
  - send H1 IP + enet (`192.31.65.7`, E2)
  - H2 caches and uses if needed
- Hosts broadcast mapping when boot
  - host looks for its own IP address
    - should get no answer, else don't boot
  - other enet hosts all can cache answer

Example 2

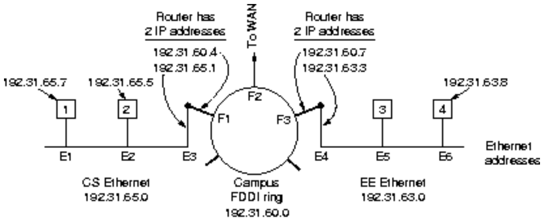


Fig. 5-51. Three interconnected class C networks: two Ethernets and an FDDI ring.

Host 1 sends message to Host 4

Router does not forward data-link layer broadcasts

Solutions

- ✦ Solution 1
  - – CS router configured to respond to ARP requests for `192.31.63.0`
  - – Host 1 makes an ARP cache entry of (`192.31.63.8`, E3)
    - ◆ sends all traffic to Host 4 to CS router
  - – Called *Proxy ARP*
- ✦ Solution 2
  - – Host 1 knows Host 4 is on different subnet
    - ◆ sends to CS router
  - – CS router doesn’t need to know about remote networks

Either way ...

- ✦ Host 1 packs IP into Enet frame to E3
- ✦ CS router receives frame, removes packet
  - – sees `192.31.63.0` to `192.31.60.7`
- ✦ Sends ARP packet onto FDDI
  - – learns `192.31.60.7` is at F3
- ✦ Puts packet into payload of FDDI frame and put on ring
- ✦ EE router receives frame, removes packet ...

Inside Out and Upside Down

- ✦ Can a host learn its IP address at boot?
  - – *Reverse Address Resolution Protocol* (*RARP*)
- ✦ Broadcast:
  - – “my enet adress 13.05.05.18.01.25”
  - – “does anyone know my IP?”
- ✦ RARP server sees request, sends IP
- ✦ Allows sharing boot images
  - – IP not hard-coded
- ✦ RARP broadcasts not across router
  - – BOOTP uses UDP

Routing on the Internet

- ✦ Internet made up of Autonomous Systems (AS)
- ✦ Standard for routing inside AS
  - – interior gateway protocol
  - – *OSPF*
- ✦ Standard for routing outside AS
  - – exterior gateway protocol
  - – *BGP*

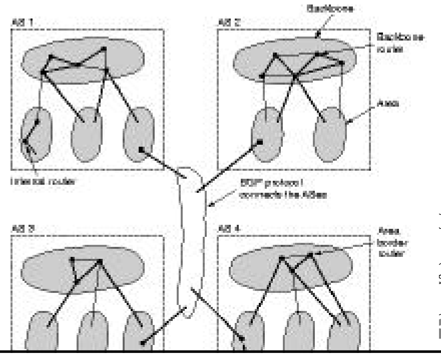
Open Shortest Path First (OSPF)

- ✦ 1979, RIP, distance vector, replaced by link-state
- ✦ In 1990, OSPF standardized
- ✦ “O” is for “Open”, not proprietary
- ✦ ASes can be large, need to scale
  - – *Areas*, that are self-contained (not visible from outside)

OSPF, continued

- ✦ Every AS has a *backbone*, area 0
  - – all areas connect to backbone, possibly by a tunnel
- ✦ Routers are nodes and links are arcs with weights
- ✦ Computes "shortest" path for each:
  - – delay
  - – throughput
  - – reliability
- ✦ Floods link-state packets

ASes, Backbones and Areas



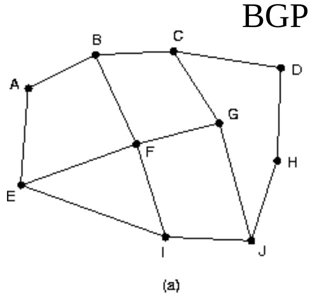
Border Gateway Protocol (BGP)

- ✦ Inside AS, only efficiency
- ✦ Between AS, have to worry about politics
  - – No transit traffic through some ASes
  - – Never put Iraq on a route starting at the Pentagon
  - – Do not use the US to get from British Columbia to Ontario
  - – Traffic starting or ending at IBM should not transit Microsoft

BGP

- ✦ Types of networks
  - – stub: only one connection
  - – multiconnected: could transit, but don't
  - – transit: handle 3rd party, but with restrictions (backbones)
- ✦ BGP router pairs communicate via TCP
  - – hides details in between
- ✦ Uses distance vector protocol
  - – but "cost" can be any metric

BGP



Information F receives from its neighbors about D

From B: "I use BCD"
From G: "I use GCD"
From I: "I use IFGCD"
From E: "I use EFGCD"

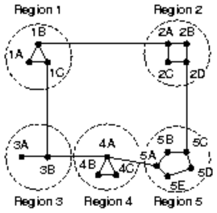
(b)

Fig. 5-55. (a) A set of BGP routers. (b) Information sent to *F*.

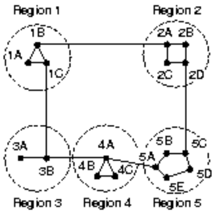
F gets all paths, uses "distance" function for best
Count to infinity fixed
RFC 1654

Hierarchical Routing

- ✦ Global picture difficult for large networks
- ✦ Divide into regions
  - – Router knows detail of its region
  - – Routers in other regions reduced to a point



Reduced Routing Table



Full table for 1A

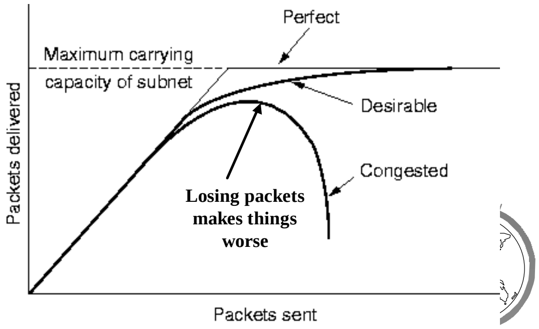
est.	Line	Hops
1A	–	–
1B	1B	1
1C	1C	1
2A	1B	2
2B	1B	3
2C	1B	3
2D	1B	4
3A	1C	3
3B	1C	2
4A	1C	3
4B	1C	4
4C	1C	4
5A	1C	4
5B	1C	5
5C	1B	5
5D	1C	6
5E	1C	5

Hierarchical table for 1A

Dest.	Line	Hops
1A	–	–
1B	1B	1
1C	1C	1
2	1B	2
3	1C	2
4	1C	3
5	1C	4

- •Cost is efficiency
- •Consider 1A to 5C
  - •via 3 better for most of 5

Congestion



Losing packets makes things worse

Causes of Congestion

- ✦ Queue build up until full
  - – Many input lines to one output line
  - – Slow processors
  - – Low-bandwidth lines
    - ◆ system components mismatch (*bottleneck*)
  - – Insufficient memory to buffer
- ✦ If condition continues, infinite memory makes worse!
  - – timeouts cause even more transmission
  - – congestion feeds upon itself until collapse

Flow Control vs. Congestion Control

- ✦ Congestion control (network layer)
  - – make sure subnet can carry offered traffic
  - – global issues, including hosts and routers
- ✦ Flow control (data link layer)
  - – point-to-point between sender and receiver
  - – fast sender does not overpower receiver
  - – involves direct feedback to sender by receiver
- ✦ Ex: Super-computer to PC w/1Gbps line
- ✦ Ex: 1000 computers w/1 Mbps lines transferring files at 1kbps to other half

Topics

- ✦ The Network Layer
  - – Introduction ✓
  - – Routing (5.2) ✓
  - – The Internet (5.5, brief) ✓
  - – Congestion Control (5.3) ¬
- ✦ The Transport Layer

Principles of Congestion Control

- ✦ Control theory: *open loop* and *closed loop*
- ✦ Open loop: ahead of time
  - – solve problem by making sure doesn't happen
  - – when to accept new traffic
  - – deciding to discard packets and which ones
  - – scheduling decisions within the network
- ✦ Closed loop: feedback
  - – detect congestion … *how*?
  - – pass information to system that can adjust

Closed Loop (cont)

- ✦ Metrics to detect congestion:
  - – percentage of dropped packets
  - – average queue length
  - – number of timed out packets
  - – average packet delay (and std dev of delay)
- ✦ Transfer info:
  - – router to send packet to traffic source(s)
    - ◆ but this *increases* the load!
  - – set bit in acks going back (ECN)
- ✦ Send probe packets out to ask other routers
  - – ala traffic helicopters to help route cars

Congestion Control Algorithms

- ✦ Lots of them
  - – taxonomy to view (Yang and Reddy 1995)
- ✦ *Open* or *Closed* (as above)
- ✦ *Source* or *Destination*
- ✦ *Explicit* or *Implicit* feedback (for closed)
  - – explicit: send congestion info back to source
  - – implicit: source deduces congestion (by looking at round-trip time for acks, say)

Congestion Fix

- ✦ Load is greater than resources
  - – increase resources or decrease load
- ✦ Increase resources
  - – adding extra leased bandwidth
  - – boost satellite power
  - – split traffic over multiple routes
  - – use backup, fault-tolerant routers
  - – …Difficult under many systems!
- ✦ Decrease load
  - – at *data link*, <u>network</u> or *transport* layer

Preventing Congestion

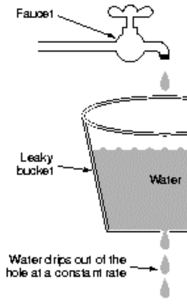
- ✦ Traffic is often bursty
  - – periods of lots of traffic
  - – followed by periods of little traffic
- ✦ If steady rate, easier to avoid congestion
- ✦ Open loop method to help manage congestion by forcing packets at more predicable rate
  - – *Traffic Shaping*

Traffic Shaping

- ✦ Limit rate data is sent
- ✦ User and subnet agree upon certain pattern (shape) of traffic
  - – especially important for real-time traffic
  - – easier on virtual circuit, but possible on datagram
- ✦ Monitoring agreement is *traffic policing*

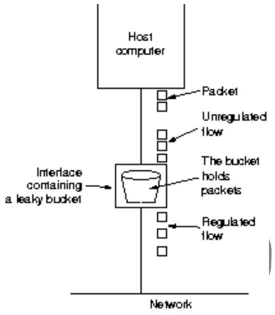
The Leaky Bucket

- ✦ No matter how fast water enters bucket, drips out at same rate
  - – ρ
- ✦ If bucket is empty,
  - – then ρ is 0
- ✦ If bucket is full, then spills over sides
  - – i.e. - lost



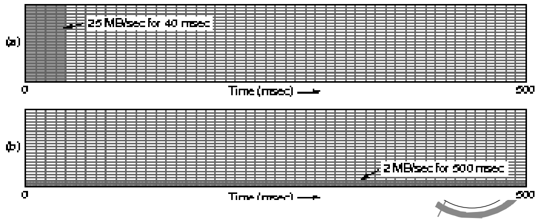
The Leaky Bucket Algorithm

- Each router has finite internal queue
  - excess packets discarded
- One packet per tick sent
  - or fixed bytes, if different sized packets



Leaky Example

- 200 Mbps network
- 2 Mbps for long intervals
- 25 MB/sec for 40 sec



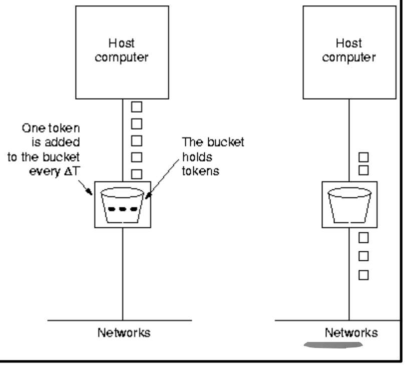
(a) is w/out bucket, (b) is with bucket

Leaky Enhancements

- Leaky bucket enforces rigid output rate
  - instead, allow some speedup of output
  - *token bucket algorithm*
- Token generated every *DT* seconds
  - to send packet, station must capture and destroy
- Example:

Token Bucket Example

- station wants to send 5 packets
- there are 3 tokens

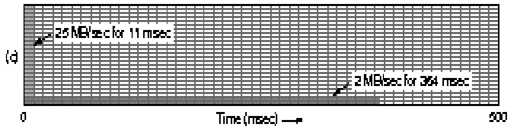


Traffic Shaping with Token Bucket

- Leaky bucket does not allow hosts to “save up” for sending later
- Token bucket host can capture up to some max *n* tokens
- Since hosts must stop transmitting when no tokens, then can avoid lost data
  - leaky bucket will just drop data, resulting in timeouts and retransmissions (or, just lost data)

Token Bucket Example

- 250 Kb token bucket
- Token rate allows 2Mb/sec
- 25 Mb/sec arrives for 40 sec
  - can drain at this rate for about 10 seconds
  - then must cut back to 2 Mb/sec



Closed-Loop Congestion Control

- Router monitors utilization (queue, cpu …)
  - ex: each line a real number 0.0 to 10.0
  - how to sample?
    - *f* is instantaneous sample (0 or 1)
    - $u_{new} = a u_{old} + (1-a) f$
    - *a* determines how fast "forgets" old state
      - consider *a* = 0 and *a* = 1
- *u* above threshold then enters a "*warning*" state
  - router sends choke packet to source
  - original packet is tagged so will not generate more choke packets

Choke Packets (cont)

- When source receives choke packet, reduces traffic by *X* percent
  - reduce window size or bucket parameters
  - decrease 0.5, 0.25, … increase slowly, too
- Ignore new choke packets from destination for some time interval
  - *why*?
- Increase flow at some time
- Variations: degrees of warning

Foul Play

- Consider A, B and C send through Router
- Router detects congestion, sends choke packet to each
- A cuts back packet rate but B and C continue blasting away
  - requires *voluntary* cutback
- Transport protocols:
  - TCP: built in flow-control helps congestion control
  - UDP: mis-behaved flows
- Solution: *fair queuing*

Fair Queuing

- Multiple queues for each output line
  - one per source
- Do round-robin among queues
  - with *n* hosts competing, get 1/*n* of bandwidth
- Sending more packets will not help
- Trouble?
  - More bandwidth to hosts with large packets
- Solution: byte-by-byte round robin