Channel Code Considerations for 10GbT Signaling

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Motivation

• Two different signaling architectures have been discussed so far
  – TCM: 10PAM 4D-8State code at 833Ms/s – Solarflare
  – LDPC: 8PAM (1723,2048) code at 1000Ms/s – Intel

• These proposals differ in other aspects too
  • Packet format, overhead bits etc.
  • Equalization approach

• This presentation compares the coding schemes while normalizing other factors out

• We also include some other well known schemes
Ideal Performance Bounds

• A “good” transceiver design would convert the ISI+Xtalk+noise channel into an (approx) AWGN channel
• Shannon capacity for and ideal AWGN channel
  \[ C = \frac{1}{2}\log_2(1+\text{SNR}) \] bits per 1D symbol (bps)
• For example, a capacity approaching code (“infinite” delay) can operate at 2.5 bps with “zero” BER at SNR of 15 dB
Practical Performance Bounds

- For uncoded MPAM, $M$ even
  - $\text{BER} \sim Q(\sqrt{3/(M^2-1)\cdot \text{SNR}})$

- Solving the equation above we have
  - $\text{Rate} = \frac{1}{2}\log_2(1+\text{SNR}/G(\text{BER}))$ per 1D symbol
  - $G(\text{BER})$ is the Gap or Loss relative to capacity and depends on the target BER.

- For uncoded PAM, $G(10^{-12}) \sim 12\text{dB}$

- For coded systems, $d$ increases and $G(\text{BER})$ is reduced
  - The reduction of $G(\text{BER})$ is called coding gain
Multi-channel SNR in code design

• Note that the IL and residual X-talk (NEXT, FEXT, ANEXT) level may vary from pair to pair due to the physical channel parameters (cable length, separation, connectors, ...)

• SNR variations should be considered in the code design
### Possible Channel Codes

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Loss from Capacity @ BER=1e-12</th>
<th>Delay [µsec]</th>
<th>Maturity</th>
<th>Receive Complexity</th>
<th>Equalizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCM + shaping</td>
<td>5-8dB</td>
<td>&lt; 0.1</td>
<td>Mature</td>
<td>Low – moderate</td>
<td>Pre-coding or receiver equalization</td>
</tr>
<tr>
<td></td>
<td>(Solarflare TCM=8dB)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TCM+RS +Shaping</td>
<td>3-6dB</td>
<td>0.75-4.5</td>
<td>Mature</td>
<td>Low – moderate</td>
<td>Pre-coding recommended</td>
</tr>
<tr>
<td>LDPC + shaping</td>
<td>1-4dB</td>
<td>0.5-2</td>
<td>New</td>
<td>High</td>
<td>Pre-coding</td>
</tr>
<tr>
<td></td>
<td>(Intel LDPC=3.8dB)</td>
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</tbody>
</table>

- Lower loss from capacity translates to better link quality
  - For each scheme, lower loss typically requires a more complex receiver and more delay (latency)
The 1GbT 5PAM-4D-TCM code

Achieves BER=1e-12 for 2 bps in an ideal (no ISI) AWGN channel at Es/N0 (dB) of

\[ 23.9 - (5.7 - 10 \log_{10}(8/5)) - 0.4 = 19.9 \text{ dB} \]

SNR required by un-coded 4PAM

Coding gain = 3.66 dB

(power ratio between 5PAM and 4PAM)

Shaping gain

Gap from capacity = 8dB
LDPC/Turbo Codes

- A large body of work (most starting mid 90s) has shown that LDPC/Turbo codes can approach the Shannon bound
  - Most of the published literature has focused on the low SNR
- Intel’s LDPC 8PAM (1753,2048) proposal:
  - Achieves BER=10^{-12} for 2774/1024=2.68 bps and SNR=19.8dB
  - The Shannon bound at 2.68 bps is SNR=(2^{2\cdot2.68}-1) \sim 16dB
  - The loss from capacity is 19.8-16 = \textbf{3.8dB}
  - The intrinsic decoding delay (i.e. with infinite HW) is 0.256 microseconds, but practical decoders will have additional delay
  - The SNR margin could be improved by using shaping algorithms, different 4D mappings, larger block sizes, etc. typically at the expense of more complexity and/or latency
Performance of current Proposals

SNR Loss from Capacity

- Uncoded
- 10PAM 4D-TCM (SF)
- LDPC (Intel)
A concatenated RS+TCM based on the 1GbT code

- Data rate of 1.875 bits per dimension
- Can easily be generalized to 10PAM (2.8125 bits per 1D-PAM symbol)
- Low complexity, mature decoding algorithms
Concatenated RS+TCM – Performance Analysis

- BER=1e-12 @ SNR of 15.4 dB – only 4.4 dB short of Shannon Capacity
- Using a standard hard decoding algorithm
- Similar gain to that of the LDPC proposed in the November meeting
- Analysis assumes ideal interleaver
Concatenated RS+TCM – Performance/Latency tradeoff

- The analysis of the code with a short interleaver is more complicated.
- We assess that the loss due to an interleaver latency of 2.5 micro-seconds is a small fraction of a dB.
- We assess that the loss due to a latency of 1 micro-second is about 1-1.5 dB.
Improved concatenated codes

- It is possible to further gain 0.5-0.7 dB by employing constellation-shaping algorithms.
- Lower latency or additional coding gain can be achieved by employing other concatenated coding schemes.
Performance-Complexity Summary

SNR[dB] @ BER=1e-12 (versus an optimal code)

Complexity (versus the 1GbT code)

- Uncoded PAM
- 1GbT code (8state Wei)
- 1GbT code +RS(240,256)
- LDPC [1]
Performance-Complexity Summary

SNR[dB] @ BER=1e-12 (versus an optimal code)

Complexity (versus the 1GbT code)
Conclusion

• We seek input from task force participants on:
  – Latency budgets
  – Performance/complexity tradeoffs

• Based on these inputs, specific codes can be optimized for the 10GBASE-T application
  – Concatenated Codes
    • Optimize for a tolerable latency range
  – LDPC
    • Optimization and more detailed evaluation of performance and complexity.
  – Optimize symbol rate and packet overhead
  – Evaluate addition of constellation-shaping gain to codes