SS7 and Frame Relay

Outline

- Signalling principles
- SS7 & telephone networks
- Nodes
- Networks and links
- Protocol stack
  - Message Transfer Part (MTP) 1
  - MTP 2
  - MTP 3
  - SCCP & ISUP
  - call example
  - TCAP
- X.25
- End-to-end arguments
- Frame Relay

Resources

- Keshav: Signalling: §14.8 (generic), § 2.5 (telephone), § 15.2.4 (SS7)

Why look at such old protocols?

SS7 is used in telephone networks:
- Important to understand such a widespread network
- Important when developing mobile phone technology
- Likely to persist: Voice payload may be carried over IP (VOIP), but SS7 signalling is entrenched (SCTP/IP may replace SS7’s lower layers, i.e. Network Services Part). SIP may eventually replace SS7.
- Basis for newer protocols, e.g. Q.931 for phones → Q.2931 for ATM

X.25: Transition from public phone networks to public data networks. VCs. Contrast with Internet protocols.

Frame Relay: Traffic management, ECN→IP in 2001
Signalling for switching

Signalling: The exchange of information for the purpose of managing a flow of information. In particular, to establish and release connections.

Tends to be implemented over a packet-switched or broadcast&select network

Examples:
- PSTN uses packet-switched SS7 signalling network
- ATM broadcasts initial signalling message on specified VP/VCI
- optical circuit-switched network may have ancillary electronic packet-switched network for signalling.

† Often spelled “signaling” by Americans

Timing of circuit establishment

Using a partial circuit
Circuit usage over time

X1 hunts for link leading to D
X2 hunts for link leading to D
(Feedback to source)

Data transfer

Separate setup and transfer phases ⇒ notion of “connection-oriented”

Tidbits about signalling

- Duration of transfer determines significance of signaling overheads
- e.g. 80ms RTT insignificant compared to voice call of minutes, but appreciable compared to transaction of single packet

- Signalling between switches:
  - Pushing reduces number of passes of signalling messages,

What is signalled

- Admission control, billing
- Routing, e.g. translate 1300 number to select line to call
  - hypothetical e.g. 132 651 = Westpac Personal loan enquiries
  - calls from Maroubra exchange → Randwick office
  - calls from Vaucluse → merchant banking department
  - calls from Redfern → debt collection department
- Resource reservation (tentative at first, then confirmed)
  - User is concerned with end-to-end performance.
  - Must translate this to local (per-hop) performance requirements.
  - Often start aggressively to see if the end performance is achievable, then relax.
- Parameter negotiation – eliminate options that aren’t supported
- Change call’s characteristics during the call, e.g. renegotiate service contract, forward call
Signalling interfaces

Signalling occurs at two different places:

- **Access signalling**: At User-Network Interface (UNI)
  - e.g. Digital Subscriber Signalling System No. 1 (DSS1 – Q.931)
- **Network signalling**: Within the network at NNIs (Network Node Interfaces or Network-Network Interfaces)
  - e.g. Signalling System No. 7 (SS7)

ATM Forum distinguishes between interfaces to Private (P) or Public (N) networks:

- **Private interfaces**: [ATM Forum] UNI, P-NNI @ NNI
- **Public interfaces**: Q.2931 @ UNI, B-ICI/B-ISUP @ NNI

Types of signalling

Q1: Are signals carried by the same channel that carries payload?

- **yes**: In-band signalling (signal also follows same path)
  - e.g. UNI: DTMF=In-band
  - ISDN D channel = out-of-band (payload on separate B channel)
- **no**: Out-of-band signalling

Q2: For out-of-band signalling: Do signals and payload follow the same path through the network?

- **yes**: Associated signalling: follows same path as payload, but in a separate channel (e.g. US phone lines: 64kb/s 8b PCM samples @ 8kHz. But 1b in 8 for signalling = maximum of 56kb/s data)
- **no**: Non-associated signalling (e.g. SS7)

† DTMF = Dual-Tone Multi-Frequency aka ‘touch tone’
Simultaneously send two tones selected from a set of 8

Out-of-band signalling: Advantages

- **Higher speed**: For signalling: e.g. 56kb/s vs DTMF pulsing
- **For payload**: Separating signalling from simpler payload transfer may simplify payload processing
- **Facilitates signalling during the call**, rather than signalling only before the call (assuming circuit-switching)
- **Signalling and payload transfer can evolve separately**, e.g. phone signalling advances
- **Signalling & payload paths can differ**, e.g. signals via databases not en-route to destination
- **Easier to ensure reliable transfer of signalling**, despite overload of payload, e.g. reduce misdelivery rate (reliable addressing of connection)

In-band signalling: Advantages

- **Detect impairments on path** used for payload when signalling
  - e.g. e2e signalling won’t succeed when payload can’t be transferred.
- **Allows piggybacking of payload** with initial signalling, reducing impact of delay

  - e.g. TCP: SYN/ACK (signalling):
    - unlikely to get through unless data segments can get through
    - can carry payload (though data not delivered until 3-way handshake is complete)
Two-pass resource reservation signalling

Signalling to reserve resources often involves negotiation:

- Initiator may have certain requirements and desires
  e.g. voice call may require e2e delay<100ms & 10kb/s
desire up to 64kb/s
- Network may not be able to satisfy all desires → negotiate
  intermediate level of service
  e.g. voice call may be allocated 32kb/s

Two-pass signalling example

First pass: initiator requests service (need 10kb/s, desire: 64kb/s)
As request propagates to target, it can:
- Collect information about the capacity of devices on the path to serve the
  request.
- Make tentative reservations for resources (64kb/s at leftmost switch, but
  scaled down to 32kb/s by middle switch, and hence only 32kb/s for
  rightmost switch).
Target can decide reservation level.
Second pass: Reply propagates to initiator, and commits to reservations, releasing
excess resources.

Sender vs receiver initiated signalling

Who initiates the signalling? Sender or receiver?
- ATM & telephone signalling: sender-initiated (“push”)
- Internet signalling (e.g. RSVP) tends to be receiver-initiated (“pull”)

Sender can’t transmit payload until resources have been confirmed
- If sender initiates signalling, then it receives confirmation through signalling
  response (1 RTT after sending request).
- If receiver initiates signalling, then sender learns about tentative reservation after
  first pass, but only confirms reservation after a third pass.
  (receiver-initiated signalling needs an extra pass & incurs more delay)

Multicast complicates sender-initiation

Sender-initiated signalling is difficult with multicast communication:
- Sender needs to know about all receivers:
  - identity (to transmit to them)
  - capabilities (to transmit at correct rate, format, etc)
- Scalability: Sender incurs a burden that increases in
  proportion to the number of receivers.
Signalling is hard

**Dumb terminals**, e.g. telephones (traditionally), so complex signalling functionality in network

Large feature set (extended by competing service providers) + feature interaction (e.g. should call filtering be enabled when calls are being forwarded to a messaging service?)

Must still be able to extend & maintain

Need speed: communication can’t progress while signalling

Need reliability, e.g. for emergency phone calls

Need interoperability between multiple vendors

### Outline

**Telephone signalling: UNI**

Originally: pulse code – for stepping switches

- Number of pulses in the digit would tell the step switch how far to rotate.
- First digits direct local exchange to go to appropriate peer exchange
- Last digits specify line within target exchange

Later: DTMF

Standard: Q.931/4.451

**Telephone signalling: NNI**

Originally: pulse code, same as UNI

Later: transmitted in-band, e.g. 1 bit of voice channel used every 2.5ms to indicate loop supervision current

- Poor security
- Inflexible: Signaling must follow same path as voice

Signalling System No. 7 (SS7)

Voice trunks originate and terminate at “Local Exchanges” (LEs) ... and may be switched through “Transit Centres” (TCs).

Each LE & TC has a Service Switching Point (SSP)

SSPs are only used for signalling. They are co-located with voice service switching points, but don’t themselves switch.

SSPs exchange signalling information using the SS7 protocol across a Common Channel Interoffice Signaling (CCIS) network

Signalling network operates in parallel with information transfer network

Note: circuit-switched network is supported with a packet-switched signalling network

SS7 nodes

Service Switching Point (SSP)
- Originates and terminates SS7 messages
- Located at end offices, or access tandem devices
- Runs the Transaction Capabilities Application Part (TCAP)
- Voice trunks (service) are switched at SSP locations, signals are switched by STPs
- Drawn as circles

Service Control Point (SCP)
- Provides database operations to another SCP or SSP, e.g.
  - Call Management Services DB: translates 1800 numbers into POTS numbers
  - Line Information DB: billing, calling card, collect/reverse-charges services
  - Mobility management: home & visitor location registers
- Drawn as cylinders

SP (Signalling Point) = SSP or SCP
SS7 nodes (continued)

Signalling Transfer Point (STP)
- Switches signalling traffic
- Includes MTP3 and SCCP
- Drawn as squares with a diagonal line (sometimes just squares)

To provide fault tolerance, SCPs and STPs are installed as "mated pairs", each in a different geographic location.

Identifying nodes

Point codes uniquely identify Signalling Points
US: 3 bytes: network-cluster-member, e.g. 124-88-31

Terminals (e.g. phone lines) are given "titles" according to the E.164 numbering plan
Initial digit of prefix indicates region:

<table>
<thead>
<tr>
<th>Region</th>
<th>Prefix</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 North America</td>
<td>1</td>
<td>US, Canada, Belize</td>
</tr>
<tr>
<td>2 Africa</td>
<td>2</td>
<td>Former USSR</td>
</tr>
<tr>
<td>3 Europe (port)</td>
<td>3</td>
<td>China, Japan and Pacific</td>
</tr>
<tr>
<td>4 Europe (port)</td>
<td>4</td>
<td>India and Middle East</td>
</tr>
<tr>
<td>5 Central and South America</td>
<td>5</td>
<td>Australia and Pacific, e.g. 61 for Australia</td>
</tr>
</tbody>
</table>

SS7 network architecture
Quad = 2 mated pairs of STPs
Network is hierarchical

SS7 link types
Letter | Name | Connects |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Access</td>
<td>STP-SP (local)</td>
</tr>
<tr>
<td>B</td>
<td>Bridge</td>
<td>STPs @ same level, but not mates</td>
</tr>
<tr>
<td>C</td>
<td>Cline</td>
<td>STPs (mated)</td>
</tr>
<tr>
<td>D</td>
<td>Dialup</td>
<td>STPs @ different levels</td>
</tr>
<tr>
<td>E</td>
<td>Extended</td>
<td>STP to non-local STP</td>
</tr>
<tr>
<td>F</td>
<td>Fully automatic</td>
<td>STP-SP</td>
</tr>
</tbody>
</table>

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Link status

Each link in the preceding figures may actually be a “link set”
3 basic link states:
- **Out-of-service** (OOS)
  - Failed: Can’t provide acceptable quality (e.g., bit error rate)
  - Deactivated by management
  - Blocked: “Processor” (node) outage at one end
  - Inhibited, e.g., standby link
- **Aligning/proving** checks that the link works. 2 types:
  - normal alignment (when there exist alternative links)
  - emergency alignment (faster than normal; take risks for early service)
  - Alignment can be lost when receive six consecutive 1s (bit stuffing has failed) or an excessively long Signalling Unit.
- **In-service / busy**

Status is indicated in Link Status Signalling Unit (LSSU)

Outline

SS7 protocol stack

<table>
<thead>
<tr>
<th>Layer</th>
<th>Functions</th>
<th>User Parts</th>
<th>Network Services Part</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>OMAP: Operations, Maintenance and Administration Part</td>
<td>ASEs: Application Service Elements</td>
<td></td>
</tr>
<tr>
<td>Presentation</td>
<td>Null</td>
<td>ISUP</td>
<td>MTP Level 1</td>
</tr>
<tr>
<td>Session</td>
<td>TCAP</td>
<td>SUP</td>
<td>MTP Level 3</td>
</tr>
<tr>
<td>Transport</td>
<td>SCCP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Network</td>
<td>MTP Level 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data Link</td>
<td>MTP Level 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Physical</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Network Services Part is being replaced with alternative transport, e.g., ATM, SCTP over IP

Message Transfer Part 1

Provides the physical layer
Signalling links are bidirectional
May have a set of links (e.g. 8) connecting adjacent nodes
Nominal rate is 56kb/s (US) or 64kb/s (European)
Even in 2001, 1.5Mb/s ATM links are rare and are considered to be “high-speed”
MTP 2

Provides reliable frame transfer between adjacent nodes

Functions:

- "proves" the link before use by monitoring error rate
- Frames SUs, using flags + bit-stuffing to ensure uniqueness of flags and prevent long runs of 1s (loss of "alignment").
- Detects errors
  - For link quality monitoring
  - For reliable transfer
- Recovers from errors using go-back-N retransmission.
  (Also offers a Preventive Cyclic Retransmission scheme for satcom, in which SUs are retransmitted before receiving nack)
- Flow control: Congested end indicates that it is "busy" by using a Link Status Signal & withholding acknowledgements

MTP 2 Signalling Unit format

<table>
<thead>
<tr>
<th>Flag</th>
<th>BSN</th>
<th>FSN</th>
<th>FIB</th>
<th>Len/Service/Status</th>
<th>CRC</th>
<th>Flag</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>7</td>
<td>1</td>
<td>7</td>
<td>1 16</td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

Flag: For framing

SN = Sequence Number
IB = Indicator Bit; requests retx
F(SN,IB) = Forward (SN,IB)
B(SN,IB) = Backward (SN,IB) (ack)

Len. # of octets between Len & Check (saturates at 63)

Note: SS7 messages are often shown with right to left transmission order.

“Signalling Units” (messages)

3 types:

- Message SUs: Carry signalling information
- Link Status SU: initiate link "alignment", indicate processor status & quality of received messages
- Fill-In SU: Fills link, when nothing else to send.
  - Provides continual error monitoring (for reliability)
  - May also carry acks (BSNs)
MTP 3
Concatenates links to form end-to-end paths
Handles: addressing, routing, alternate routing, congestion control (in contrast to IP that has no congestion control in the network layer)

2 functions:
• Signalling Message Handling:
  • “Message discrimination” = packet classification: determine if SU is destined to:
    • this signalling point ⇒ feed to “message distribution” – to distribute to subsystem within this SP
    • (or, for STPs): another SP reachable through this signalling point ⇒ feed to “message routing” component
• Signalling Network Management

MTP 3 (continued)

2 functions:
• Signalling Message Handling:
• Signalling Network Management:
  • Reconfigure in case of failure
  • Control traffic during congestion
  • Messages must not be lost, duplicated or resequenced
    • MTP 2 provides link reliability; MTP 3 provides path reliability (e.g. no loss from STP buffer)
    • Much more complicated than best-effort IP router

Signalling “traffic management” procedures

Link-based operations:
• Changeover: response to link failure
• Changeback: response to link recovery
• Signalling point restart

Route-based operations:
• Rerouting: Forced or controlled. e.g. redirect traffic when a route becomes “restricted”
• Signalling route set test
• Signalling route set congestion test
• Transfer controlled: response to link congestion: Return control messages to source for all messages received with priority less than threshold
• Transfer prohibited: When STP has no routes to DPC
• Transfer restricted: STP has routes, but knows of better routes.
• Transfer allowed

A route through a STP to a destination may be:
• Available
• Restricted: destination is reachable, but alternate route is preferred, e.g. less congested
• Unavailable
**MTP 3 headers**

Start with a 7B “routing label”, indicating

- Destination Point Code (3B)
- Originating Point Code (3B)
- Signalling Link Selection (SLS) – for load balancing. Originator selects at random (keeping same value for SUs that must be kept in sequence)

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**Signalling Connection Control Part (SCCP)**

Partially analogous to TCP operating over IP

- Provides connection-oriented service
- Segmentation and reassembly for long messages
- Allows addressing of subsystems within a node, not just nodes themselves (like TCP port numbers). Examples of subsystems: 1800 call processing, calling-card processing, etc.
- Transaction Capabilities Application Part (TCAP) is the protocol used to communicate with these subsystems, and so runs over SCCP.

Partially analogous to network-layer functions:
- Provides “Global Title Translation” (like DNS): A “title” (e.g. 1800 number) is translated into a Destination Point Code that can be used for routing

---

**Format of SCCP and ISUP messages**

MTP 3 (Routing Label)

CIC (ISUP only)

Message Type

Mandatory fixed param. 1

Mandatory fixed param.

optional part

Optional variable 1

Optional variable

---

ISUP messages include a Circuit Identification Code (see later example) immediately after the routing label

SCCP & ISUP messages contain a message type code followed by:

- Mandatory parameters (depending on type)
- First fixed-length parameters, then pointers to variable-length parameters
- Pointer to optional parameters
- Pointer to message (length, value) of variable-length parameters

Optional parameters (name, length, value)

Placing mandatory fields first makes their position predictable, simplifying STPs.
ISDN User Part (ISUP)

To establish & tear-down calls, both voice and data, and ISDN and non-ISDN. Successor to Telephone User Part (TUP).

Supplementary services:
- **Closed User Groups** (Virtual Private Networks): Calls are permitted only between members of the user group. ISUP messages used to verify membership.
- **Call forwarding**
- **Calling Line Identification** (& Restriction: don’t disclose ID)
- **User-to-user signalling** (payload across signalling channel)

ISUP call setup example

1. Left SSP selects an idle trunk to right SSP
2. Sends an **Initial Address Message** (IAM) to right SSP
3. When target picks up phone, SSP on right sends an **Answer Message** to SSP on left, indicating selected trunk
4. Caller hangs up, SSP on left generates **Release message**
5. SSP on right responds with **Release Complete** after disconnecting trunk

Transaction Capabilities Application Part

Remote Procedure Calls, like ROSE of OSI, in particular, to consult databases, e.g.:
- **1800 numbers**
- **1300 numbers**

Local Number Portability:
- Allows consumers to retain their number when changing carriers, promoting competition between carriers.

Mobile Application Part (MAP) runs over TCAP & provides services for mobile networks, e.g. roaming & SMS.
Outline

X.25

Designed
- for character transfer to/from dumb terminals (⇒ low rate), e.g. banking & airline reservations
- by the CCITT (now ITU-T) – dominated by public network operators
- in mid-1970s when:
  - copper lines were the dominant transmission technology ⇒ high error rates
  - terminals were dumb, e.g. telephones, screen+keyboard
  - public network concept that the network should provide the service, rather than the terminals
  ⇒ network provides strong error protection
Mainly important for the legacy that it leaves (e.g. virtual circuits & LAPB, LLC)
Amateur (radio) X.25 still used – e.g. included in Linux distributions

End-to-end vs point-to-point

Definitions:
- Ends are physical systems where the information originates or terminates.
- Points are systems (including switches) that information traverses on its route end-to-end.
- An end is a point, not all points are ends.
End-to-end arguments

The principal argument:

Certain functions can only be implemented “completely and correctly” at the transfer end-point

Implementations elsewhere may be justified as performance enhancements


File transfer example

In a file transfer, integrity and secrecy can be compromised at various points on the end-to-end path

Local (re)transmission may aid performance

Performance implications

Error checks within the network could aid or impede performance.

Advantages of local checks:

✓ Save bandwidth by confining the propagation of:
  • errored information
  • retransmitted information
✓ Allow matching of error control to link characteristics
✓ Can be integrated with other bit manipulations, e.g. Ethernet CRC

Performance implications (continued)

Disadvantages of local checks:

✦ Require processing within the network
  • Added complexity
  • Store-and-forward delay (only significant if no output queuing)
✦ May be inappropriate for apps that tolerate errors, e.g. voice

Ethernet (802.3) verifies integrity, but doesn’t recover
Wi-Fi (802.11) verifies integrity and recovers contrary to e2e, but powerful marketing as “wire-equivalent”
Additional end-to-end arguments

For correctness; extreme form: fate sharing
Appropriate service, e.g. ARQ may delay voice
Simpler network (more general?)
- Faster operation & reduced development time
- More transparent, easier to understand
- Functions that aren’t in the network won’t interfere with new apps
User-pays (but aggregate may pay more)
Ease of deployment, e.g web-browser plug-ins
Decentralist politics

Outline

Frame Relay

Another CCITT standard, driven by ANSI (representing US)
- Initially (1988) to convey signalling information over ISDN ‘D’ channel (called LAPD)
- Later, intended as a public service for LAN interconnection
e.g. Frame Relay interface cards on routers
LAPF (Link Access Protocol for Frame Relay)
- Designed to operate faster than X.25 by simplifying network processing: eliminate error recovery.
- Often operates at 2Mbs, and up to 45Mbs

Frame Relay frames

Flag (standard 0x7E) for framing
10b: Data Link Connection Identifier (DLCI) identifies the virtual circuit
only local significance, i.e. DLCI can change as frame propagates
Command/Response C/R: not defined
Discuss these soon

EA: Extend Address: set to 1 in last addressing byte (0 in others)
- allows indication of 3 or 4 byte header
FECN, BECN: Forward & Backward Explicit Congestion Notification
DE: Discard Eligibility
Information: Up to 16000 bytes (FCS may limit length to 4096B)
FCS: 16-bit CRC
Flag for framing
FR congestion control

Congestion control is important in Frame Relay because there is no reservation of resources ⇒ network can readily become congested + designed for bursty LAN interconnect

Two techniques:
- Consolidated Link-Layer Management (T1.618)
  Switch sends congestion indications to a source using DLCI 1023, indicating the type of congestion and DLCIs involved
- Explicit Congestion Notification (ECN)

Implicit congestion notification: e.g. TCP source detects loss through missing ack and interprets as congestion (FR provides no SNs to indicate loss)

2001: Internet protocols adopt ECN (RFC 3168)

Forward ECN

Forward ECN: On path from source to destination
- Switches that are nearing congestion set this bit.
- Downstream nodes (in particular, destination) learn about the congestion (provided the frame isn’t lost, e.g. due to congestion); hopefully tell source
- Doesn’t require any new packets ⇒ won’t exacerbate congestion
- Roundabout path delays source awareness of congestion

Backward ECN

Backward ECN: Switch that is, or is nearing, congestion sets this bit, assuming that dest of this frame may send frames through this switch.
- Signal may experience less delay reaching source ⇒ faster response to congestion.
- Signal may propagate when frames are being lost due to congestion
- There may not be any frames propagating to the source to carry the signal

FR Traffic Management

Client and provider agree (during signalling) on a Leaky Bucket traffic profile:
- \( T_c \): Interval
- \( B_c \): Committed Burst Size = committed bursts will pass
- \( B_e \): Excess Burst Size = excess bursts may pass (congestion permitting)

Committed Information Rate (CIR) = \( B_c / T_c \)

Discard Eligibility (DE) bit is set in frames that are in excess of Committed Information Rate, and so should be discarded first. (DE may also be set by policer.)

Regulation process:
- Regulator maintains a counter \( C \):
  - Incremented by length \( L \) of each frame transmitted
  - Decremented by \( B_c \) every \( T_c \), saturating at 0
- \( C + L < B_c \) ⇒ transmit frame with DE=0
- \( B_c + L < B_c + B_e \) ⇒ transmit frame with DE=1
- \( C + L > B_c \Rightarrow discard frame \)
**FR TM numerical example**

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Frame Len. (bytes)</th>
<th>Output</th>
<th>C (bytes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td>10</td>
<td>yes, DE=0</td>
<td>15</td>
</tr>
<tr>
<td>1.2</td>
<td>20</td>
<td>yes, DE=0</td>
<td>20</td>
</tr>
<tr>
<td>1.3</td>
<td>5</td>
<td>yes, DE=1</td>
<td>25</td>
</tr>
<tr>
<td>1.4</td>
<td>10</td>
<td>no</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>2.1</td>
<td>10</td>
<td>yes, DE=0</td>
<td>15</td>
</tr>
</tbody>
</table>

Reminder: $C = C - B_c$ every $T_c$, saturating at 0
- $C < B_c \Rightarrow$ tx frame with DE=0
- $B_c \leq C < B_c + B_e \Rightarrow$ tx frame with DE=1

Small burst is allowed to pass ("committed" to accept these)
- Forget about up to 20B every second.
- "Excess" burst is marked for preferential discard
- Bigger burst is truncated immediately

Long-term rate $\leq CIR = B_c / T_c$