



QoS routing and CAC (Connection Admission Control)

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QoS routing and CAC

- Preventive traffic control technique (in principle it can become reactive)
- Permits to determine whether to accept or not a new incoming call
 - QoS routing selects a set (possibly one) of tentative paths
 - CAC checks whether enough resources are available over each link of each path
 - * Cannot be done at the routing level because routing operates on less detailed info to ensure scalability
 - Resources are allocated to guarantee QoS
- The call is accepted if there are enough network resources to:
 - Satisfy the requested QoS
 - With the constraint of keeping at the same level the QoS offered to already accepted calls
- Can be applied to unicast and multicast calls
 - Multicast calls are routed over a tree rooted at the source and covering all receivers
- Call definition?
 - In ATM, each VPI/VCI
 - In Frame Relay each DLCI
 - In Internet? Flow identification problem

QoS routing

- Network modeled as a graph $G(V,E)$
 - Nodes represent switches, routers
 - Edges represent communication links
- Traditional routing problem
 - Call request from user a to user b (or to a set of users B)
 - Costs associated with edges
 - Find over G a path (tree) that minimize costs to route the call from a to b (or B)
 - * If all edges have the same cost, shortest path "optimizes" network performance
- QoS routing problem
 - Call request from user a to user b (or to a set of users B) with a given set of QoS requirements
 - Nodes may have a state related to QoS metrics
 - Edges have a state, related to QoS metrics, associated
 - Find over G a feasible path (tree)
 - * It must have enough residual resources to satisfy call QoS constraints
 - Among several feasible paths, it may choose the one which minimizes cost

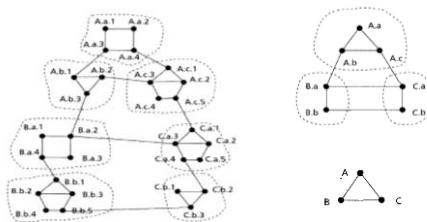
QoS routing

- Difficult problem
 - QoS constraints may be very diverse
 - Bit rate, delay, delay jitter, loss ratio
 - Additive constraints (hop count, delay)
 - Multiplicative constraints (loss ratio)
 - Concave constraints (bit rate)
 - Multiple constraints often make the QoS routing problem NP-hard
 - Integration with best-effort traffic
 - QoS traffic not affected, but best effort may suffer
 - Network state may change dynamically
 - Difficult to gather up-to-date state information
 - Performance may degrade dramatically if state information outdated

State information

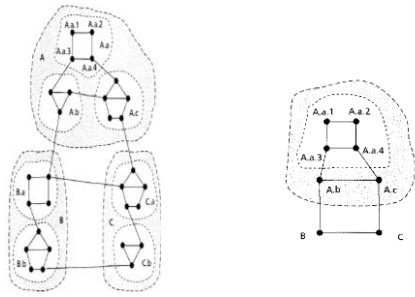
- Link state may be a triple
 - Bandwidth, Delay, Cost
- Node state may simply be a combination of its link state
 - CPU bandwidth may be taken into account
- Local state measured and kept by each node
- Global state exchanged through link-state or distance vector protocols
- Scalability may be achieved by information aggregation, exploiting the hierarchical structure of the network
 - Not only for link state info but also for addressing

Hierarchical network model: network layers



Taken from Chen, Nahrstedt AN Overview of QoS Routing..., IEEE Network 1998

Hierarchical network model: hiding topological details



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Unicast (Multicast) QoS routing

- Unicast (Multicast) QoS routing definition
- Given
 - A network topology
 - A source node s
 - A destination node d (set of destinations R)
 - A set of QoS constraints C
 - Possibly an optimization goal
- Find
 - The best feasible path from s to d (tree covering s and all nodes in R) which satisfies C
- Constraint
 - Algorithmic complexity
- Multicast routing is a generalization of unicast routing

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Unicast QoS routing classification

- Link-Optimization (LO) or Link-Constrained (LC)
 - The state of a path is determined by the bottleneck link
 - Residual bandwidth and residual buffer space
 - Min-max operations on non additive metrics
 - Optimization:
 - Ex: find a path that has the largest bandwidth on a bottleneck link
 - Constrained
 - Ex: find a path whose bottleneck link is above a given value
 - Link-constrained can be mapped to link optimization
- Path-Optimization (PO) or Path-Constrained (PC)
 - The state of the path is determined by the combined state over all links of the path
 - Delay
 - Combinatorial operation over additive metrics
 - Optimization
 - Ex: find a path whose total cost is minimum
 - Constrained
 - Ex: find a path whose delay is bounded by a given value

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Composite unicast routing problems

- Elementary routing problems can be combined to create composite routing problems
- LC-PO problem
 - Bandwidth constrained least delay routing
 - Can be solved by a shortest path algorithm on the graph obtained by removing links violating the bandwidth constraint
- LOLC, LCPO, LCPC, PCLO can be solved in polynomial time
- PCPO (find the least cost path with bounded delay) and Multi-Path Constrained (path with both bounded delay and jitter) are NP if
 - Two metrics are independent
 - Measured as real numbers or unbounded integers

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QoS routing strategies

- Classification according to
 - how state information is maintained and distributed and
 - how the search of a feasible path is performed
- Strategies
 - Source routing
 - Distributed routing
 - Hierarchical routing
 - Can be combined

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QoS routing strategies

- Source routing
 - Each source node
 - Maintains the complete global state (received by all other nodes)
 - Network topology, state information
 - Locally computes a feasible path
 - Sends a control message along the selected path to inform intermediate nodes of their precedent and successive nodes or insert the end to end path on each packet header
- Distributed routing
 - Path computed through a distributed computation
 - Each node keeps a partial (global) state
 - Routing done on a hop-by-hop basis
- Hierarchical routing
 - Nodes clustered into groups, further clustered in higher-level groups recursively, creating a multi-level hierarchy
 - Each physical node maintains an aggregated global state
 - Detailed information about the nodes in the same cluster and aggregated state information about the other groups

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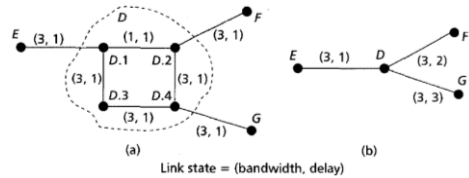
QoS routing strategies

- Source routing
 - Centralized solution
 - Avoids problem with distributed solutions (deadlock, distributed terminations, loops)
 - Large communication overhead to update state
 - Imprecision in the global state information
 - Large computation overhead
- Distributed routing
 - More scalable
 - Parallel search possible
 - Loop due to inconsistencies
 - Large communication overhead
- Hierarchical routing
 - Often used in conjunction with source routing
 - Routing computation shared by many nodes (source and border nodes)
 - Adds imprecision due to aggregation (mandatory to scale)

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Hierarchical aggregation: loss of detailed info



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Unicast QoS routing: examples

- Examples of proposed distributed algorithms
 - Widest Path
 - Path with the maximum bottleneck bandwidth
 - Shortest Path
 - Path with smallest delay
 - Shortest-Widest Path
 - Among widest paths, select the one with smallest delay
 - Widest-Shortest Path
 - Among shortest paths, select the one with the maximum bottleneck bandwidth
 - Delay constrained least-cost routing
 - Each node keeps a cost and a delay vector for the best next hop for any destination
 - A control message is sent from the source to construct a delay-constrained path
 - Any node can select one of two alternative links (least cost path or the least delay path)
 - Least cost path has priority as long as the delay constraint is not violated
 - Loops detected if control messages seen twice
 - Roll back until reaching a node who chooses the least cost path

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Unicast QoS routing: examples

- Examples of proposed source routing algorithms
 - Bandwidth-delay constrained
 - All links with not enough bandwidth are eliminated, then the shortest path is searched for
 - Transform delay, jitter and buffer space bounds in bandwidth bounds when traffic is token bucket controlled and nodes are running proper scheduling algorithms

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QoS routing: issues

- For high loads, maximum throughput is provided by the minimum hop
- For medium-low loads algorithm performance depend on network topology and traffic pattern
- Some algorithms may be implemented only in a centralized way
 - Hop-by-hop decisions may be sub-optimal
- The more complex the link/node metric used
 - Increase in signaling bit rate to distribute status
- The more dynamic the link/node metric used
 - Increase in the frequency of status update
 - Need to re-run the routing algorithm

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Multicast QoS routing classification

- Similar to the unicast QoS case, but optimization or constraints must be applied to the full tree
 - Link optimization or constrained
 - Tree optimization or constrained
- Steiner tree problem (tree optimization) is to find the least-cost tree
 - Tree covering all destinations with the minimum total cost over all links
 - It is NP-hard
 - If destination set includes all network nodes, the Steiner tree problem reduces to the minimum spanning tree problem which can be solved in polynomial time

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Composite multicast routing problems

- Elementary multicast routing problems can be combined to create composite routing problems
- LCLO, MLC (Multi-link constrained: Bandwidth buffer-constrained), LCTC, TCLO can be solved in polynomial time
- LCTO, TCTO, and MTC (Multi-tree constrained: delay-delay jitter constrained) are NP if
 - Two metrics are independent
 - Measured as real numbers or unbounded integers

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Issues in multicast traffic

- Multicast trees are dynamic
 - Users leave and join
 - Maintain or update the tree while the call is on
 - Pruning easier than extending
 - Heuristic: Adding to the current tree via a minimum cost path
 - Periodic tree re-design possible
- Receiver heterogeneity
 - Allocate for the most demanding user but only if using hierarchical coding at the source
 - Generate a set of flows at different rate
 - Run the application according to the minimal capabilities
- ACK explosion for reliable multicast

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CAC algorithm

- INPUT DATA
 - Traffic characterization at network ingress
 - Call QoS requirements
 - Path(s) selected by (QoS) routing algorithms
 - Network status (available bit rate, buffer occupancy, ...) and data traffic already accepted in the network
- OUTPUT
 - Accept (if QoS requirements can be satisfied) or refuse the call
- CONSTRAINTS
 - Not violate QoS requirements of already accepted calls

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CAC algorithm

- Algorithm executed
 - In all network nodes through which the call is routed
- It is possible to envision QoS parameters re-negotiation in case of negative answer
- Main CAC methodologies
 - Parameter based admission control
 - Peak rate, average rate
 - Worst case analysis
 - Equivalent bandwidth
 - Measurement based admission control

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Peak rate CAC

- Peak rate allocation
 - Call k is accepted if available bandwidth is larger than the peak bandwidth of call k :

$$B_P^{(k)} \leq C - \sum_{i \text{ acc.}} B_P^{(i)}$$
- Rationale
 - Worst case dimensioning
- CBR traffic
 - Bit rate guarantees
 - Delay guarantees as a function of the number of accepted calls
 - Zero losses if buffer size proportional to number of accepted calls
- VBR traffic
 - Same guarantees as of CBR traffic
 - Link utilization proportional to: $\frac{B_M}{B_P}$

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Peak rate CAC

- Simple
- Does not exploit potential benefits of statistical multiplexing
- Very good QoS guarantees
- Transmission link capacity may be largely under-utilized for VBR traffic
- Network behaves very similarly to circuit switched networks
 - Bit rate guaranteed, loss probability negligible or null
 - Data transmission is not synchronous
 - Delay guarantee depends on other user behavior
- Many multiplexing stages could increase B_P over a short time interval, thus partly worsening QoS guarantees

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Average rate CAC

- Average rate allocation

– Call k accepted if:

$$B_M^{(k)} \leq C - \sum_{i \text{ acc.}} B_M^{(i)}$$

- Rationale

– Over a long period of time the network is never overloaded

Average rate CAC

- Simple
- Very high link utilization
- Zero loss only with infinite buffer
- With finite buffers
 - Congestion (link overload proportional to source burstiness)
 - Uncontrolled losses
 - Uncontrolled delays
 - Unless more tight constraints on the traffic source
- Network behaves similarly to packet switched networks with datagram service
 - But permanent overload is avoided
- May take some safety margin from 100% utilization to statistically control losses and delays

An example

- Focus on a single node
 - Focus on an output link with capacity 100Mbit/s
- Incoming calls are VBR with peak rate 10Mbit/s and average rate 1Mbit/s (burstiness 10)
- If using peak rate CAC
 - At most 10 calls are accepted
 - Average output link utilization 10%
- If using average rate CAC
 - At most 100 calls are accepted
 - Worst case overload is 1Gbit/s (10 times larger than link speed)

Worst-case analysis: examples

- Suppose a source is constrained by a token bucket
- Can accept calls when
 - The summation of token rates is smaller than link capacity
 - The summation of token depth is less than available buffer space
- Properties
 - Zero losses
 - Delay guarantees depending on number of calls and token depth
 - Low utilization
- If used scheduler is WFQ (see slides on scheduling)
 - Can allocate bandwidth to
 - Satisfy the worst case delay along the path
 - Bound the buffer size to avoid packet losses

Example of statistical guarantees

- Adopting statistical instead of deterministic guarantees provides significant benefits
- Example
 - 10 identical sources with rate 1.0
 - Each source active with probability 0.1
- What is the probability of overloading a link of capacity 8.0?
- If sources are independent, probability of having n active sources

$$\binom{10}{n} 0.1^n 0.9^{10-n}$$
- Probability of overloading smaller than 10^{-6}
- By allowing a very small overflow probability, resource requirements are reduced by 20%

Equivalent bandwidth CAC

- DATA:
 - Traffic characterization (peak rate, average rate, burst duration,...)
 - QoS requirements (mainly cell loss)
 - Traffic behavior of other calls
- OUTPUT:
 - Equivalent bandwidth (bandwidth needed to satisfy call QoS requirements)
- Call k is accepted over a link with capacity C if:

$$B_{eq}^{(k)} \leq C - \sum_{i \text{ acc.}} B_{eq}^{(i)}$$

How to compute equivalent bandwidth: traffic model

- To compute B_{eq} a traffic model must be used:
 - Define the source stochastic behavior
 - Emulate (or solve) the system under study, which comprises all previously accepted calls plus the new call
 - Determine the bit rate that should be allocated to the new call to satisfy the QoS needs
- Several models were proposed
 - Some take into account even buffer size
- B_{eq} often assumes a value ranging between B_M and B_P
 - B_{eq} can be larger than B_P if delay constraints are very tight
 - B_{eq} is never smaller than B_M

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Equivalent bandwidth: an example

- Assume a fluid approximation
 - Buffer size B
 - Buffer is drained at a constant rate e
 - Worst case delay B/e
 - The equivalent bandwidth is the value of e that makes the loss probability smaller than a given value
 - Jointly provides bandwidth, loss and delay guarantees

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Equivalent Bandwidth CAC

- Permits to compute a service rate adequate to guarantee call QoS
 - This rate can be used to allocate bit rate resources within nodes
- The method works properly if the traffic model is realistic, i.e. if the traffic generated by the call is similar to the one defined by the model
- Difficult to extend to sequence of links
 - Multiplexing effect modifies traffic shape
- Can be computation intensive to solve the model on-line, i.e. for each new incoming call

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Equivalent Bandwidth CAC

- As an alternative, it is possible to define a (small) set of traffic classes, where each class is identified by the same
 - Traffic characterization
 - QoS requests
- If the traffic classes are known a-priori, it is possible to pre-compute (off-line)
 - B_{eq} required by each call of each class, therefore the number of calls acceptable on each link for each class
 - Since it is off-line, it is also possible to use more complex (and hopefully more efficient) models

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Equivalent Bandwidth

- The off-line approach constraints user traffic generation and QoS requirements to simplify the on-line CAC procedure
- Traffic classes are derived from applications run by the users
 - Applications development much faster than network standard modification
- Mix the off-line and the on-line approach?
 - Not easy
 - Can be done by statically partitioning link bandwidth
 - Create two virtual infrastructures and manage them separately

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Measurement based CAC

- Normally used with a very simple traffic characterization
 - E.g., call peak rate B_p
- Basic idea
 - Measure the traffic load on each link in real time
 - this is normally done anyway in network devices
 - This measure, performed over a pre-defined measurement interval, permits to compute the residual available bandwidth
 - Call k is accepted if: $B_p^{k,i} \leq B_{measured_available_bit_rate}$
- Note that after acceptance, calls are accounted for their real traffic, not on the basis of declared parameters
- Useful if traffic characterization parameters or network status are unknown or known with a large error
- Normally leads to high link utilization
 - Difficult to guarantee QoS

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Measurement based CAC

- Disadvantages/problems:
 - Measurement parameter setting (e.g., measurement window duration)
 - Window too large implies more stable but less reactive estimate
 - Window too short may provide unreliable estimate
 - Implicit assumption that accepted call behavior is similar during a measurement interval
 - Measurement errors
 - If too many calls arrive during a measurement period
 - Many calls are rejected, since they are accepted on the basis of their peak rate
 - Useful for CAC only, but no information on the bit rate that should be allocated to calls to guarantee QoS
 - Very difficult to predict call QoS a priori

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CAC issues

- Un-fairness for calls requiring higher bit rate in saturated conditions
 - Resource partitioning
- Difficult to extend algorithms to several consecutive links
 - Users are interested in end to end quality, non in single hop behavior
- Renegotiation may be interesting?

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