Internet2 DCN and Ethernet over SONET

Joint Techs 2008 Tutorial
John S. Graham
Hybrid Optical/Packet Networks

- **IP**
  - **Ethernet**
    - 10 G LAN PHY
    - 10 G WAN PHY
    - 1 G PHY
  - **HDLC**
    - GFP (G.7041)
  - **SONET**
- **Optical Fibre**
Wide-Area Ethernet

- Ethernet Through IP WAN
  - MPLS Tunnels
  - L2TPv3
- Ethernet Through Circuit-Switched WAN
  - Deprecated Techniques
    - ATM, POS, LAPS
  - New ANSI and ITU-T Standards
    - GFP with VCAT and LCAS
  - 10 Gigabit Ethernet
A Typical DCN Site
Salt Lake Installation
Ciena In Close-up
Purposes of DCN

• Production IP Backhaul
  – Long term
  – Default mesh protection with optional improvements
  – Internet2 provide a contracted assured service
  – Created and supported by GRNOC
  – Fee assessed

• Dynamically Provisioned Circuits
  – Short duration (max. 2 weeks)
  – Unprotected
  – Created using DCN software
  – Currently no fee for use
Connecting to Internet2 DCN

- One must have a connection to the Internet2 circuit infrastructure in order to access the Internet2 circuit services.
- The circuit connection is separate from the IP connection.
- The standard connection to the circuit infrastructure is either 1GE or 10GE – other interface types are supported at an additional fee.
- ONE physical connection to the circuit infrastructure on the Ciena CoreDirectors will support BOTH the static circuit service AND the Dynamic Circuit Network.
- For the first year (2008), the connection to DCN is available to IP connectors at no additional fee for a standard connection (1GE or 10GE) that is equal in bandwidth to the contracted IP connection, e.g. 10G IP connectors receive the use of a 10G circuit connection. (Non-connectors may be subject to additional port fees)
- Circuit connections are available to Connectors, members and peers.
# Long-Term Static Circuits

<table>
<thead>
<tr>
<th>Site</th>
<th>Type</th>
<th>‘A’ End</th>
<th>‘Z’ End</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drexel University</td>
<td>GE</td>
<td>PHIL</td>
<td>WASH</td>
</tr>
<tr>
<td>PSC/3ROX</td>
<td>GE</td>
<td>PITT</td>
<td>WASH</td>
</tr>
<tr>
<td>University of New Mexico</td>
<td>GE</td>
<td>ALBU</td>
<td>SALT</td>
</tr>
<tr>
<td>PAIX Peers</td>
<td>GE</td>
<td>SUNN</td>
<td>SALT</td>
</tr>
<tr>
<td>University of Memphis</td>
<td>STS-48c</td>
<td>NASH</td>
<td>ATLA</td>
</tr>
<tr>
<td>Indiana Gigapop</td>
<td>GE</td>
<td>INDI</td>
<td>CLEV</td>
</tr>
<tr>
<td>University of South Florida</td>
<td>STS-48c</td>
<td>JACK</td>
<td>ATLA</td>
</tr>
</tbody>
</table>
Types of Service

Line Service

- E1
- S1

Bridging Service

- P1
- P2
- P3
- P4
EFLOW Policy is Simplex

From Juniper (6 rules)

1-A-6-1-1

505-506

1-A-6-1-1:1-21

1-A-6-1-1:22-42

136

153

166

81-82

201-202

Towards Juniper (2 rules)

1-A-6-1-1

1-A-6-1-1:1-21

1-A-6-1-1:22-42

ALL

ALL

81-82

201-202
Time Division Multiplexing

A → Z:1

E → Z:1
SONET Frame

1 3 90

3

Section

5

Line

87 columns

SPE

PTR
Payload Mapping

Section
- PTR
- Line

STS-1 SPE
SONET Layers
Section Overhead

Section

<table>
<thead>
<tr>
<th>Framing A1</th>
<th>Framing A2</th>
<th>Trace J0</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIP-8 B1</td>
<td>Orderwire E1</td>
<td>User F1</td>
</tr>
<tr>
<td>Data Com D1</td>
<td>Data Com D2</td>
<td>Data Com D3</td>
</tr>
</tbody>
</table>
### Line Overhead

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>BIP-8</td>
<td>APS</td>
<td>APS</td>
</tr>
<tr>
<td>B2</td>
<td>K1</td>
<td>K2</td>
</tr>
<tr>
<td>Data Com</td>
<td>Data Com</td>
<td>Data Com</td>
</tr>
<tr>
<td>D4</td>
<td>D5</td>
<td>D6</td>
</tr>
<tr>
<td>Data Com</td>
<td>Data Com</td>
<td>Data Com</td>
</tr>
<tr>
<td>D7</td>
<td>D8</td>
<td>D9</td>
</tr>
<tr>
<td>Data Com</td>
<td>Data Com</td>
<td>Data Com</td>
</tr>
<tr>
<td>D10</td>
<td>D11</td>
<td>D12</td>
</tr>
<tr>
<td>Sync</td>
<td>REI</td>
<td>Orderwire</td>
</tr>
<tr>
<td>S1</td>
<td>M0</td>
<td>E2</td>
</tr>
</tbody>
</table>

**Diagram:**

- Line
- BIP-8 (B2)
- APS (K1, K2)
- Data Com (D4, D7, D10)
- Sync (S1)
- REI (M0)
- Orderwire (E2)
Path Overhead

- Path Trace
  - J1
- BIP-8
  - B3
- Signal Label
  - C2
- Path Status
  - G1
- User Channel
  - F2
- Multi-frame
  - H4
Concatenation

STS-1

STS-3 (Channelized)

STS-3c (Concatenated)
Provisioning Example

STS-12
1 – 12 (622 Mb/s)

= STS-1
= STS-3
Bandwidth Fragmentation...

Drop Interface (Node F)  STS-3c

Blocked!

Ring  STS-12c

2  6  8
... Solved by Virtual Concatenation

Drop Interface (Node F)

Ring

| 2 | 6 | 8 |

STS-3c
STS-1-3v
STS-12c
## The Magic of VCAT

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Client Rate</th>
<th>Contiguous Concatenation</th>
<th>Virtual Concatenation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethernet</td>
<td>10</td>
<td>STS-1</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>VT1.5-7v</td>
</tr>
<tr>
<td>Fast Ethernet</td>
<td>100</td>
<td>STS-3c</td>
<td>67%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STS-1-2v</td>
</tr>
<tr>
<td>Gigabit Ethernet</td>
<td>1000</td>
<td>STS-48c</td>
<td>42%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STS-3c-7v</td>
</tr>
<tr>
<td>ESCON</td>
<td>160</td>
<td>STS-12c</td>
<td>26%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STS-1-4v</td>
</tr>
<tr>
<td>Fibre Channel 2</td>
<td>1700</td>
<td>STS-48c</td>
<td>71%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STS-3c-12v</td>
</tr>
<tr>
<td>ATM</td>
<td>25</td>
<td>STS-1</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>VT1.5-16c</td>
</tr>
</tbody>
</table>
Differential Delay

[Diagram with labels: STS-n-2v, VC-n-2v on either side of a cloud labeled SONET/SDH, with links 1 and 2 showing differential delay.]
# Multiframe Indicator

<table>
<thead>
<tr>
<th>Bit 1</th>
<th>Bit 2</th>
<th>Bit 3</th>
<th>Bit 4</th>
<th>Bit 5</th>
<th>Bit 6</th>
<th>Bit 7</th>
<th>Bit 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFI2 MSBs (bits 1 - 4)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MFI2 LSBs (bits 5 – 8)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CTRL</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
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<tr>
<td>GID</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>CRC-8</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CRC-8</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>MST</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MST</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>RS-Ack</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
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<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>SQ MSBs (bits 1 – 4)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SQ LSBs (bits 5 – 8)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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</tbody>
</table>
Signalling in VCAT

<table>
<thead>
<tr>
<th>MFI = 0</th>
<th>MFI = 1</th>
<th>MFI = 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 7</td>
<td>1 7</td>
<td>1 7</td>
</tr>
<tr>
<td>2 8</td>
<td>2 8</td>
<td>2 8</td>
</tr>
<tr>
<td>3 9</td>
<td>3 9</td>
<td>3 9</td>
</tr>
<tr>
<td>4 10</td>
<td>4 10</td>
<td>4 10</td>
</tr>
<tr>
<td>5 11</td>
<td>5 11</td>
<td>5 11</td>
</tr>
<tr>
<td>6 12</td>
<td>6 12</td>
<td>6 12</td>
</tr>
</tbody>
</table>

$t + 125 \mu s$

$t - 125 \mu s$
VCAT Puzzle

• An STS-1-2v between Chicago and London
• One STS-1 sent via geostationary satellite
• The other STS-1 sent via transatlantic fibre
• Will it work? ;-}
# Theoretical Buffer Requirements

<table>
<thead>
<tr>
<th>Concatenation Unit</th>
<th>Carrier Signal</th>
<th>Max Bundle Size</th>
<th>Buffer Capacity (256 ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STS-1</td>
<td>STS-12c</td>
<td>12</td>
<td>18 MB</td>
</tr>
<tr>
<td>STS-3c</td>
<td>STS-12c</td>
<td>4</td>
<td>18 MB</td>
</tr>
<tr>
<td>STS-1</td>
<td>STS-48c</td>
<td>48</td>
<td>73 MB</td>
</tr>
<tr>
<td>STS-3c</td>
<td>STS-48c</td>
<td>16</td>
<td>73 MB</td>
</tr>
<tr>
<td>STS-1</td>
<td>STS-192c</td>
<td>192</td>
<td>293 MB</td>
</tr>
<tr>
<td>STS-3c</td>
<td>STS-192c</td>
<td>64</td>
<td>293 MB</td>
</tr>
</tbody>
</table>
# Practical Buffer Requirements

<table>
<thead>
<tr>
<th>Concatenation Unit</th>
<th>Maximum Bundle Size</th>
<th>Backplane Switching Capacity</th>
<th>Buffer Capacity (64 ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VC-4</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VC-3</td>
<td>24</td>
<td>2.488 Gb/s</td>
<td>18 MB</td>
</tr>
<tr>
<td>VC-11 or VC-12</td>
<td>64</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figures apply to Ciena CN3616 Ethernet module*
Low Order Path Overhead

VT-2

125 µs

500 µs super-frame
Low Order VCAT

32 × 500 µs = 16 ms

Z7 Bit #1
Alignment | Extended Signal Label | 0 | Reserved

Z7 Bit #2
MFI | SQ | CTRL | 0x0 | MST | CRC-3

GID

RS-Ack
Link Capacity Adjustment Scheme

• Remove members from a VC bundle:
  – Under failure conditions (Hold off timer)
  – Operator requests

• Add or restore members to a VC bundle:
  – Failure condition clears (WTR timer)
  – Operator requests
LCAS Messaging

- Source → Sink messages are unique to each member
- Sink → Source MST reports are repeated across all members
  - Equipment can derive status of all bundle members from monitoring only one member
## LCAS Signalling Flows (1/3)

<table>
<thead>
<tr>
<th>Source</th>
<th>Sink (N-1)</th>
<th>Sink (N)</th>
<th>Sink (N+1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTRL = NORM</td>
<td>CTRL = EOS</td>
<td>CTRL = IDLE</td>
<td>CTRL = EOS</td>
</tr>
<tr>
<td>SQ = 0</td>
<td>SQ = 1</td>
<td>SQ = 255</td>
<td>SQ = 2</td>
</tr>
<tr>
<td>CTRL = NORM</td>
<td>CTRL = EOS</td>
<td>CTRL = ADD</td>
<td></td>
</tr>
<tr>
<td>SQ = 0</td>
<td>SQ = 1</td>
<td>SQ = 2</td>
<td></td>
</tr>
<tr>
<td>MST = FAIL (#2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTRL = NORM</td>
<td>CTRL = EOS</td>
<td>CTRL = EOS</td>
<td></td>
</tr>
<tr>
<td>SQ = 0</td>
<td>SQ = 1</td>
<td>SQ = 2</td>
<td></td>
</tr>
<tr>
<td>MST = OK (#2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTRL = NORM</td>
<td>CTRL = NORM</td>
<td>CTRL = EOS</td>
<td></td>
</tr>
<tr>
<td>SQ = 0</td>
<td>SQ = 1</td>
<td>SQ = 2</td>
<td></td>
</tr>
<tr>
<td>RS-ACK</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTRL = NORM</td>
<td>CTRL = NORM</td>
<td>CTRL = EOS</td>
<td></td>
</tr>
<tr>
<td>SQ = 0</td>
<td>SQ = 1</td>
<td>SQ = 2</td>
<td></td>
</tr>
</tbody>
</table>
### LCAS Signalling Flows (2/3)

<table>
<thead>
<tr>
<th>Source</th>
<th>Sink (N-2)</th>
<th>Sink (N-1)</th>
<th>Sink (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTRL = NORM SQ = 0</td>
<td>CTRL = NORM SQ = 1</td>
<td>CTRL = EOS SQ = 2</td>
<td></td>
</tr>
<tr>
<td>CTRL = IDLE SQ = 255</td>
<td>CTRL = NORM SQ = 1</td>
<td>CTRL = EOS SQ = 2</td>
<td></td>
</tr>
<tr>
<td>MST = FAIL (#0)</td>
<td>CTRL = NORM SQ = 0</td>
<td>CTRL = EOS SQ = 1</td>
<td></td>
</tr>
<tr>
<td>RS-ACK</td>
<td>CTRL = NORM SQ = 0</td>
<td>CTRL = EOS SQ = 1</td>
<td></td>
</tr>
</tbody>
</table>
## LCAS Signalling Flows (3/3)

<table>
<thead>
<tr>
<th>Source</th>
<th>Sink (N-2)</th>
<th>Sink (N-1)</th>
<th>Sink (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTRL = NORM, SQ = 0</td>
<td>CTRL = NORM, SQ = 1</td>
<td>CTRL = EOS, SQ = 2</td>
<td></td>
</tr>
<tr>
<td>MST = FAIL (#2)</td>
<td>CTRL = NORM, SQ = 0</td>
<td>CTRL = NORM, SQ = 1</td>
<td>CTRL = IDLE, SQ = 255</td>
</tr>
<tr>
<td>RS-ACK</td>
<td>CTRL = NORM, SQ = 0</td>
<td>CTRL = EOS, SQ = 1</td>
<td></td>
</tr>
</tbody>
</table>

- INVREF
LCAS as a UNI Client
GFP: Functional Model

Adapted from: IEEE Communications Magazine, May 2002
Generic Framing Procedure

- ITU-T G.7041 and ANSI T1.105.02
- Defines mapping for many types of service onto SONET/SDH or OTN:
  - Ethernet, IP/PPP
  - GbE, Fibre Channel (inc. DVB), FICON etc
- Excellent bandwidth utilization; efficiency tailored to suit different client types
- Simple delineation and robust error control
- Extensible
Tasks Performed by GFP

• Major
  – Client frame delineation
  – Client payload mapping
  – Client-to-carrier rate adaptation

• Minor
  – Limited OA&M (Link Loss Forwarding)
  – Optional client frame multiplexing
Alternatives to GFP

• ATM
  – Cell overhead causes 10% bandwidth inflation
  – Adaptation functions needlessly complex
• Packet over SONET (POS)
  – Requires all frames to be converted to PPP over HDLC
  – Byte stuffing causes non-deterministic bandwidth inflation
  – QoS hard to monitor or guarantee
GFP: Frame Structure

Source: IEEE Communications Magazine, May 2002

CID - Channel identifier
FCS - Frame Check Sequence
EXI - Extension Header Identifier
HEC - Header Error Check
PFI - Payload FCS Indicator
PTI - Payload Type Indicator
UPI - User payload Identifier
GFP: Types of Frame

GFP

Client Frames
- Data Frames
- Management Frames

Control Frames
- Idle Frames
- OA&M Frames
# Client Payload Mapping

<table>
<thead>
<tr>
<th>PTI Field</th>
<th>Type</th>
<th>UPI Field</th>
<th>Payload</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x00</td>
<td>Data</td>
<td>0x01</td>
<td>Ethernet</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0x02</td>
<td>PPP</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0x03</td>
<td>Fibre Channel</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0x04</td>
<td>FICON</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0x05</td>
<td>ESCON</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0x06</td>
<td>Gigabit Ethernet</td>
<td></td>
</tr>
<tr>
<td>0x04</td>
<td>CMF</td>
<td>0x01</td>
<td>Loss of client signal</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0x02</td>
<td>Loss of character synchronization</td>
<td></td>
</tr>
</tbody>
</table>
GFP Scrambling (*vide* ATM)

- SONET/SDH line code is NRZ
- Frame-synchronous scrambler vulnerable to DOS attacks
- Two separate self-synchronous scrambling operations in GFP
  - Core Header XORed with fixed bit pattern (no feedback)
  - Payload area scrambled using a self-synchronous $X^{43}+1$ shift register.
GFP: Frame Delineation
GFP: Synchronization

- Hunt
  - cHEC Match
  - No CHEC Match
- Presync
  - No 2nd cHEC Match
- Sync
  - cHEC Mismatch
  - 2nd cHEC Match
GFP-F 802.3 MAC Awareness

• At Source:
  – Remove preamble & SFD (8 Bytes)
  – Remove IPG (12 Bytes)

• At Sink:
  – Regenerate valid frame
  – Insert minimum IPG
Encapsulation of Ethernet by GFP

Ethernet Client Frame

GFP-F Carrier Frame

Preamble
Start of Frame
Destination
Source
Length/Type
Data
FCS

Client Payload
Payload FCS

Payload Header
Core HEC
PLI

X = 4 to 64
0 to 65535 - X

50
GFP-F Summary

✓ Minimal overhead
✓ Transport of client PDUs in native format
✓ Designed for optimized processing in hardware
✓ Easy aggregation of frames from multiple client and multiple protocols into shared bandwidth channels
Processing of Client Frames by GFP-T

Client Data

10B → 8B

64 bytes

CRC
GFP-T: 64B/65B Payload

<table>
<thead>
<tr>
<th>Octet Number</th>
<th>000</th>
<th>001</th>
<th>010</th>
<th>011</th>
<th>100</th>
<th>101</th>
<th>110</th>
<th>111</th>
</tr>
</thead>
<tbody>
<tr>
<td>64B Sequence</td>
<td>D1</td>
<td>K1</td>
<td>D2</td>
<td>D3</td>
<td>D4</td>
<td>K2</td>
<td>D5</td>
<td>D6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Octet Number</th>
<th>F</th>
<th>000</th>
<th>001</th>
<th>010</th>
<th>011</th>
<th>100</th>
<th>101</th>
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<th>111</th>
</tr>
</thead>
<tbody>
<tr>
<td>65B Sequence</td>
<td>1</td>
<td>1001 C1</td>
<td>0101 C2</td>
<td>D1</td>
<td>D2</td>
<td>D3</td>
<td>D4</td>
<td>D5</td>
<td>D6</td>
</tr>
</tbody>
</table>
GFP-T: Superblocks

67-Byte Superblock

1
2
3
4
5
6
7
8

CRC (MSB)
CRC (LSB)
Why Append a CRC?

- The 8B/10B \(\rightarrow\) 64B/65B remapping process causes loss of redundancy.
- Four sources of error:
  - Leading flag bit is errored
  - Error affects ‘Last control-code’ indicator
  - Control-code location address received in error
  - Error causes 4-bit control code to be modified
Pros and Cons: GFP-F

👍 Higher bandwidth efficiency

👎 Higher Latency
👍 More buffer memory required
👎 Core header fields must be calculated
Pros and Cons: GFP-T

👍 Low latency
👍 Ingress core header fields need not be calculated

👎 Less bandwidth efficient
👎 More logic required
### Gigabit Ethernet (802.3z)

<table>
<thead>
<tr>
<th>ANSI X3T11 Fibre Channel</th>
<th>IEEE 802.3 Ethernet</th>
<th>IEEE 802.3z Gigabit Ethernet</th>
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</thead>
<tbody>
<tr>
<td>FC-4 Upper Layer Mapping</td>
<td>IEEE 802.2 LLC</td>
<td>IEEE 802.2 LLC</td>
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<tr>
<td>FC-3 Common Services</td>
<td>IEEE 802.3 CSMA/CD</td>
<td>IEEE 802.3 MAC</td>
</tr>
<tr>
<td>FC-2 Signalling</td>
<td>IEEE 802.3 PHY</td>
<td>PCS</td>
</tr>
<tr>
<td>FC-1 Encode/Decode</td>
<td></td>
<td>PMA</td>
</tr>
<tr>
<td>FC-0 Interface &amp; Media</td>
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<td>PMD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MDL</td>
</tr>
</tbody>
</table>

IEEE 802.3 PHY

IEEE 802.3 CSMA/CD

IEEE 802.2 LLC
10 G Ethernet – 802.3ae

Full Duplex 802.3 MAC

XGMII

64B/66B PCS

Serial PMA

WIS

Serial PMA

PMD

{ E  L  S }

PMD

10GBASE-R

10GBASE-W

S = 850 nm  MM  300 m
L = 1310 nm  SM  10 km
E = 1550 nm  SM  40 km
The STS-192c WIS Frame

<table>
<thead>
<tr>
<th>Fixed Stuff</th>
<th>802.3 Frame</th>
<th>Idle</th>
<th>...</th>
</tr>
</thead>
</table>

9.58464 Gbs\(^{-1}\) Capacity

Synchronous Payload Envelope (SPE) = 16704 Columns
10GE WAN-PHY Overhead

Section Overhead

Supported by WAN PHY

Unused by WAN PHY

Defined by WAN PHY as Fixed Value

Optional for SONET/SDH

Unused by WAN PHY

Undefined for SONET/SDH
That's All Folks...