Transmission techniques and multiplexing hierarchies

Transmission of data signals
Timing and synchronization
Transmission techniques and multiplexing
  – PDH
  – ATM
  – IP/Ethernet
  – SDH/SONET
  – OTN
  – GFP

Switching Technology S38.165
http://www.netlab.hut.fi/opetus/s38165
Transmission of data signals

• Encapsulation of user data into layered protocol structure
• Physical and link layers implement functionality that have relevance to switching
  – multiplexing of transport signals (channels/connections)
  – medium access and flow control
  – error indication and recovery
  – bit, octet and frame level timing/synchronization
  – line coding (for spectrum manipulation and timing extraction)

Encapsulation of user data

- error coding/indication
- octet & frame synchronization
- addressing
- medium access & flow control
- line coding
- bit level timing
- physical signal generation/recovery
Synchronization of transmitted data

- Successful transmission of data requires bit, octet, frame and packet level synchronism
- Synchronous systems (e.g. PDH and SDH) transfer additional information (embedded into transmitted line signal) for accurate recovery of clock signals
- Asynchronous systems (e.g. Ethernet) transfer additional bit patterns to synchronize receiver logic

Timing accuracy

- Inaccuracy of frequency classified in telecom networks to
  - jitter (short term changes in frequency > 10 Hz)
  - wander (< 10 Hz fluctuation)
  - long term frequency shift (drift or skew)
- To maintain required timing accuracy network nodes are connected to a hierarchical synchronization network
  - Universal Time Coordinated (UTC): error in the order of $10^{-13}$
  - Error of Primary Reference Clock (PRC) of the telecom network $10^{-11}$
Timing accuracy (cont.)

- Inaccuracy of clock frequency causes
  - degraded quality of received signal
  - bit errors in regeneration
  - slips: in PDH networks a frame is duplicated or lost due to timing difference between the sender and receiver
- Based on applied synchronization method, networks are divided into
  - fully synchronous networks (e.g. SDH)
  - plesiochronous networks (e.g. PDH), sub-networks have nominally the same clock frequency but are not synchronized to each other
  - mixed networks

Methods for bit level timing

- To obtain bit level synchronism receiver clocks must be synchronized to incoming signal
- Incoming signal must include transitions to keep receiver’s clock recovery circuitry in synchronism
- Methods to introduce line signal transitions
  - Line coding
  - Block coding
  - Scrambling
Line coding

Line coding (cont.)

- ADI, ADI RZ and codes alike introduce DC balance shift
  => clock recovery becomes difficult
- AMI and AMI RZ introduces DC balance, but lacks effective ability to introduce signal transitions
- HDB3 (High Density Bipolar 3) code, used in PDH systems, guarantees a signal transition at least every fourth bit
  - 0000 coded by 000V when there is an odd number of pulses since the last violation (V) pulse
  - 0000 coded by B00V when there is an even number of pulses since the last violation pulse
Line coding (cont.)

- When bit rates increase (> 100 Mbit/s) jitter requirements become tighter and signal transitions should occur more frequently than in HDB3 coding.
- CMI (Coded Mark Inversion) coding was introduced for electronic differential links and for optical links.
- CMI doubles bit rate on transmission link -> higher bit rate implies larger bandwidth and shortened transmission distance.

Block coding

- Entire blocks of \( n \) bits are replaced by other blocks of \( m \) bits \((m > n)\).
- \( nBmB \) block codes are usually applied on optical links by using on-off keying.
- Block coding adds variety of “1”s and “0”s to obtain better clock synchronism and reduced jitter.
- Redundancy in block codes (in the form of extra combinations) enables error recovery to a certain extent.
- When \( m > n \) the coded line signal requires larger bandwidth than the original signal.
- Examples: 4B5B (FDDI), 5B6B (E3 optical links) and 8B10B (GbE).
### Coding examples

<table>
<thead>
<tr>
<th>4B5B coding</th>
<th>5B6B coding</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input word</strong></td>
<td><strong>Output word</strong></td>
</tr>
<tr>
<td>0 0 0 0</td>
<td>1 1 1 0</td>
</tr>
<tr>
<td>0 0 0 1</td>
<td>0 1 0 0</td>
</tr>
<tr>
<td>0 0 1 0</td>
<td>0 1 0 0</td>
</tr>
<tr>
<td>0 0 1 1</td>
<td>1 0 1 0</td>
</tr>
<tr>
<td>0 1 0 0</td>
<td>0 1 0 0</td>
</tr>
<tr>
<td>0 1 0 1</td>
<td>0 1 0 1</td>
</tr>
<tr>
<td>0 1 1 0</td>
<td>0 1 1 0</td>
</tr>
<tr>
<td>0 1 1 1</td>
<td>0 1 1 1</td>
</tr>
<tr>
<td>1 0 0 0</td>
<td>1 0 0 0</td>
</tr>
<tr>
<td>1 0 0 1</td>
<td>1 0 0 1</td>
</tr>
<tr>
<td>1 0 1 0</td>
<td>1 0 0 0</td>
</tr>
<tr>
<td>1 0 1 1</td>
<td>0 1 1 0</td>
</tr>
<tr>
<td>1 1 0 0</td>
<td>0 1 0 1</td>
</tr>
<tr>
<td>1 1 0 1</td>
<td>1 0 0 1</td>
</tr>
<tr>
<td>1 1 1 0</td>
<td>1 1 0 0</td>
</tr>
<tr>
<td>1 1 1 1</td>
<td>1 1 1 0</td>
</tr>
</tbody>
</table>

### Scrambling

- Data signal is changed bit by bit according to a separate repetitive sequence (to avoid long sequences of “1”s or “0”s)
- Steps of the sequence give information on how to handle bits in the signal being coded
- A scrambler consists of a feedback shift register described by a polynomial \((x^N + \ldots + x^m + \ldots + x^k + \ldots + x + 1)\)
- Polynomial specifies from where in the shift register feedback is taken
- Output bit rate is the same as the input bit rate
- Scrambling is not as effective as line coding
Scrambler example

SDH/STM-1 uses $x^7+x^6+1$ polynomial

Methods for octet and frame level timing

- Frame alignment bit pattern
- Start of frame signal
- Use of frame check sequence
Frame alignment sequence

- Data frames carry special frame alignment bit patterns to obtain octet and frame level synchronism
- Data bits scrambled to avoid misalignment
- Used in networks that utilize synchronous transmission, e.g., in PDH, SDH and OTN
- Examples
  - PDH E1 frames carry bit sequence 0011011 in every other frame (even frames)
  - SDH and OTN frames carry a six octet alignment sequence (hexadecimal form: F6 F6 28 28 28) in every frame

Start of frame signal

- Data frames carry special bit patterns to synchronize receiver logic
- False synchronism avoided for example by inserting additional bits into data streams
- Used in synchronous and asynchronous networks, e.g., Ethernet and HDLC
- Examples
  - Ethernet frames are preceded by a 7-octet preamble field (10101010) followed by a start-of-frame delimiter octet (10101011)
  - HDLC frames are preceded by a flag byte (0111 1110)
Frame check sequence

- Data frames carry no special bit patterns for synchronization
- Synchronization is based on the use of error indication and correction fields
  - CRC (Cyclic Redundancy Check) calculation
- Used in bit synchronous networks such as ATM and GFP (Generic Framing Procedures)
- Example
  - ATM cells streams can be synchronized to HEC (Header Error Control) field, which is calculated across ATM cell header

Transmission techniques

- PDH (Plesiochronous Digital Hierarchy)
- ATM (Asynchronous Transfer Mode)
- IP/Ethernet
- SDH (Synchronous Digital Hierarchy)
- OTN (Optical Transport network)
- GFP (Generic Framing Procedure)
Plesiochronous Digital Hierarchy (PDH)

- Transmission technology of digitized telecom network
- Basic channel capacity 64 kbit/s
- Voice information PCM coded
  - 8 bits per sample
  - A or µ law
  - Sample rate 8 kHz (125 µs)
- Channel associated signaling (SS7)
- Higher order frames obtained by multiplexing four lower order frames bit by bit and adding some synchr. and management info
- The most common switching and transmission format in the telecommunication network is PCM 30 (E1)

PDH E1-frame structure (even frames)

- Multi-frame
  - F0, F1, ..., F14, F15
- Voice channels 1-15
  - T0, T1, T2, ..., T15
- Voice channels 16-30
  - T16, T17, ..., T30
- Frame alignment time-slot
- Error indicator bit (CRC-4)
- Frame alignment signal (FAS)
- Signaling time-slot
- Multi-frame alignment bit sequence in F0
- Multi-frame alarm
- Multi-frame
- Voice sample amplitude
- Polarity
- Voice channel 28
PDH E1-frame structure (odd frames)

PDH-multiplexing

- Tributaries have the same nominal bit rate, but with a specified, permitted deviation (100 bit/s for 2.048 Mbit/s)
- Plesiochronous = tributaries have almost the same bit rate
- Justification and control bits are used in multiplexed flows
- First order (E1) is octet-interleaved, but higher orders (E2, ...) are bit-interleaved
PDH network elements

- **concentrator**
  - $n$ channels are multiplexed to a higher capacity link that carries $m$ channels ($n > m$)
- **multiplexer**
  - $n$ channels are multiplexed to a higher capacity link that carries $n$ channels
- **cross-connect**
  - static multiplexing/switching of user channels
- **switch**
  - switches incoming TDM/SDM channels to outgoing ones

Example PDH network elements

![Diagram of Concentrator, Multiplexer, Cross-connect, and Switch]

© P. Raatikainen Switching Technology / 2004
Synchronous digital hierarchy

Major ITU-T SDH standards:
- G.707
- G.783

Notice that each frame transmitted in 125 µs!

SDH reference model

- DXC Digital gross-connect
- MPX Multiplexer
- R Repeater

Path layer connection
SDH-multiplexing

- Multiplexing hierarchy for plesiochronous and synchronous tributaries (e.g. E1 and E3)
- Octet-interleaving, no justification bits - tributaries visible and available in the multiplexed SDH flow
- SDH hierarchy divided into two groups:
  - multiplexing level (virtual containers, VCs)
  - line signal level (synchronous transport level, STM)
- Tributaries from E1 (2.048 Mbit/s) to E4 (139.264 Mbit/s) are synchronized (using justification bits if needed) and packed in containers of standardized size
- Control and supervisory information (POH, path overhead) added to containers => virtual container (VC)

SDH-multiplexing (cont.)

- Different sized VCs for different tributaries (VC-12/E1, VC-3/E3, VC-4/E4)
- Smaller VCs can be packed into a larger VC (+ new POH)
- Section overhead (SOH) added to larger VC
  => transport module
- Transport module corresponds to line signal (bit flow transferred on the medium)
  - bit rate is 155.52 Mbit/s or its multiples
  - transport modules called STM-N (N = 1, 4, 16, 64, ...)
  - bit rate of STM-N is Nx155.52 Mbit/s
  - duration of a module is 125 µs (= duration of a PDH frame)
SDH network elements

- regenerator (intermediate repeater, IR)
  - regenerates line signal and may send or receive data via communication channels in RSOH header fields
- multiplexer
  - terminal multiplexer multiplexes/demultiplexes PDH and SDH tributaries to/from a common STM-n
  - add-drop multiplexer adds or drops tributaries to/from a common STM-n
- digital cross-connect
  - used for rearrangement of connections to meet variations of capacity or for protection switching
  - connections set up and released by operator

Example SDH network elements

Cross-connect

Add-drop multiplexer

Terminal multiplexer
Generation of STM-1 frame

Three main fields:
- Regeneration and multiplexer section overhead (RSOH and MSOH)
- Payload and path overhead (POH)
- AU (administrative) pointer specifies where payload (VC-4 or VC-3) starts

STM-n frame
Synchronization of payload

- Position of each octet in a STM frame (or VC frame) has a number
- AU pointer contains position number of the octet in which VC starts
- Lower order VC included as part of a higher order VC (e.g. VC-12 as part of VC-4)

ATM concept in summary

- cell
  - 53 octets
- routing/switching
  - based on VPI and VCI
- adaptation
  - processing of user data into ATM cells
- error control
  - cell header checking and discarding
- flow control
  - no flow control
  - input rate control
- congestion control
  - cell discarded (two priorities)
### ATM protocol reference model

<table>
<thead>
<tr>
<th>AAL</th>
<th>Convergence sublayer (CS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Segmentation and reassembly (SAR)</td>
</tr>
<tr>
<td>ATM</td>
<td>Generic flow control</td>
</tr>
<tr>
<td></td>
<td>VPI/VCI translation</td>
</tr>
<tr>
<td></td>
<td>Multiplexing and demultiplexing of cells</td>
</tr>
<tr>
<td>Phys</td>
<td>Cell rate decoupling</td>
</tr>
<tr>
<td></td>
<td>HEC header sequence generation/verification</td>
</tr>
<tr>
<td></td>
<td>Cell delineation</td>
</tr>
<tr>
<td></td>
<td>Transmission frame adaptation</td>
</tr>
<tr>
<td></td>
<td>Transmission frame generation/recovery</td>
</tr>
<tr>
<td>PM</td>
<td>Timing</td>
</tr>
<tr>
<td></td>
<td>Physical medium</td>
</tr>
</tbody>
</table>

### Reference interfaces

- **ATM network**
- **NNI**: Network Node Interface
- **UNI**: User-Network Interface
- **EX**: Exchange
- **TE**: Termination Equipment
ATM cell structure

- **ATM header for UNI**
  - GFC
  - VPI
  - VCI
  - PTI
  - VCI
  - VCI
  - HEC

- **ATM header for NNI**
  - VPC
  - VPI
  - VCI
  - PTI
  - VCI
  - VCI
  - HEC

**UNI** - User Network Interface
**NNI** - Network-to-Network Interface
**VPI** - Virtual Path Identifier
**VCI** - Virtual Channel Identifier
**GFC** - Generic Flow Control
**PTI** - Payload Type Identifier
**CPL** - Cell Loss Priority
**HEC** - Header Error Control

HEC = 8 x (header octets 1 to 4) / (x^4 + x^3 + x + 1)

ATM connection types

- **Physical channel**
  - VPI 1
  - VCI 1
  - VCI 2
  - VCI 3
  - VPI 2
  - VCI 1
  - VCI 2
  - VCI 3
Physical layers for ATM

- **SDH** (Synchronous Digital Hierarchy)
  - STM-1 155 Mbit/s
  - STM-4 622 Mbit/s
  - STM-16 2.4 Gbit/s

- **PDH** (Plesiochronous Digital Hierarchy)
  - E1 2 Mbit/s
  - E3 34 Mbit/s
  - E4 140 Mbit/s

- **TAXI** 100 Mbit/s and IBM 25 Mbit/s

- **Cell based interface**
  - uses standard bit rates and physical level interfaces (e.g. E1, STM-1 or STM-4)
  - HEC used for framing

---

Transport of data in ATM cells

- IP packet
- **AAL 5 payload**
- **Pad** 0 - 47 octets

Octet labels:
- **P** - Padding octets
- **UU** - AAL layer user-to-user indicator
- **CPI** - Common part indicator
- **LEN** - Length indicator
ATM cell encapsulation / SDH

- STM-1 frame
- VC-4 frame
- VC-4 POH

ATM cell encapsulation / PDH (E1)

- TS0
  - frame alignment
  - F3 OAM functions
  - loss of frame alignment
  - performance monitoring
  - transmission of FERF and LOC
  - performance reporting

- TS16
  - reserved for signaling
Cell based interface

Frame structure for cell based interfaces:

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>L</td>
<td>H</td>
<td>ATM layer</td>
</tr>
</tbody>
</table>

- PL cells processed on physical layer (not on ATM layer)
- IDLE cell for cell rate adaptation
- PL-OAM cells carry physical level OAM information (regenerator (F1) and transmission path (F3) level messages)
- PL cell identified by a pre-defined header
  - 00000000 00000000 00000000 00000001 (IDLE cell)
  - 00000000 00000000 00000000 00001001 (phys. layer OAM)
  - xxxx0000 00000000 00000000 0000xxxx (reserved for phys. layer)

H = ATM cell Header, PL = Physical Layer, OAM = Operation Administration and Maintenance

ATM network elements

- Gross-connect
  - switching of virtual paths (VPs)
  - VP paths are statically connected
- Switch
  - switching of virtual channel (VCs)
  - VC paths are dynamically or statically connected
- DSLAM (Digital Subscriber Line Access Multiplexer)
  - concentrates a larger number of subscriber lines to a common higher capacity link
  - aggregated capacity of subscriber lines surpasses that of the common link
Ethernet

• Originally a link layer protocol for LANs (10 and 100 MbE)
• Upgrade of link speeds
  => optical versions 1GbE and 10 GbE
  => suggested for long haul transmission
• No connections - each data terminal (DTE) sends data when ready - MAC is based on CSMA/CD
• Synchronization
  – line coding, preamble pattern and start-of-frame delimiter
  – Manchester code for 10 MbE, 8B6T for 100 MbE, 8B10B for GbE

Ethernet frame

- Preamble - AA AA AA AA AA AA AA (Hex)
- SFD - Start of Frame Delimiter AB (Hex)
- DA - Destination Address
- SA - Source Address
- T/L - Type (RFC894, Ethernet) or Length (RFC1042, IEEE 802.3) indicator
- CRC - Cyclic Redundance Check
- Inter-frame gap 12 octets (9.6 µs /10 MbE)
1GbE frame

Preamble - AA AA AA AA AA AA AA (Hex)
SFD - Start of Frame Delimiter AB (Hex)
DA - Destination Address
SA - Source Address
T/L - Type (RFC894, Ethernet) or Length (RFC1042, IEEE 802.3) indicator
CRC - Cyclic Redundancy Check
Inter-frame gap 12 octets (96 ns /1 GbE)
Extension - for padding short frames to be 512 octets long

Ethernet network elements

- **Repeater**
  - interconnects LAN segments on physical layer
  - regenerates all signals received from one segment and forwards them onto the next

- **Bridge**
  - interconnects LAN segments on link layer (MAC)
  - all received frames are buffered and error free ones are forwarded to another segment (if they are addressed to it)

- **Hub and switch**
  - hub connects DTEs with two twisted pair links in a star topology and repeats received signal from any input to all output links
  - switch is an intelligent hub, which learns MAC addresses of DTEs and is capable of directing received frames only to addressed ports
Optical transport network

- Optical Transport Network (OTN) being developed by ITU-T (G.709) specifies interfaces for optical networks
- Goal to gather for the transmission needs of today’s wide range of digital services and to assist network evolution to higher bandwidths and improved network performance
- OTN builds on SDH and introduces some refinements:
  - management of optical channels in optical domain
  - FEC to improve error performance and allow longer link spans
  - provides means to manage optical channels end-to-end in optical domain (i.e. no O/E/O conversions)
  - interconnections scale from a single wavelength to multiple ones

OTN reference model

- OCh Optical Channel
- OA Optical Amplifier
- OMS Optical Multiplexing Section
- OMPX Optical Multiplexer
- OTS Optical Transport Section
OTN layers and OCh sub-layers

- OTN layers
  - Optical transport section (OTSn)
  - Optical multiplexing section (OMSn)
  - Optical transport section (OTSn)

- OCh sub-layers
  - Optical channel transport unit (OTU)
  - Optical channel data unit (ODU)
  - Optical channel payload unit (OPU)

OTN frame structure

- Three main fields
  - Optical channel overhead
  - Payload
  - Forward error indication field
OTN frame structure (cont.)

- Frame size remains the same (4x4080) regardless of line rate
  => frame rate increases as line rate increases
- Three line rates defined:
  - OTU1  2.666 Gbit/s
  - OTU2  10.709 Gbit/s
  - OTU3  43.014 Gbit/s

Generation of OTN frame and signal

OTN frame generation

Client signal \(\rightarrow\) OPU \(\rightarrow\) ODU \(\rightarrow\) OTU

+ OPU-OH + OTU-OH + FEC

OTN signal generation

Client signal \(\rightarrow\) OCh \(\rightarrow\) OMUX \(\rightarrow\) OMS \(\rightarrow\) OTS
OTN network elements

- **optical amplifier**
  - amplifies optical line signal
- **optical multiplexer**
  - multiplexes optical wavelengths to OMS signal
  - add-drop multiplexer adds or drops wavelengths to/from a common OMS
- **optical cross-connect**
  - used to direct optical wavelengths (channels) from an OMS to another
  - connections set up and released by operator
- **optical switches**
  - when technology becomes available optical switches will be used for switching of data packets in optical domain

---

Generic Framing Procedure (GFP)

- Recently standardized traffic adaptation mechanism especially for transporting block-coded and packet-oriented data
- Standardized by ITU-T (G.7041) and ANSI (T1.105.02) (the only standard supported by both organizations)
- Developed to overcome data transport inefficiencies of existing ATM, POS, etc. technologies
- Operates over byte-synchronous communications channels (e.g. SDH/SONET and OTN)
- Supports both fixed and variable length data frames
- Generalizes error-control-based frame delineation scheme (successfully employed in ATM)
  - relies on payload length and error control check for frame boundary delineation
• Two frame types: client and control frames
  – client frames include client data frames and client management frames
  – control frames used for OAM purposes

• Multiple transport modes (coexistent in the same channel) possible
  – Frame-mapped GFP for packet data, e.g. PPP, IP, MPLS and Ethernet
  – Transparent-mapped GFP for delay sensitive traffic (storage area networks), e.g. Fiber Channel, FICON and ESCON
GFP client data frame

- Composed of a frame header and payload
- Core header intended for data link management
  - payload length indicator (PLI, 2 octets), HEC (CRC-16, 2 octets)
- Payload field divided into payload header, payload and optional FCS (CRC-32) sub-fields
- Payload header includes:
  - payload type (2 octets) and type HEC (2 octets) sub-fields
  - optional 0 - 60 octets of extension header
- Payload:
  - variable length (0 - 65,535 octets, including payload header and FCS) for frame mapping mode (GFP-F) - frame multiplexing
  - fixed size N x [536, 520] for transparent mapping mode (GFP-T) - no frame multiplexing

Source: IEEE Communications Magazine, May 2002
GFP relationship to client signals and transport paths

| SDH/SONET path | GFP client-independent |
| OTN ODUk path | GFP client-dependent |

- **ESCON**: Enterprise System CONnection
- **FICON**: Fiber CONnection
- **IP/PPP**: IP over Point-to-Point Protocol
- **MAPOS**: Multiple Access Protocol over SONET/SDH
- **RPR**: Resilient Packet Ring

Source: IEEE Communications Magazine, May 2002

Adapting traffic via GFP-F and GFP-T

### GFP-F frame

- **PLI**: Payload Length Indicator (2 bytes)
- **cHEC**: Core Header Error Control (2 bytes)
- **Payload header**: 4 bytes
- **Client PDU**: (PPP, IP, Ethernet, RPR, etc.)
- **FCS**: Frame Check Sequence (optional) 4 bytes

### GFP-T frame

- **PLI**: Payload Length Indicator (2 bytes)
- **cHEC**: Core Header Error Control (2 bytes)
- **Payload**: 8x64B/65B superblock #1, ... #N-1, #N
- **FCS**: Frame Check Sequence (optional) 4 bytes

- **FCS**: Frame Check Sequence
- **cHEC**: Core Header Error Control
- **PDU**: Packet Data Unit
- **PLI**: Payload Length Indicator
GFP-T frame mapping

- 64B/65B code block
- 8 x 64B/65B code blocks
- Superblock (8 x 64B/65B code blocks + CRC-16)
- GFP-T frame with five superblocks
- Core header and payload header
- FCS (optional)