Ideal SNR Penalties

400 Gb/s Ethernet Task Force
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Duplex SMF & PSM4 PMDs Decision Tree

SMF PMDs studied

802.3bs today

bit rate per λ

50G

NRZ modulation

50Gb/s NRZ

PAM-4 modulation

50Gb/s PAM-4

100G

PAM-4 modulation

100Gb/s PAM-4

DMT modulation

100Gb/s DMT

50Gb/s PAM-4
Introduction

- Bit Rate = Channels * Baud Rate * Bits/Baud
  - Channels = fiber pairs * lambdas * polarizations * I & Qs
  - Baud Rate: limited by $B_{NQ}$ (Nyquist)
  - Bits/Baud: limited by SNR (Shannon)

- Ex.1: 10GBASE-LR, -SR (1\(\lambda\), 1 fiber pair)
  
  \[10\text{Gb/s} = 1 \text{ channel} \times 10\text{GBaud} \times 1 \text{ bit/Baud}\]

- Ex.2: 100GBASE-LR4, -SR4 (4\(\lambda\)s or 4 fiber pairs)

  \[100\text{Gb/s} = 4 \text{ channels} \times 25\text{GBaud} \times 1 \text{ bit/Baud}\]

- Ex.3: 100G DP-QPSK Coherent (1\(\lambda\), 1 fiber pair)

  \[100\text{Gb/s} = 4 \text{ channels} \times 25\text{GBaud} \times 1 \text{ bit/Baud}\]

Ex. reference for analyzing I & Q as separate channels:

Bits/Baud Examples

- NRZ: 1 bit/Baud
- PAM-M bits/Baud = \log_2(M)
  - M=2: 1 bit/Baud
  - M=4: 2 bits/Baud
- QAM-M bits/Baud = \log_2(\sqrt{M}) = 0.5*\log_2(M)
  - M=4: 1 bit/Baud (i.e. M_I = 2, M_Q = 2)
  - M=16: 2 bits/Baud (i.e. M_I = 4, M_Q = 4)
- DMT-k QAM-M bits/Baud = \log_2(\sqrt{M}) = 0.5*\log_2(M)
  - k is the number of DMT sub-carriers
  - M=4: 1 bit/Baud (i.e. M_{I_{K=1\rightarrow k}} = 2, M_{Q_{K=1\rightarrow k}} = 2)
  - M=16: 2 bits/Baud (i.e. M_{I_{K=1\rightarrow k}} = 4, M_{Q_{K=1\rightarrow k}} = 4)
## Bit Rate Examples

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Channels</th>
<th>Baud</th>
<th>Bits/Baud</th>
<th>Bit Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRZ</td>
<td>1</td>
<td>2*BW</td>
<td>1</td>
<td>2*BW</td>
</tr>
<tr>
<td>PAM-4</td>
<td>1</td>
<td>2*BW</td>
<td>2</td>
<td>4*BW</td>
</tr>
<tr>
<td>QAM-16</td>
<td>2</td>
<td>BW</td>
<td>2</td>
<td>4*BW</td>
</tr>
<tr>
<td>DMT-k QAM-16</td>
<td>2*k</td>
<td>BW/k</td>
<td>2</td>
<td>4*BW</td>
</tr>
</tbody>
</table>

- $\text{BW} = B_{\text{NQ\_PAM-4}} = B_{\text{NQ\_QAM-16}} = k * B_{\text{NQ\_DMT-k\_QAM16}}$
- QAM has 2 channels (I&Q) on one $\text{BW}/2$ sub-carrier
- DMT has $k$ $\text{BW}/k$ spaced sub-carriers ($1^{\text{st}}$ is $\text{BW}/(2*k)$)
- DMT cyclic prefix overhead is ignored in these examples
DMT TX ‘SIGNAL VARIANCE’ AND CLIPPING

- Red = PAM-4 probability
- Blue = DMT example with moderate clipping at +/- 3*sigma
  - ‘Clipping ratio’ = 9.5dB
- Mean time to ‘clipping’ is about 370 Bauds, so average more than one clip per Block of N=512 Baud samples.
  - Many blocks will have multiple clippings
- The ‘Signal Variance’ (which is communication theory TX power) is 7 dB lower than that of PAM-4
- Note that the laser has the same peak-peak power range and equal average power
SNR (Electrical) Examples

<table>
<thead>
<tr>
<th>Modulation</th>
<th>S</th>
<th>N</th>
<th>SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRZ</td>
<td>P</td>
<td>$2^*BW^*N_0$</td>
<td>$P/(2^*BW^*N_0)$</td>
</tr>
<tr>
<td>PAM-M</td>
<td>P</td>
<td>$2^*BW^*N_0$</td>
<td>$P/(2^*BW^*N_0)$</td>
</tr>
<tr>
<td>QAM-M</td>
<td>P/2</td>
<td>$BW^*N_0$</td>
<td>$P/(2^*BW^*N_0)$</td>
</tr>
<tr>
<td>DMT-k QAM-M</td>
<td>$\beta_{PAPR}*P/(2^*k)$</td>
<td>$(BW/k)^*N_0$</td>
<td>$\beta_{PAPR}*P/(2^*BW^*N_0)$</td>
</tr>
</tbody>
</table>

- S & N are for single channel (I or Q for QAM and DMT)
- $BW = B_{NQ\_PAM-4} = B_{NQ\_QAM-16} = k \times B_{NQ\_DMT\_K\_QAM16}$
- $N_0 = $ Noise Power Density (two sided)
- $\beta_{PAPR} = $ DMT Peak to Average Power Ratio loss coeff.
PAM, QAM SNR Modulation Penalty

- All penalties on this and following pages are in dB optical
- PAM-M modulation penalty = \(10 \log_{10}(M-1)\)
  - PAM-2 (NRZ) = 0 dB
  - PAM-4 = 4.8 dB
  - PAM-16 = 11.8 dB
- QAM-M modulation penalty = \(10 \log_{10}(\sqrt{M}-1)\)
  - QAM-4 = 0 dB
  - QAM-16 = 4.8 dB
  - QAM-256 = 11.8 dB
- Modulation penalty decreases S in SNR therefore:
  - Reduces TX OMA of symbol eye
DMT SNR Modulation Penalty

- \( \beta_{\text{PAPR}} = \text{DMT PAPR loss coeff. (see page 7)} \)
  - \( 10 \times \log_{10}(1/\sqrt{\beta_{\text{PAPR}}}) \) @ +/- 3\( \sigma \) clipping = 3.5 dB

- DMT-k QAM-M mod. penalty = \( 10 \times \log_{10}((\sqrt{M} -1)/\sqrt{\beta_{\text{PAPR}}}) \)
  - DMT-k QAM-4 = 0.0 + 3.5 = 3.5 dB
  - DMT-k QAM-16 = 4.8 + 3.5 = 8.3 dB
  - DMT-k QAM-256 = 11.8 + 3.5 = 14.3 dB

- Modulation penalty decreases S in SNR therefore:
  - Reduces TX OMA of symbol eye
SNR Bandwidth Penalty

- Bandwidth penalty = 5*log10(B_{SIG}/B_{REF})
  - 19G → 30G = 1.0 dB
  - 25G → 50G = 1.5 dB
  - 25G → 100G = 3.0 dB

- Bandwidth penalty increases N in SNR, therefore:
  - does not show up directly in normative specs.
  - decreases RX Sens. in spec. comparisons

- Ideal SNR penalty = modulation + bandwidth penalties
## Ideal SNR Penalties of 100G PMDs

<table>
<thead>
<tr>
<th>Modulation</th>
<th>λs</th>
<th>GBaud</th>
<th>BW GHz</th>
<th>Penalty dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>25G NRZ</td>
<td>4</td>
<td>25</td>
<td>12.5</td>
<td>0</td>
</tr>
<tr>
<td>50G NRZ</td>
<td>2</td>
<td>50</td>
<td>25</td>
<td>1.5</td>
</tr>
<tr>
<td>50G PAM-4</td>
<td>2</td>
<td>25</td>
<td>12.5</td>
<td>4.8</td>
</tr>
<tr>
<td>100G PAM-4</td>
<td>1</td>
<td>50</td>
<td>25</td>
<td>6.3</td>
</tr>
<tr>
<td>100G PAM-16</td>
<td>1</td>
<td>25</td>
<td>12.5</td>
<td>11.8</td>
</tr>
<tr>
<td>100G QAM-16</td>
<td>1</td>
<td>25</td>
<td>25</td>
<td>6.3</td>
</tr>
<tr>
<td>DMT-k QAM-16</td>
<td>1</td>
<td>25/k</td>
<td>25</td>
<td>9.8</td>
</tr>
<tr>
<td>DMT-k QAM-256</td>
<td>1</td>
<td>12.5/k</td>
<td>12.5</td>
<td>15.3</td>
</tr>
</tbody>
</table>

KR4, KP4, BCH FEC Gains: 2.6, 3.2, 3.8 dB, respectively
Ideal SNR Penalties

Thank you