Hints on capacity planning
(and other approaches)

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Some economical principles

• Assume users have a utility function that translates a given quality to a level of satisfaction
• Function may be known to users only (and may be difficult to identify)
  – Can be derived by observing user behaviour (which depends also on pricing policy)
• Assume users are rationale
  – Take action to maximize their utility
Example (Keshav)

• Let utility of a file transfer $u = S - at$
  – $u$: utility of the file transfer
  – $S$: satisfaction when transfer at infinite speed
  – $t$: transfer time
  – $a$: rate at which satisfaction decreases (as time increases)

• If $t > S/a$ utility becomes negative

• $S$ and $a$ can be experimentally determined?

Example (Keshav)

• Let utility of a videoconference (hard delay on packet arrival) $u = S$ if $(t < D)$ else $-B$
  – $t$: end-to-end packet delay
  – $D$: delay deadline
  – $S$: satisfaction
  – $B$: cost of missing a deadline (pay for something useless)

• More complex utility functions could be defined

• Utility functions should completely capture user requirements

• If known, we can optimize network to maximize utility
Example

- Single switch, two users with load 0.4
- User A utility: 4-d
- User B utility: 8-2d (more sensitive to delay)
  - d is the average packet delay
- Conservation law states
  - 0.4d+0.4d=constant=C
    - d=1.25C and the sum of the utilities is 12-3.75C
- Reduce delay of B to 0.5C
  - Delay of A =2C
  - Sum of utilities= 12-3C
- Increase in social welfare, but A is less satisfied
  - A may get reduced price

Some economic principles

- A single integrated network is “better” that a dedicated network
  - Unused capacity can be used for other users
  - E.g. ADSL and IP Telephony
- We show that lowering delays of delay sensitive traffic increase welfare
  - Can increase welfare by matching service to user needs
  - Need to know user requirements
  - E.g. Give to 5% of the traffic lower delay
- Welfare increases more than linearly with increase in capacity
  - Overprovisioning
  - E.g. moving form 20% loaded 10Mbit/s to 20% loaded 100Mbit/s improves social welfare
- Is cheaper to match user requirements or to increase capacity in a blind way?
Another approach: peak load pricing

- Deal with cyclic demand
  - Hourly or daily or weekly traffic behavior
- Suppose capacity varies in time
  - Peak capacity $C_1$ for two hours a day
  - But capacity below $C_2 < C_1$ for 90% of the time
- If size the network for $C_1$
  - Waste capacity
- If size the network for $C_2$
  - Overload during peak hour (two hours a day)
- Can shift the demand to off-peak hours?
  - Maybe using pricing
  - Charge more during peak hours

Pricing: an example

- Network capacity $C$
- Peak demand=100, off-peak demand 10
- Price =1 per unit during peak and off-peak
  - Revenues = 110
- User utility
  - Defined as $(\text{price} - \text{overload}) = -110 - (100 - C)$
- Network utility
  - Defined as $(\text{revenues}-\text{idleness}) = 110 - (C - \text{off peak load})$
- Increasing user utility decreases network utility
  - If $C=100$, user utility= -110, network utility=20
  - If $C=60$, user utility = -150, network utility=60
Pricing: an example

- Suppose peak price=1, off-peak price=0.2
- Suppose that, as a consequence, peak load decreases to 60, off-peak load increase to 50
- Revenue=60*1+50*0.2=70
  - It was 110
- But since the peak is 60, C=60
- User utility = -70
  - Larger than before
- Network utility = 60
  - Same as before
- User utility increases at no cost for the network
- Issues
  - What is the meaning of peak time in a global network?
  - How to choose parameter values?

Capacity (re)planning

- Design from scratch (or modify) network topology, link capacity, routing, to
  - efficiently use resources
  - satisfy user requirements
- In circuit switching networks more standard approaches
- In packet switched networks mostly done by trial and error approaches
- Steps
  - Define node position and estimate (or measure) user traffic (during busy hour?)
    • to derive traffic matrix
  - Define logical topology
    • Includes logical link capacity assignment
  - (Map to a physical topology)
Traffic models as a key to enable capacity assignment

- Traffic model: how users and aggregation of users behave
- Examples
  - How long a user uses an ADSL modem
  - Average size of a file transfer
- Models change with network usage (and applications)
  - Guess about the future
- Models are based on
  - Measurements
  - Estimates (... Guesses 😊 …)

Telephone traffic models

- Call dynamics?
  - Call arrival model
  - Shown that call inter-arrival time to be well approximated by an exponential distribution
  - Call arrival process follows a Poisson distribution
    - Memoryless: the fact that a certain amount of time has passed since last call gives no information of time to next call
- Call duration?
  - Also modelled as an exponential distribution
  - Some measurements show it is heavy tailed
    - A non negligible number of calls last for a very long time
      - Normally neglected
- Poisson models are easy to manage and well accepted
Internet traffic models

• More difficult
  – Many different applications (although all rely on file transfer over UDP and TCP)
  – Few applications account for most of the traffic
    • But this change over time
    • Web, P2P
  – Difficult to model destination distribution

• Two main features
  – LAN connections are different from WAN connections
    • Higher bandwidth and longer holding times
  – Many parameters are heavy tailed
    • #bytes in a call
    • Call duration
    • Few calls are responsible for most of the traffic
    • Means that even large aggregate of traffic are not smooth (law of large numbers)

Telephone network capacity planning

• How to size a link to obtain a blocking probability smaller that a target value

• Erlang-B formula gives blocking probability as a function of
  – Avg number of calls (in erlangs) on a link
  – Avg call arrival rate r
  – Avg call holding time h
    • Call load E = r h
  – Trunk capacity m
  – Infinite number of sources
  – m=5, E=3, blocking probability = 0.11
  – For a fixed load, as m increases the call blocking probability decreases exponentially

\[ P_b = B(E, m) = \frac{E^m}{m!} \sum_{i=0}^{m} \frac{E^i}{i!} \]
Telephone network capacity planning

- Blocking probability along a path
- Assume traffic on links is independent
  - Blocking probability is the product of the probability on each link
- Routing table and traffic matrix determine the load on a link
- Assign capacity to each link given the load and target blocking probability
  - Or add new link
  - And/or change routing table

Packet switching (?) capacity planning

- Very complex
  - Often relies on trial and error procedures
- Planning problem often divided in two problems
  - Logical Topology Design
  - Routing (and Wavelength) Assignment
- May be formalized as an optimization problem
  - Joint optimization
    - Unfeasible for complexity and organizational reasons
    - Heuristics
  - Two step formulation
    - Each step may independently be formalized as an optimization problem
    - Often heuristics needed for the two separate problems
  - See class “Operations research: theory and applications to networking” for LTD and RWA examples
Measure or estimate traffic to create traffic matrix

- Build for the worst case (?
  - Pick the busiest hour (over which time-scale?)
- Add some safety margin to allow for
  - Measurement or estimate errors
  - Future traffic growth
  - Provisioning against failures?
- Traffic matrix definition assumes that current pattern predicts future
- Time scale critical (traffic over shorter time scale may be heavier)
- When adding endpoints traffic matrix become obsolete
- Not always possible to measure all traffic on all links
  - Privacy issues
- Routing policies interact with link load measurements
- Not always easy to rebuild flow infos from packet info

Define topology and assign capacity

- Logical topology definition
  - Define network connectivity (may include alternative paths for robustness to failures)
  - Geographical/cost considerations
    - Some links may be easier to be obtained
  - Available capacity may impose some constraints (see later)

- Capacity assignments
  - Enough capacity to carry traffic defined in the traffic matrix
  - Actual paths depend on routing
    - May define optimal paths dynamically (look at link load?)
    - Risk of reaction (higher capacity, become more attractive for routing, requires more capacity, etc etc)
    - Easier to assign capacity for static routing
Logical Topology Design

- Input
  - Traffic matrix
  - Costs (e.g. number and speed of links I can pay for, price, performance)

- Output
  - Logical topology that “best” suits the traffic matrix with the cost constraints

- “Extreme” solutions if costs is the number of links
  - No cost constraint
    - Full mesh
    - Single-hop approach
    - Each node process only generated/received traffic
    - Circuit switching like solution
  - Minimize costs
    - Tree/ring/star topologies
    - Multi-hop approach
    - Nodes must process also in-transit traffic
    - Permits grooming to “match” traffic load to channel capacity

Routing (and wavelength) assignment

- Need to map to a physical topology the defined logical topology
  - Create physical links, or virtual circuits, or lightpaths
  - Any difference? Lightpath, if transparent, imply no processing of local traffic

- Often done by the organization/provider that owns the physical infrastructure
  - Often different from the one that has defined the logical topology

- Physical topologies may impose constraints on logical topologies feasibility due to lack of resources

- Once established, the logical topology, owners “do not see” the physical topology
  - Performance depend on the logical topology layout only

- Besides selecting routes on the physical topology, in WR networks, also wavelengths should be assigned
Trivial example

Examples

• Start with a traditional first-generation telephone network (which has only point-to-point optical links and electronic switching)
  – Typical current solutions consider a SONET/SDH ring topology, in which OC48-STM16 (2.5 Gb/s) links are used
  – Add-drop multiplexers (ADM) and digital cross-connects (DCX) are used
• Then we extend it to a ring that exploit WDM as a transmission technology
• Finally, we examine the possibility of moving to a WR solution
First example

- The following (normalized) traffic matrix must be carried:

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>TOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-</td>
<td>0.25</td>
<td>0.25</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>0.25</td>
<td>-</td>
<td>0.25</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>0.25</td>
<td>0.25</td>
<td>-</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>D</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>-</td>
<td>1.5</td>
</tr>
<tr>
<td>TOT</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1.5</td>
<td></td>
</tr>
</tbody>
</table>

- If traffic grows, a capacity increase must be introduced

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>TOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>0.5</td>
<td>2.5</td>
</tr>
<tr>
<td>C</td>
<td>2</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
<td>-</td>
<td>2.5</td>
</tr>
<tr>
<td>TOT</td>
<td>4</td>
<td>2.5</td>
<td>4</td>
<td>2.5</td>
<td></td>
</tr>
</tbody>
</table>

- A WDM upgrade may be an alternative

**Traditional SONET ring**

*ADM = Add-Drop Multiplexer*

*DCS = Digital Cross-Connect*
WDM ring: WDM on links

Traffic routing becomes:

<table>
<thead>
<tr>
<th>flow</th>
<th>wavelength</th>
<th># OC-48</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>$\lambda_1$</td>
<td>1</td>
</tr>
<tr>
<td>BD</td>
<td>$\lambda_1$</td>
<td>1</td>
</tr>
<tr>
<td>AD</td>
<td>$\lambda_1$</td>
<td>1</td>
</tr>
<tr>
<td>AC</td>
<td>$\lambda_2$</td>
<td>2</td>
</tr>
<tr>
<td>BC</td>
<td>$\lambda_3$</td>
<td>1</td>
</tr>
<tr>
<td>BD</td>
<td>$\lambda_3$</td>
<td>1</td>
</tr>
<tr>
<td>CD</td>
<td>$\lambda_3$</td>
<td>1</td>
</tr>
</tbody>
</table>

3 wavelengths are needed.
WR ring

- By using WR, we build a logical topology, in which links are optical lightpaths, on top of the physical topology, in which point-to-point connections on a ring are available.

- No need to process in-transit traffic.

WR ring

- Optical switches may be used to add flexibility: in case of traffic changes, or to manage faults, the logical topology may change.
Second example

Three IP routers, A, B e C, with 10 Gb/s interfaces
50 Gb/s of traffic for each router pair

Without OADM

With OADM

• 10 wavelengths are required in both fibers
• Without OADMs, the physical topology and the logical topology are the same, being a bus topology in both cases; router B has 20 interfaces
• With OADMs, the logical topology is a ring; router B has only 10 interfaces
• The cheapest solution depends on the relative cost of components (OADMs vs. router ports)
Third example

- Three different logical topologies overlaid on the same bidirectional ring physical topology. Compare them considering:
  - the number of interfaces at routers
  - the number of wavelengths
  - the distance (number of hops) in the logical topology
- Traffic is uniform, so that each router transmits \( \frac{t}{N-1} \) of the capacity of a WDM channel to all other routers (\( t/N-1 \) from router to router)

<table>
<thead>
<tr>
<th></th>
<th>PWDM</th>
<th>Hub</th>
<th>Full-mesh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of ports (Q)</td>
<td>( Q = 2W )</td>
<td>( Q = \left\lceil \frac{t}{N} \right\rceil )</td>
<td>( Q = (N-1) \left\lceil \frac{t}{N-1} \right\rceil )</td>
</tr>
<tr>
<td>Number of wavelengths (W)</td>
<td>( W = \left\lceil \frac{t}{8(N+1+1/(N-1))} \right\rceil )</td>
<td>( W = \left\lceil \frac{t}{N} \right\rceil )</td>
<td>( W = \left\lceil \frac{t}{N-1} \right\rceil )</td>
</tr>
<tr>
<td>Distance (number of hops)</td>
<td>( N/2 )</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>
Third example: # of ports

Third example: # of λ’s
Third example

- Previous plots refer to the case N=8, for different values of t
- In the design of an optical network, it is likely better to minimize the number of ports (transceivers) rather than optimizing bandwidth usage
- Fully-optical solution
  - Limited grooming (multiplexing of traffic flows in a single wavelength)
  - For small t, lightpaths are underutilized
    - Coarse quantization in the plots