National
Semiconductor
The Sight & Sound of Information

FEC for EFM

Introduction and Tutorial

IEEE 802.3ah EFM Task Force
Interim Meeting, Los Angeles
October 2001

Lawrence Rennie, National Semiconductor.
with contributions from Steven McLaughlin, Calimetrics; Ajay Gummalla, Broadcom; Lior Khermosh, Passave.

Outline

- What can be achieved with FEC?
- What is FEC and its benefits? Definitions, FEC Types.
- How do block codes work?
- Constructing FEC codes.
- Examples of FEC in existing optical networks.
- Issues with FEC in EFM.

Earlier presentations dealing with FEC for Optical Networks include:

1. Kamran Azadet, July 1999, Montreal, “Forward Error Correction (FEC) techniques for optical communications.

http://www.ieee802.org/3/10G_study/public/july99/azadet_1_0799.pdf

2. Hal Roberts, July 2001,Portland, “Cost Effective High Split Ratios for EPON”

http://www.ieee802.org/3/efm/public/jul01/presentations/roberts_1_0701.pdf

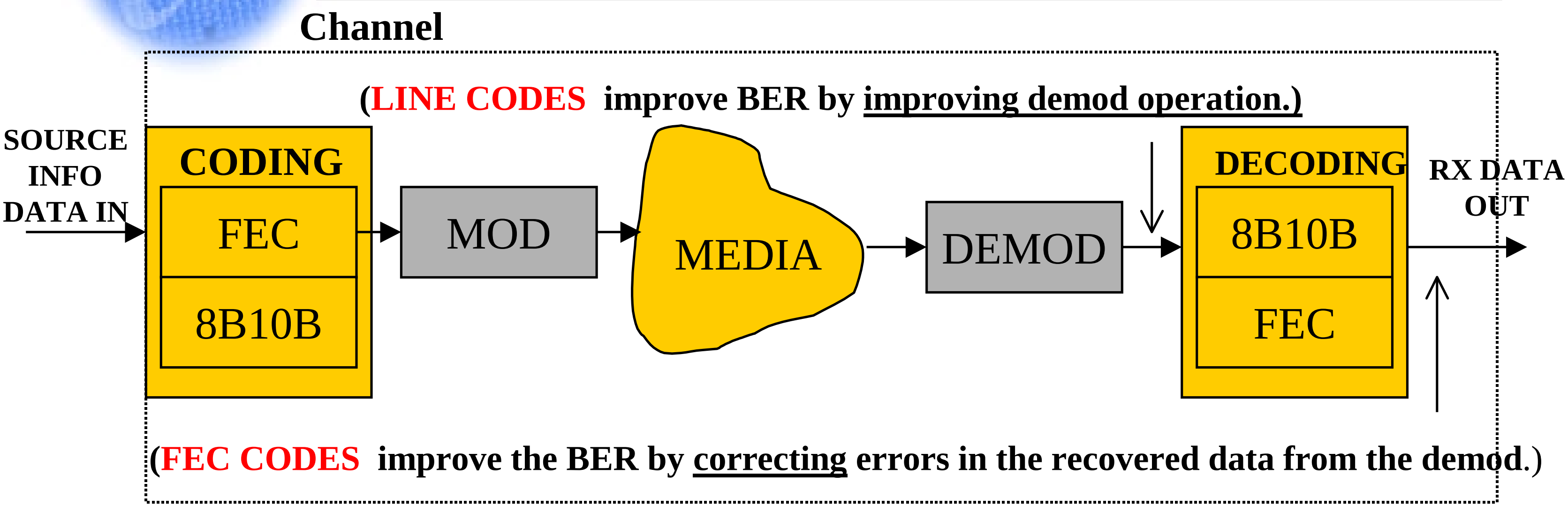
What will be achieved with FEC? Its Cost?

I. We will achieve a net coding gain (defined later) improvement that can be used to:

1. Decrease transmit power.
2. Increase distance.
3. Decrease receive BER.
4. Increase PON splitter ratio.

II. The Cost?
Increased bit overhead (line rate), delay, and processing complexity.

What is FEC?
The Generic Communication Channel



Channel

(LINE CODES improve BER by improving demod operation.)

SOURCE INFO DATA IN

CODING

FEC

8B10B

MOD

MEDIA

DEMOD

DECODING

8B10B

FEC

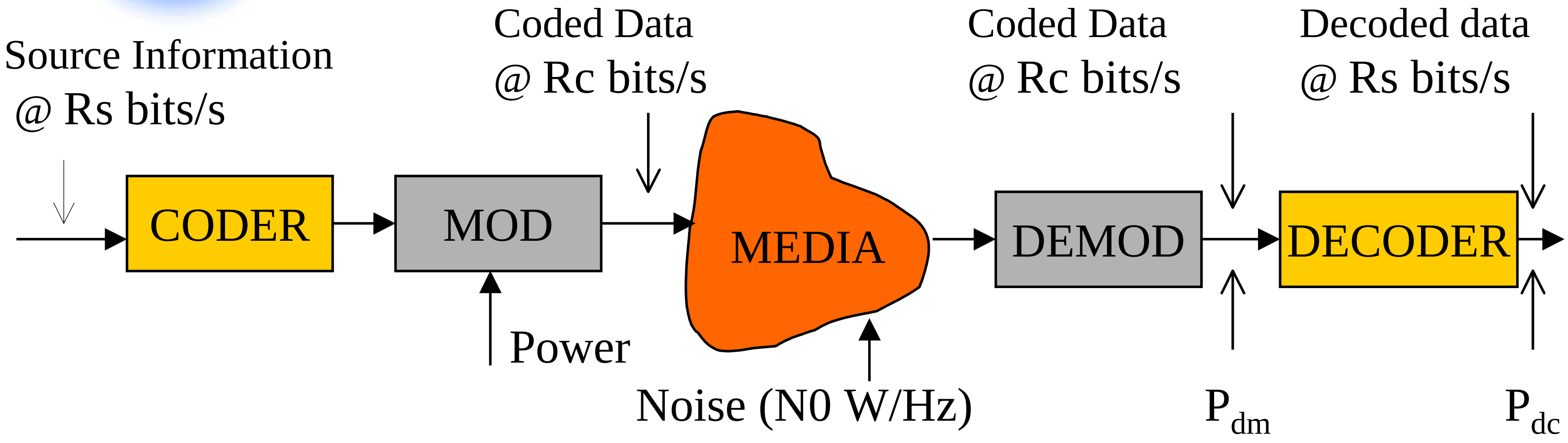
RX DATA OUT

(FEC CODES improve the BER by correcting errors in the recovered data from the demod.)

1. The whole communication channel determines the RX BER at the channel output. Both coding and modulation play key roles. The value of FEC is directly linked with the performance of the mod/demod scheme.

2. FEC is one form of coding the source data to improve the RX data BER by correcting recovered bit errors in the demodulator output. Other coding methods, such as the 8B10B line code, effectively improve the RX BER by improving demodulation.

What is FEC?
Channel Parameters of Interest



Source Information
@ Rs bits/s

Coded Data
@ Rc bits/s

Coded Data
@ Rc bits/s

Decoded data
@ Rs bits/s

CODER

MOD

MEDIA

DEMOD

DECODER

Power

Noise (N0 W/Hz)

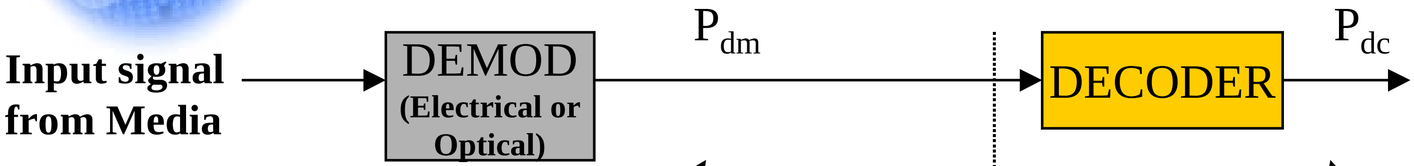
P_{dm}

P_{dc}

- **Rs bits/s= Source Information bit rate.**
- **Rc bits/s= Coded data bit rate= F^n (Code Overhead and info rate)**
- **Eb Joules= Energy per info bit = (Power watts)/(Rs bits/s)**
- **Ec Joules= Energy per channel bit = (Power watts)/(Rc bits/s)**
- **N0 Watts/Hz = Noise spectral power density.**
- **P_{dm}= Prob of error at demod output= F^n(Ec/N0, code overhead, mod/demod, code)**
- **P_{dc} = Prob of error at decoder output = F^n(P_{dm}, FEC Decoder algorithm)**

What is FEC?

Demodulator and Decoder output BER



For BSC (m=2), Hard Decision:

Electrical

$$\mathbf{P_{dme} = erfc[sqrt(2Ec/N0)],}$$

$$P_{dme} \approx (1/2)e^{-Ec/N0}$$

Optical (PD detector)

$$\mathbf{P_{dmo} = \tfrac{1}{2}\, erfc(Q/sqrt2)}$$

P_{dmo} (upper bound) $\approx (1/\mathrm{sqrt}\ 2\pi)e^{-Q^2/2}/Q$, where,

Q = (Ave PD Current)/(rms Noise Current) = I/i_{noise}

I = R*P0, where R= Responsivity A/W, P = Optical Pwr

i_{noise} is thermal for pin PD and shot for APD

$$P_{dc} = 1/n \sum_{i=t+1}^{i=n} \binom{n}{i} p^i (1-p)^{n-i}$$

where,

p = input prob of error (P_{dm})

t = # bits of error correction

n = CW length in bits

Approx. for small p and t=1:

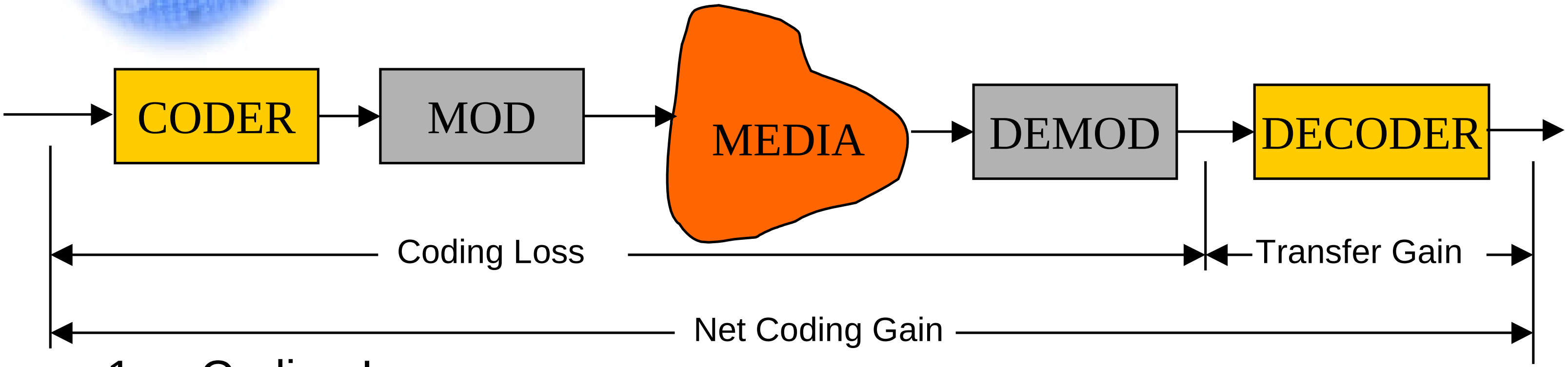
$$P_{dc} \approx n * p^2$$

FEC Definitions
Coding Gain

1. Coding gain (loss) resulting from a coding operation is the power decrease (increase) required to maintain the same BER as that achieved without the coding operation. Depending upon where BER is measured, there are 3 components associated with Coding Gain: <u>Coding Loss, Transfer Coding Gain and Net Coding Gain.</u>

2. Values for Electrical and Optical coding gains are different because the modulation schemes are different and the SNR's are measured differently.

FEC Definitions
Coding Gain (Loss, Transfer and Net)



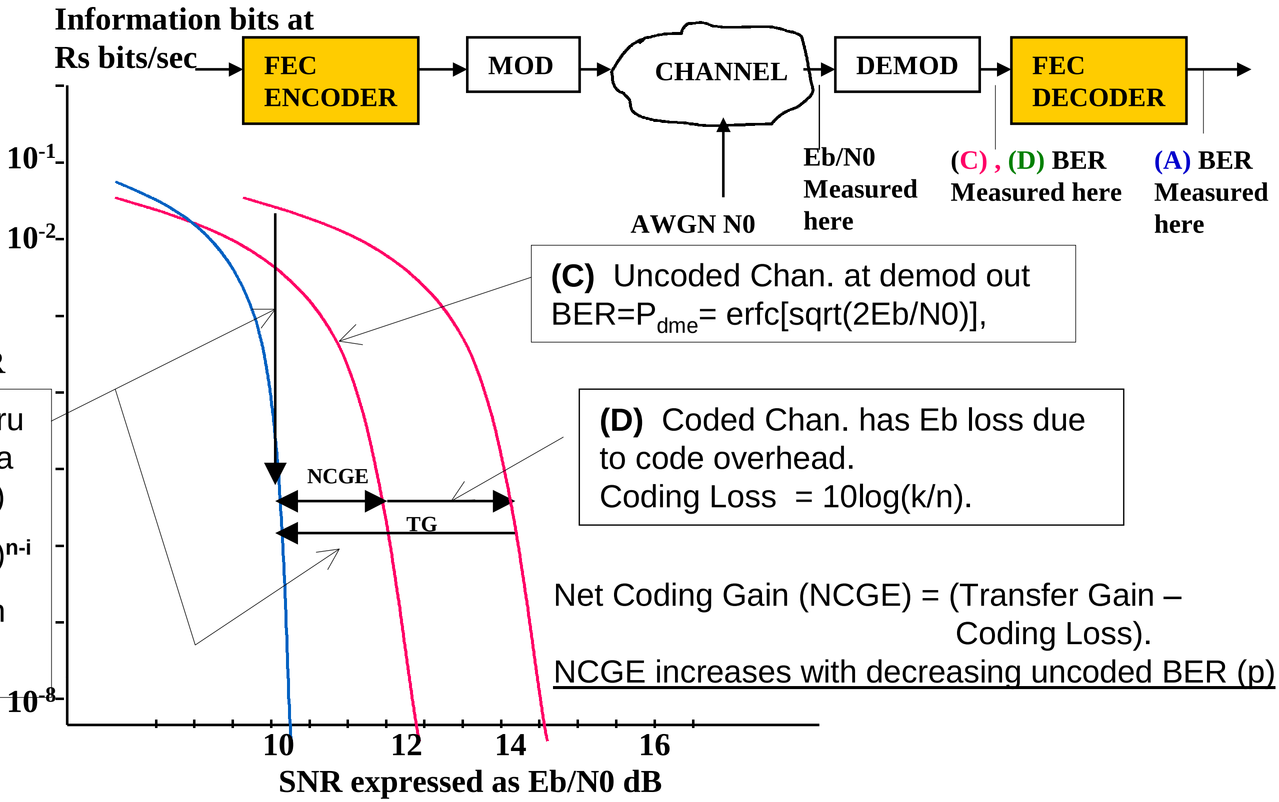
1. Coding Loss
   Power increase, due to coder overhead bits, required to maintain same BER as the uncoded channel. BER is measured at demod output (decoder input).

2. Transfer Coding Gain
   Power decrease, due to decoder error correction, required to obtain a decoder output BER equal to the decoder input BER.

3. Net Coding Gain = Transfer Gain – Coding loss

FEC Definitions
Coding Gain (Loss, Transfer and Net)

- Information rate fixed at Rs bits/sec.
- Eb = Power/Rs



(C) Uncoded Chan. at demod out BER=P_{dme}= erfc[sqrt(2Eb/N0)],

(D) Coded Chan. has Eb loss due to code overhead.
Coding Loss = 10log(k/n).

(A) BER improvement thru decoder results in a Transfer Gain (TG)

$$P_{dc} = 1/n \sum_{i=t+1}^{i=n} \binom{n}{i} p^{i}(1-p)^{n-i}$$

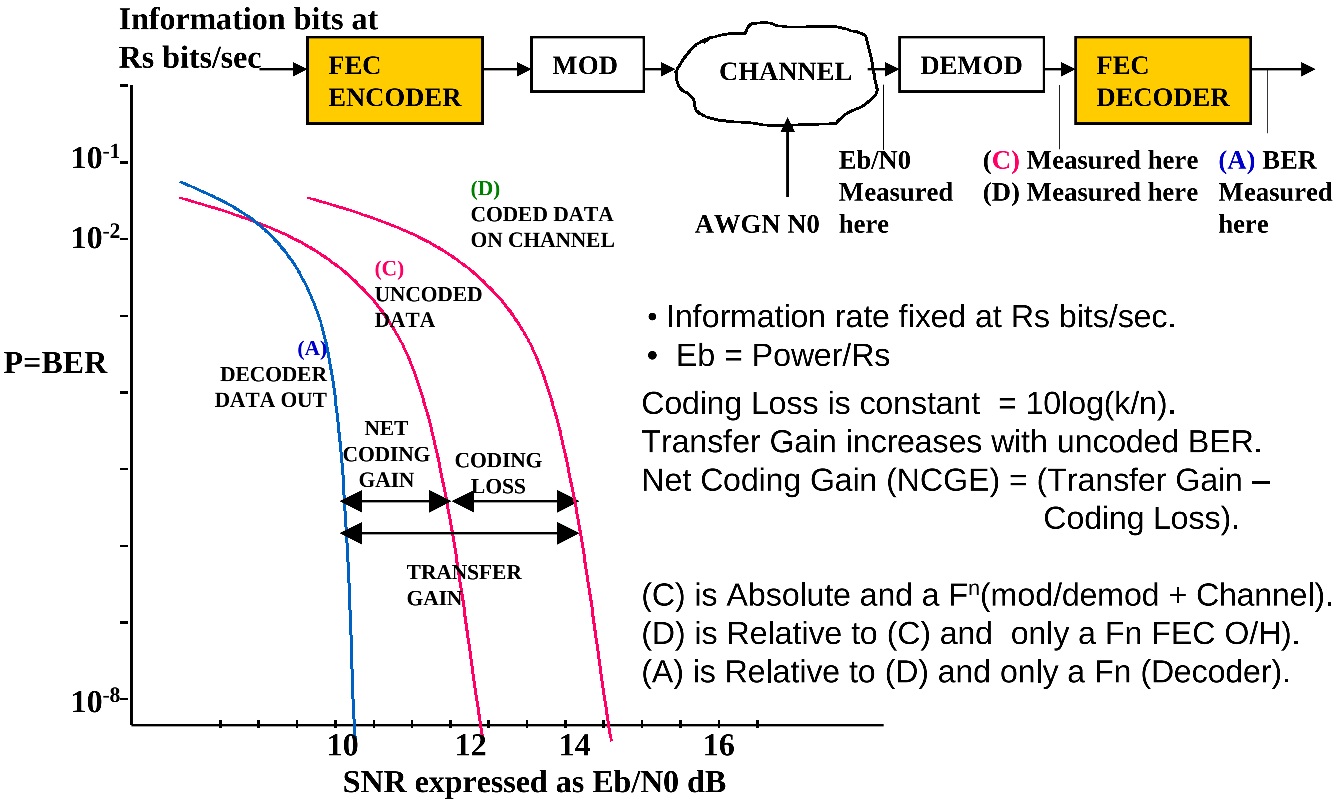
where, t = error correction

p = uncoded BER

Net Coding Gain (NCGE) = (Transfer Gain – Coding Loss).

<u>NCGE increases with decreasing uncoded BER (p)</u>

FEC Definitions
Coding Gain (Loss, Transfer and Net)



- Information rate fixed at Rs bits/sec.
- Eb = Power/Rs

Coding Loss is constant = 10log(k/n).
Transfer Gain increases with uncoded BER.
Net Coding Gain (NCGE) = (Transfer Gain – Coding Loss).

(C) is Absolute and a F^n(mod/demod + Channel).
(D) is Relative to (C) and only a Fn FEC O/H).
(A) is Relative to (D) and only a Fn (Decoder).

FEC Definitions

Electrical Coding Gain for RS(255,239,8)

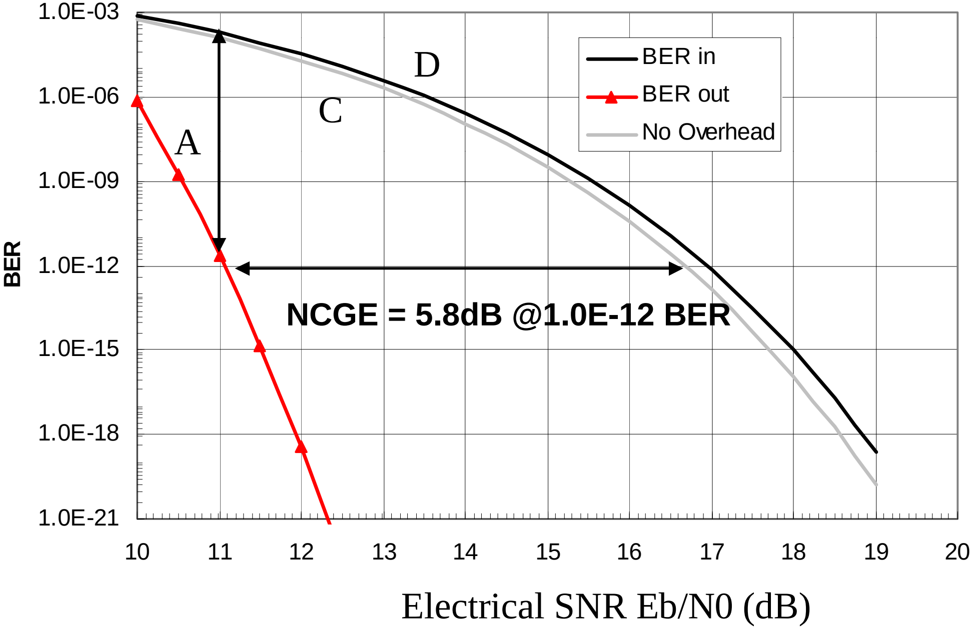
Binary (m=2), Coherent FSK

BER ≈ $e^{-A_b/2}/\mathrm{sqrt}(2\pi A_b)$,
where, A_b = Eb/N0 (dB)

D = coded channel at demod out
C = uncoded channel at demod out
A = Coded channel at decoder out

Thanks to Ajay Gummalla of Broadcom for this plot.

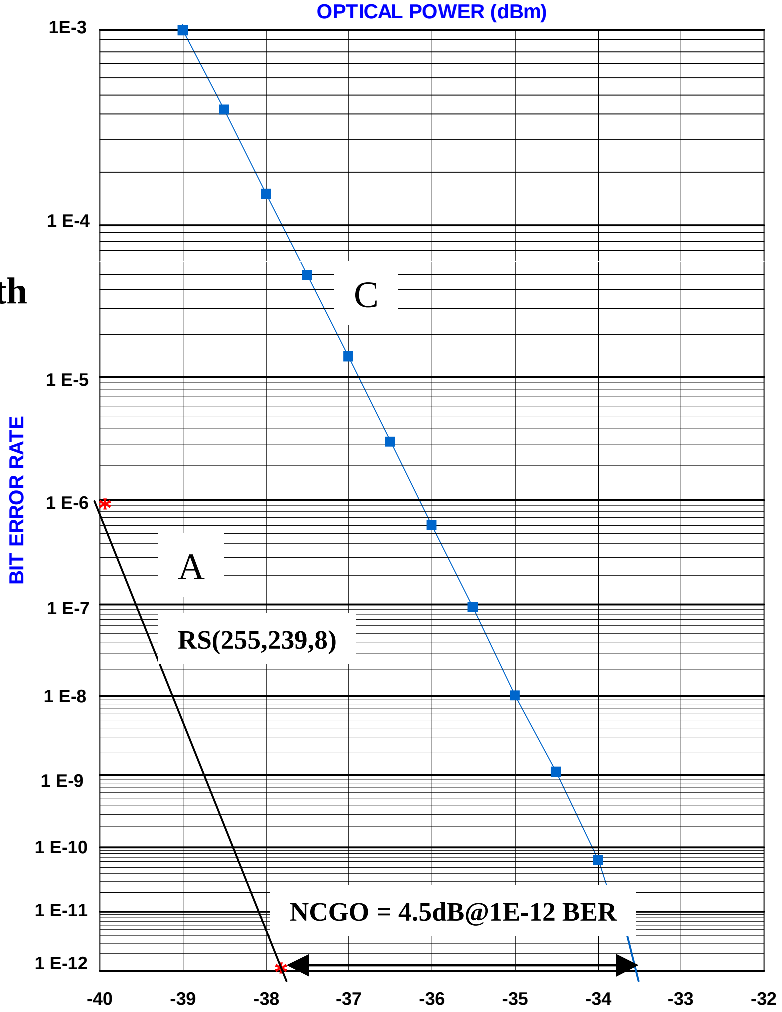
BER vs Eb/N0 for R-S 255 Code (t = 8)



FEC Definitions

Optical Coding Gain for RS(255,239,8)

NCGO achieved with the RS(255,239) FEC code used with an APD based optical receiver. APD receivers are,
in general, shot noise limited.



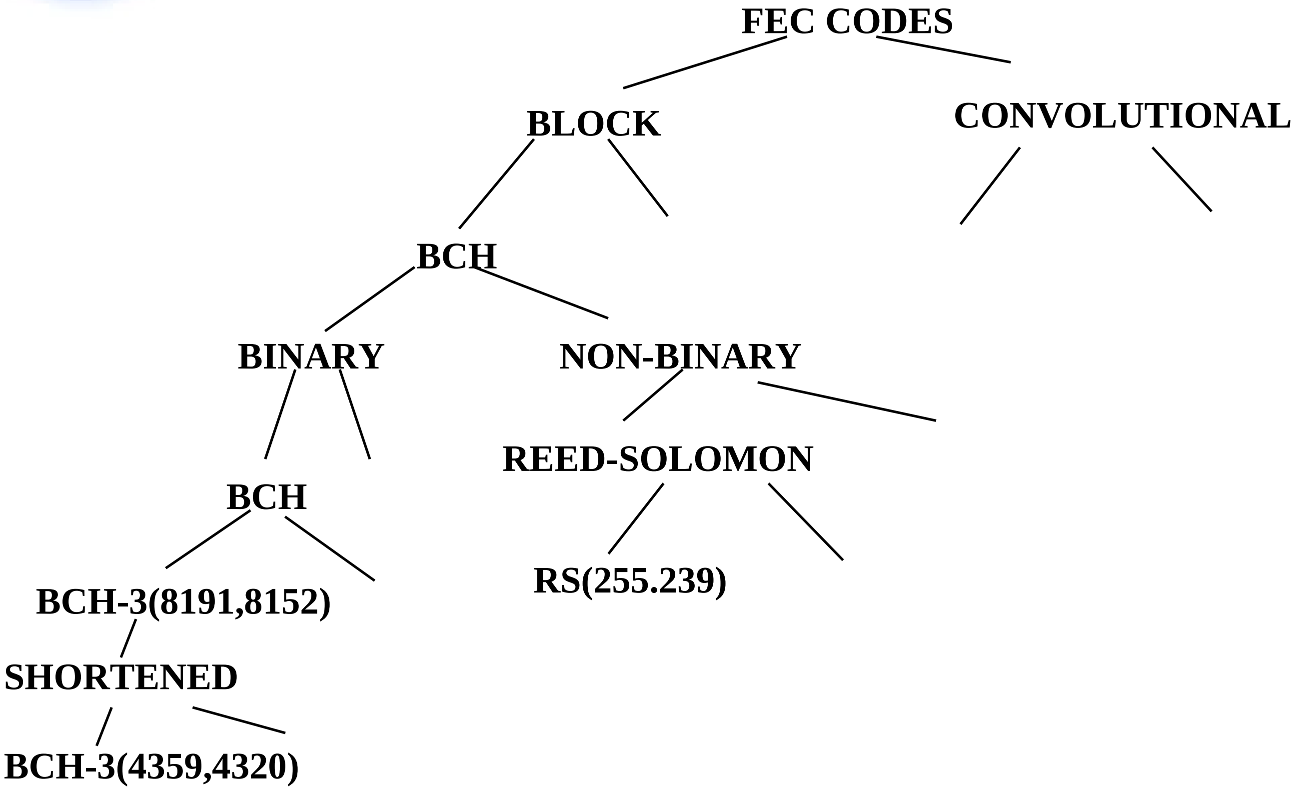
FEC Definitions
Coding Gain Comments

1. Transfer gain increases for decreasing uncoded channel BER (i.e., increasing E_b/N_0). Since the coding loss is constant over E_b/N_0, the net coding gain increases for increasing E_b/N_0.

2. This means that whenever net coding gain is specified it must be specified at a particular E_b/N_0 or corresponding uncoded channel BER.

3. It can be seen from point 1 that at some very low uncoded channel BER, adding FEC to the channel will actually worsen the channel output BER.

Types of FEC Codes



FEC CODES

BLOCK

CONVOLUTIONAL

BCH

BINARY

NON-BINARY

BCH

REED-SOLOMON

BCH-3(8191,8152)

RS(255.239)

SHORTENED

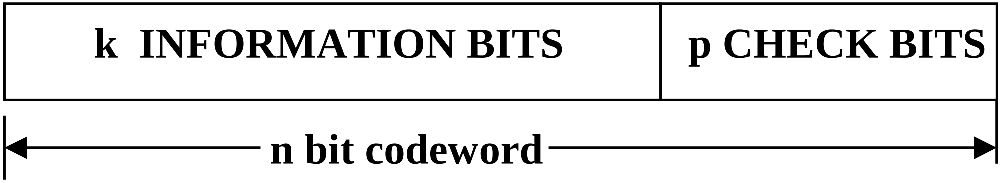
BCH-3(4359,4320)

How Does a Block FEC Code Work? The Systematic Block Code

1. Append **p** parity check bits to each **k** block of information bits to form an **n** bit codeword with the property that it is a minimum distance d (hamming distance d_{min}) from any other codeword. Errors in CW's can be corrected if errored CW in VCW space is closer to the correct CW than any other.

2. To correct all e errors in the cw:
   $d_{min} = 2e + 1$

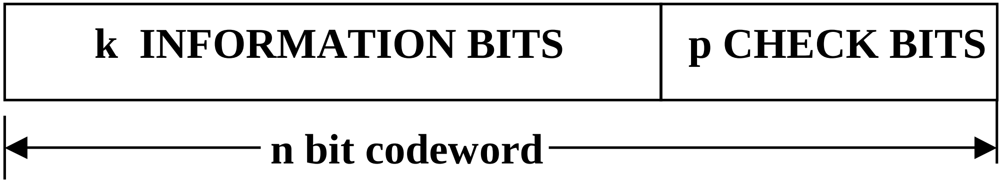
3. Code rate = k/n



How Does a Block FEC Code Work? The Systematic Block Code

4. We will deal only with systematic block codes which are codes which append the p parity check bits to the k information bits. The k information remain are unchanged within the codeword.

How Does a Block FEC Code Work? The BCH Codes. Large Number.



k INFORMATION BITS | **p CHECK BITS**

n bit codeword

For <u>any</u> positive integer m there exists a t error correcting binary BCH code such that:

$n = 2^m – 1$

$d_{min} \geq 2^t + 1$

$p = (n-k) = mt$ for all $t = 1,2$

$p < mt$ for $t \geq 3$

How Does a Block FEC Code Work? Codeword Manipulation

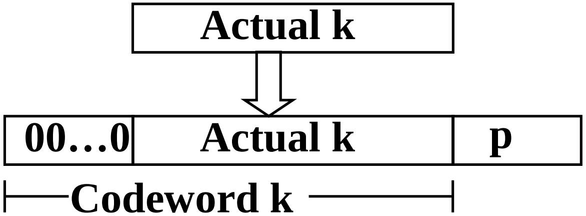
Two of the more useful codeword "manipulation" schemes used to improve the performance or usability of FEC codes are:

1. Codeword **Shortening** to obtain an exact CW size, and,
2. Codeword **Interleaving** to correct burst errors.

How Does a Block FEC Code Work? Shortening code to fit CW size.

1. **It is often necessary to have a CW block size that is different from the block size dictated by the code. For example, tailor the k info bits or block size n to a specific size. This is can be accomplished by <u>shortening the code.</u>**

2. **Choose a code with a block size greater than needed and then trim the block size by setting the appropriate number of unneeded (consecutive) information bits to zero. The zeroes are not transmitted but are reinserted before decoding. Error correction capability is the same as unchanged code.**



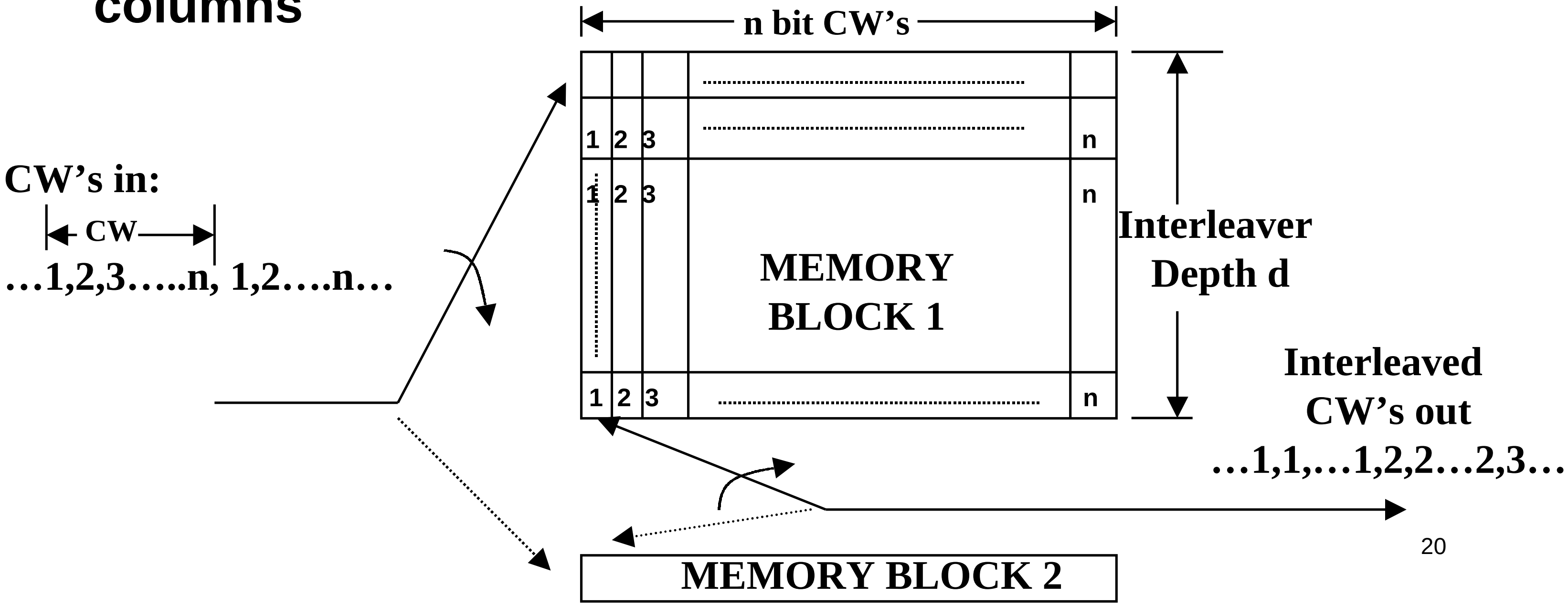
Actual k

00…0 | Actual k | p

Codeword k

How Does a Block FEC Code Work? Interleaving to correct burst errors.

Interleaving is a technique that reorders (in time) individual codeword bits with other codeword bits to effectively spread error bursts over many different codewords. A straightforward way to implement interleaving is to store the CW's in the rows of a block memory and transmit the columns



CW's in:

CW

…1,2,3…..n, 1,2….n…

n bit CW's

1 2 3 n

1 2 3 n

MEMORY BLOCK 1

1 2 3 n

Interleaver Depth d

Interleaved CW's out

…1,1,…1,2,2…2,3…

MEMORY BLOCK 2

How Does a Block FEC Code Work? Interleaving to correct burst errors.

1. **The max burst size correctable is:**
   #burst errors = d x e, where,
   e = code’s symbol error correction capability.
   d = Interleaver depth.

2. **The main limiting cost of interleaving is the delay resulting from the time to load the interleaver and deinterleaver memory blocks.**

3. **Other costs are the increased silicon needed for the memory blocks and deinterleaver synchronization.**

4. **Other interleaver implementations include the use of shift registers and the use of multiple encoders/ decoders (the technique used by the OTN digital wrapper RS(255,239) FEC).**

What is theoretically possible? Shannon capacity

For an AWGN channel, the theoretical, error free Channel capacity (C) is given by the Shannon channel capacity theorem:

$C = W\log_2(1 + P/(N_0W))$ bits/s, where,

P = Power in watts
W= Channel bandwidth
N_0 = Noise power spectral density in Watts/Hz
Spectral Efficiency = $C/W = \log_2(1 + (Eb/N_0)(C/W))$

Prob bit error = $p = e^{-nE_b(R)}$

Where, n = CW size, R = Information rate, Eb (R) = Positive Fn.

Bottom Line:
For any information rate R<C, the recovered BER can be made increasingly small by applying codes of increasing block size n while holding code rate k/n constant.

FEC codes in Existing Networks

FEC codes are currently specified for use in communication networks. Two examples are:

1. The RS(255,238,8) code is specified in the optical digital wrapper of the ITU G.709 “Network Node Interface for the Optical Transport Network”. Out of band code.

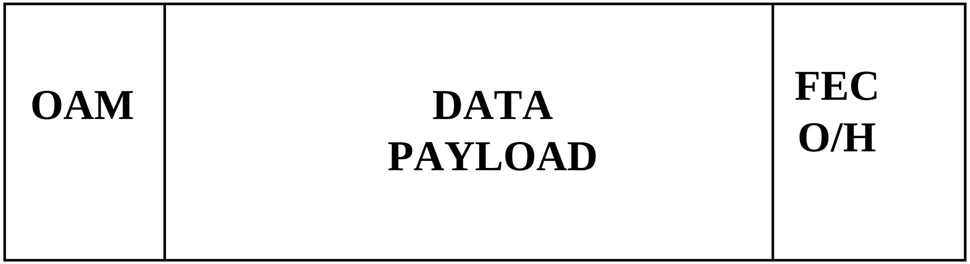
2. The BCH-3(4359,4320) shortened, in-band FEC code for optional use in SONET. Specified in ATIS T1.105.08 standard and, for SDH, in ITU-T G.707 recommendation.

FEC codes in Networks

ITU-T G.709 Out of Band RS(255,239)

1. Specified in the G.709 Digital Wrapper (DW). This code is implemented as 16 parallel encoder/decoders to:
   (a) reduce the clock rate of each encoder/decoder, and,
   (b) effectively interleave to a depth d = 16.

2. G.709 adopted the G.975 RS(255,239) FEC now used in current submarine fiber optic networks (improves submarine fiber distance by 2x to 4x).



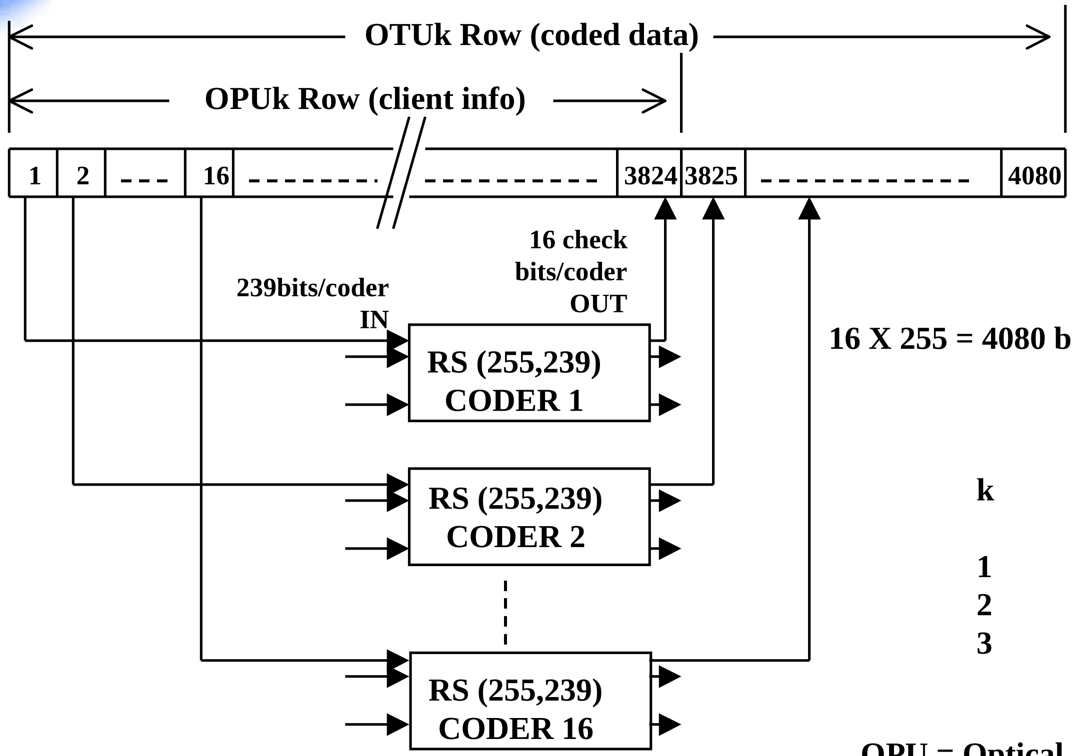
OAM

DATA PAYLOAD

FEC O/H

The OTN Digital Wrapper

FEC codes in Networks
ITU-T G.709 RS(255,239)


OTUk Row (coded data)
OPUk Row (client info)
1
2
16
3824
3825
4080
239bits/coder IN
16 check bits/coder OUT
RS (255,239) CODER 1
RS (255,239) CODER 2
RS (255,239) CODER 16

16 X 255 = 4080 bytes/OTUk row

k	OPUk	OTUk
1	2.48G	2.67G
2	9.95G	10.71G
3	39.81G	43.01G

Interleaving depth of 16 with 16 Codecs.

OPU = Optical Channel Payload Unit
OTU = Optical Channel Transport Unit

FEC codes in Networks

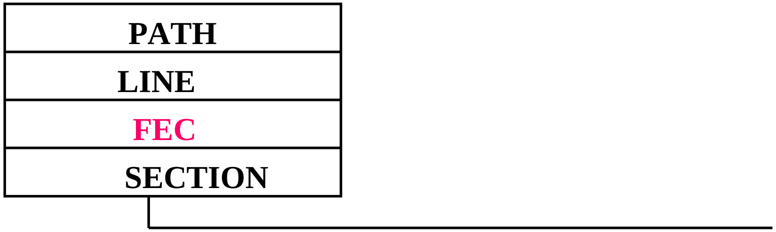
ITU-T G.709 RS(255,239) Performance

1. Burst error correction = e symbols x # bits/sym x d
   8 sym x 8bits/sym x 16 = 1024 bits
2. Interleaving to a depth = d =16 accomplished with d=16 parallel encoders/decoders.
3. Encode/decode clock rate = 10G/16 = 644MHz
4. Code efficiency = 93.72% (equivalent to 6.7% overhead)
5. Coding loss (due to overhead) = 0.28dB
6. Net coding gain Optical (NCGO) = 4.3dB at 10^{-12} corrected BER

FEC codes in Networks

BCH-3 (4359,4320) In-band FEC for SONET

- Code specified in T1X1.5, ANSI T1.105.08 standards.
- Provides a correction service to the SONET line layer.



PATH

LINE

FEC

SECTION

- In band because the 39 bits of FEC overhead are inserted into unused section and line overhead locations (i.e., in-band).

- This is a shortened version of the triple error correcting (8191,8152) BCH-3 code. CW size shortened so that 8, bit-interleaved CW's cover exactly one row of a SONET STS-48 SPE plus line overhead:

[(87+3)bytes/ STS-1 x 48 STS-1/STS-48 x 8bits/byte]/8 CW = 4320 data bits/CW

FEC codes in Networks

BCH-3 (4359,4320) In -band FEC for SONET

- The codewords are interleaved to a depth of 8 to provide 3x8 = 24 bits of burst error correction.
- 99% efficient
- Net coding gain electrical (NCGE)= 2dB at 10^{-15} corrected BER
- Compatible with existing non-FEC LTE and LRE.

Issues with FEC in EFM.

1. How integrate the 8b10b line code with FEC. 8b10b before or after FEC?
2. $ Cost?
3. Delay.
4. Performance increase worth the costs?

Note: The above important issues will be addressed in other presentations.