Shedding Some Light on Coding Gain

IEEE 10GBASE-T Interim Meeting
January 2004

Scott Powell
Broadcom

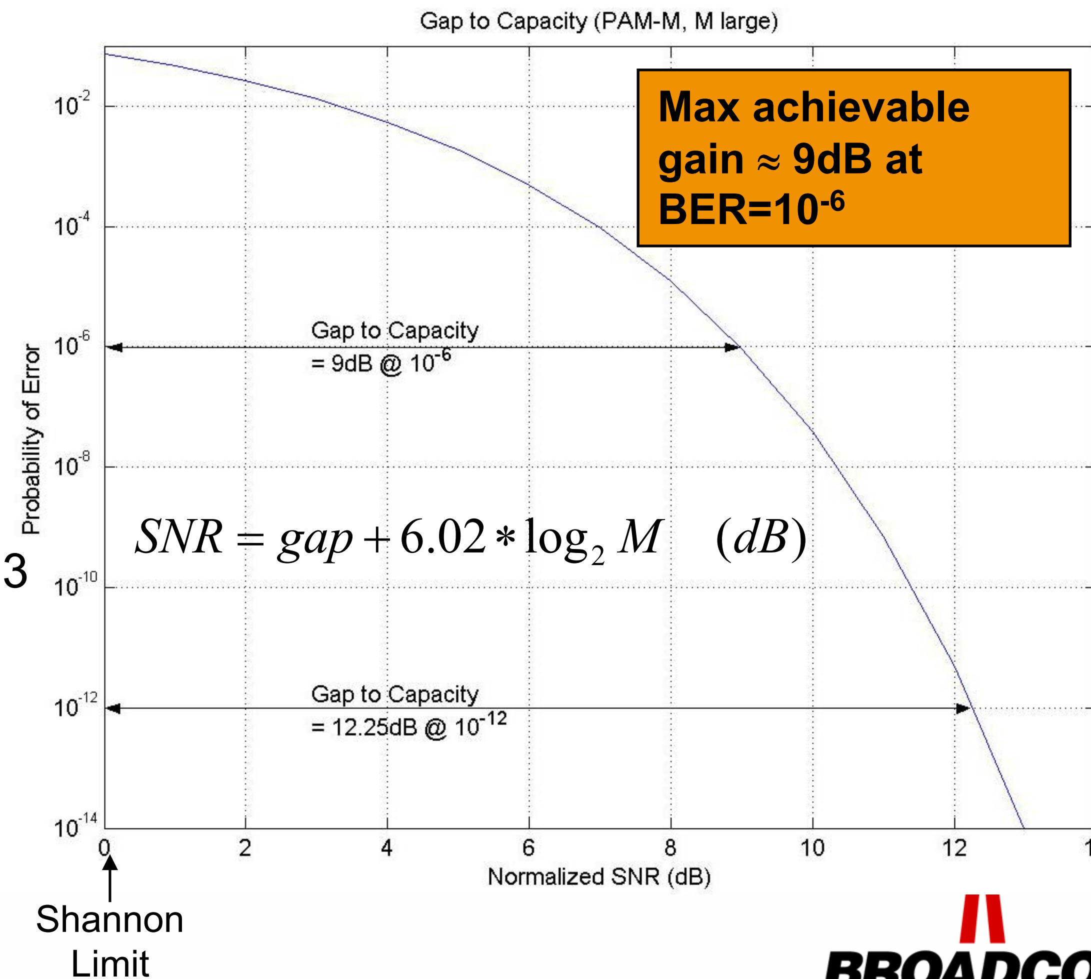
Supported by: Ofir Shalvi TI
Sanjay Kasturia Teranetics

Shannon Limit & Coding

- Ideal **capacity–achieving system for AWGN channel**
  - Capacity $C_{bit/dim} = 1/2 \log_2 (1+SNR) \rightarrow SNR_{dB} \approx 6 \times n$ bit/dim
  - Example: PAM-8 $\rightarrow$ 3 bit/dim requires $SNR_{dB} \approx 18$dB
- **System “A” employing** practical **modulation & coding**
  - Rate $R_{bit/dim}$(“A”) = 1/2 $\log_2$ (1+SNR/ G(“A”)) , G > 1 (“gap to capacity”) expresses additional SNR required by practical scheme to achieve same rate as capacity-achieving scheme
  - Uncoded modulation: $G_{dB} \approx 9$ dB @ BER = 10^{-6}, 12.3dB @ BER = 10^{-12}
    - Maximum possible coding gain is 7.5dB 10^{-6} @ and 10.8dB @ 10^{-12}
- **Precoding (Tx) + whitened matched filter (Rcv)**
  - Any linear channel can be transformed into an AWGN-like channel
  - Small penalty if “water-pouring” Tx spectrum not used

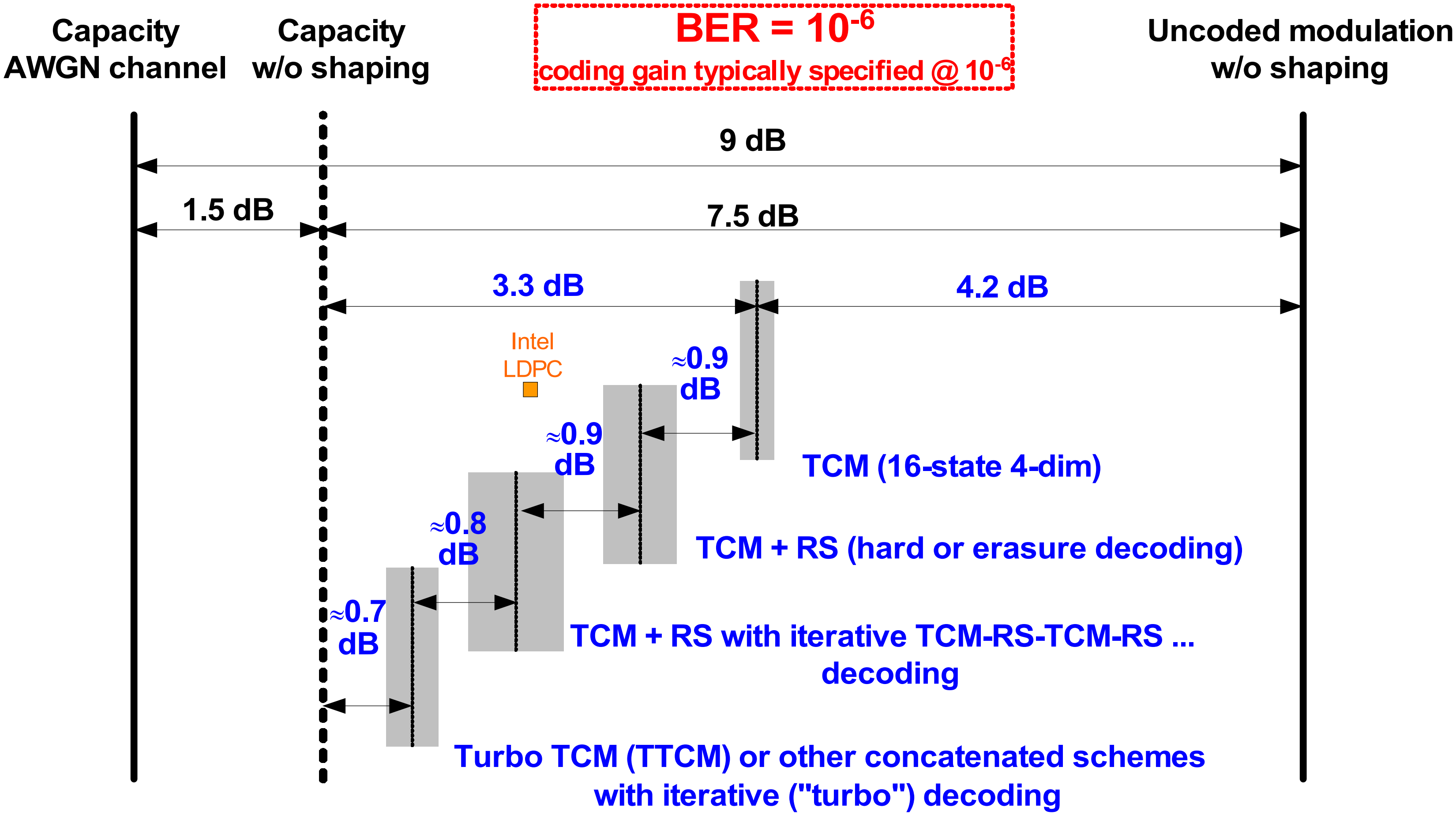
Gap to Capacity for PAM (AWGN channel)

- **Approximately independent of the number of PAM levels (M large)**
  - "normalized" $SNR_{norm} \equiv SNR/(M^2-1)$
  - Defines baseline curve for any M-PAM
- **Example: PAM-8**
  - Requires 12.25 + 6.02∗3 = 30.3dB to achieve 10^{-12} error rate (uncoded)



Achievable Coding Gain

(slide adapted from “Advanced Downstream Physical Layer for Cable Systems (AdDnPhy)” by G. Ungerboeck presented in Irvine on March 10, 2000)

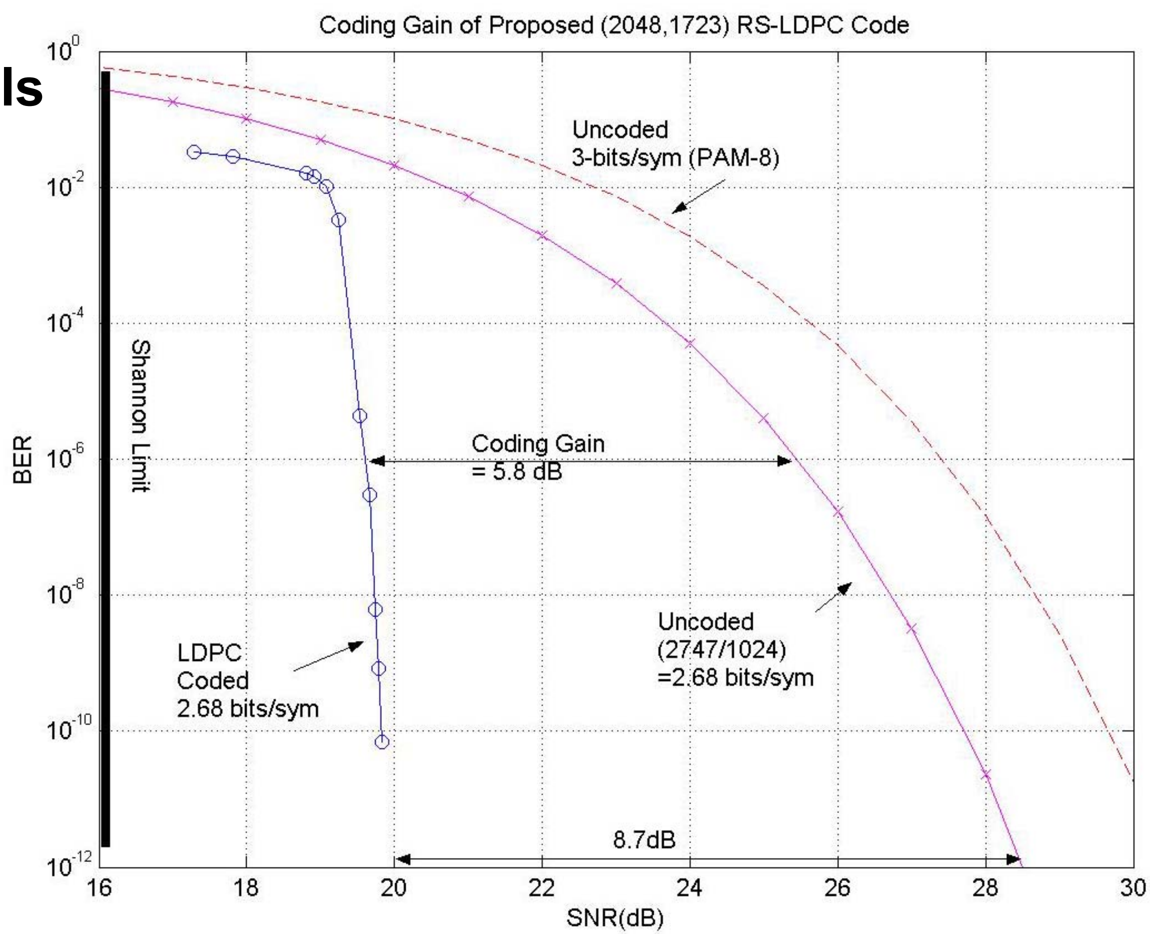


Practical high-rate coding schemes w/o shaping

Coding Gain of Proposed LDPC Scheme*

* Proposed by Intel in November 2003 Plenary

- **Proposed scheme maps 2747 bits to 1024 symbols**
  - Effective bits/symbol = (2747/1024) = 2.68 bits/sym
  - Approximately "PAM-6.5"
- **Coding gain 5.8dB @ BER=10^{-6}, 8.7dB @ 10^{-12}**
- **Note: The fact that PAM symbols are simultaneously transmitted over four pairs does not make the code "4-D"**
  - Overall error rate will be 4x the error rate of each "1-D" pair



Connecting everything™

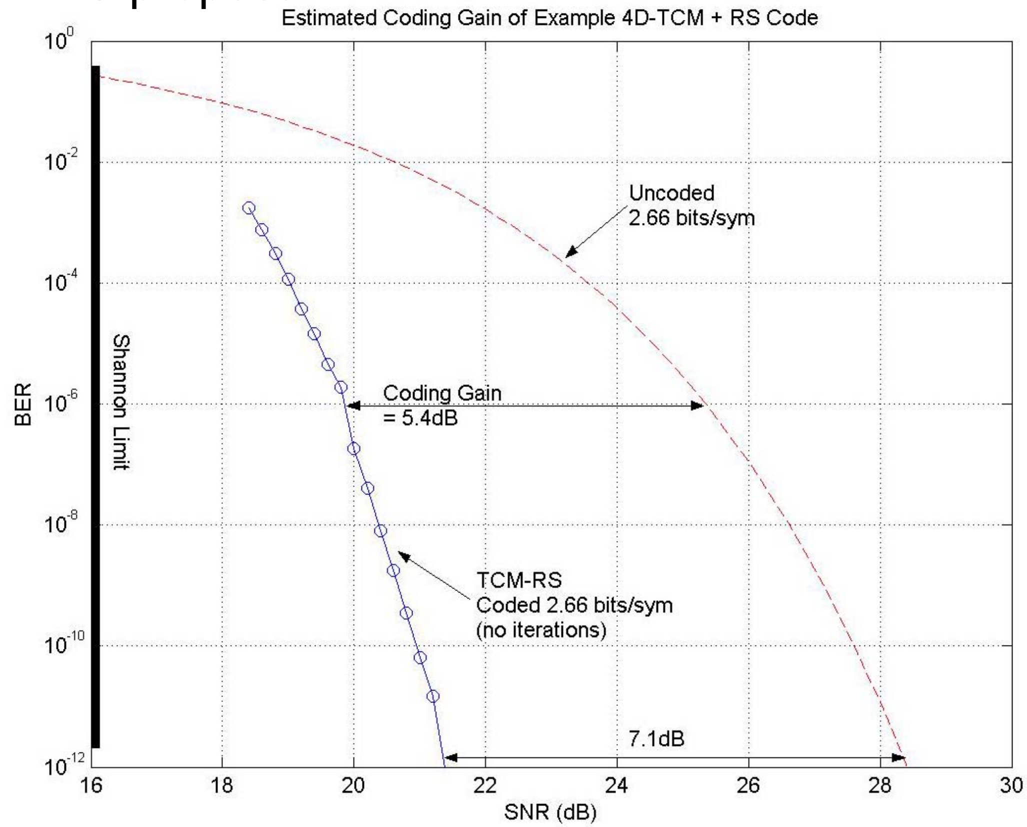
BROADCOM®

Coding Alternatives

- **More traditional approaches can offer code gains similar to LDPC**
- **Concatenated block + convolutional codes widely used**
  - Reed-Solomon, Viterbi, block/convolutional interleaver
  - Decoding complexity well understood
  - Code performance well proven over several decades of use
  - No “error floor” issues
- **Application-driven latency requirements must also be considered in the coding choice**

Example 1: Traditional Concatenated TCM+RS

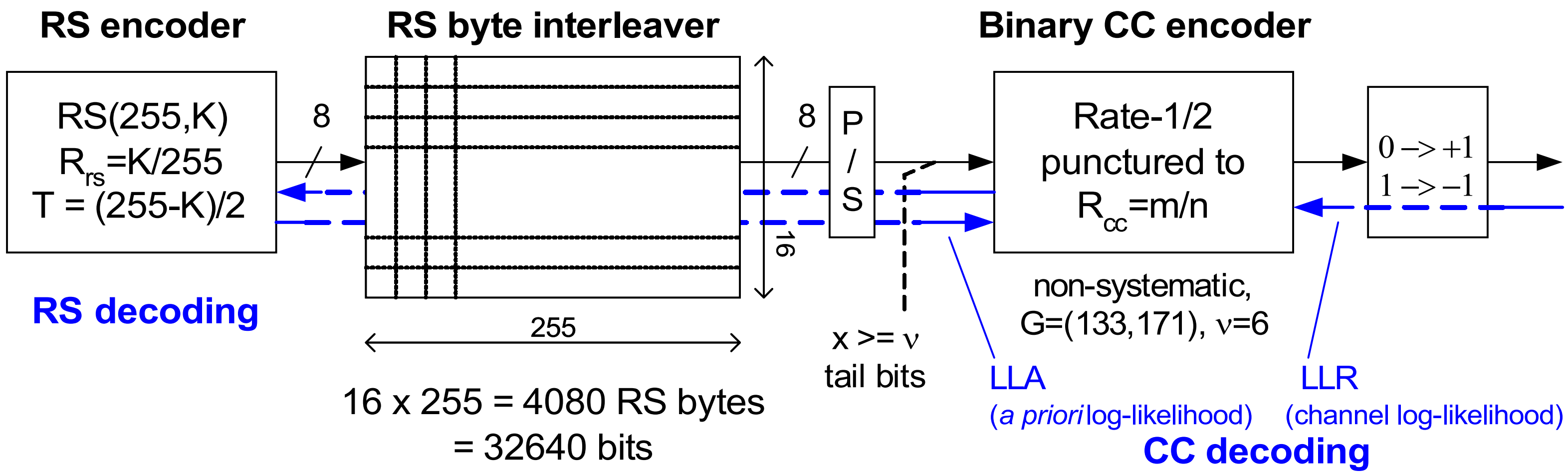
- PAM-8, 16-state 4-D TCM + RS(253,245)
  - Each wire carries 1 dimension (PAM-8) with 2.663 effective bits/sym
    - Approx equal to rate of LDPC proposal
  - Non-iterative, single pass
  - F_{baud} = 938.8Msps
  - Each 253 byte RS block contains 184 11-bit 4D symbols
  - Estimated coding gain assumes ideal interleaving



***Illustrative example meant to match the LDPC rate, not intended as a proposal**

Example 2: Concatinated RS + Binary CC (RSCC) with Iterative Decoding

System Considered for Optical Application



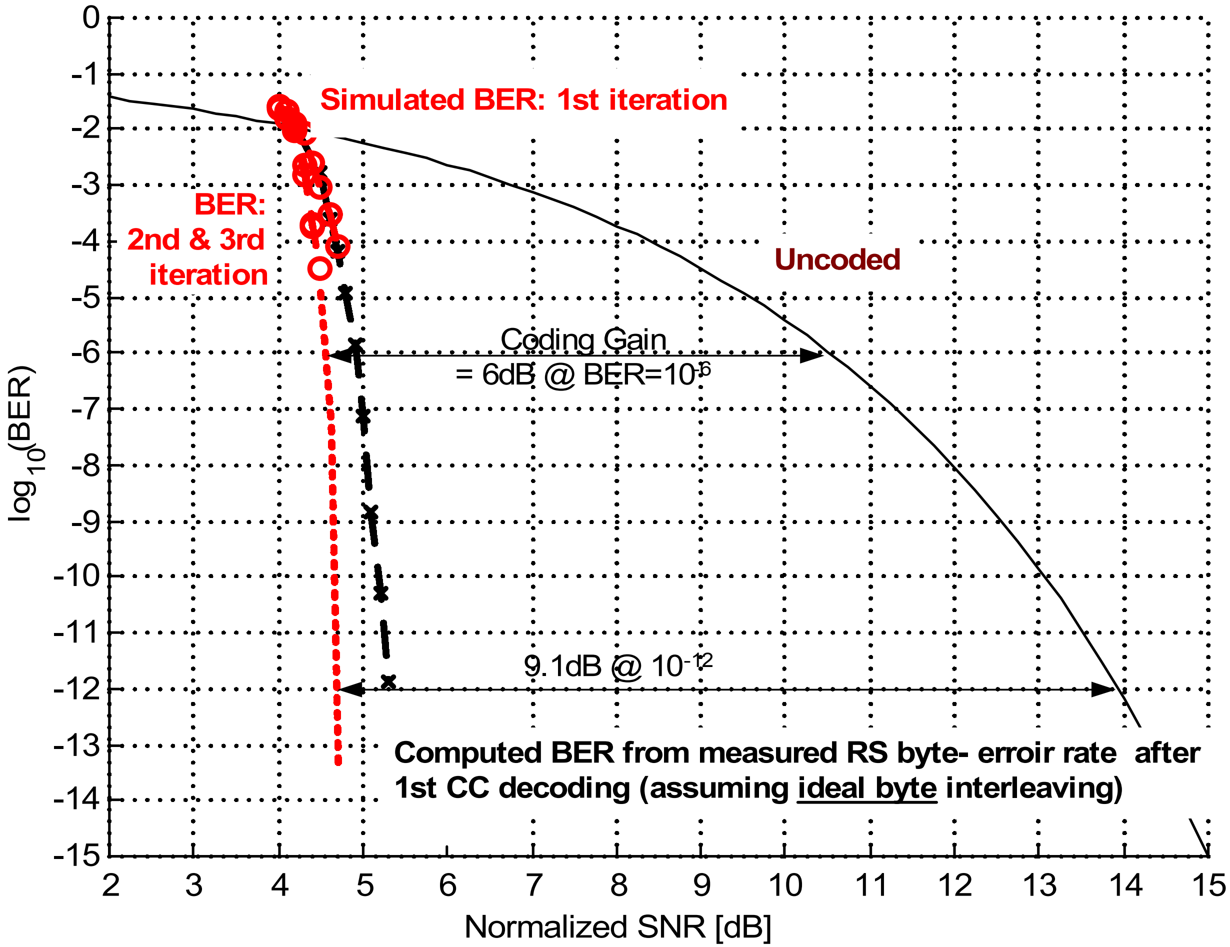
RS(255,243), T=6, R_{rs}=0.9529; R_{cc}=9/10 -> R_c=0.8573 (14.26%)

Iterative decoding

1. SIHO CC decoding by VA with *a priori* information LLA and channel information LLR
2. De-interleaving and HIHO RS decoding
3. Successfully decoded RS codewords considered reliable, update LLA ; go to 1.

Serially concatenated RS and binary CC (RSCC) with iterative decoding

RS(255,243),T=6 + rate-9/10 64-state CC : R_c=0.8575



Connecting everything™

BROADCOM®

Conclusions

- **The true coding gain offered by the "LDPC PAM-8" scheme is about 5.8dB @ BER=10^{-6}, 8.7dB @ 10^{-12}**

- **Similar coding gain may be achieved in other ways with well understood performance and complexity**
  - Straight forward TCM+RS achieves about 7.1 dB @ BER=10^{-12}
  - Iterative CC+RS achieves over 9dB @ BER=10^{-12}

- **A decision on the coding scheme for 10GBASE-T must be made on the basis of real coding gains versus carefully evaluated decoding complexity**
  - Latency must also be considered