Responses to FEC St. Louis Work Item List.

1. Noise: Characteristics of the MPN and its effects on FEC.

2. Evidence that FEC can achieve an additional 10km given it may require 4-4.5dB extra.

3. 8b10b encoding and decoding in a high error rate environment.

4. To compare the frame based application of FEC to a bit stream application FEC.

5. Inter-symbol interference.

1. Characteristics of MPN and its effects on FEC

By Lawrence Rennie, National Semiconductor
IEEE 802.3ah (EFM) Interim Meeting
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Presentation Supporters:

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Outline

1. **What is Mode Partition Noise (MPN)?**
2. **How does MPN interact with the various network components to degrade the received BER?**
3. **The pertinent parameters associated with BER degradation due to MPN.**
4. **The Equations relating BER to MPN. The “BER Floor”.**
5. **MPN is approximately Gaussian.**
6. **BER improvement with a RS(255,239) FEC code.**
7. **References.**

What is MPN? How does it affect receiver BER?

1. **Mode Partition Noise (MPN) is a result of the laser power fluctuating between different λ modes within the laser. The different mode λ's travel at different speeds in the fiber as determined by the fiber's dispersion. The resulting ISI due to dispersion and pulse amplitude variations due to mode power fluctuations can be characterized as additional receiver noise with variance r_{mpn} .**

2. **MPN results in a MPN power penalty and a BER floor. <u>The BER floor can not be penetrated by increasing the power</u>. Other techniques such as FEC must be used to get below the floor.**

MPN Noise Statistics.

1. "In a multimode laser, both main and side modes are above threshold and their fluctuations are well described by a Gaussian probability density function".
   Ref.1, Mode Partition Noise, Section 5.4.3, page 218.

2. In multimode lasers, "The total power carried by each pulse is constant while the power in each mode fluctuates." A Gaussian assumption for the mode power spectrum, p(λ), "provides a reasonable fit for the central part of the experimental spectrum". Ref.2, pp. 621-623.

3. Burst errors not an issue, i.e., no interleaving required:

   a) Broad-light testing shows a modal lifetime of around 3ns. Therefore, over more than three bit times (at 1Gb/s) the MPN is uncorrelated (i.e., burst error pattern size, determined by correlation time, is small).

   b) Naval Surface Warfare Center testing on the waveform/eye pattern of a single FP mode lamda modulated at 622Mbps shows random noise on long term histogram measurements of the "1" level. The bit power within a bit time (1.61nsec) changed in an apparent uncorrelated fashion.

MPN Noise Statistics.

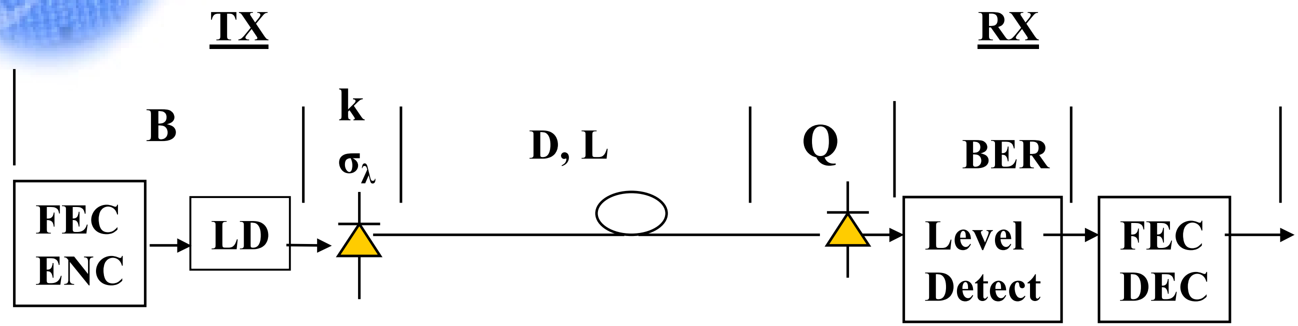
c) Preliminary testing by Terawave shows that the distribution of MPN induce bit errors are not bursty

Conclusions:

1. **MPN is approximately Gaussian and uncorrelated over less than about 3 bit times (at 1Gbit/s). Therefore , the resultant noise at the receiver will have the same statistics and <u>FEC will be effective</u> in correcting the resulting bit errors.**

2. **In fact, because the proposed RS code is based on symbol values, it is likely that a bit error distribution with a higher probability of short error bursts (2 or 3 bits) than that expected from pure AWGN will perform better!**

The Parameters that Relate MPN to BER. (see Appendix for details)



Three independent variables determine the MPN Power Penalty (δ_{mpn}):

k = A factor that characterizes the laser source MPN. $0 \leq k \leq 1$

Q = Rx SNR (dB), BER = bit error rate at Rx.

$BLD\sigma_{\lambda}$ = Normalized dispersion (dimensionless), where,

B= Information bit rate (bits/sec).

σ_{λ} = Source spectral width variance (nm)

D = Fiber Dispersion (ps/(Km-nm))

L = Fiber length (Km).

MPN Power Penalty = δ_{mpn} = $F^{\underline{n}}[k, Q, (BLD\sigma_{\lambda})]$ (See Appendix for equations)

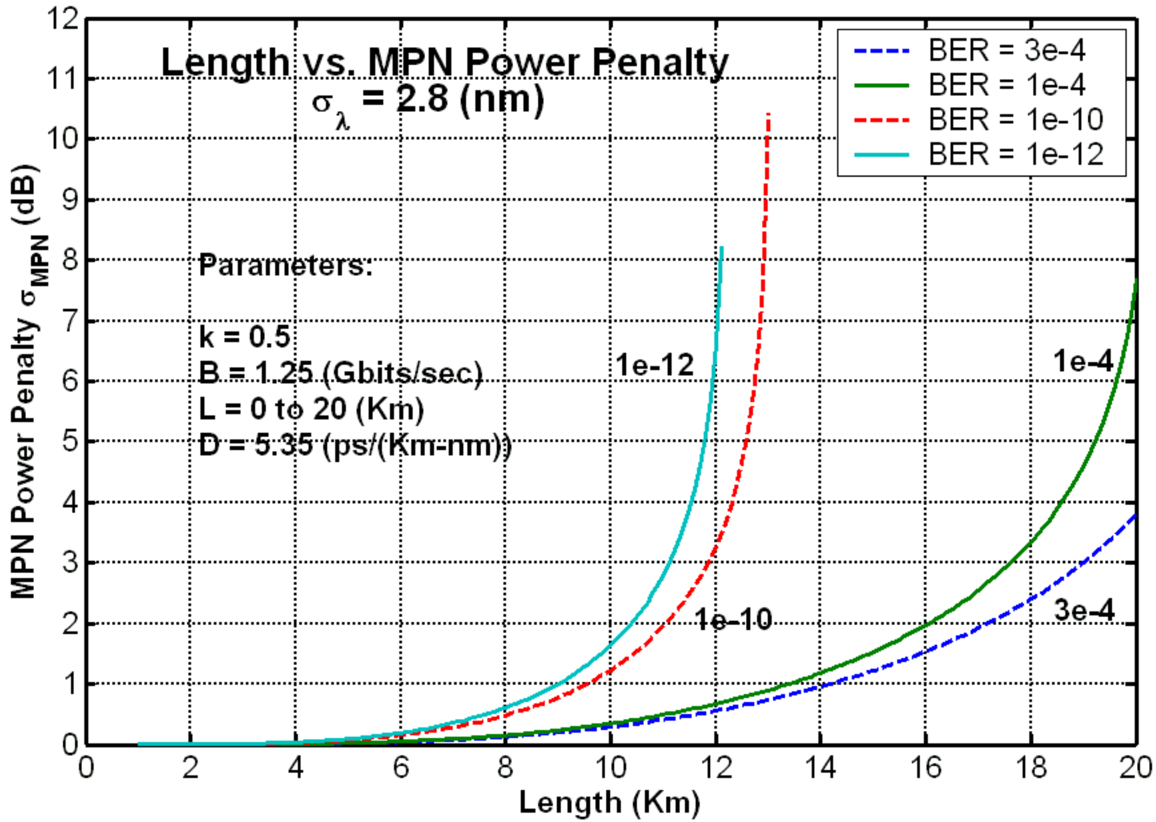
MPN Creates a limit on the SNR Q resulting in a BER Floor

The SNR Q approaches a finite limit as optical power is increased because the the MPN noise is a function of the laser spectral fluctuations and fiber dispersion. Thus, increasing the power also increases the MPN induced noise.

The Q_{limit} is independent of power and is given by:

$$Q_{\lim it} = \frac{1}{r_{mpn}} = \frac{\sqrt{2}}{k\left(1 - e^{-\pi^2 (BLD\sigma_\lambda)^2}\right)} \cong \frac{\sqrt{2}}{k(\pi BLD\sigma_\lambda)^2}$$

FEC Improvement, Example 1

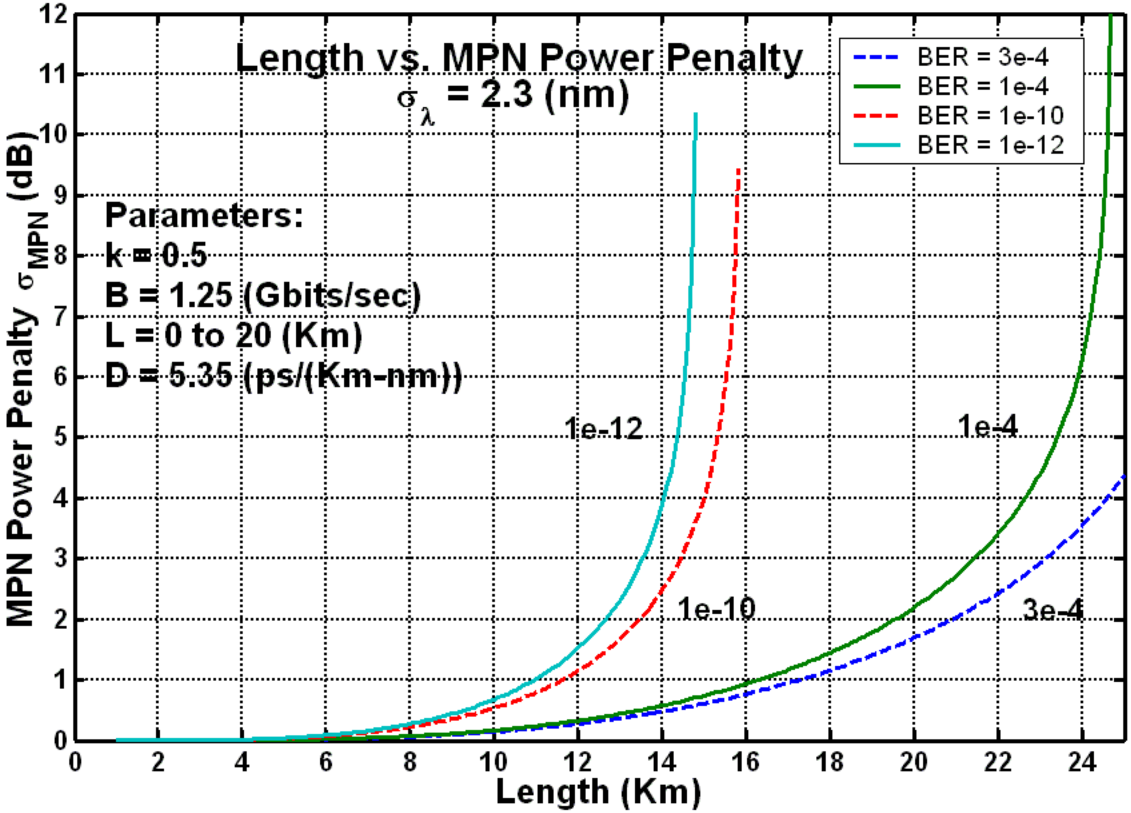


The RS(255,239) FEC code can correct:
BER 1e-4 to 1e-12
BER 3e-4 to 1e-10

1e-12 Improvement Examples:

1. **At about 11.5Km, FEC can achieve about 3.5dB of optical coding gain.**
2. **Increase reach from 10Km to 15.5Km**

FEC Improvement, Example 2



The RS(255,239) FEC code can correct:

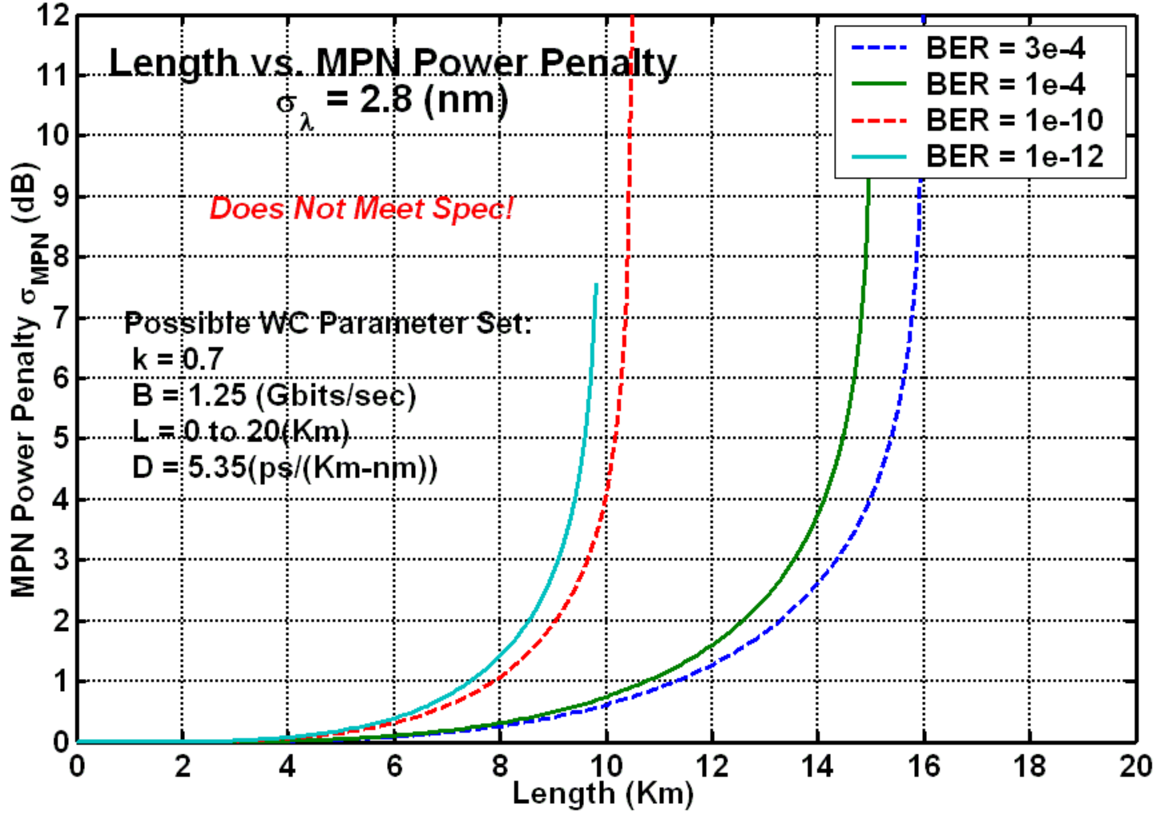
BER 1e-4 to 1e-12

BER 3e-4 to 1e-10

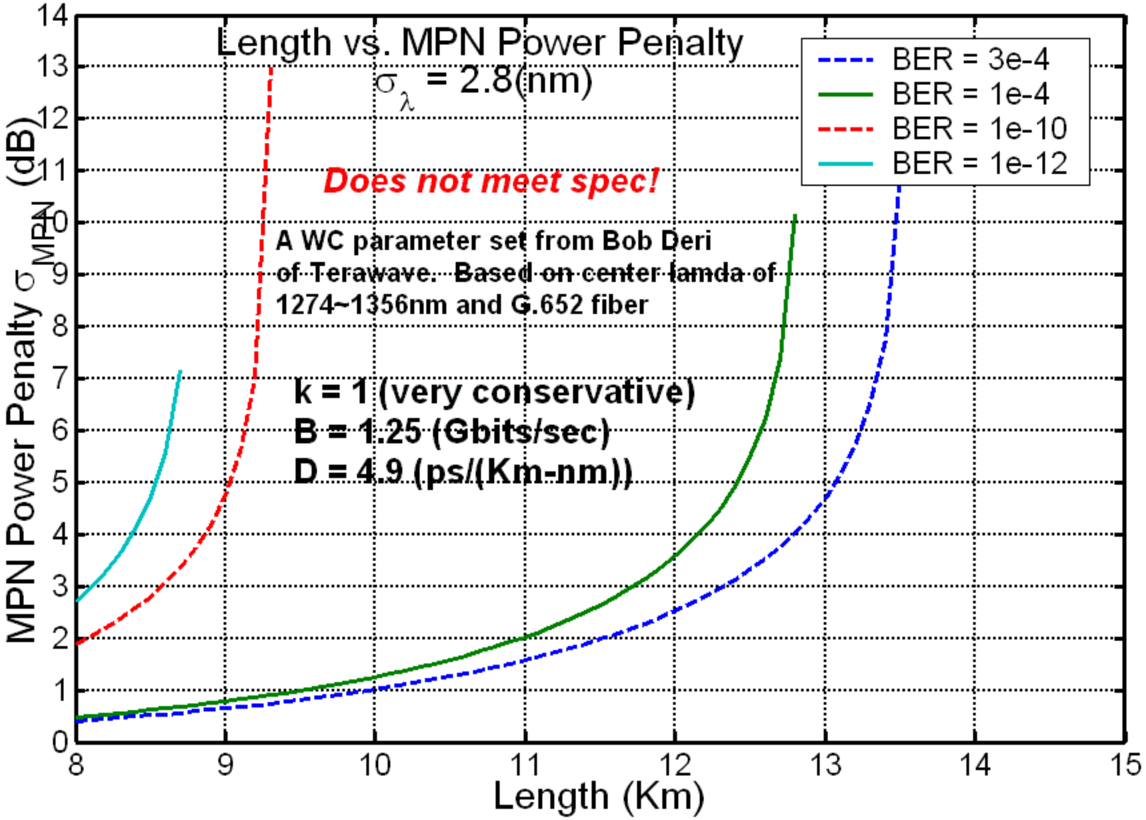
1e-12 Improvement Examples:

1. **At about 14 Km, FEC can achieve about 3.5dB of optical coding gain.**
2. **Increase reach from 12.5Km to 20Km**

Can Fail to meet 10Km under possible WC conditions. Ex.1



Can Fail to meet 10Km under possible WC conditions. Ex.2



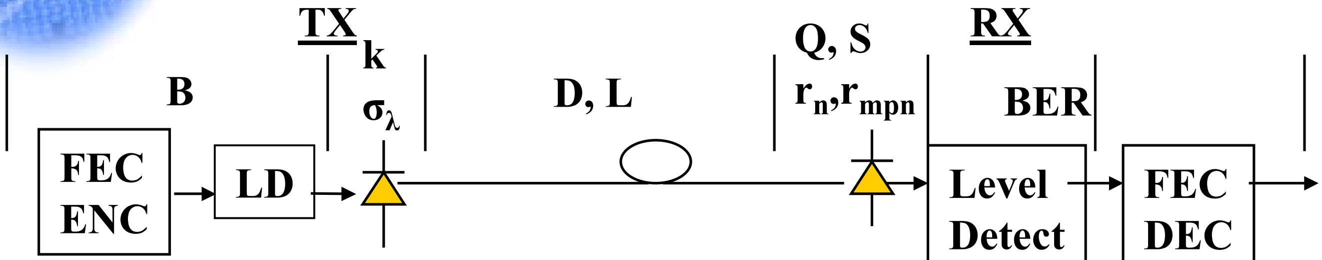
Matlab Program for Calculating MPN Effects on BER.

Matlab GUI program written to easily plot results for any combination of MPN parameters (δ_{mpn}, k, BER, BLDσ_{λ}).

Further MPN Tests Planned

Several companies are planning independent lab testing of an FP optical link to assess the level of MPN induced errors and the effectiveness of correcting these errors with FEC. Test results are planned to be presented at the next EFM TF meeting in July 2002.

Appendix: The Equations that Relate MPN to BER.



Assuming the MPN mode spectrum is Gaussian then a resulting receiver noise component variance, r_{mpn}, can be defined as :

$$r_{mpn} = \frac{k}{\sqrt{2}}\left[1 - e^{-\pi^2 (BDL\sigma_\lambda)^2}\right] \approx \frac{k}{\sqrt{2}}(\pi BDL\sigma_\lambda)^2 x10^{-24}$$

This additional noise component combines with the other receiver noise to produce an effective (and lower) SNR Q :

$$Q^2 = \frac{S^2}{r_n^2 + S^2 r_{mpn}^2} \quad \text{where } S = \text{received signal power}$$

Note that the MPN Noise component Increases with S.

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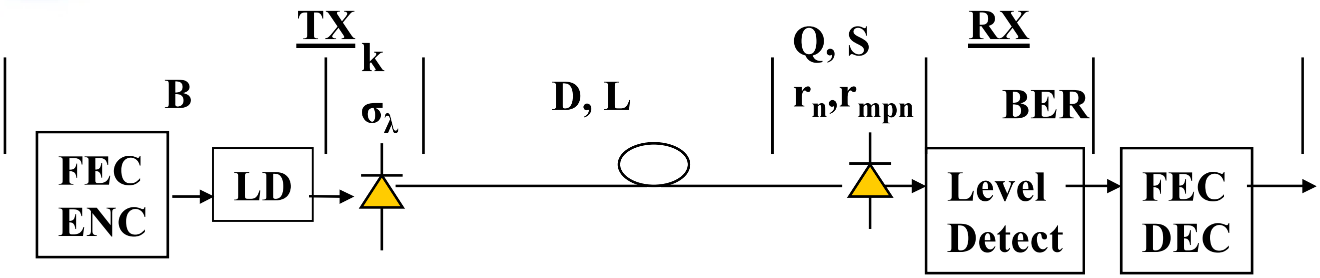

The decreased SNR Q can be characterized as a MPN Power Penalty

$$\delta_{mpn} = 5\log\left[\frac{1}{1-Q^2 r_{mpn}^2}\right]$$

The Q also determines the BER as follows:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{2}\right) \approx \frac{e^{\frac{-Q^2}{2}}}{Q\sqrt{2\pi}}$$

References

Reference:

1. **G. P. Agrawal, <u>Fiber-Optic communication Systems</u>, Wiley and Sons, 1997.**

2. **Agrawal, Anthony and Shen, “Dispersion Penalty for 1.3-um Lightwave Systems with Multimode Semiconductor Lasers”, IEEE Journal of Lightwave Technology, May 1988, pp. 620-625.**

3. **Lasky, Osterberg and Stigliani, <u>Optoelectronics for Data Communication</u>, Academic Press, 1995**

Responses to FEC St. Louis Work Items 2,3,4 and 5

2. **Evidence that FEC can achieve an additional 10km given it may require 4-4.5dB extra.**
3. **8b10b encoding and decoding in a high error rate environment.**
4. **To compare the frame based application of FEC to a bit stream application FEC.**
5. **Inter-symbol interference.**

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Lior Khermosh, Passave.

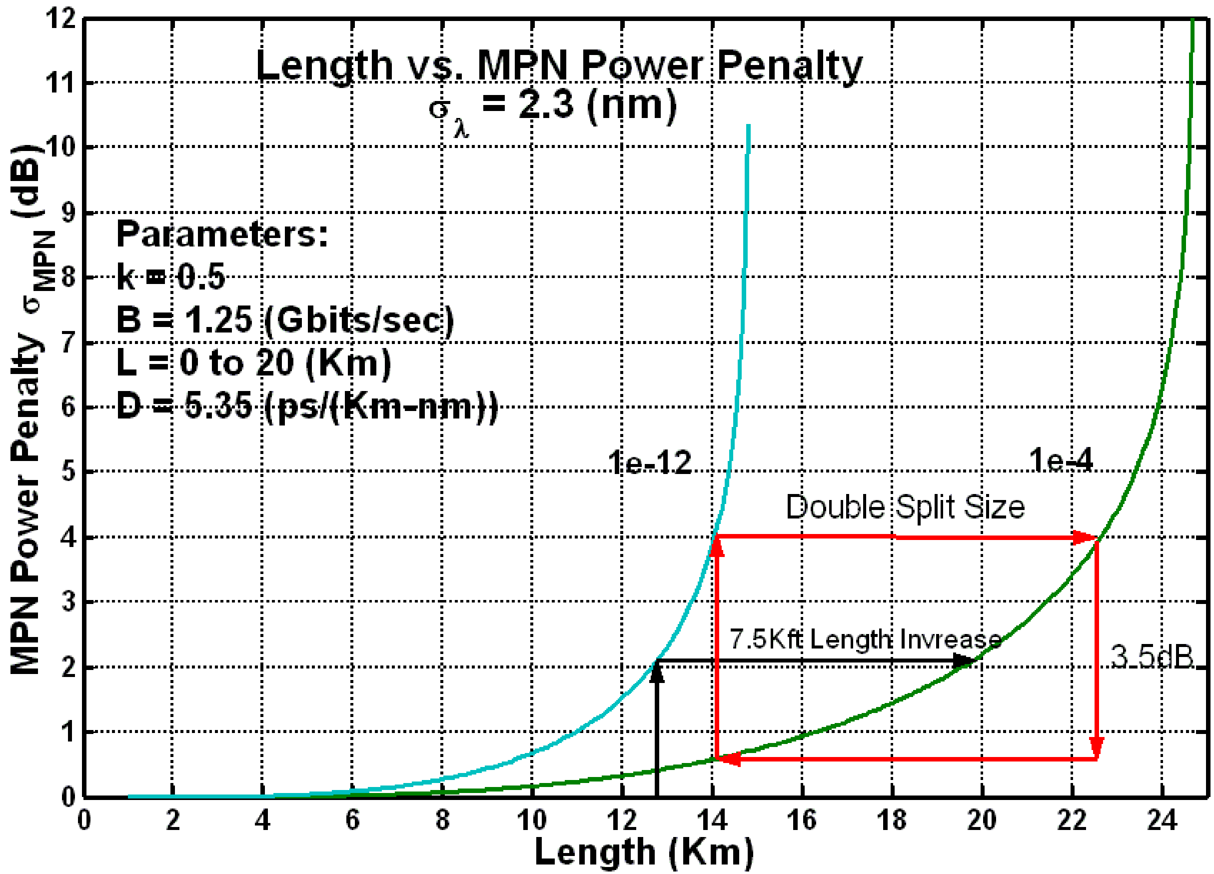
Edinburgh, May 2002

2. Evidence that FEC can achieve an additional 10km given it may require 4-4.5dB extra.

1. **The amount of improvement with FEC, in terms of BER or Coding Gain, is determined by the link parameters and is different for each set of link parameters (k, Q, (BLDσ_λ)).**

2. **Several companies are planning to have some actual link BER tests in time for the next meeting in July.**

2 (Cont'd). Evidence that FEC can achieve an additional 10km given it may require 4-4.5dB extra.



3. 8b10b encoding and decoding in a high error rate environment.

1. Not a problem because, even though an incorrectly decoded 10b codeword can produce an 8b word with many bit errors, the RS code proposed is based on 8-bit bytes and it does not matter if the byte has 1 bit or all 8 bits in error. Also, it does not matter if just 1 or all 10 bits in the 10B word are in error.

2. Can choose to track or not track disparity. Negligible effect on FEC performance.

3. The best techniques to deal with the non-FEC'd 10b framing control codes in a 1e-4 BER environment are being discussed. Majority vote, etc.

4. To compare the frame based application of FEC to a bit stream application FEC.

1. **A detailed framing based approach was presented by Lior Khermosh at Raleigh meeting (khermosh_1_0102.pdf).**

2. **Other FEC implementation ideas have been recently been presented over the reflector.**

3. **If FEC is voted in as an objective, then an FEC ad hoc group will form with responsibility for generating the best FEC implementation architecture. A goal will be to present this architecture to the group at the next EFM meeting in July.**

5. Inter-symbol interference

MPN will result in both ISI and amplitude noise components.

Conclusions

1. **MPN is a serious problem that under certain WC temperature conditions and component specifications can limit reach to less than 10Km for BER's less than 1e-10.**

2. **This problem can be mitigated with the addition of FEC.**