High-Performance Networking
The University of Kansas EECS 881
Control and Signalling

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Network Control and Signalling

Outline

CS.1 Signalling paradigms
CS.2 Traffic management
CS.3 Path routing dynamics
CS.4 Monitoring and management (brief)
Network Control and Signalling

Outline

CS.1. Signalling paradigms
CS.2. Traffic management
CS.3. Path routing dynamics
CS.4. Monitoring & management
Network Control and Signalling

CS.1 Signalling Paradigms

CS.1 Signalling paradigms
- CS.1.0 Delay constituents
- CS.1.1 Message and circuit switching
- CS.1.2 Packet switching
- CS.1.3 Fast packet switching
- CS.1.4 Intermediate control mechanisms
- CS.1.5 Fast circuit and burst switching

CS.2 Traffic management
CS.3 Path routing dynamics
CS.4 Monitoring and management
Signalling Paradigms
Delay Constituents

- **Propagation delay** $t_p$
  
  $= \frac{x_{ij}}{kc}$

  - distance $x_{ij}$
  
  - velocity of light $c$

  - medium dependent constant $k \approx 0.7$

- **Transmission delay** $t_b$
  
  $= \frac{b \ [b]}{r \ [b/s]}$

- **Switching delay** $t_s$ or $t_r$
  
  $= t_f + t_q$

  - forwarding delay $t_f$

  - queuing delay $t_q$
Signalling Paradigms

Delay Constituents

- Packets are parallelograms \((t_b\) thick)  
- Messages are directed line segments (ignore \(t_b\))
Signalling Paradigms

1st Generation

- Message switching
- Circuit switching
Signalling Paradigms

Message Switching

- Messages
  - variable length messages
  - transmitted on link as needed

Examples?
Signalling Paradigms
Message Switching

- Messages
  - variable length messages
  - transmitted on link as needed

- Examples
  - early data networks
Signalling Paradigms
Message Switching

- First generation (<1970)
  - data switching technique

"characteristics?"
Signalling Paradigms
Message Switching

- Characteristics
  - no setup latency
Signalling Paradigms
Message Switching

• Characteristics
  + no setup latency
  – significant delay
    • store-and-foreword delay
Signalling Paradigms
Message Switching

- Characteristics
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    • store-and-forward delay
Signalling Paradigms
Message Switching

- Characteristics
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    • store-and-foreword delay
  + some multiplexing efficiency
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    • store-and-foreword delay
    • small messages delayed (buffered) behind large ones
Signalling Paradigms
Message Switching

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Message Switching

- Characteristics
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    - significant delay
      - store-and-foreword delay
      - small messages delayed
      - $d_r \gg d_t$
Signalling Paradigms

Circuit Switching

- Circuits
  - physical path established
  - circuit state to establish and maintains path

Examples?
Signalling Paradigms
Circuit Switching

• Circuits
  – physical path established
  – circuit state to establish and maintains path

• Examples
  – early PSTN
  – early X.21 circuit switched networks
  – modern optical WDM lightpaths
Signalling Paradigms

Circuit Switching

- Circuit signalling
  - PSTN switching technique

characteristics?
Signalling Paradigms

Circuit Switching

- Circuit signalling characteristics
  - setup latency
Signalling Paradigms

Circuit Switching

- Circuit signalling characteristics
  - setup latency
Signalling Paradigms

Circuit Switching

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Signalling Paradigms
Circuit Switching

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Signalling Paradigms

Circuit Switching

- Circuit signalling characteristics
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Signalling Paradigms
Circuit Switching

- Circuit signalling characteristics
  - setup latency

CONNECT
Signalling Paradigms
Circuit Switching

- Circuit signalling characteristics
  - setup latency: RTT *before* data transfer
  - circuit seized *implication?*
Signalling Paradigms

Circuit Switching

• Circuit signalling characteristics
  – setup latency: RTT *before* data transfer
  – circuit seized
    • no multiplexing efficiency
Signalling Paradigms

Circuit Switching

- Circuit signalling characteristics
  - setup latency: RTT before data transfer
  - circuit seized
    - no multiplexing efficiency
Signalling Paradigms

Circuit Switching

- Circuit signalling characteristics
  - setup latency: RTT before data transfer
  - circuit seized
    - no multiplexing efficiency
    - silence unusable by others
Signalling Paradigms

Circuit Switching

- Circuit signalling characteristics
  - setup latency: RTT *before* data transfer
  - no multiplexing efficiency
  - negligible switch latency
Signalling Paradigms

Circuit Switching

- Circuit signalling characteristics
  - setup latency: RTT *before* data transfer
  - no multiplexing efficiency
  + negligible switch latency
  - resources must be released
Signalling Paradigms

Circuit Switching

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Signalling Paradigms
Circuit Switching

- Circuit signalling characteristics
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Signalling Paradigms

1st Generation Comparison: Circuit vs. Message
Signalling Paradigms

2nd Generation

• How to do better than

message switching?

circuit switching?
Signalling Paradigms
2nd Generation

• How to do better than…
  – ...message switching: (connectionless) packet switching
    circuit switching?
Signalling Paradigms
Datagram Packet Switching

- Packetise message into *datagrams*
  - improvement over message switching
  - reduces queueing delay behind long messages
Signalling Paradigms
Datagram Packet Switching

- Connectionless
  - no per flow state *required* to forward information
  - but there still is state
    *what?*
Signalling Paradigms
Datagram Packet Switching

• Connectionless
  – no per flow state *required* to forward information
  – but there still is state
    • forwarding tables
  – other state may be used to improve performance
    • per-flow queueing
    • soft state flow identification to improve performance

*Examples?*
Signalling Paradigms
 Datagram Packet Switching

• Connectionless
  – no per flow state *required* to forward information
  – but there still is state
    • forwarding tables
  – other state may be used to improve performance
    • per-flow queueing
    • soft state flow identification to improve performance

• Examples
  – IP (Internet protocol)
  – CLNP (connectionless layer network protocol)
    [ISO/IEC 8473 / ITU X.223]
Signalling Paradigms

Datagram Packet Switching

- Each datagram contains a *destination address*
Signalling Paradigms

Datagram Packet Switching

- Each datagram contains a *destination address*
- Each switch hop does a *lookup in a forwarding table*
  - outgoing port = lookup (destination address)

*lecture SR*
Signalling Paradigms
Datagram Packet Switching

• Each datagram contains a *destination address*
• Each switch hop does a *lookup* in a *forwarding table*
  – outgoing port = lookup (destination address)
• Table lookup efficiency depends on:
  – address structure (e.g. class-based IP vs. CIDR)
  – address length
  – tables length (# destinations per switch/router)

*Example?*
Signalling Paradigms
Datagram Packet Switching

- Each datagram contains a *destination address*
- Each switch hop does a *lookup* in a *forwarding table*
  - outgoing port = lookup (destination address)
- Table lookup efficiency depends on:
  - address structure (e.g. class-based IP vs. CIDR)
  - address length
  - tables length (# destinations per switch/router)
- Example: IP
  - note: IP lookup could not be done at line rate in 1980s
  *more later*
Signalling Paradigms
Datagram Packet Switching

- Connectionless signalling
  *characteristics?*
Signalling Paradigms
Datagram Packet Switching

- Characteristics
  + no setup latency
Signalling Paradigms
Datagram Packet Switching

- Connectionless signalling
  + no setup latency
  - store-and-foreword lookup delay

Diagram showing the flow of information between nodes S, 1, 2, and R.
Signalling Paradigms
Datagram Packet Switching

- Connectionless signalling
  + no setup latency
  - store-and-forward lookup delay
Signalling Paradigms
Datagram Packet Switching

- Connectionless signalling
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  + multiplexing efficiency
Signalling Paradigms
Datagram Packet Switching

- Connectionless signalling
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- large messages broken into packets
Signalling Paradigms
Datagram Packet Switching

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Signalling Paradigms
Datagram Packet Switching

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  + other flows interleave
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Datagram Packet Switching

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- large messages broken into *packets*
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Signalling Paradigms
Datagram Packet Switching

- Connectionless signalling
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Signalling Paradigms
Datagram Packet Switching

- **Connectionless signalling**
  - + no setup latency
  - - store-and-foreword lookup delay
  - + multiplexing efficiency
- **large messages broken into packets**
- + other flows interleave
Signalling Paradigms
Datagram Packet Switching

- Connectionless signalling
  - no setup latency
  - store-and-foreword lookup delay
  - multiplexing efficiency
- large messages broken into packets
- other flows interleave
- $d_r > d_t$
Signalling Paradigms

Improvement of Packet over Message Switching

\[ d_t \]

\[ d_r \]
Signalling Paradigms
3rd Generation

• How to do better than...
  – ...message switching: (connectionless) packet switching
    circuit switching?
Signalling Paradigms
3rd Generation

- How to do better than...
  - ...message switching: (connectionless) packet switching
  - circuit switching: virtual circuit fast packet switching
Signalling Paradigms
Connection-Oriented Fast Packet Switching

• Connection-oriented
  – improvement over circuit switching
  – no *physical circuit* reserved
  – connection state *required*
  – performance optimisations possible to reduce setup latency
    • fast reservations
    • optimistic connection establishment
    • per hop acknowledgements
    • parameter negotiation

*Examples?*
Signalling Paradigms
Connection-Oriented Fast Packet Switching

• Examples
  – CONS (connection-oriented network service)
    PSPDNs (packet-switched public data networks)
    [ISO/IEC 8878+8208 / ITU X.25]
  – ATM
  – MPLS
  – modern PSTN
    • wired
    • wireless (although migrating to IP)
Signalling Paradigms
Connection-Oriented Fast Packet Switching

- Combine benefits of datagram and circuits
  - statistical multiplexing gains of datagrams
  - forwarding performance circuits
    - eliminate store-and-forward
    - high-performance switch design
    *details in Lecture SR*
  - provision of QOS
    - admission control
    - resource reservation per connection
Signalling Paradigms

Connection-Oriented Fast Packet Switching

Characteristics?
Signalling Paradigms
Connection-Oriented Fast Packet Switching

• Connections:
  establish state once to reduce per packet processing
  - RTT delay before data transfer
    o amortised for long flows
    - expensive for transactions
  + high throughput possible
  + optimisations to reduce setup latency (later)
Signalling Paradigms
Comparison of Characteristics

- Connectionless vs. connection-oriented networks
  - major debate in 1980s and 1990s

- Comparison of characteristics

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*in theory, but higher-level (TCP) connections may time out
## Signalling Paradigms
### Comparison of Characteristics

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Signalling Paradigms
Connections vs. Connectionless

- Connections enabled fast switching in the 1980s
  - standardised as ATM, but with serious flaws
- Difficult tradeoffs between two paradigms
  - trade setup latency vs. throughput efficiency

Intermediate schemes?

Connectionless vs. Connection Tradeoff

The latency of connection setup must be traded against the reduction in the end-to-end data transfer delay due to the elimination of store-and-forward delay, and faster transmission of due to nodes capable of increased bandwidth.
Signalling Performance
Efficiency and Robustness

- Signalling complexity tradeoff between
  - needed functionality
  - simple state machines and message formats
- Signalling protocols must be robust to lost messages
  - state machine must account for this
  - messages should fit in single packet
    - reliable hop-by-hop protocols add significant complexity
    - (e.g. ATM S-AAL)

**Efficiency of Signalling**

*Signalling messages should be simple in coding format and fit in a single packet to minimise the latency in processing. The signalling protocol should be robust to lost messages.*
Signalling Performance
Round Trips Minimisation

• Techniques to minimise control round trips problem?
Signalling Performance
Round Trips – E2E ACKs

- E2E handshake
  - requires RTT timeout
  - for all connect failures

Alternative?
Signalling Performance
Round Trips – HBH Supplemental ACKs

- E2E handshake
  - requires RTT timeout
  - for all connect failures

- HBH ACKs
  - quicker local recovery
Signalling Performance
Round Trips Minimisation

• Techniques to minimise control round trips
  – hop-by-hop acknowledgements
    *what about failure in SETUP parameters?*
Signalling Performance
Round Trips – Negotiation Failures

- Specific parameters
  - exact match or...
  - another RTT attempt

*Alternative?*
Signalling Performance
Round Trips – Range Parameters

- Specific parameters
  - exact match or...
  - another RTT attempt

- Incremental negotiation
  - initiator gives range or set
  - destination ACKs capabilities
Signalling Performance
Round Trips Minimisation

• Techniques to minimise control round trips
  – hop-by-hop acknowledgements
  – parameter ranges
    • desired – minimum acceptable
    • desired, alternate

*is one RTT before data flows necessary?*
Signalling Performance
Round Trips – Data Waits for Control

• Separate phases
  – control to establish path
  – when successful: transfer data

*Alternative?*
Signalling Performance
Round Trips – Overlap Control/Data

- Separate phases
  - control to establish path
  - when successful: transfer data

- Overlap control/data
  - control to establish path
  - optimistically transfer data
  - when successful continue transferring
Signalling Performance
Round Trips Minimisation

- Techniques to minimise control round trips
  - hop-by-hop acknowledgements
  - parameter ranges
    - desired – minimum acceptable
    - desired, alternate
  - overlap of control and data

Minimise Round Trips

Structure control messages and the information they convey to minimise the number of round trips required to accomplish data transfer.
Signalling Paradigms
Intermediate Mechanisms

Tradeoffs between packet and circuit switching?
Signalling Paradigms
Intermediate Mechanisms

• Spectrum of signalling paradigms
  – per message forwarding (message switching)
  – per packet datagram forwarding
  – data-driven soft state accumulation
  – control-driven soft state accumulation
  – optimistic connection establishment
  – fast reservation
  – explicit virtual connection setup – fast packet switching
  – scheduled connection sharing – burst switching
  – explicit physical connection setup – circuit switching

• Intermediate mechanisms benefit from extremes
Signalling Paradigms

Intermediate Mechanisms

- Intermediate mechanisms benefit from extremes
  - benefits of state accumulation (from connections)
  - benefits of immediate transmission of data (from datagrams)

Network Path Establishment

The routing algorithms and signalling mechanisms must be capable of forwarding datagrams or establishing connections on sufficiently high-performance paths and with low latency to meet application needs.
Intermediate Signalling Paradigms
Soft State Accumulation

- **Features**
  - allow immediate packet send
  - once state established: fast lookup and forwarding

- **Variants**
  - data driven
    - switch detects flow from headers
  - control driven
    - explicit inter-switch signalling
      - e.g. MPLS
Intermediate Signalling Paradigms
Optimistic Connection Establishment

- Significant delay results from round trips
  - overlapping connection setup with data transfer to reduce

Overlap Signalling Messages with Data Transfer

To reduce unneeded end-to-end latency, signalling messages should be overlapped with data transfer.
Intermediate Signalling Paradigms

Optimistic Connection Establishment

• **Features**
  – data sent with signalling
  – until COMMIT returned:
    • best effort or
    • per hop fast reservation
Intermediate Signalling Paradigms
Burst Switching

- **Features**
  - packets group into bursts
  - bursts scheduled in circuit

- **Role**
  - optical networks: no photonic header processing

- **Variants**
  - release: signalled or timed
  - in- or out-of band signalling
Multicast Signalling

Root vs. Leaf Join

- Root join
  + simple
  - doesn’t scale

- Leaf join
  - complex
  + scales

Root vs. Leaf Multicast Control

Root multicast control is appropriate when a single entity has knowledge of the multicast group. Leaf-controlled multicast is needed for large multicast groups.
Session Control
Signalling Efficiency

- Session control (layer 5)
  - set of transport layer associations (layer 4)
  - point-to-point or multipoint (may be mixed)
  - connection oriented or connectionless (may be mixed)
Session Control
Signalling Efficiency

• Session control (layer 5)
  – cross-layer controls
  – allow overlap of signalling
  – reduction in round trips

Session–Connection Interlayer Awareness

Session control awareness of network layer control parameters allows the overlap of session and connection control signalling to reduce overall latency.
Session Control

Signalling Efficiency

- Latency reduction
  - minimise round trips
  - parallelise session and network signalling
  - properly locate resources
Network Control and Signalling

CS.2 Traffic Management

CS.1 Signalling paradigms

CS.2 Traffic management
  CS.2.1 Resource reservation
  CS.2.2 Network-based congestion control

CS.3 Path routing dynamics

CS.4 Monitoring and management
Traffic Management

Goals

• Conflicting goals:
  – path protection:
    sufficient resources to deliver required QOS to users
  – minimise network resource use to keep costs low

Network Path Protection

QOS mechanisms must be capable of guaranteeing bandwidth and latency bounds, when needed.
Traffic Management
Optimality

• Support for mixed traffic
  – distinct networks (1st and 2nd generations through 1980s)
  – virtual network partitioning
  – differentiated services: coarse grained service grades
  – integrated services: fine grained traffic classes
    • e.g. ATM-TM and intserv with RSVP
Traffic Management

Optimality

• Optimal bandwidth reservation
  – significant cost in reservation processing
  – significant cost in state management

• Balance
  – simpler admission control with some overengineering

Optimal Resource Utilisation vs. Overengineering

Tradeoff

Balance the tradeoff of optimal resource utilisation and its associated complexity and cost against the cost of suboptimal resource utilisation resulting from overengineering the network.
Network Congestion Control

Motivation

• Limit transmission to prevent overwhelming network
  – reservations are generally statistical
    • congestion can occur if there is any overbooking of resources
  – best-effort traffic must be limited to avoid congestion
  – not all end users will behave as they should

• Benefits from network assistance

Congestion Control in the Network Improves Performance

Even though the end-to-end protocols must perform congestion control, there is substantial performance benefit in assistance from the network.
Network Congestion Control

Performance Goal

- Goals
  - congestion control in the network reduces control loop delay
Network Congestion Control

Congestion Avoidance

- Congestion Avoidance
  - reacts to impending congestion *before* damage is done
    - e.g. RED (random early detection)
  - keep queues as short as possible
    - jitter and bursty arrivals

Avoid Congestion and Keep Queues Short

Avoid congestion by network engineering, traffic management with resource reservation, and by dropping packets. Buffers should be kept as empty as possible, with queueing only for transient situations, to allow cut-through, and avoid the latency of FIFO queueing.
Network Congestion Control
Fairness vs. Complexity

• Fairness
  – desirable to allow fair sharing of network
  – difficult to discriminate well-behaved and misbehaving flows
  – fair mechanisms substantially more complex to implement
    • but can be done with current technology

Congestion Control Fairness vs. Complexity

The lack of fairness in simple congestion control and avoidance mechanisms must be traded against the complexity of fair implementations.
Network Control and Signalling

CS.3 Path Routing Dynamics

CS.1 Signalling paradigms
CS.2 Traffic management
CS.3 Path routing dynamics
  4.3.1 Multipoint groups
  4.3.2 Node mobility
CS.4 Monitoring and management
Path Routing Dynamics
Dynamic Network Behaviour

- Dynamic network behaviour
  - leads to low performance paths over time
  - multipoint groups
    - prune and reroute to maintain optimal topology
  - node mobility
    - reconfigure topology to maintain performance

Dynamic Path Rerouting

*Dynamic behaviour can require adjustments to topology to maintain a high-performance path. The overhead and frequency of topology maintenance must be traded against the lack of optimality.*
Path Routing Dynamics

Node Mobility

- Node mobility changes path characteristics

- Example
  - $d_1 + d_2 < D_a$
  - intermediate node moves away
  - latency bound exceeded: $d_1 + d_2 > D_a$
  - reroute path
  - $d_3 < D_a$
Path Routing Dynamics
Multipoint Groups

- Multipoint spanning tree
  - optimised to receiver group...
  ...at a particular point in time
Path Routing Dynamics

Multipoint Groups

- Dynamic behavior
  - changes topology
  - latency bounds may be exceeded
  - bandwidth wasted
- Receivers leave group
  - inefficient path to remaining members
  - links carrying traffic to no receiver
Path Routing Dynamics

Multipoint Groups $\text{3}$

- Prune and reroute tree
  - optimise to remaining group
  - reroute to group members
  - prune unneeded leaf hops
Network Control and Signalling
Monitoring and Management

CS.1  Signalling paradigms
CS.2  Traffic management
CS.3  Path routing dynamics
CS.4  Monitoring and management
Monitoring and Management

Issues

- Coarse granularity
  - management not high-speed, per se
- Issues
  - management must keep up with rapidly changing conditions
  - massive amounts of data must be filtered and reduced
  - monitoring should not interfere with high-speed flows

Network Monitoring Locality

Network monitoring functions must be built into the critical path to provide non-intrusive local filtering and aggregation of statistics.
Control and Signalling

Acknowledgements

Some material in these foils comes from the textbook supplementary materials:

- Sterbenz & Touch, *High-Speed Networking: A Systematic Approach to High-Bandwidth Low-Latency Communication*
  http://hsn-book.sterbenz.org