Forward Error Correction in Optical Networks

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Agenda

- Why FEC?
- In-band SONET/SDH FEC
- Digital wrapper
  - Frame format
  - Overhead octets
- Summary

A companion white paper is available at http://members.cox.net/michael.henderson, titled "Forward Error Correction in Optical Networks."

Why FEC?

- Many different kinds of impairments affect optical transmission.
  - Chromatic dispersion.
  - Polarization mode dispersion.
  - Four wave mixing, and others.
- As rates are increased, many of these impairments become more pronounced.
- Without new technology, amplifier spacing might have to be decreased as we transition from OC-192/STM-64 to OC-768/STM256.
- Forward error correction is one technique which helps to mitigate this problem.

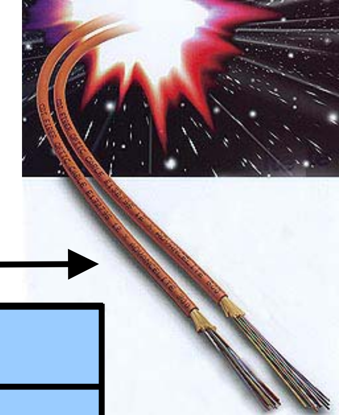
Status of FEC Work in the ITU

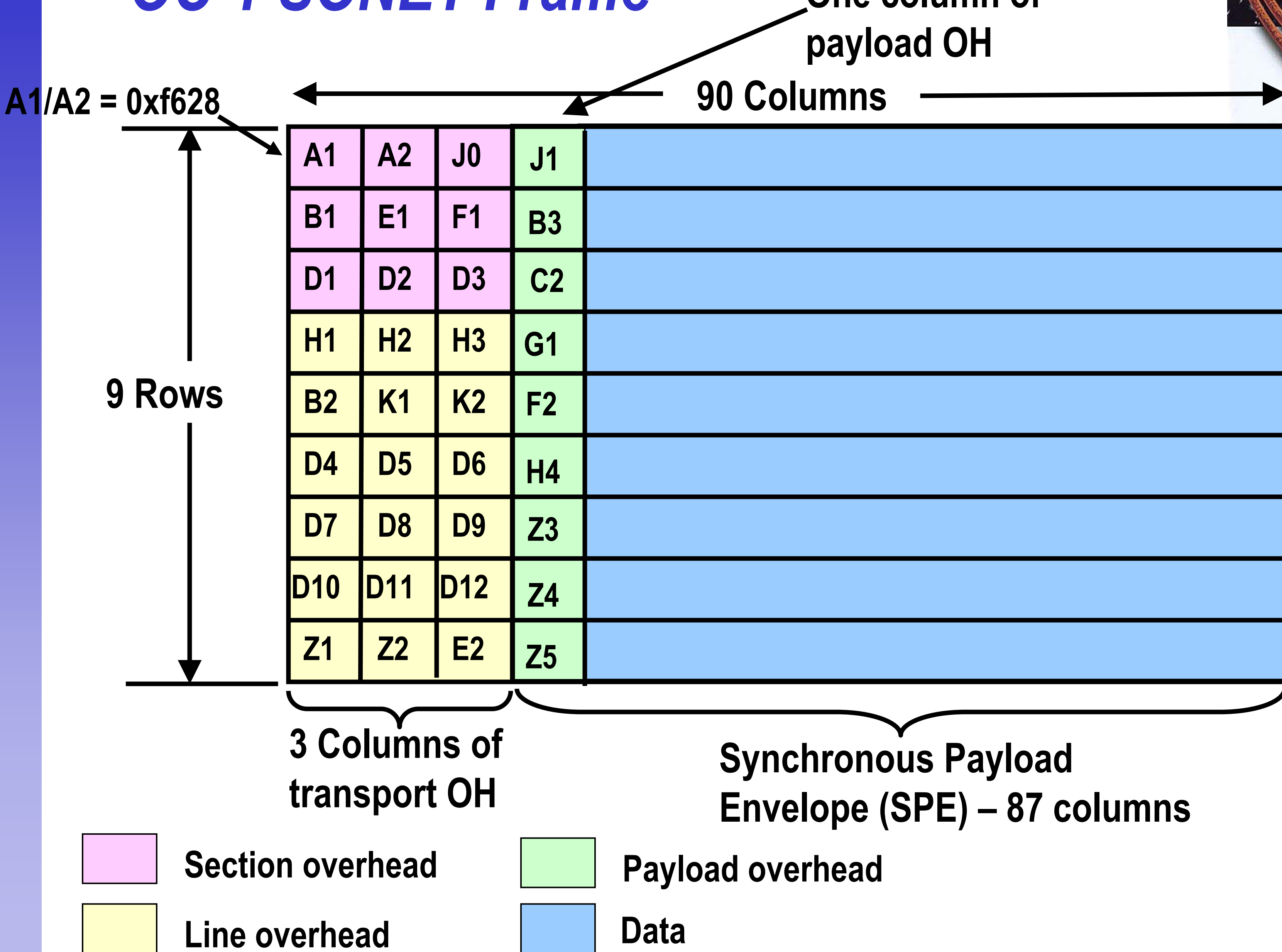
- A technique which adds FEC to SONET/SDH, while preserving the existing line rates, is covered in the revision to G.707.
  - Called “in-band” FEC, or the “rate preserving” technique.
- A technique which provides a payload rate equal to existing SONET/SDH rates, but which operates at a higher line rate, is covered in new recommendation G.709.
  - Called the “Digital wrapper” technique.
- The revised G.707 was ratified in October 2000. G.709 was approved at the February 2001 ITU meeting in Geneva.

In-Band FEC

- SONET/SDH frames are not a fixed size (except in time).
  - But, FEC codes apply to a specific number of bits or symbols.
- There are a limited number of available, unused overhead octets.
  - At the lowest rates, essentially none are available.
- Therefore, G.707 FEC only applies to OC-48/STM-16 line rates.
  - One row is 4320 octets, with 4176 payload octets
- Higher rates are handled by disinterleaving, taking 16 consecutive octets at a time.
- In-band FEC is not defined for rates below OC-48/STM-16.

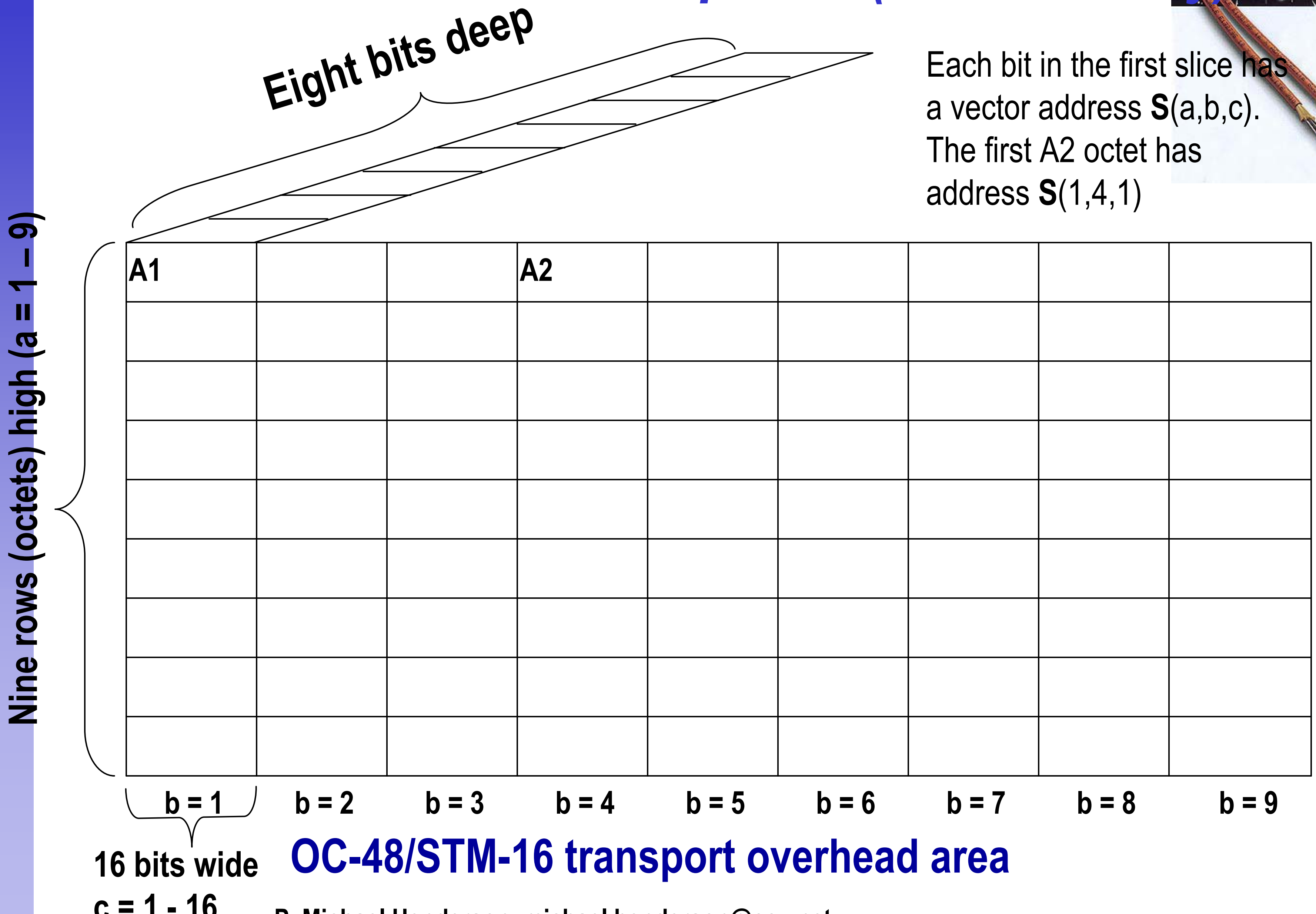
OC-1 SONET Frame





Frame View for FEC Purposes (OH area only)

Each bit in the first slice has a vector address **S**(a,b,c). The first A2 octet has address **S**(1,4,1)



OC-48/STM-16 transport overhead area

In-Band FEC Code

- BCH-3 code chosen.
  - Utilizing a shortened version of a (8191,8152) parent code.
  - Covers 4320 bits, utilizing 39 redundant bits.
- BCH-3 code can correct three bits in error.
  - Eight way interleaving allows error burst of up to 24 bits to be corrected.
- Since each b in the address vector is only 16 bits, the 39 redundant bits are broken into three sets of 13 bits.
- Redundant bits are placed in the same row, or next row, to minimize delay.
  - Transmit time for each row is about 14 μs. One row must be buffered on both encode and decode.

Location of the FEC Redundant Bits

Eight bits deep

Nine rows (octets) high (a = 1 – 9)

b = 1	b = 2	b = 3	b = 4	b = 5	b = 6	b = 7	b = 8	b = 9
A1	A1	A1	A2	A2	A2	J0	X	X
FEC			FEC		FEC			
FEC			FEC		FEC	FEC	FEC	FSI FEC
H1	H1	H1	H2	H2	H2	H3	H3	H3
			FEC	FEC	FEC	FEC	FEC	FEC
						FEC	FEC	FEC
						FEC	FEC	FEC
						FEC	FEC	FEC
FEC	FEC	FEC						

16 bits wide
c = 1 - 16

Location of Redundant FEC bits

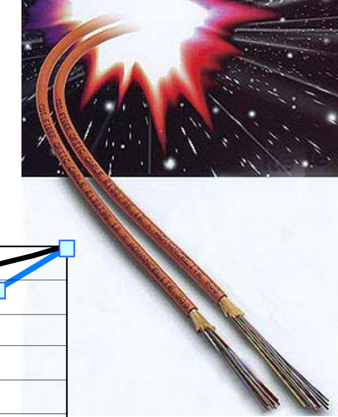
Row	(a, b) for a_n $26 \le n \le 38$	(a, b) for a_n $13 \le n \le 25$	(a, b) for a_n $0 \le n \le 12$
1	**2,1**	**2,4**	**2,6**
2	**3,1**	**3,4**	**3,6**
3	**3,7**	**3,8**	**3,9**
4	**5,4**	**5,5**	**5,6**
5	**5,7**	**5,8**	**5,9**
6	**6,7**	**6,8**	**6,9**
7	**7,7**	**7,8**	**7,9**
8	**8,7**	**8,8**	**8,9**
9	**9,1**	**9,2**	**9,3**

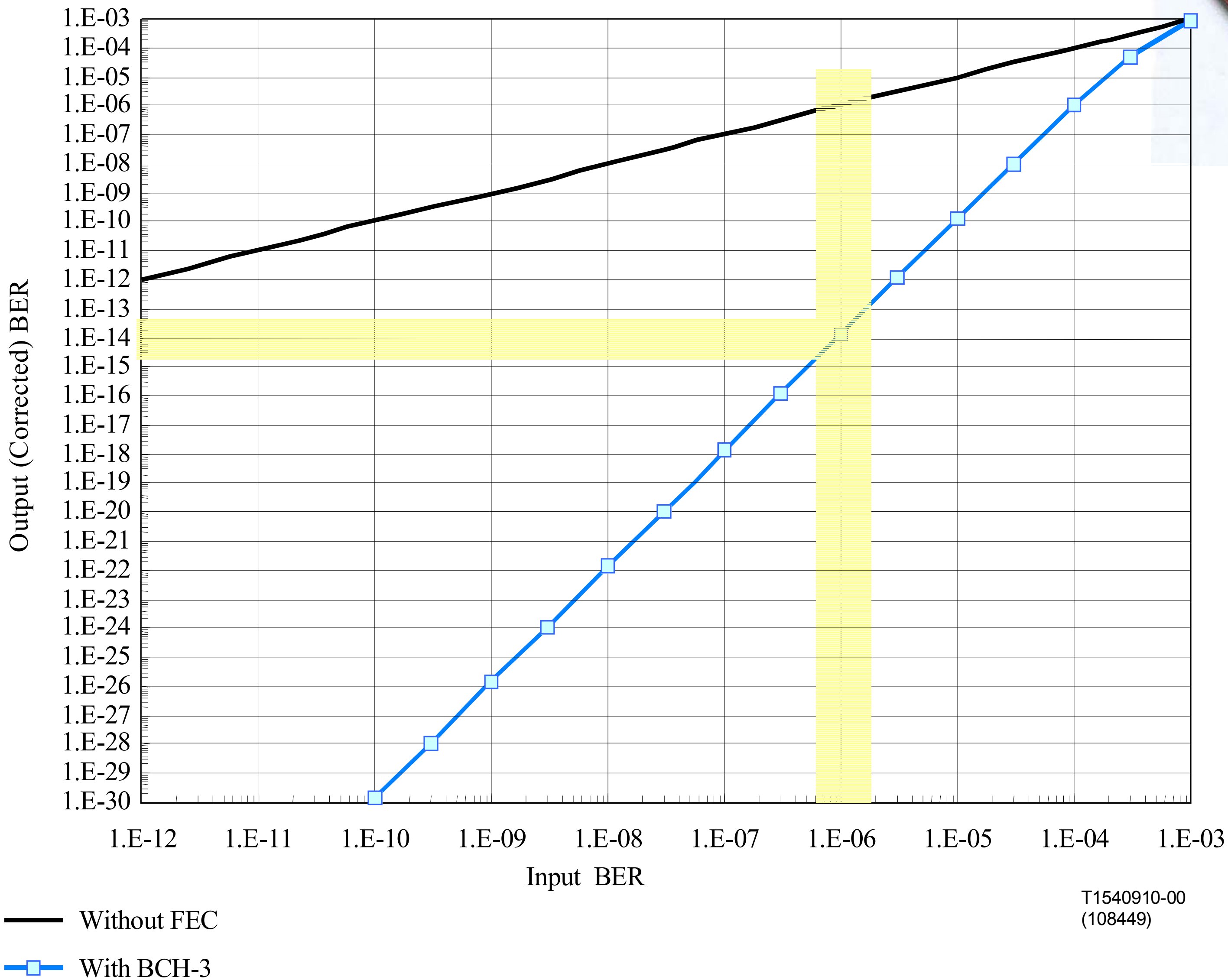
All a_n bits are in “c” address 4 through 16

Controlling FEC usage

- FEC Status Indicator (FSI) used to indicate use of FEC.
  – If receiver attempted to apply FEC when the transmitter was not utilizing it, serious errors would occur.
- FSI located at S**(3,9,3)**.
  – Vector addresses one octet.
  – Bits 7 and 8 of this octet are used as the FSI indicator.
  – A value of 01 indicates FEC on, 00 indicates FEC off.
  – Values of 10 and 11 are invalid.
- Designed for hitless state change.
  – State change is indicated for 7 frames prior to switch.
  – Switch occurs on 8^{th} frame.

BER Improvement with In-band FEC





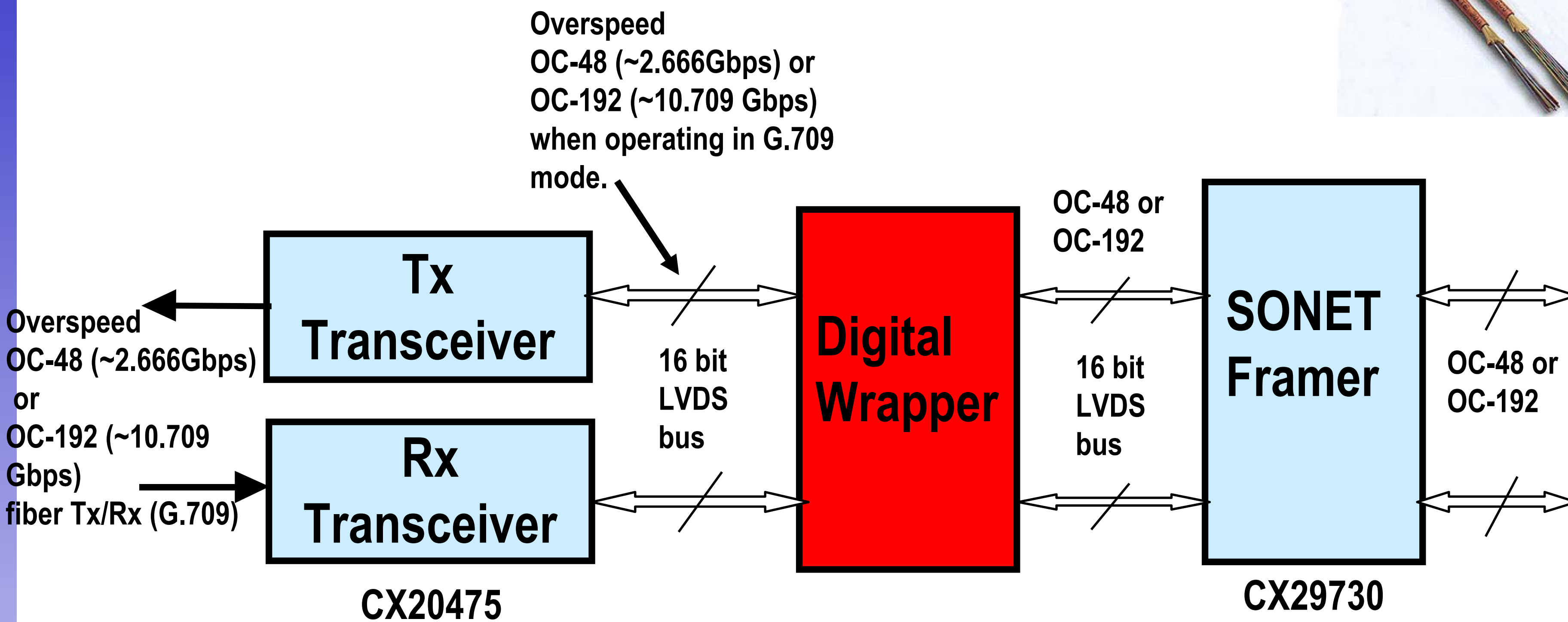
Digital Wrapper

- The basic concept is to take payload octets and “wrap” them with a FEC.
  - Means that the line rate is higher than standard OC-N/STM-N.
- Basic building block is a Reed-Solomon code, specifically a RS(255,239) code.
  - Reed Solomon codes operate on symbols instead of bits. Here, a symbol is an octet (8 bits).
  - RS(255,239) code can correct up to 8 symbols in error or detect up to 16 symbols in error.
- RS codes are 16 interleaved to form a row.
  - Can correct an error burst of up to 128 octets.
- Four rows form a frame.

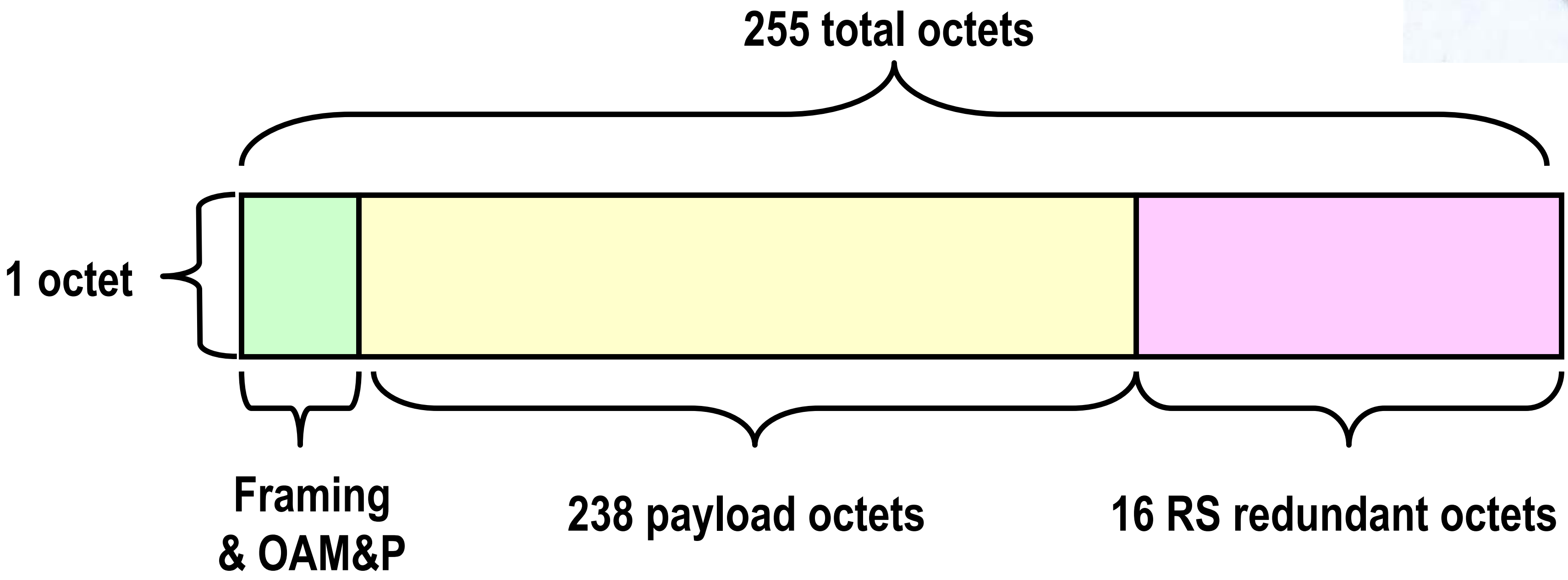
Digital Wrapper (continued)

- Three line rates have been defined.
  - Levels 1, 2, and 3, corresponding roughly to 2.5 Gbps, 10 Gbps, and 40 Gbps.
- Payload rates are standard SONET/SDH rates.
  - Payload rate of level 1 signal is exactly OC-48/STM-16.
  - Payload rate of level 2 signal is exactly OC-192/STM-64, etc.
- Overhead is 17/255 (6.67%), 18/255 (7.06%) or 19/255 (7.45%).
  - However, payload is equal to standard SONET/SDH rates.
  - User may actually gain line speed if SONET/SDH is not used in G.709 payload.

Digital Wrapper Implementation

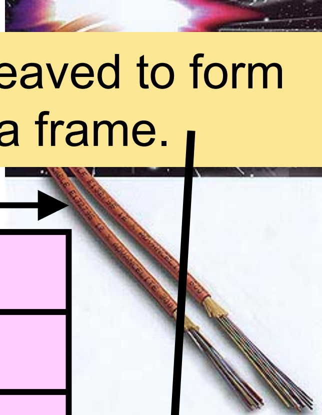
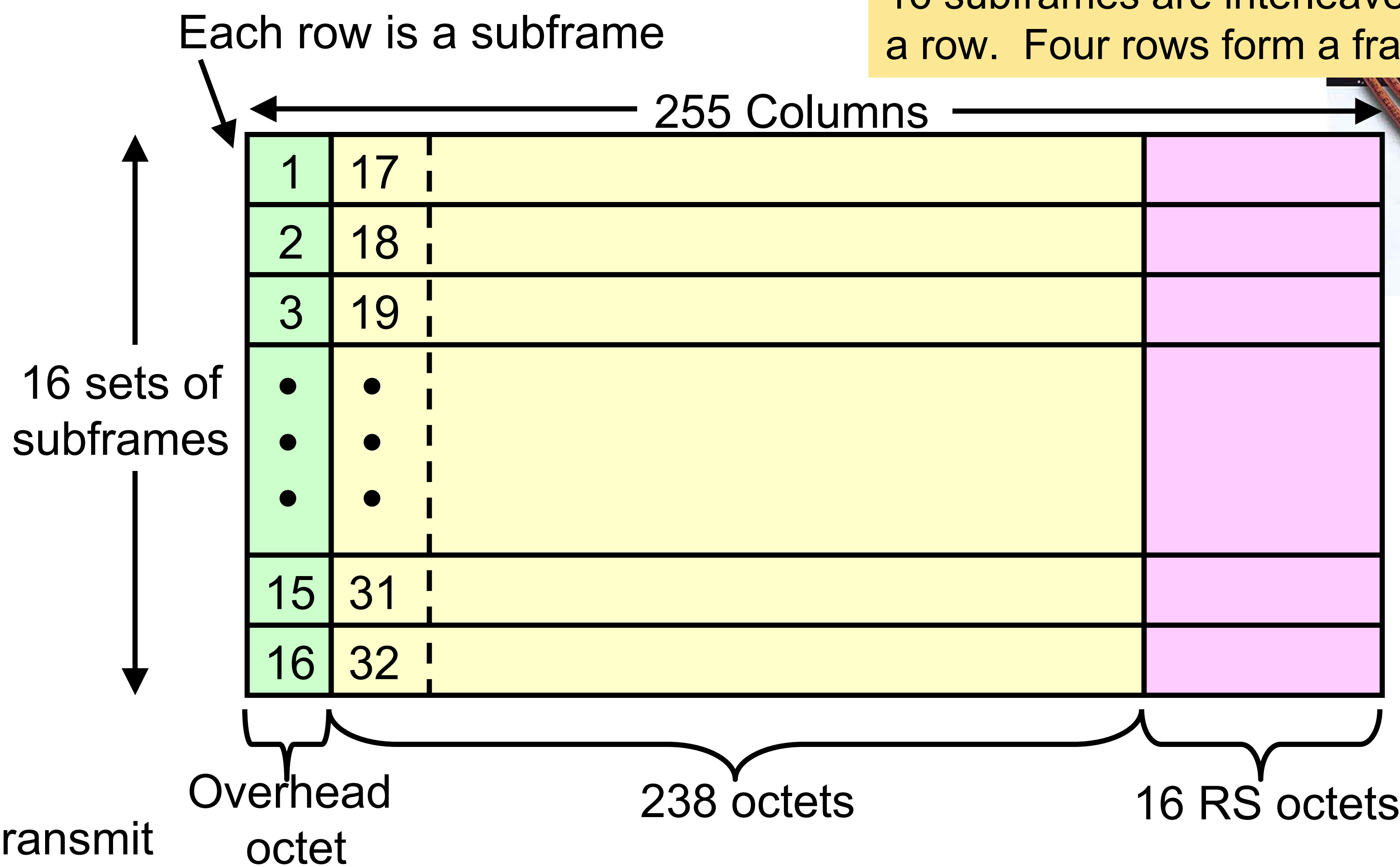


Basic Reed-Solomon Frame



This octet wide package is repeated to create a frame.

16 subframes are interleaved to form a row. Four rows form a frame.

Transmit order

1	2	• • •	16	17	18	• • •	3824	• • •	4080
4081	4082	• • •	4096	4097	4098	• • •	7904	• • •	8160
8161	8162	• • •	8173	8174	8175	• • •	11984	• • •	12240
12241	12242	• • •	12256	12257	12258	• • •	16064	• • •	16320

G.709 Performance Improvement

Input BER	Output BER
10^{-4}	5×10^{-15}
10^{-5}	6.3×10^{-24}
10^{-6}	6.4×10^{-33}

Source: ITU G.975

The output BER accounts for the BER loss due to the higher line rate

G.709 Overhead

<table>
<tr><th></th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th></tr>
<tr><td>1</td><td colspan="14">Transport OH</td><td colspan="2" rowspan="4">Pay-
load
OH</td></tr>
<tr><td>2</td><td colspan="14" rowspan="3">Data OH</td></tr>
<tr><td>3</td></tr>
<tr><td>4</td></tr>
</table>

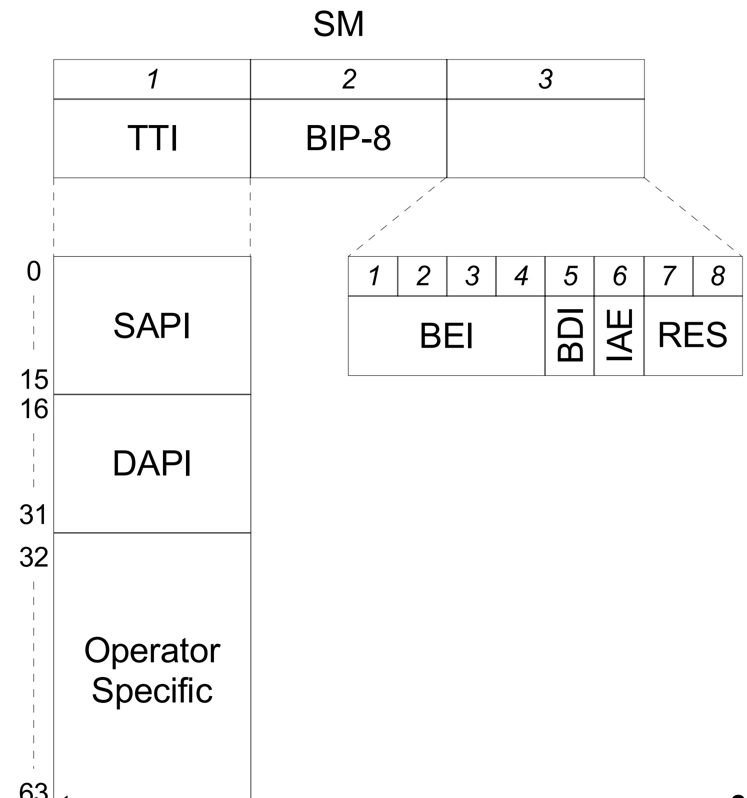
The G.709 overhead is divided into three areas: Transport, Data, and Payload

Transport Overhead

A1 = 1111 0110
A2 = 0010 1000

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	A1	A1	A1	A2	A2	A2	MFAS	SM			GCC0		RES			
2																
3																
4																

FAS (bytes 1–6 of row 1)



FAS Frame alignment signal
MFAS Multi-frame alignment signal
SM Section monitoring
GCC General communication channel
RES Reserved for future standardization

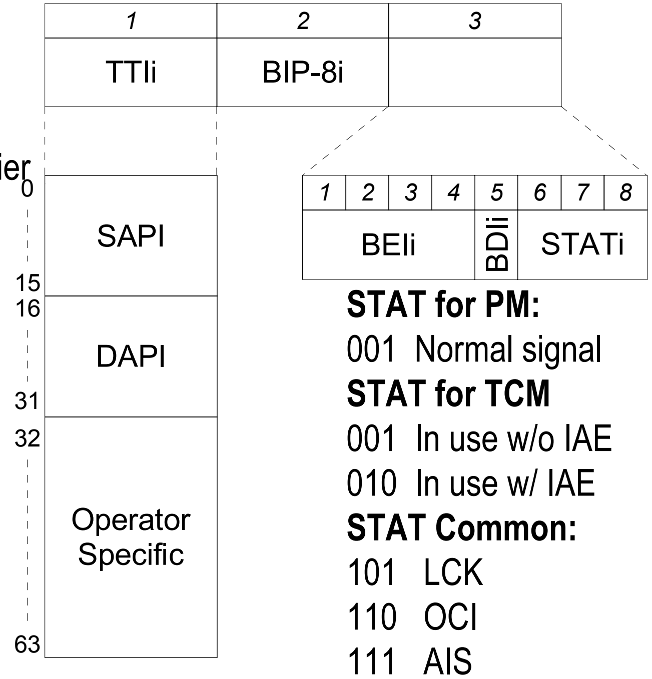
TTI Trail trace identifier
SAPI Source access point identifier
DAPI Destination access point identifier
BIP-8 Bit interleaved parity –8
BEI Backward error indication
BDI Backward Defect Indication
IAE Incoming alignment error

Data Overhead

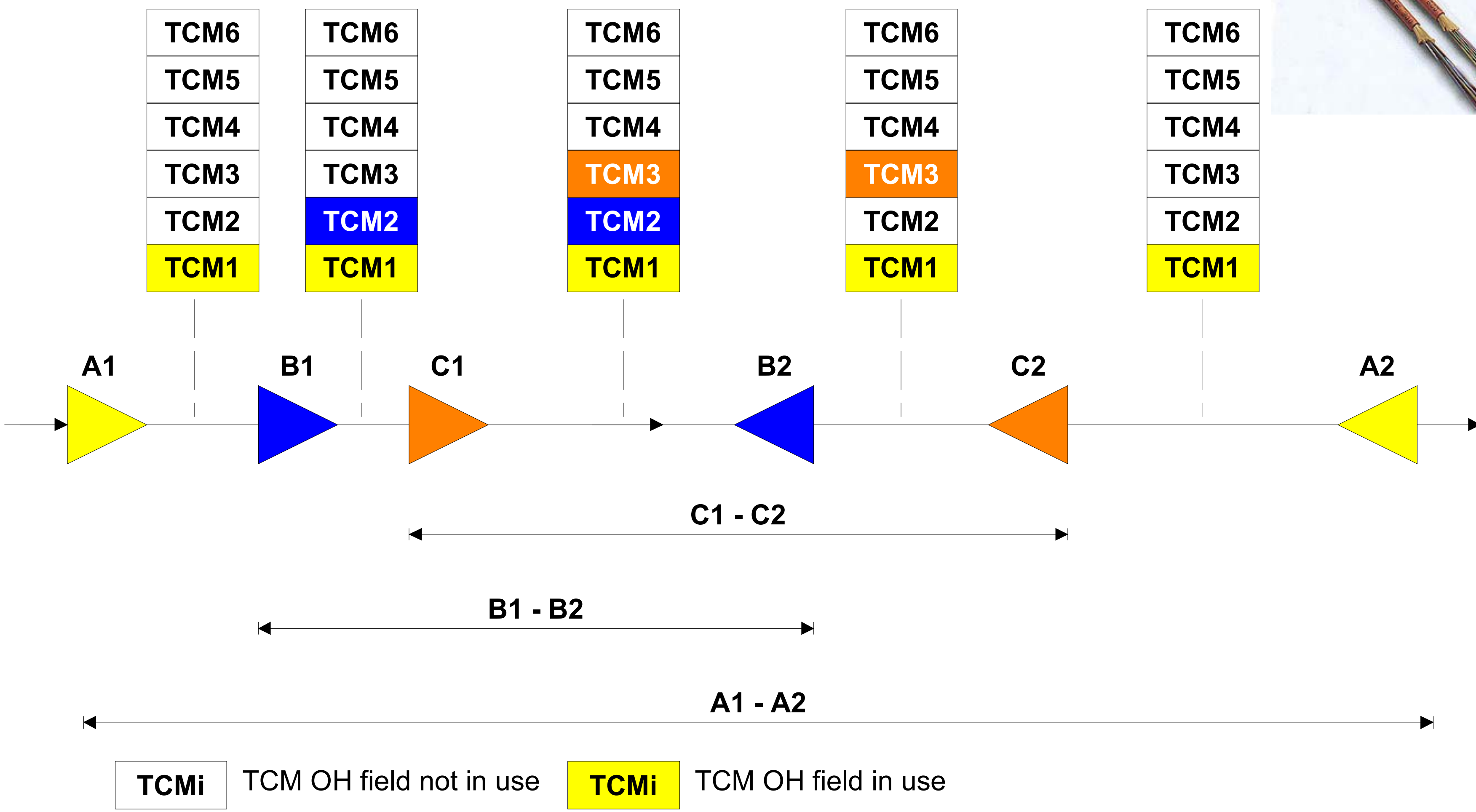
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Frame alignment OH							Transport Specific OH							Pay-load OH	
2	RES			TCM ACT	TCM6			TCM5			TCM4			FTLT		
3	TCM3			TCM2			TCM1			PM			EXP			
4	GCC1		GCC2			APS/PCC				RES						

PM	Path monitoring
TCM	Tandem connection monitoring
RES	Reserved for future standardization
ACT	Activation/deactivation control channel
FTFL	Fault type & fault location
GCC	General communication channel
APS	Automatic protection & switching channel
PCC	Protection communication control channel

TTI	Trail trace identifier
SAPI	Source access point identifier
DAPI	Destination access point identifier
BIP-8	Bit interleaved parity –8
BEI	Backward error indication
BDI	Backward Defect Indication
STAT	Status indicator
IAE	Incoming alignment error
LCK	Locked signal
OCI	Open connection indication
AIS	Alarm indication signal



Tandem Connections



Payload Overhead

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	Frame alignment OH							Transport OH							RES	JC	D	D
2	Data OH														RES	JC	D	D
3															RES	JC	D	D
4															PSI	NJO	PJO	D

PSI Payload structure identifier
RES Reserved for future standardization
JC Justification control
NJO Negative justification opportunity
PJO Positive justification opportunity
D Payload data

Future Developments

- There are some things missing from G.709.
  - Multiplexing.
  - Automatic protection switching (APS), used for switching to protection fiber when failure occurs.
  - Data framing.
- Provisions have been made for multiplexing.
  - When a higher level signal carries a lower level signal, the redundant octets of the lower signal are not needed.
  - The one OH octet per RS subframe must be carried.
  - Means that 16 extra octets per row must be allocated for carrying next lower level traffic.

Multiplexing into Higher Rate Signals

Redundant RS octets are stripped off of lower rate signals, but OH octets remain. Therefore, 16 additional octets must be provided for each rate increment.

	15	16	17	……… 1904	1905 ….. 1920	1921 ……… 3824
1	RES	JC	118 x 16D		16FS	119 x 16D
2	RES	JC	118 x 16D		16FS	119 x 16D
3	RES	JC	118 x 16D		16FS	119 x 16D
4	PSI	NJO	PJO	15D + 117 x 16D	16FS	119 x 16D

Framing of a level 2 payload to allow for multiplexing

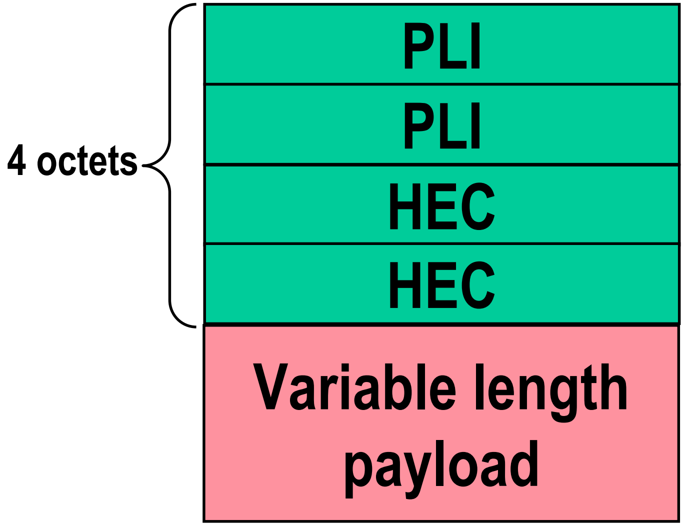
	15	16	17	……… 1264	1265 ……. 1280	1281 ……… 2544	2545 ……. 2560	2561 ……… 3824
1	RES	JC	78 x 16D		16FS	79 x 16D	16FS	79 x 16D
2	RES	JC	78 x 16D		16FS	79 x 16D	16FS	79 x 16D
3	RES	JC	78 x 16D		16FS	79 x 16D	16FS	79 x 16D
4	PSI	NJO	PJO	15D + 77 x 16D	16FS	79 x 16D	16FS	79 x 16D

FS = fixed stuff octets

Framing of a level 3 payload to allow for multiplexing

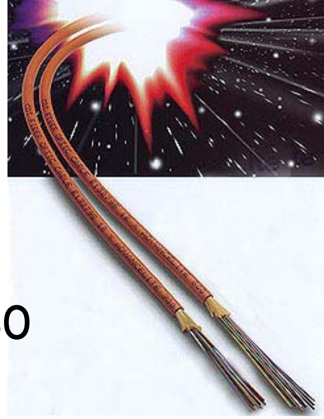
Future Developments (continued)

- APS has not yet been defined.
  - This is a serious shortcoming which will surely be addressed in the next revision of G.709.
- Data framing is being defined.
  - Called "Generic Framing Procedure" (GFP). Will be G.7041.
  - Can be thought of a variable length ATM type of framing.
  - Header has header check octets and payload length. GFP frame delineation is similar to finding ATM header.



PLI = Payload length indicator
HEC = Header error control (CRC-16)

Which to Choose?



- "One of the great things about standards is that there are so many to choose from".
- The in-band G.707 provides reasonable gain but uses overhead octets that may not be passed along by older equipment.
- G.709 provides higher gain but is all new and uses higher line rates.
- G.709 appears to be targeted at data traffic.
  - But data within SONET/SDH works fine.
- There can be little doubt that G.709 has been designed to replace SONET/SDH.

Summary

- Forward error correction will likely show its greatest value at the highest line rates.
- Two technologies are proposed – in-band and digital wrapper.
- The market seems to be favoring the digital wrapper approach. I have not seen any announcements of in-band FEC yet, but it's possible that future SONET framers will include it.

Questions?