QAM-Based Transceiver Solutions for Full-Duplex Gigabit Ethernet Over 4 Pairs of UTP-5 Cable

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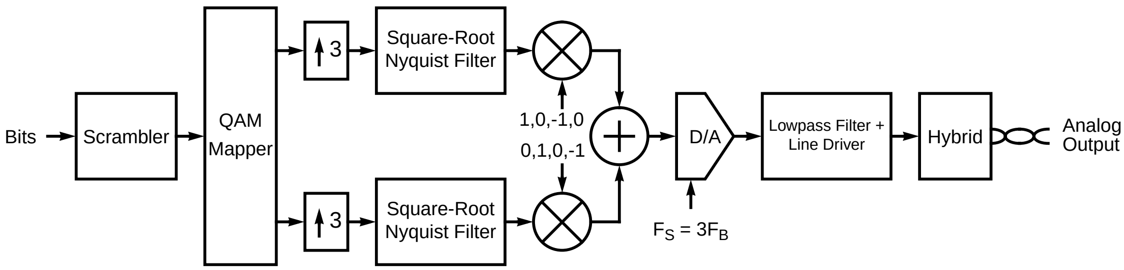
Motivation for Using QAM

- **Passband scheme - no baseline wander effects**
- **Mature and well-understood technology**
- **Widely deployed in voiceband modems, digital cable-TV set-top boxes, cable modems**
- **Public domain technology**

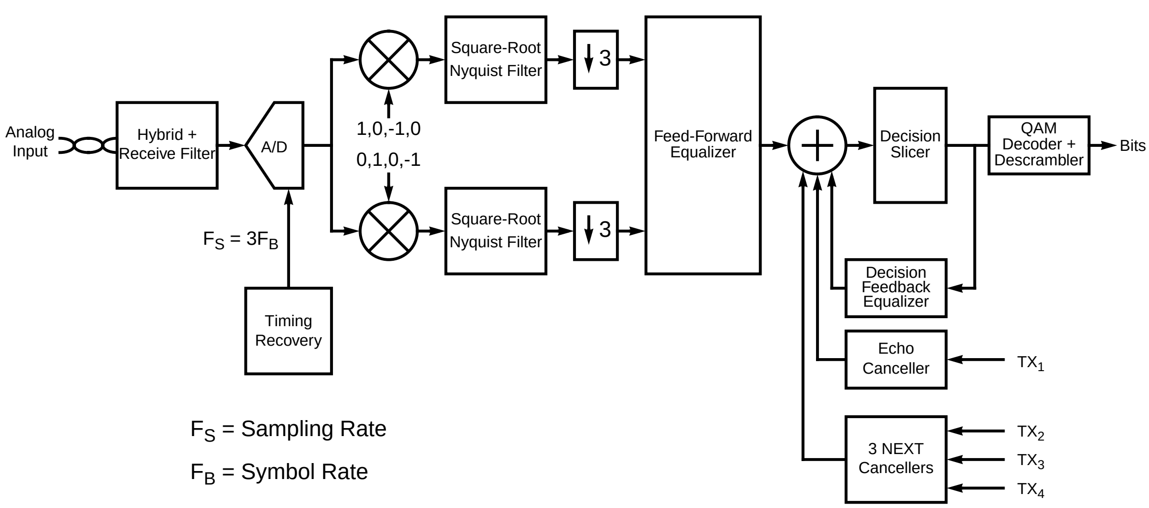
QAM Transmitter



F_S = Sampling Rate

F_B = Symbol Rate

QAM Receiver



F_S = Sampling Rate

F_B = Symbol Rate

System Assumptions

- 4 pairs of UTP-5 cable up to 100 meters
- 250 Mb/s full-duplex per pair
- Broadcom measured attenuation characteristics scaled to worst-case EIA/TIA models
- Worst-case NEXT and echo curves from 802.3z reflector
- No echo attenuation in the analog hybrid
- Bit accurate simulations

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Candidate QAM Systems

Throughput Goal = 250 Mb/s

Constellation	Symbol Rate (MBaud)	Data Bits Per Symbol	Extra Points (for signaling)	Sampling Rate (MHz)	Center Frequency (MHz)	Required SNR (dB) (BER = 10^{-10})
6x6	50	5	4	150	37.5	27.0
5x5	62.5	4	9	187.5	46.875	25.3
3x3	83.3	3	1	250	62.5	20.5

- Key Trade-Offs
  - Performance margin for BER=10^{-10}
  - Implementation complexity
  - Data converter precision

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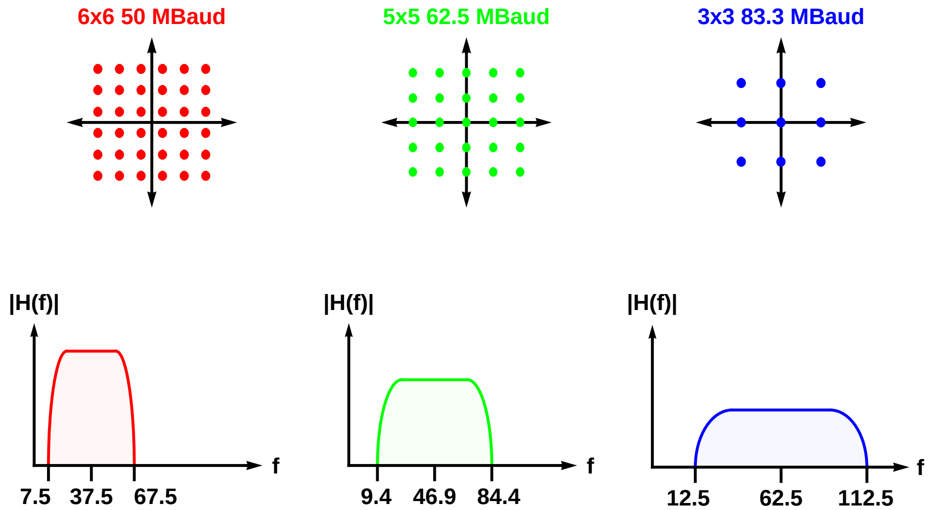
802.3, Vancouver, Nov. 1996

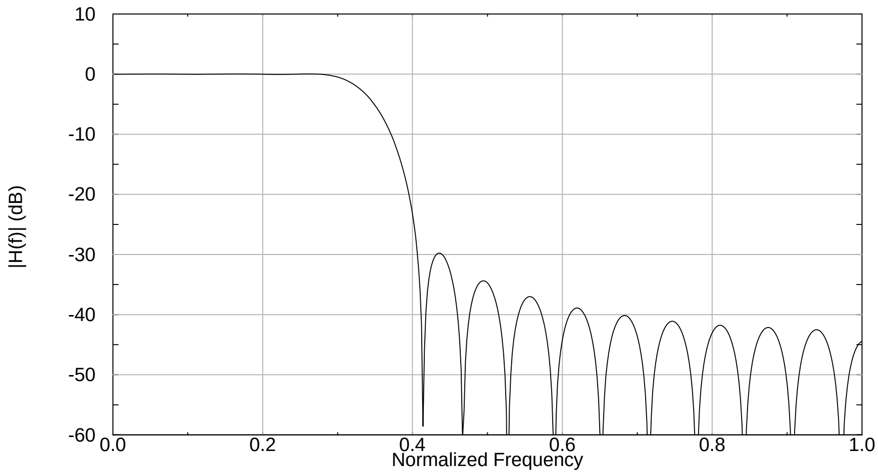
QAM Spectra



System Comparisons

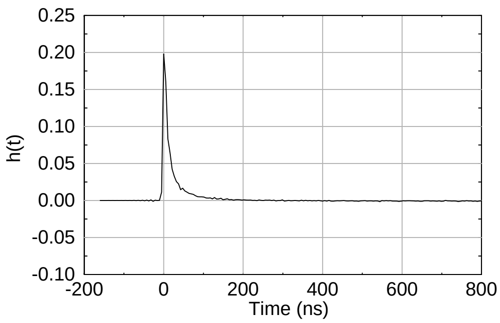
- **50 MBaud 6x6 System**
  - Lower signal bandwidth and center frequency => lower channel loss and decreased susceptibility to high frequency noise
  - Lower symbol rate => shorter adaptive filters to cover the same time span
  - Higher-order modulation => increased precision requirements
- **62.5 MBaud 5x5 System**
  - Excessive signaling points reduce SNR margin
- **83.3 MBaud 3x3 System**
  - Higher signal bandwidth and center frequency => higher channel loss and increased susceptibility to high frequency noise
  - Higher symbol rate => longer adaptive filters to cover the same time span
  - Lower-order modulation => decreased precision requirements

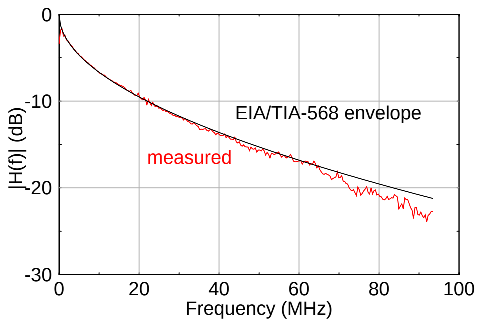
Shaping Filters



- **31-tap, 20% excess bandwidth**

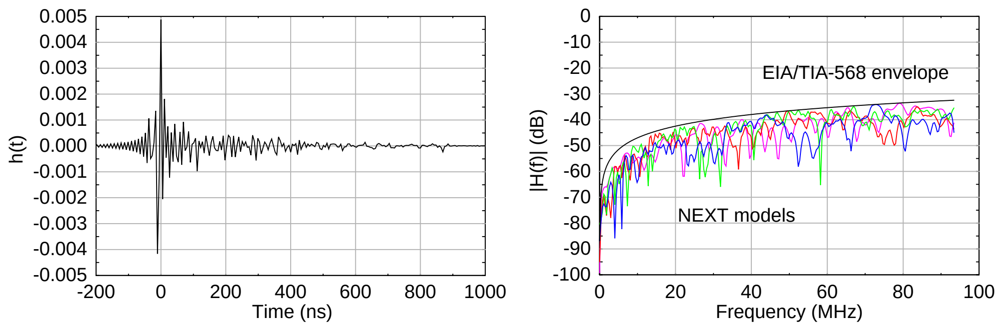
Channel Models





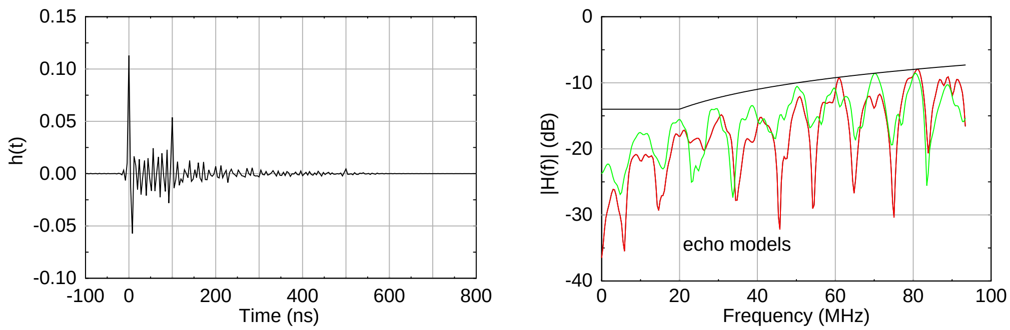
- **Measured 100m UTP-5 loss characteristic**
  - Includes attenuation roughness
- **Scaled down by 0.5 dB to match worst-case envelope**
- **Impulse response spans ~150 ns**

Self-NEXT Models



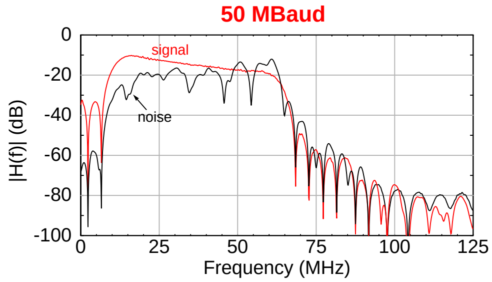
- **Worst-case UTP-5 self-NEXT from 802.3z reflector**
- **Different worst-case models used for each of 3 channels**
- **Impulse response spans ~500 ns**

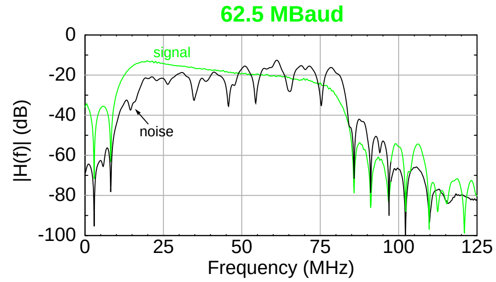
Echo Models



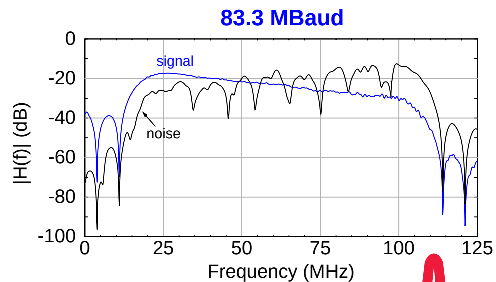
- **Worst-case characteristics from 802.3z reflector**
- **Impulse response spans ~500 ns**

Received Spectra

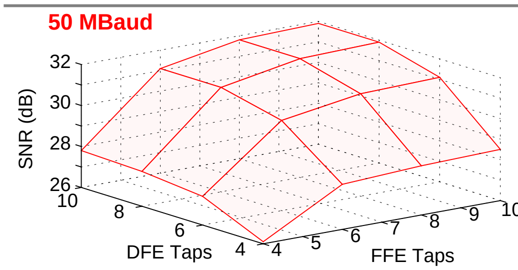


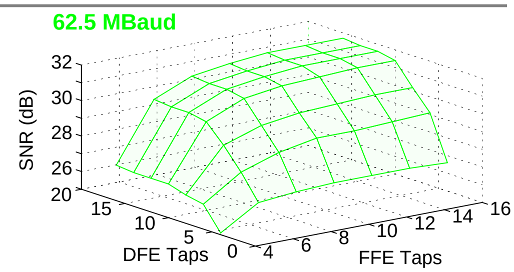


- Noise power = echo power + NEXT power
- High baud rate system appears more suscepti-ble to high-pass noise, but *required* SNR (BER = 10^{-10}) is 6.5 dB lower

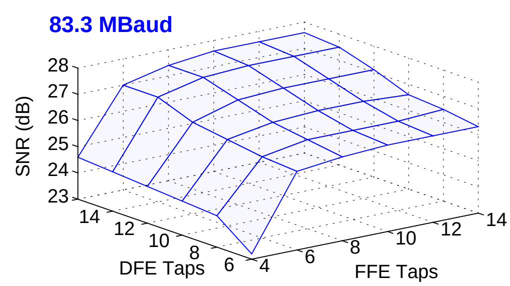


Equalizer Tap Trade-Off

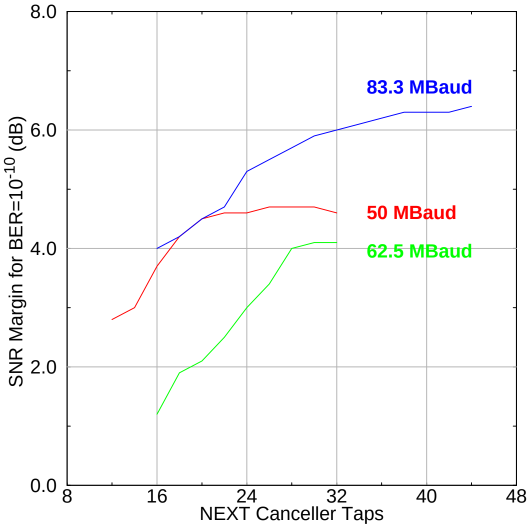


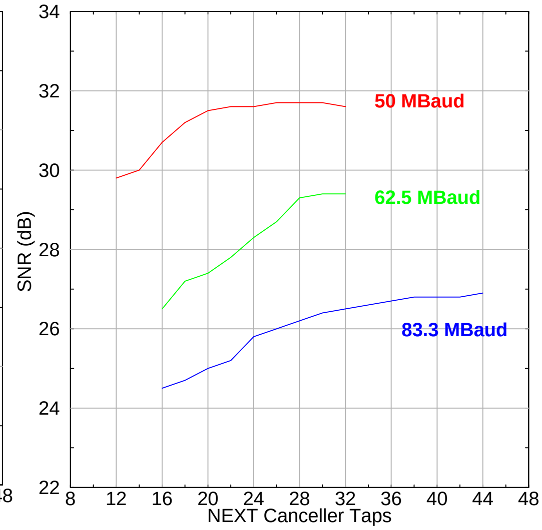


- T-spaced feed-forward equalizer
- Feed-forward taps necessary to compensate pre-cursor ISI plus pulse shaping and analog filtering
- 50 MBaud and 62.5 MBaud systems require com-plete post-cursor ISI cancellation for reasonable margin - 83.3 MBaud system can trade-off margin for taps



NEXT Canceller Tap Trade-Off





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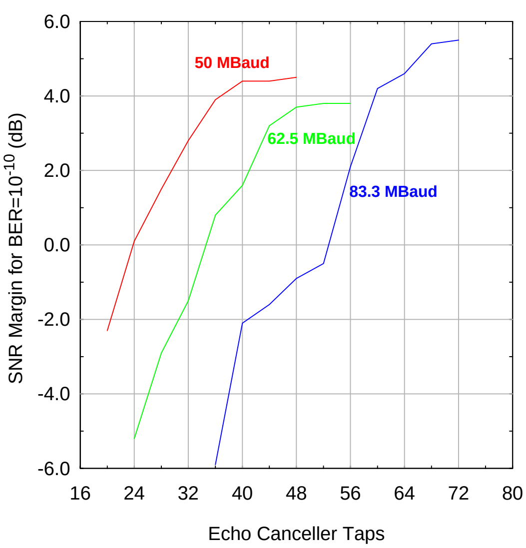
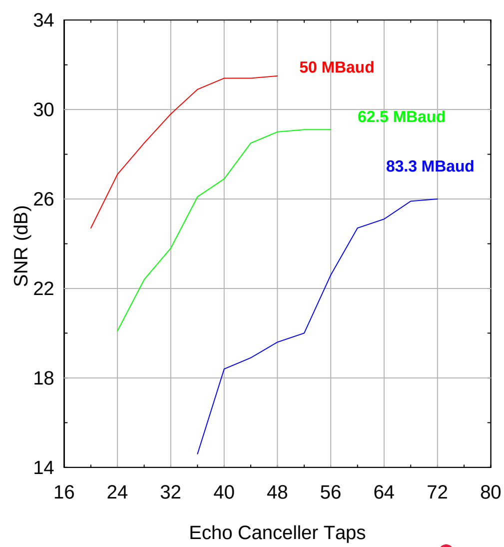
Echo Canceller Tap Trade-Off





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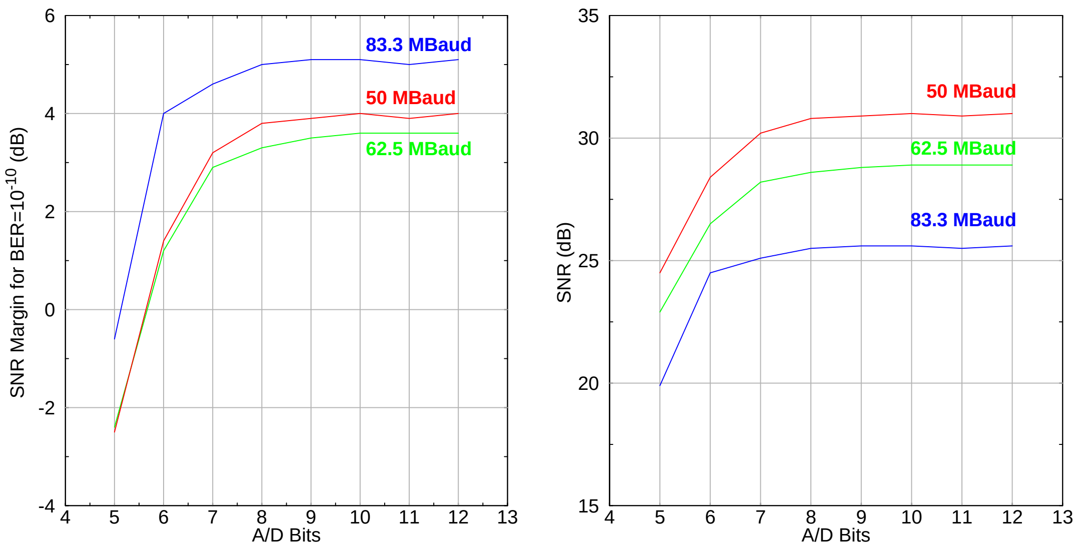
A/D Precision



Simulation Summary

System	50 MBaud (36-QAM)	62.5 MBaud (25-QAM)	83.3 MBaud (9-QAM)
FFE Taps	8	8	8
DFE Taps	8	10	8
NEXT Canceller Taps	20	28	36
Echo Canceller Taps	36	40	56
A/D Precision / Rate	7 bits / 150 MHz	7 bits / 187.5 MHz	6 bits / 250 MHz
Relative Hardware Complexity (digital)	1.1	1	1
SNR	30.2 dB	28.1 dB	24.5 dB
Margin (BER = 10^{-10})	3.2 dB	2.8 dB	4.0 dB

Conclusions

- **QAM line coding is well-suited for Gigabit Ethernet**
- **Smaller constellation sizes achieve slightly higher SNR margins**
  - Higher speed data converters are required (6-bit 250MHz vs. 7-bit 150MHz)
- **Accurate comparisons of various line codes requires consensus on a common set of simulation models**
  - Echo return loss characteristic is a major factor in determining system complexity

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