New Results on QAM-Based 1000BASE-T Transceiver

Oscar Agazzi, Mehdi Hatamian, Henry Samueli

Broadcom Corp.

16251 Laguna Canyon Rd.
Irvine, CA 92618
714-450-8700

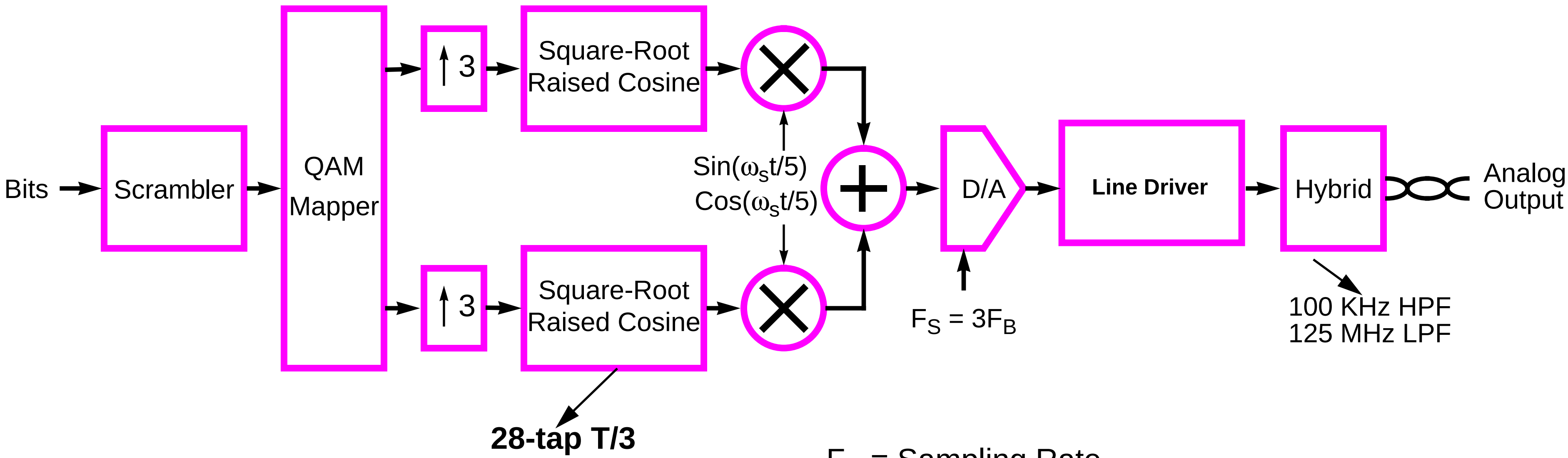
Outline

- Transceiver parameters
- 3dB and 10dB design points
- Latency budget
- Discussions on the use of Viterbi decoder
- 8D lattice coding
- Conclusions

System Assumptions

- 4 pairs of UTP-5 cable up to 100 meters
- 250 Mb/s full-duplex per pair
- Lucent's worst-case NEXT, echo, and channel models
- Bit accurate simulations

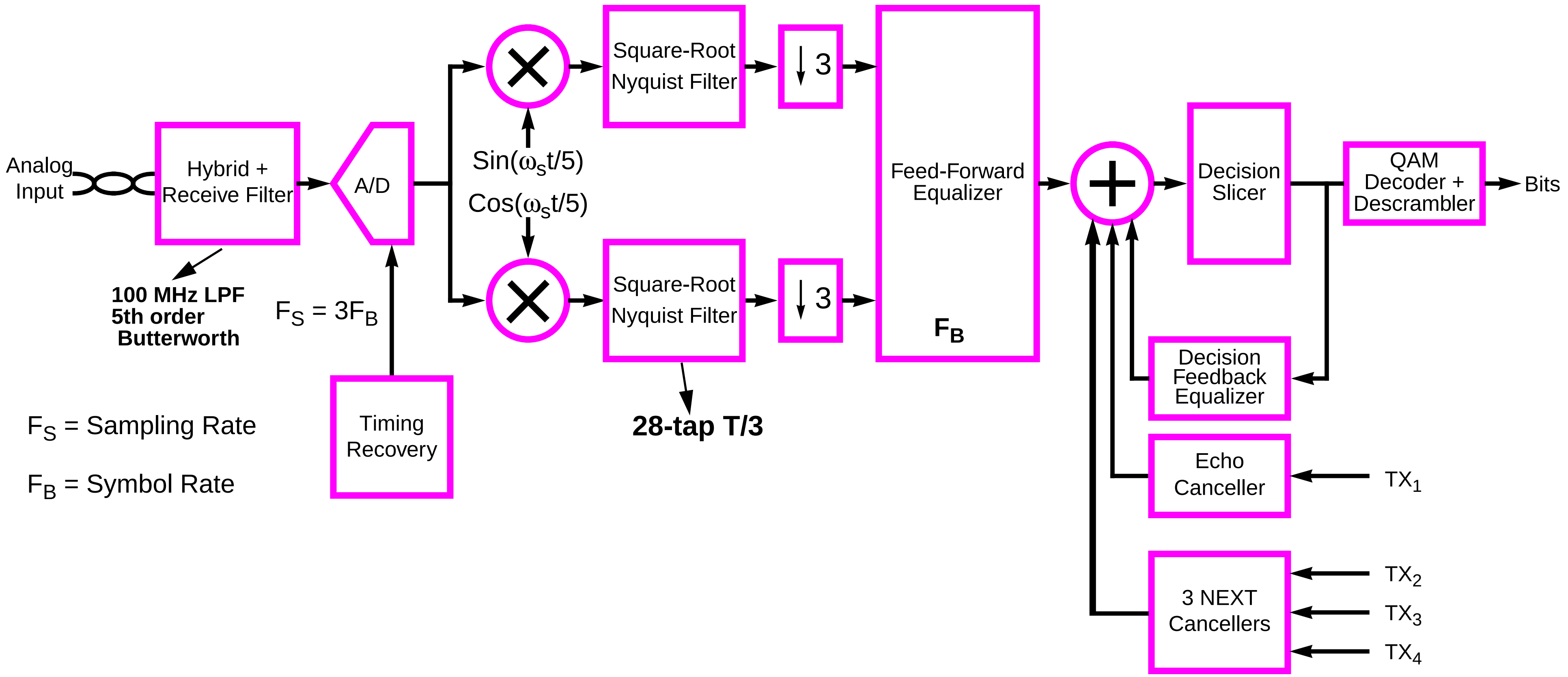
QAM Transmitter



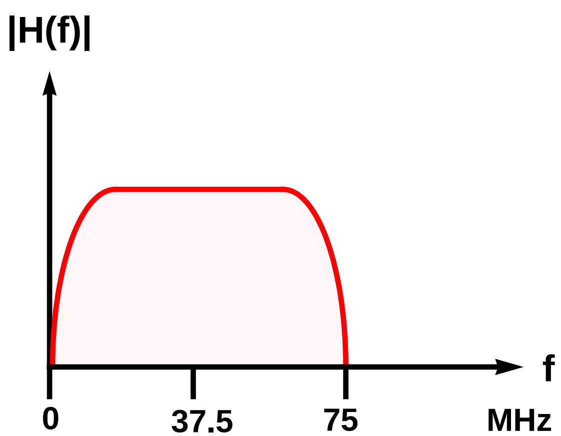
F_S = Sampling Rate

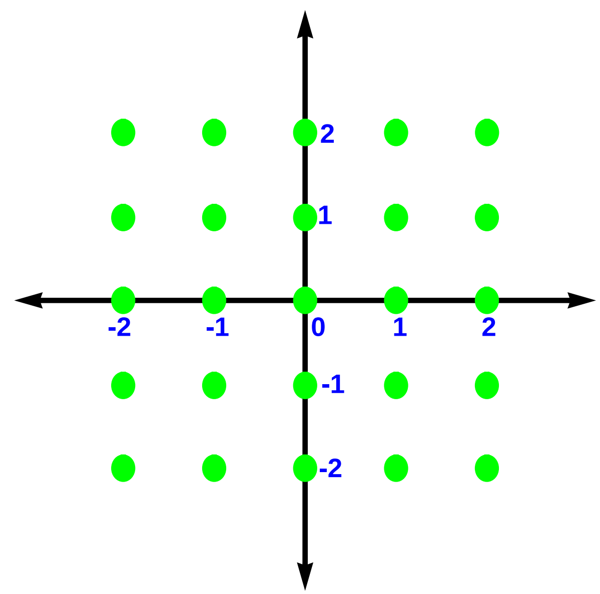
F_B = Symbol Rate

QAM Receiver



QAM Spectra





Symbol rate:	62.5 MHz
Bits/symbol:	4
Excess Bandwidth:	20%

QAM 3dB Design Points

Parameters	A 4D Lattice	B 4D Lattice
A/D resolution	5.5 @187.5MHz	5.5 @187.5 MHz
D/A resolution	6 @187.5MHz	6 @187.5MHz
Baud Rate	62.5 MHz	62.5 MHz
FFE #Real Taps	18	14
DFE #Real Taps	12	12
NEXT #Real Taps	60	60
Echo #Real Taps	90	90
Viterbi Decoder	NO	NO
BLW cancellation	NO	NO
Actual Margin	3.61dB	2.94dB

The actual number of complex taps in the FFE, DFE, NEXT and Echo cancellers are half of those shown in the table running at 62.5 MHz. The Real taps shown in the table run at the 125 MHz clock rate.

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QAM 10dB Design Points

Parameters	A 8D Lattice	B 8D Lattice
A/D resolution	6 @187.5MHz	7 @187.5 MHz
D/A resolution	7 @187.5MHz	7 @187.5MHz
Baud Rate	62.5 MHz	62.5 MHz
FFE #Real Taps	30	20
DFE #Real Taps	20	20
NEXT #Real Taps	90	60
Echo #Real Taps	120	120
Viterbi Decoder	NO	NO
BLW cancellation	NO	NO
Actual Margin	8.9dB	9.4dB

The actual number of complex taps in the FFE, DFE, NEXT and Echo cancellers are half of those shown in the table running at 62.5 MHz. The Real taps shown in the table run at the 125 MHz clock rate.

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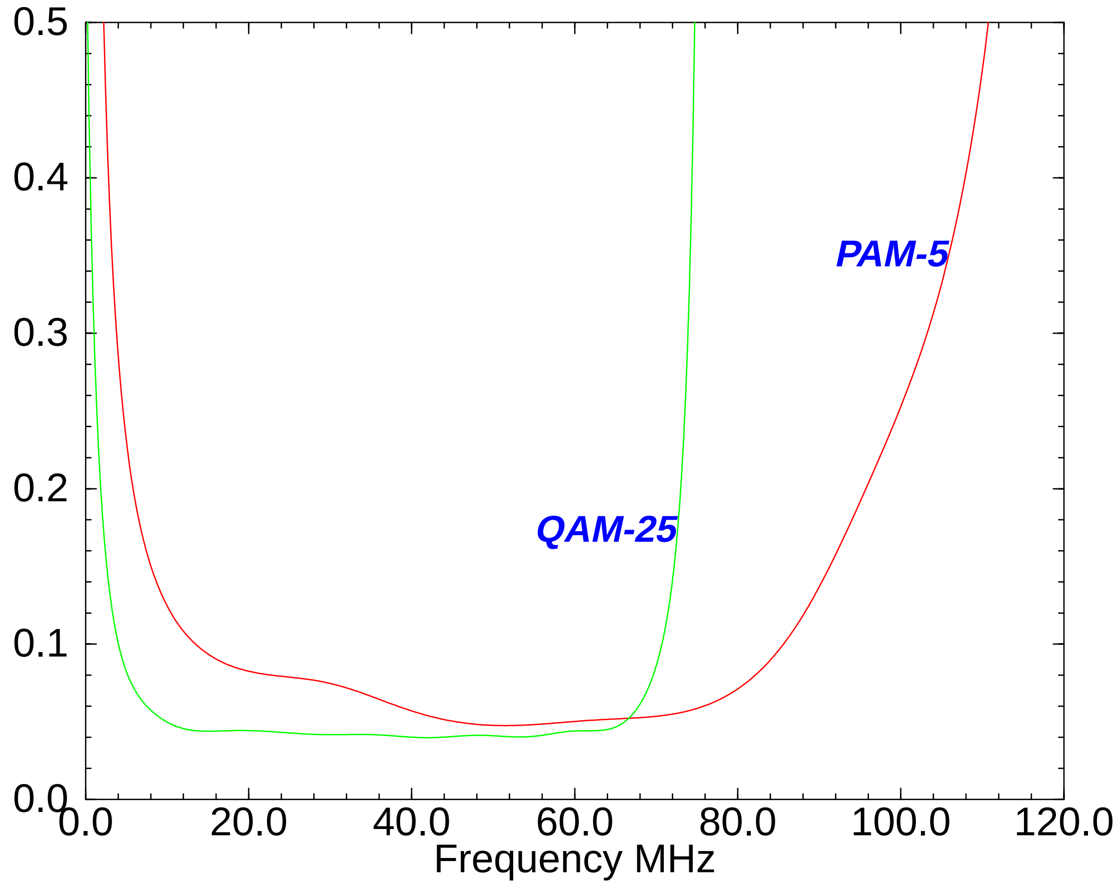
Relative Sinusoidal Noise Immunity

- **Inverse of the transfer function from the input of the receiver to the output of the FFE for the same transmit power normalized to 1.**
- **While PAM-5 has better tolerance in the low frequency region, QAM-25 shows better performance in the high frequency range.**
- **The strictly limited bandwidth of raised cosine front-end filters avoids aliasing of high frequency interference components into the operational band of the receiver which improves performance in presence of high frequency interference.**



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Latency

Transmitter

MII to Shaping Filter	4
Shaping Filter	9
DAC and Analog Transmit	1.5
	14.5 BT

Receiver

Analog input to A/D output	1.5
Receive Filter	9
FFE	8
Descramble & Decode	3
Decode to MII output	1
	22.5 BT

Total PHY Latency = 37 BT without a Viterbi decoder

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To Viterbi or not to Viterbi

- **In practice, the Viterbi decoder is not likely to achieve the theoretical gain of 3dB.**

- **Evaluation of the performance of the Viterbi decoder must be done either with error rate simulations or by building prototypes.**

- **In an ISI channel, the use of trellis coding and Viterbi decoder *in conjunction* with a DFE is not likely to produce much of gain, if any, due to the error propagation effects in the DFE**
  - Precoding methods (e.g., Tomlinson precoding) can be used to solve the probelm. The DFE filter coefficients have to be determined during initial training and sent back to the transmitter for pre-coding. The implementation is rather awkward.
  - The V.34 modem standard uses 4D trellis codes and a precoding filter.

References on Precoding

- M.V. Eyuboglu and G.D. Forney, Jr., "Trellis Precoding: Combined Coding, Precoding, and Shaping for Intersymbol Interference Channels," IEEE Trans. Inf. Theory, Vol. 36, Mar 1992

- Motorola Information Systems Group, "A Flexible Form of Precoding for V.fast," Cont. D194, CCITT SG XVII, Geneva, Switzerland, June 1992.

- General Datacomm, Inc., "Distribution-Preserving Tomlinson Algorithm," Cont. D189, CCITT SG XVII, Geneva, Switzerland, June 1992

- R. Laroia, S. Tretter, and N. Farvardin, "A Simple and Effective Precoding Scheme for Noise Whitening on Intersymbol Interference Channels," IEEE Trans. Comm., Vol.41, Oct. 1993

- AT&T, "ISI Coder - Combined Coding and Precoding," Cont. D24, ITU-T SG 14, Geneva, Switzerland, Sept. 1993.

- United States of America, "Recommendation for V.fast - Precoding," Cont. D17, ITU-T SG 14, Geneva, Switzerland, Sept. 1993.

8D Lattice Coding

- **The four N-point two-dimensional QAM constellations on the 4 pairs can be combined to create an 8D constellation with N^4 points.**
- **The 16 bits to be transmitted on the 4 pairs use 2^{16} points in the 8D space. The code redundancy is almost a factor of 6 for N=25. It is possible to construct a code in this 8D space that offers up to 6dB of gain in margin.**
- **The same technique can also be applied to a baseband PAM system by combining two consecutive symbols on each pair.**
- **The 8D lattice code is a viable alternative to using 4D trellis coding with a Viterbi decoder offering higher margins with less complexity and no latency issues.**

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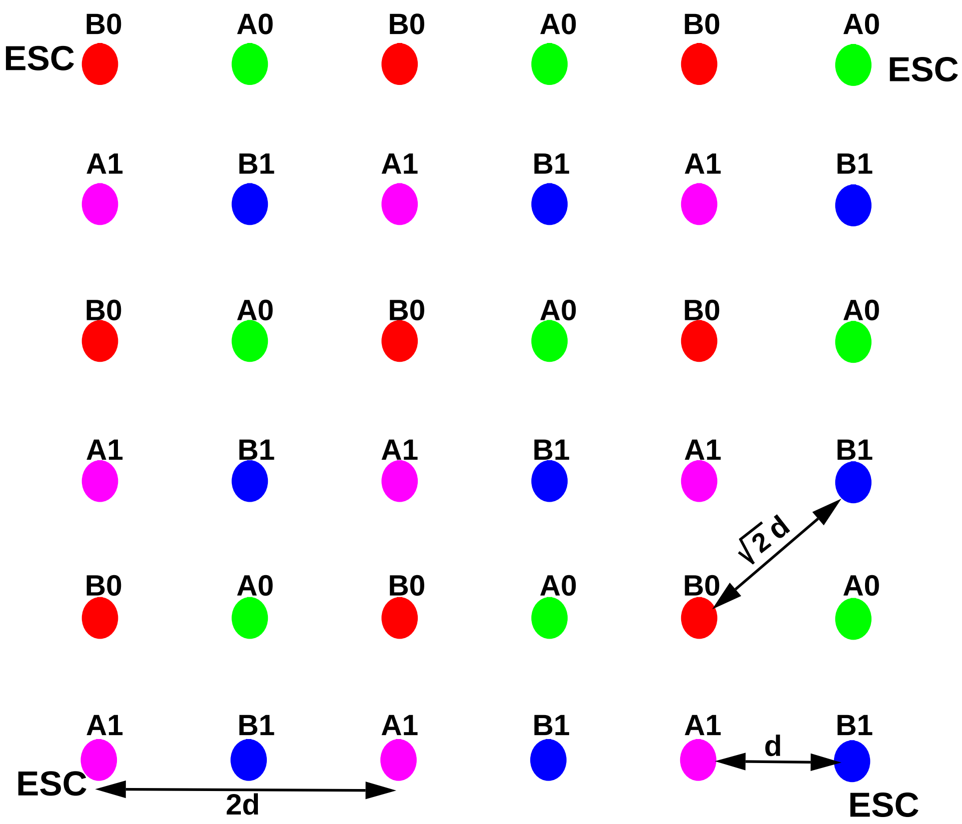
Subsets of QAM/CAP-36 2D Constellation



Minimum squared distances:

- Within subsets = $4d^2$
- Between subsets

  $d(A0,A1) = 2d^2$

  $d(B0,B1) = 2d^2$

  $d(A0,B0) = d(A1,B1) = d^2$

Assuming equiprobable signalling, the penalty paid for the 36 point vs. 25 point constellation is 1.63 dB.

Assuming low probability for the ESC points, we get 0.66 dB back.

Total gain due to 8D lattice coding is 5 dB without the need for a Viterbi decoder.

Building 8D Subsets

S0:	(A0 A0 A0 A0)	**S8:**	(B0 B0 B0 B0)
S1:	(A0 A0 A1 A1)	**S9:**	(B0 B0 B1 B1)
S2:	(A0 A1 A0 A1)	**S10:**	(B0 B1 B0 B1)
S3:	(A0 A1 A1 A0)	**S11:**	(B0 B1 B1 B0)
S4:	(A1 A0 A0 A1)	**S12:**	(B1 B0 B0 B1)
S5:	(A1 A0 A1 A0)	**S13:**	(B1 B0 B1 B0)
S6:	(A1 A1 A0 A0)	**S14:**	(B1 B1 B0 B0)
S7:	(A1 A1 A1 A1)	**S15:**	(B1 B1 B1 B1)

Simple encoding:

4 bits select subset

12 bits select point within subset. Each “A” or “B” has 9 points, 8 data and one ESC; $8^4 = 2^{12}$

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Maximum Likelihood Decoding

Pair 1	Pair 2	Pair 3	Pair 4
d(X,A)	d(X,A)	d(X,A)	d(X,A)
d(X,B)	d(X,B)	d(X,B)	d(X,B)

X: Equalizer output

- **Find closest "A" and "B" points in each wire pair. This is simple slicing but we need to keep the distance value**
- **Check parity for the "A" group across 4 pairs. If parity fails, select the next nearest "A" point for the leat reliable pair (which must come from the other subset).**
- **Repeat for "B" groups**
- **Select the best of "A" or "B"**

Lee-Fang Wei, "Trellis-Coded Modulation with Multidimentional Constellations," IEEE Trans. Inf. Theory, Vol IT-33, No. 4, July 1987.

G. David Forney, Jr., et. al, "Efficient Modulation for Band Limited Channels," IEEE JSAC, Vol. SAC-2, No. 5, Sept. 1984.

8D Lattice Coding & PAM-6

- **The baseband PAM modulation can also benefit from the proposed 8D lattice code in a 6-level modulation scheme and by combining two consecutive symbols on each wire pair.**

- **Needs further investigation.**

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Other Benefits of 8D Lattice Code

- **The gain from 8D lattice coding is applied to the decision feedback by the DFE which implies reduced error propagation. In a Viterbi decoder approach, the decision feedbacks to the DFE are *tentative* and do not enjoy the gain from coding.**

- **Lower error propagation and better burst error performance in presence of impulsive noise.**

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Higher Than 8D?

- The lattice codes can be extended to N=16 or N=24 with an increase in complexity and coding gain of 6.5dB and 8dB at the cost of using larger constellations and increased latency.
- In the case of PAM systems, the use of 8D, 16D or 24D coding schemes would cause some problems with the DFE due to the fact that the decoding delay would prevent us from feeding these decisions to the feedback filter (use of tentative decisions decoded with less reliability may be acceptable).
- Similar problems would occur with QAM/CAP systems fo N=16 or 24.

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Conclusions

- QAM line code can offer comfortable margins without the Viterbi decoder.
- The practicality of using a Viterbi decoder in conjunction with a DFE should be carefully studied.
- The *practical* gain of the 8D lattice code is similar to the 4D trellis code + Viterbi with less complexity and no long latency problems.
- More work to be done!

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