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

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 $t_p$
  \[ t_p = \frac{x_{ij}}{kc} \]
  - distance $x_{ij}$
  - velocity of light $c$
  - medium dependent constant $k \approx 0.7$

• Transmission delay $t_b$
  \[ t_b = \frac{b \text{ [b]}}{r \text{ [b/s]}} \]

• Switching delay $t_s$ or $t_r$
  \[ t_s = t_f + t_q \]
  - forwarding delay $t_f$
  - queuing delay $t_q$

Packets are parallelograms ($t_p$ thick)
Messages are directed line segments (ignore $t_b$)
Signalling Paradigms

1st Generation

- Message switching
- Circuit switching

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
  - significant delay
    - store-and-forward delay
Signalling Paradigms
Message Switching

- Characteristics
  + no setup latency
  - significant delay
    • store-and-foreword delay

+ some multiplexing efficiency
Signalling Paradigms

Message Switching

• Characteristics
  + no setup latency
  - significant delay
    • store-and-forward delay
  + some multiplexing efficiency
  - small messages delayed (buffered) behind large ones
Signalling Paradigms

Message Switching

• Characteristics
  + no setup latency
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  - significant delay
    • store-and-foreword delay
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[Diagram showing message switching]
Signalling Paradigms
Message Switching

• Characteristics
  + no setup latency
  + some multiplexing efficiency
  - significant delay
    • store-and-forward delay
    • small messages delayed (buffered) behind large ones
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

• First generation (<1970)
  - PSTN switching technique

Characteristics?

- setup latency
Signalling Paradigms

Circuit Switching

• Characteristics
  - setup latency
Signalling Paradigms

Circuit Switching

• Characteristics
  - setup latency
Signalling Paradigms

Circuit Switching

• Characteristics
  - setup latency

CONNECT SR 12

• Characteristics
  - setup latency: RTT before data transfer
  - circuit seized implication?
Signalling Paradigms

Circuit Switching

• Characteristics
  - setup latency: RTT before data transfer
  - circuit seized
    • no multiplexing efficiency
Signalling Paradigms

Circuit Switching

- **Characteristics**
  - **setup latency**: RTT *before* data transfer
  - circuit seized
    - no multiplexing efficiency
    - silence unusable by others

![Diagram of Circuit Switching]
Signalling Paradigms

Circuit Switching

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

Circuit Switching

• Characteristics
  - setup latency: RTT before data transfer
  - no multiplexing efficiency
  + negligible switch latency
  - resources must be released

[Diagram showing circuit switching process]
Signalling Paradigms

1st Generation Circuit vs. Message Switching

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?*

• 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?

• 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]

• 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)

*Example?*
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

connectionless signalling

characteristics?
Signalling Paradigms

Datagram Packet Switching

- Characteristics
  - no setup latency
  - store-and-forward delay
Signalling Paradigms

**Datagram Packet Switching**

- Characteristics
  + no setup latency
  - store-and-forward lookup delay
  + multiplexing efficiency
Signalling Paradigms

**Datagram Packet Switching**

- Characteristics
  - no setup latency
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  - large messages broken into *packets*

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Signalling Paradigms

Datagram Packet Switching

• Characteristics
  + no setup latency
  - store-and-forward lookup delay
  + multiplexing efficiency
  • large messages broken into *packets*
  + other flows interleave
Signalling Paradigms

Datagram Packet Switching

• Characteristics
  + no setup latency
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  • large messages broken into packets
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HSN-CS-59
Signalling Paradigms
Datagram Packet Switching

- Characteristics
  + no setup latency
  - store-and-foreword lookup delay
  + multiplexing efficiency
  • large messages broken into packets
  + other flows interleave

• $d_r > d_f$
Signalling Paradigms

Improvement of Packet over Message Switching

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

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)

• 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 5R
  - provision of QOS
    • admission control
    • resource reservation per connection
Signalling Paradigms
Connection-Oriented Fast Packet Switching

*Characteristics?*

- Connections:
  establish state once to reduce per packet processing
  - RTT delay before data transfer
    - amortised for long flows
    - expensive for transactions
  + high throughput possible
  + optimisation 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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### Signalling Paradigms

#### Comparison of Characteristics

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

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<td>datagrams lost</td>
<td>connections terminated</td>
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<td>QOS</td>
<td>difficult</td>
<td>connection reservation</td>
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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

  \textit{what about failure in SETUP parameters?}

Signalling Performance

Round Trips – Negotiation Failures

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

  \textit{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

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.

• 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

• 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.

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\textsubscript{2}

- 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\textsubscript{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
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CS.4 Monitoring and management

Monitoring and Management

- 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