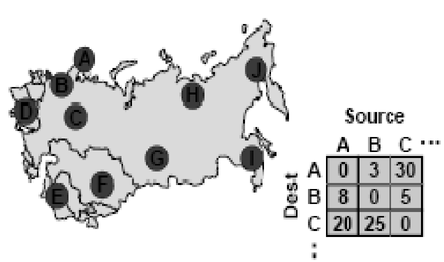
WAN Network Design

David Tipper
Graduate Telecommunications and Networking Program
University of Pittsburgh
Slides 10
Telcom 2110 Network Design

WAN Network Design

- Given
  - Node locations (or potential locations)
  - Traffic Demand (mean, peak, etc)
  - Performance Goals (blocking rate, delay,etc.)
- Determine Topology
  - Link/node location
  - Link capacity
  - Traffic Routing



WAN Network Design

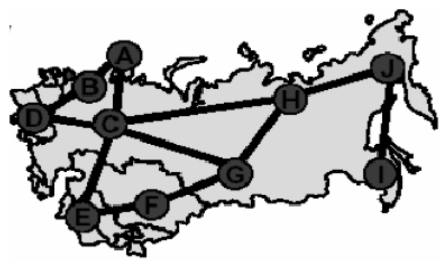
•Design Variables

- Network Topology (possibly facility location as well)
- Channel Capacity
- Routing Policy

•Performance Metrics

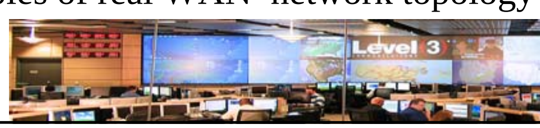
depends on network application and layer

- Circuit Switched Network
  - •Call Blocking, Availability
- Packet network
  - Delay
  - Delay Jitter
  - Throughput
  - Packet Loss

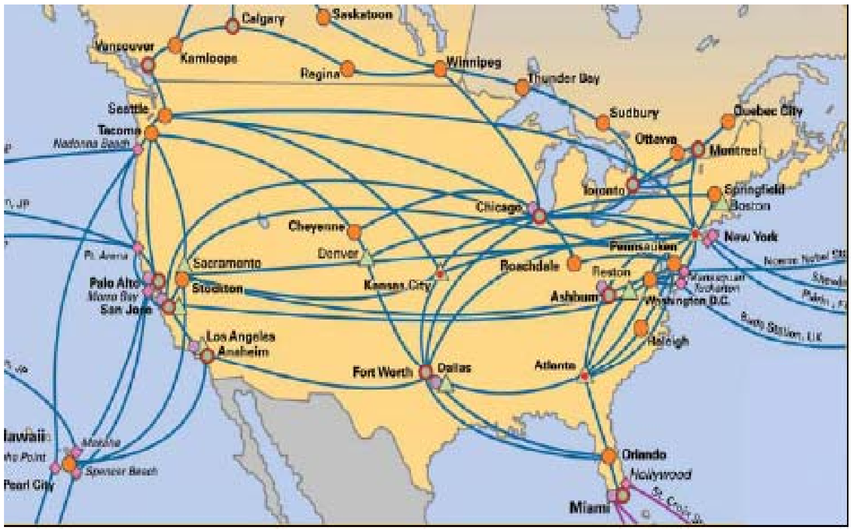


Basic WAN Network Design

- Minimize total cost
- Subject to Constraints … for example
  - – Link capacity must exceed some min, and be less than some max
  - – Average Packet Delay must be < maximum
  - – Reliability requirements
  - – Throughput, etc.
- General goals
  - – Short path between all sources and destinations.
  - – Well-utilized components with high speed lines to achieve economy of scale.
  - – These are somewhat contradictory goals
- Some Examples of real WAN network topology

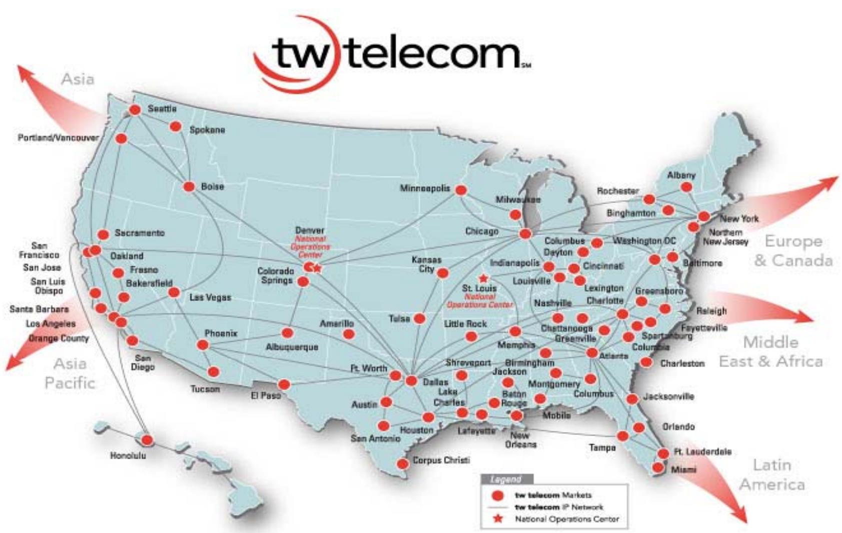


Sprint IP Backbone

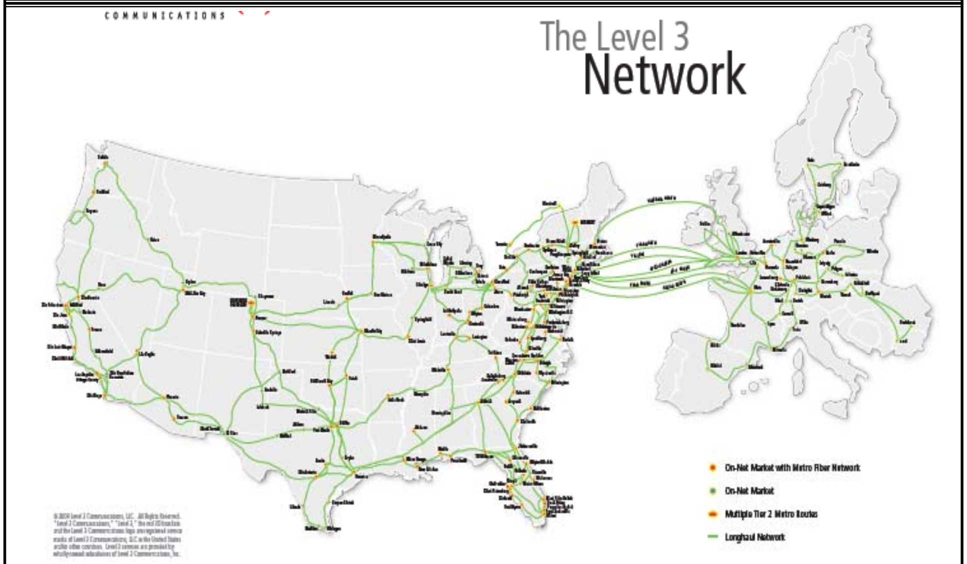


Mostly OC-192 links)

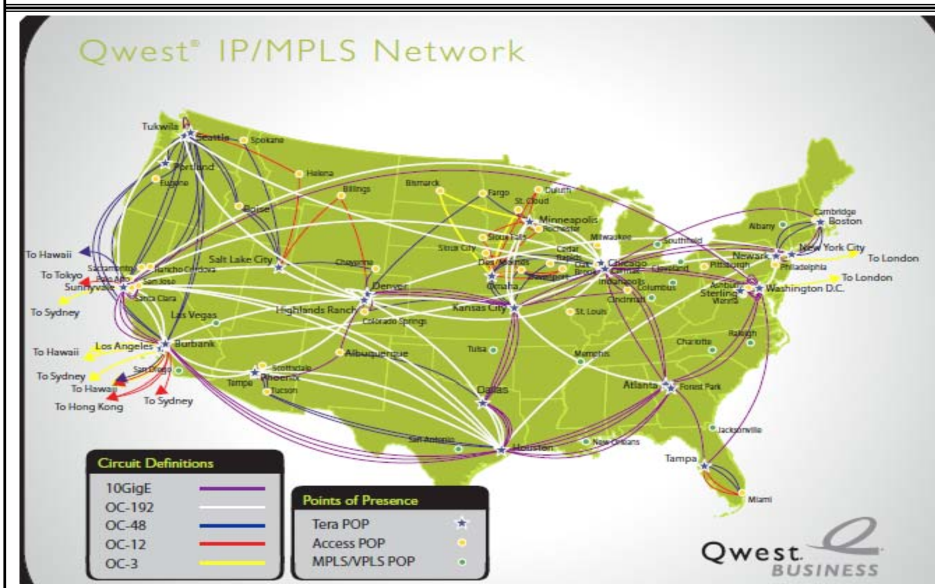
Example Time Warner



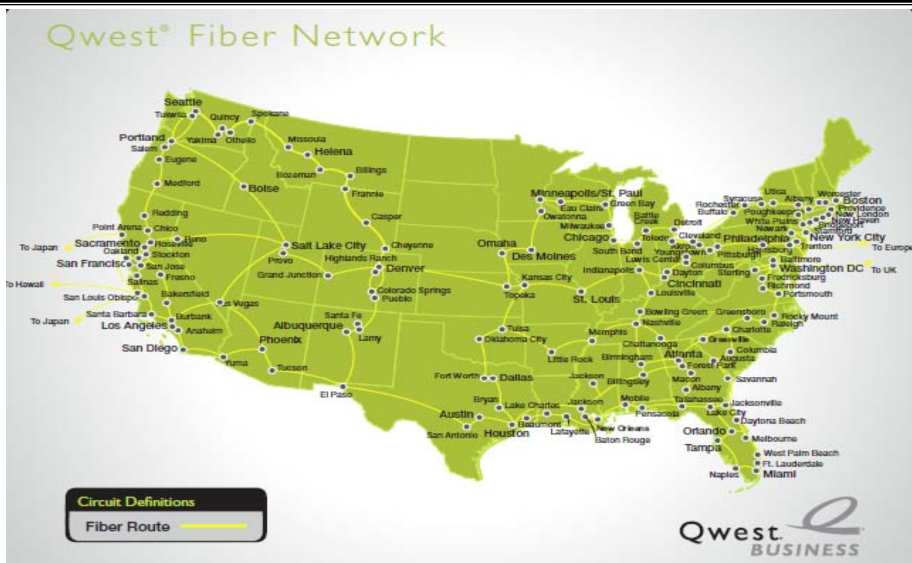
Example:Level 3



Example: QWest

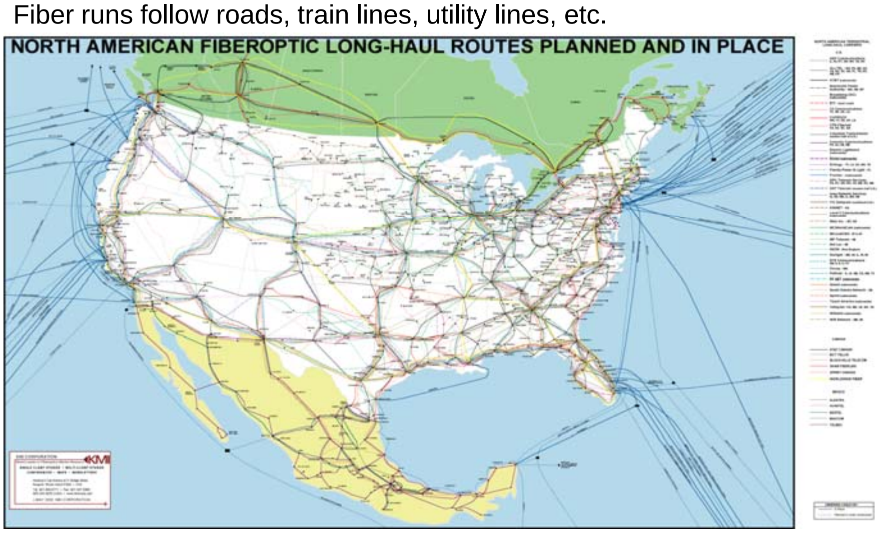


Example: QWest



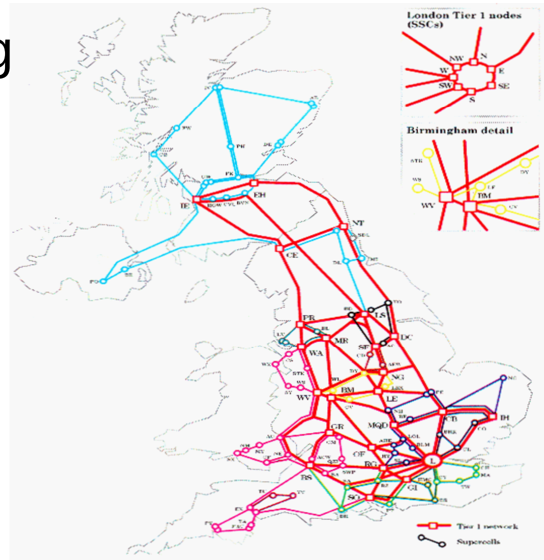
Fiber Runs

Many of the networks use the same fiber runs
Fiber runs follow roads, train lines, utility lines, etc.



British Telecom Backbone

Multi-Ring Network



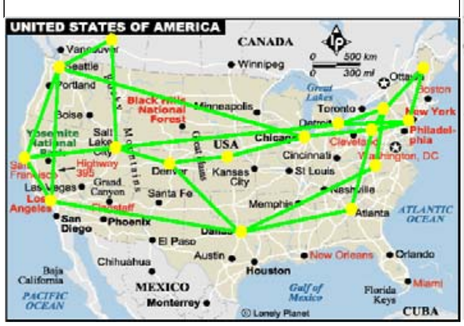
Ring vs Mesh Architectures

Advantages of Rings:

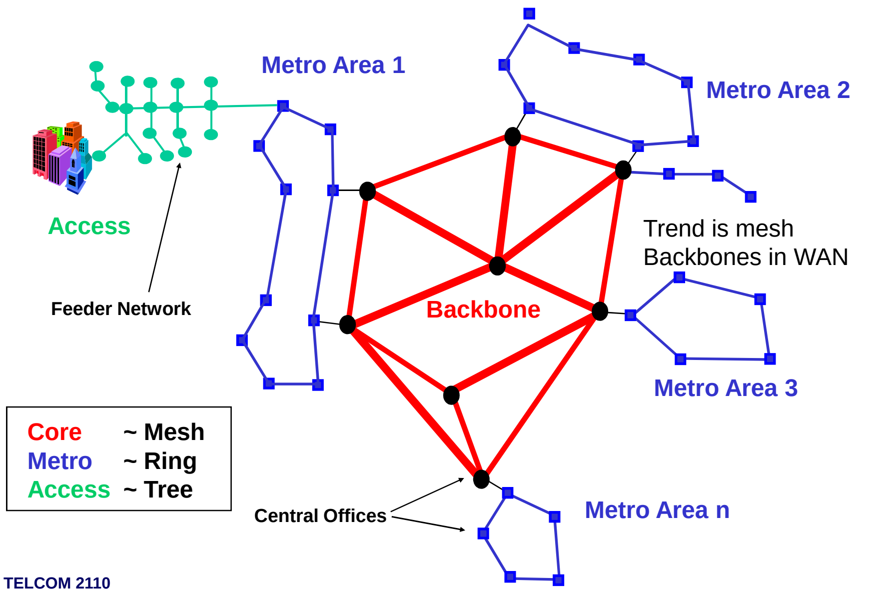
- More cost efficient at low traffic volumes
- Fast protection switching, some capacity sharing

Advantages of Mesh:

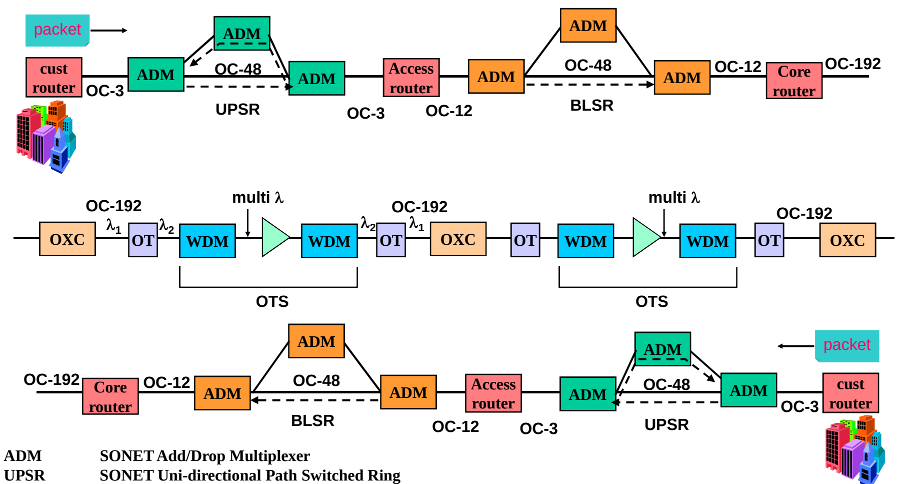
- More cost efficient at high traffic volumes
- Facilitates capacity and cost efficient mesh restoration
- More flexible channel re-configuration
- Easier to cover large distances



Wired Network Structure

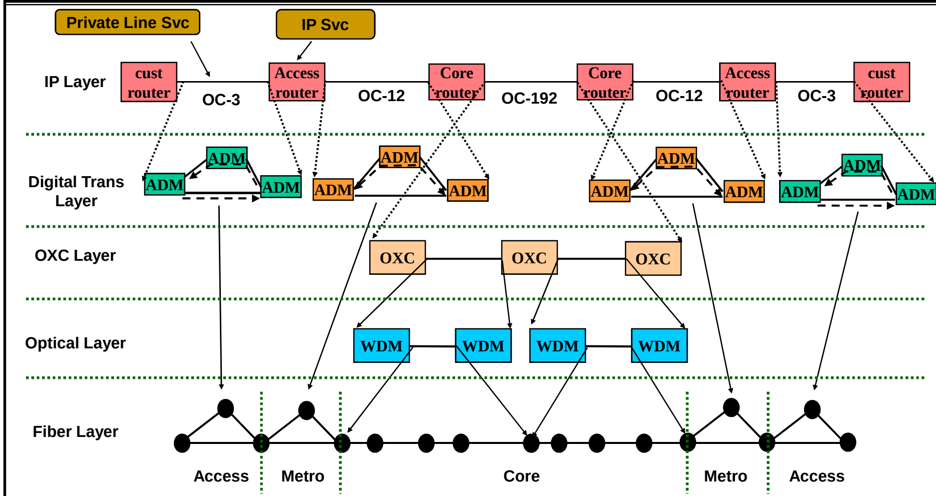


What equipment does a packet encounter across WAN?



ADM	SONET Add/Drop Multiplexer
UPSR	SONET Uni-directional Path Switched Ring
BLSR	SONET Bi-directional Line Switched Ring
OXC	Optical Cross-Connect
OTS	Optical Transport System
OT	Optical Transponder

End-end Example Layered

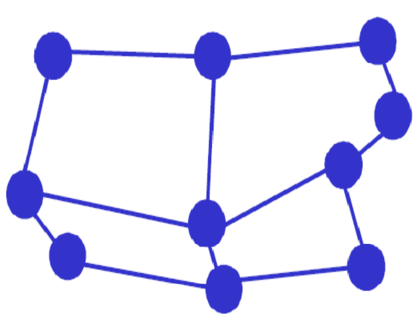


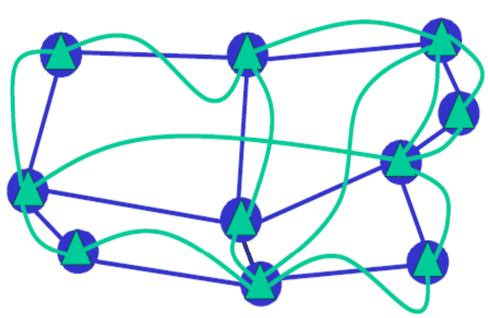
ADM	SONET Add/Drop Multiplexer	OXC	Optical Cross-Connect
UPSR	SONET Uni-directional Path Switched Ring	OTS	Optical Transport System
BLSR	SONET Bi-directional Line Switched Ring	OT	Optical Transponder

Layering Topologies

- Fiber Network

IP Network over Fiber





WAN Networking Technologies

Circuit Based
(constant rate)

- TDM Telephony
- SONET/SDH
- DWDM

Packet Based
(variable rate, store-and-forward)

Virtual Circuits

- Frame Relay
- ATM
- Multiprotocol Label Switching (MPLS)

Connection Oriented

Connectionless

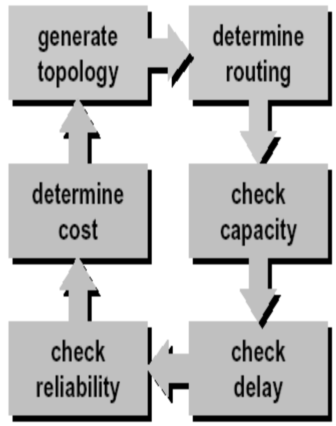
- IP

WAN Network Design

- WAN typically have a mesh or multi-ring design
- Mesh topologies introduce the problem of routing traffic
- Many algorithms/optimization formulations/design tools for WAN packet network design
  - Tend to be imbedded in network topology /data rate layer
  - Different design techniques and metrics at different layers – most core networks are now IP/MPLS/WDM
    - IP
    - MPLS – VPN design
    - WDM – circuit switched routing and wave length assignment

WAN Network Design

- Many algorithms - optimization formulations for WAN packet network design
- Commercial tools
  - VPIsystems, WANDL, OPNET, etc.
- Basic approaches
  - Design topology – then route traffic
  - Route traffic – then capacitate design
  - Joint Optimization
  - Heuristics (Mentor, Genetic Algorithms, etc.)
- Consider Simple Routing approach



Routing Based Approach

- Given node locations and traffic matrix and *initial topology*

1. Route traffic according to appropriate routing algorithms
2. Determine traffic on each link
3. Check or assign capacity to each link
4. Check Delay
5. Check Cost and possibly iterate by generating a new initial topology

Packet Network Design

- Consider IP layer design
- Capacity assignment is not straightforward as in circuit switched networks.
- Rules of thumb
  - want link utilization ~30-40%, upgrade links if utilization= 50%, etc.
- Can also base on delay objectives and cost limitations
- Remember a first cut model of the delay in a packet network is a M/M/1 queue

Network Delays

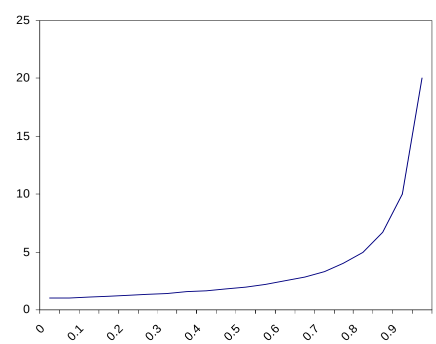
- Router delay
  - – Time for router to process/transmit packet + delay in router queues
  - – Time to process/transmit packet depends on router switch speed and link speed – for high bandwidth links and core network routers small amount of time 10 – 20 μsecs

Queueing Delay

–Time waiting in router buffers for processing and transmission

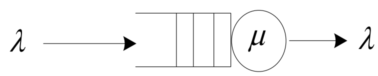
–Value highly dependent on load and QoS mechanisms deployed in router 10’s msec to 10’s secs

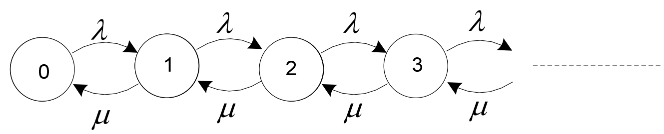
•Queueing Delay nonlinear with increases of network load



M/M/1 Queue

- Single server system with infinite capacity.





$$\lambda\pi_0 = \mu\pi_1 \qquad j = 0$$

$$(\lambda + \mu)\pi_j = \lambda\pi_{j-1} + \mu\pi_{j+1} \qquad j > 0$$

M/M/1 Continued

$$\pi_n = \rho^n (1-\rho)$$

where $\left(\rho = \frac{\lambda}{\mu}\right) < 1$

Mean Number in System L

$$L = \sum_i i \times \pi_i = \frac{\rho}{(1-\rho)}$$

Mean Delay W

$$W = \frac{1}{(\mu - \lambda)}$$

Variance of number in system σ_L

$$\sigma_L = \frac{\rho}{(1-\rho)^2}$$

Variance of Delay σ_W

$$\sigma_W = \frac{1}{\mu^2(1-\rho)^2}$$

M/M/1 Example

- Consider a concentrator that receives messages from a group of terminals and transmits them over a single transmission line.
- The packets arrive according to a Poisson process with one packet every 2.5 ms and the packet transmission times are exponentially distributed with a mean of 2 ms. That is the arrival rate = 1 packet/2.5 ms = 400 packets/sec
- Service rate = 1packet/2ms = 500 packets/sec
  - Find the average delay through the system
    - Utilization = $\rho = 400/500$ = .8
  - Delay W = 1/(500 – 400) = .01 secs = 10 msecs

Delay Calculations

- Given a topology and traffic matrix and traffic routing
- Estimate the network delay using Jackson queueing network model, that is assume each queue is a M/M/1
- Assume there are *M* links in the network at Link *i*
  - F_i is the total traffic arrival rate (flow) in bps
  - C_i is the link capacity in bps
  - For stability $C_i > F_i$
  - Mean Delay

$$D_i = \frac{1}{(C_i - F_i)}$$

Delay Calculations

- For the network as a whole
  - let γ_{sd} denote the mean traffic rate from source *s* to destination *d*,
  - let γ denote the total offered network traffic load

$$\gamma = \sum_{s,d} \gamma_{sd}$$

  - Average delay in the network T is

$$T = \sum_{i=1}^{M} \frac{F_i}{\gamma} D_i = \frac{1}{\gamma} \sum_{i=1}^{M} \frac{F_i}{(C_i - F_i)}$$

Delay Calculations

- Average delay for each source destination pair (s,d)
  - determined by summing link delays on the path

$$D_{s,d} = \sum_{i \in path(s,d)} D_i$$

- In general one tries to minimize some function of the network delay or capacity

$$f(T) \qquad \text{or} \qquad \sum_i \text{cost}(C_i)$$

Minimize Delay Formulation

- **Minimize Average Network Delay**

$$T = \frac{1}{\gamma} \sum_{i=1}^{M} \frac{F_i}{(C_i - F_i)}$$

- With respect to

$$C_i$$

- Under constraint (where C = total capacity)

$$C = \sum_{i=1}^{M} C_i$$

Solution to Minimization Problem

- Use Lagrange Multiplier technique
- Let α denote the Lagrange multiplier
- Incorporate the constraint and minimize the following with respect to C_{ij} and

$$Q = \frac{1}{\gamma} \sum_{i=1}^{M} \frac{F_i}{(C_i - F_i)} + \alpha \left[\left(\sum_{i=1}^{M} C_i \right) - C \right]$$

- Minimize by taking partial derivatives setting equal to zero

Solution to Minimization Problem

- Yields

$$\frac{\partial Q}{\partial C_i} = 0 \qquad \text{…M equations}$$

$$\frac{\partial Q}{\partial \alpha} = 0 \qquad \text{1 equation from constraint}$$

- M+1 (non-linear) equations with M+1 unknowns
- Solve using algebra

Solution to Minimization Problem

- Yields

$$C_i = F_i + (C - \sum_{i=1}^{M} F_i)\frac{\sqrt{F_i}}{\sum_{i=1}^{M}\sqrt{F_i}}$$

for i = 1, 2,…, M

- F_i is the minimum C_i since $\rho_i = F_i/C_i < 1$
- The excess capacity $(C - \sum_{i=1}^{M} F_i)$ should be distributed among the links in proportion to the square root of the traffic

Mean Network Delay

- Resulting Average Network Delay

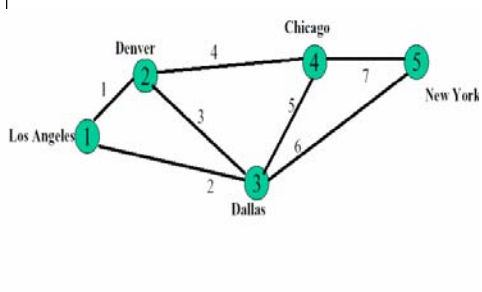
$$T = \frac{1}{\gamma}\sum_{i=1}^{M}\frac{F_i}{(C_i - F_i)} = \frac{\left(\sum_{i=1}^{M}\sqrt{F_i}\right)^2}{\gamma C(1-\rho)}$$

- Where ρ denotes the mean network traffic intensity.

$$\rho = \frac{1}{C}\sum_{i=1}^{M} F_i$$

Example

- Consider mesh topology below
  - links are numbered for reference
  - traffic matrix gives mean rate from source to destination in packets per second,
  - average packet length = 1000 bits
  - budget for link bandwidth results in C = 48 Kbps



Destination

Source	1	2	3	4	5
1	—	0.75	0.61	2.4	2.94
2	0.75	—	0.13	0.63	0.61
3	0.61	0.13	—	0.82	0.94
4	2.4	0.63	0.82	—	9.34
5	2.94	0.61	0.94	9.34	—

Routing/Flows

- Assume Static routing
- Traffic routed on shortest hop paths
- Where multiple shortest hop paths
  - Traffic 1 to/from 4 routed through 2
  - Traffic 1 to/from 5 routed through 3
  - Traffic 2 to/from 5 routed through 4
- Links are bi-directional and symmetric
- Consider traffic in 1 direction – for example
- $F_1 = \gamma_{12} + \gamma_{14} = .75 \times 1000 + 2.4 \times 1000 = 3150$ bps
- $F_2 = \gamma_{13} + \gamma_{15} = .61 \times 1000 + 2.94 \times 1000 = 3550$ bps

Routing/Flows

Link	PPS	F_i	C_i	D_i
1	3.15	3150	6546	.294
2	3.55	3550	7155	.277
3	.13	130	820	1.45
4	3.64	3640	7291	.274

Routing/Flows

Link	PPS	F_i	C_i	D_i
5	.82	820	2553	.577
6	3.88	3880	7649	.265
7	9.95	9950	15986	.116
Total/Avg	25.12	25120	48000	.249

Min-Max Capacity

- **Notice, while minimizing delay, the capacity assignment – favors links with high arrival rates – they get lower delay.**
- **Alternate approach**
  - **minimize maximum delay: min-max solution**
- **Seek to make delays equal for all links**
- **Results in**

$$C_i = F_i + (C - \sum_{i=1}^{M} F_i)\frac{1}{M}$$

Repeat Example Using Min-Max

Link	C_i	D_i
1	6418.6	.306
2	6418.6	.306
3	3398.6	.306
4	6908.6	.306
5	4088.6	.306
6	7148.6	.306
7	13218.6	.306

Cost Constraint Functions

- More realistic Cost constraint.
  - **Fixed cost per link, a_i.**
  - **Distance-based or other variable factor per link, d_i**

$$J = \sum_{i=1}^{M} (d_i C_i + a_i)$$

  - Available cost J_a

$$J_a = J - \sum_{i=1}^{M} (d_i F_i + a_i)$$

  - Results are similar to previous on excess capacity

Solution

- Yields for Minimum Average Delay

$$C_i = F_i + \frac{J_a}{d_i}\left(\frac{\sqrt{d_i F_i}}{\sum_{i=1}^{M}\sqrt{d_i F_i}}\right)$$

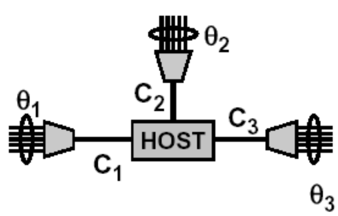
- For the min-max delay case

$$C_i = F_i + \frac{J_a}{\sum_{i=1}^{M} d_i}$$

Example

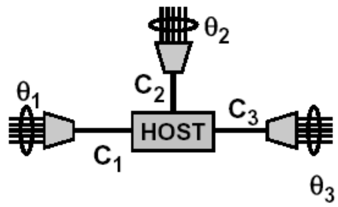
- Consider a star type of topology where three branch offices connect to a central database and the main office
  - C1: West Branch ; 20 terminals, 10 miles from main office
  - C2: North Branch : 20 terminals, 30 miles from main office
  - C3: East Branch: 1 terminal, 30 miles from main office

  All terminals have identical statistics: mean packet rate 2000 /sec mean packet length 128 bytes
- Cost
  - Variable: $0.002 bps per mile
  - Fixed: $1000. per link
  - Allowed total cost J = $4M



Example

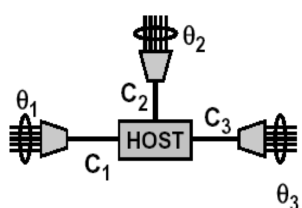
Link	KPkt/s	F_i *(Mbps)*	d_i *($/bps)*
1	40	40.96	.02
2	40	40.96	.06
3	2	2.048	.06



Minimum Delay Example

Link	C_i (Mbps)	D_i *(msec)*	$Cost_i$ *($M)* $d_iC_i + a_i$
1	50.53	.107	1.01
2	46.49	.185	2.79
3	3.28	.828	.20
Total	100.3	Mean = .163	4.00

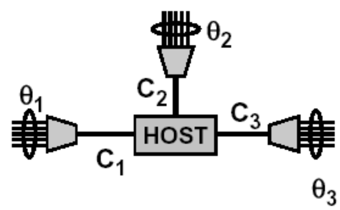
$$C_i = F_i + \frac{J_a}{d_i}\left(\frac{\sqrt{d_i F_i}}{\sum_{i=1}^{M}\sqrt{d_i F_i}}\right)$$



Min-Max Example

Link	C_i	D_i (msec)	$Cost_i$ ($M)
1	45.23	.24	.91
2	45.23	.24	2.71
3	6.31	.24	.38
Total	96.77	.24	4.00

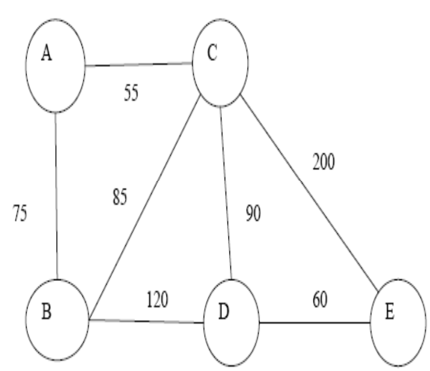
$$C_i = F_i + \frac{J_a}{\sum_{i=1}^{M} d_i}$$



Additional Example

- Consider the network below - the link distances in miles are shown
- The traffic matrix in Mbps is given below - traffic is assumed symmetric and the demand shown is the sum or the two way demand
- Traffic is routed as follows
  - Traffic from A-D goes through B, Traffic from A-E goes through C
  - Traffic from B-E goes through C
- Cost is a fixed cost of $500.00 + a variable cost of $.00001 bps per mile.

	A	B	C	D	E
A		2	1	1	2
B			3	.5	.5
C				1	3
D					1



Example

- Assuming the budget for link bandwidth is C = 22.5 Mbps, determine the minimum delay capacity assignment, and the average network delay.
- Capacity assigned on link *i*, $C_i = F_i + (C - \sum_{i=1}^{M} F_i)\frac{\sqrt{F_i}}{\sum_{i=1}^{M}\sqrt{F_i}}$

Link	F_i (Mbps)	C_i (Mbps)	D_i (µs)
A-B	2+1 = 3	3.635	1.574
A-C	1+2 = 3	3.635	1.574
B-C	3+0.5 = 3.5	4.186	1.457
B-D	1+0.5 = 1.5	1.949	2.226
C-D	1	1.367	2.726
C-E	2+0.5+3 = 5.5	6.360	1.162
D-E	1	1.367	2.726
Total	18.5	22.5	13.445

- Average network delay

$$T = \frac{1}{\gamma}\sum_{i=1}^{7}\frac{Fi}{(Ci - Fi)}$$ = [29.725]/15 = 1.9817 ms

Example

- Total network cost of network capacity assignment

Link	Ci (Mbps)	Distance (miles)	d_i ($ / bps)	Cost ($)
A-B	3.571	75	$7.5x10^{-4}$	3226.50
A-C	3.571	55	$5.5x10^{-4}$	2499.43
B-C	4.071	85	$8.5x10^{-4}$	4058.30
B-D	2.071	120	$1.2x10^{-3}$	2839.10
C-D	1.571	90	$9.0x10^{-4}$	1730.13
C-E	6.071	200	$2.0x10^{-3}$	13220.48
D-E	1.571	60	$6.0x10^{-4}$	1320.08
Total	22.5			$28,894.02

Total Cost $J = \sum C_i d_i + a_i$

d_i = distance [miles]*0.00001 [$/bps/miles], a_i = $500.00

→ J = $ 28,894.02

Example

- Minimum delay capacity assignment with cost constraint
- Total budget = $80,000

$$C_i = F_i + \frac{J_a}{d_i}\left(\frac{\sqrt{d_i F_i}}{\sum_{i=1}^{M}\sqrt{d_i F_i}}\right) \qquad J_a = 80{,}000 - \sum_{i=1}^{7}(d_i F_i + 500)$$

Link	Fi (Mbps)	Ci (Mbps)	$Delay_i$ (μs)
A-B	3	13.160	0.098
A-C	3	14.864	0.084
B-C	3.5	13.808	0.097
B-D	1.5	7.180	0.176
C-D	1	6.355	0.187
C-E	5.5	13.924	0.119
D-E	1	7.558	0.152
Total	18.5	76.849	2.143

Average Network Delay $T = \frac{1}{\gamma}\sum_{i=1}^{7}\frac{Fi}{(Ci - Fi)}$ = 0.1429 μs

This average delay is smaller than 1.9817 μs in previous design. The delay performance is significantly improved since each link has much greater bandwidth.

WAN Packet Design

- Many Routing based design approaches based on tradeoff of cost, capacity, performance
- Note Routing approach assumed given initial topology – How to find??
- A simple extension to the routing based approaches previously discussed is successive minimum cost routing
- Route traffic – create initial topology – evaluate performance metrics (cost, delay etc.) try to improve by rerouting traffic.
- Include some randomness in the problem to avoid local minimum (basically a hill climbing approach)
- O(N*Log(n)) complexity – scales to large networks
- When compared to optimization based approaches – near optimum results (~3%)

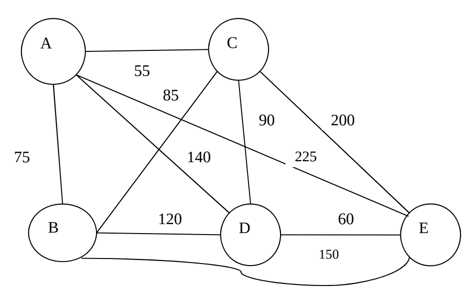
Heuristic Algorithm

```
Begin
   Let D = set of traffic demands or flows;
   Let E = set of all potential links;
   do {
        randomly select an order of traffic demands in D to be routed;
        for each traffic demand k in the order
        {
          if (traffic demand k has an existing route)
             temporarily remove its required bandwidth along the route;

          calculate new link-cost metric for all links in E based on the
          updated topology, reserved bandwidth, and  traffic demand k;

          find minimum-cost path from the calculated link metric for
          traffic demand k;

          if (new route has been found)
               update network topology for new links and capacity;
          else
               maintain previous solution;
        }
   } until ( update improvement < epsilon OR iteration > max_iteration);
End
```


Example

- Consider the network below - the potential link distances in miles are shown
- The traffic matrix in Mbps is given below - traffic is assumed symmetric
- Cost is a fixed cost of $500.00 + a variable cost of $.00001 bps per mile.
- In general traffic does not have to follow same route in both directions for each node pair so we treat them separately

	A	B	C	D	E
A		1	0.5	0.5	1
B	1		1.5	.25	.25
C	0.5	1.5		.5	1.5
D	0.5	.25	1.5		0.5
E	1	.25	1.5	0.5	



Example

- Following the heuristic algorithm – generate a random demand order
- 17 9 2 12 11 3 10 8 7 4
  16 6 18 5 14 19 1 13 15 20
- Route each demand pair for an initial topology
  - For example demand 17 is the demand from E to A with bit rate 1 Mbps
  - The possible routes with fewer than 3 hops are given below with cost of route
  - EA ($2750)
  - EC-CA ($2500+1050 = $3550)
  - ED-DA, ($1100 + $1900= $3000)
  - EB-BA, (
  - .....
  - EB-BD-DA
  - One can see that in this case the minimum cost route for this demand is EA – subsequent demands routed over link EA will not need the additional $500 fixed cost of setting up the link)
- After routing each demand have feasible topology
- Iterate by picking a new random ordering and repeating

Demand Pair	Numeric Label
(AB)	1
(AC)	2
(AD)	3
(AE)	4
(BA)	5
(BC)	6
(BD)	7
(BE)	8
(CA)	9
(CB)	10
(CD)	11
(CE)	12
(DA)	13
(DB)	14
(DC)	15
(DE)	16
(EA)	17
(EB)	18
(EC)	19
(ED)	20

Packet Based WAN Design

- Consider basic WAN network design
  - Network Layers
- Looked at routing based approach to WAN Packet Design
- Different Capacity assignment variations
- Simple successive routing heuristic for topology design
- How can QoS be provided?
  - Differentiated Services (Diff. Serve)
  - MPLS
  - Combination