10GBASE-T Tutorial

IEEE 802.3

Kauai, Hawaii

November 11, 2002

SolarFlare Communications

Agenda

- Introduction, Cabling & Challenges -

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  Founder

- Implementation & Performance -

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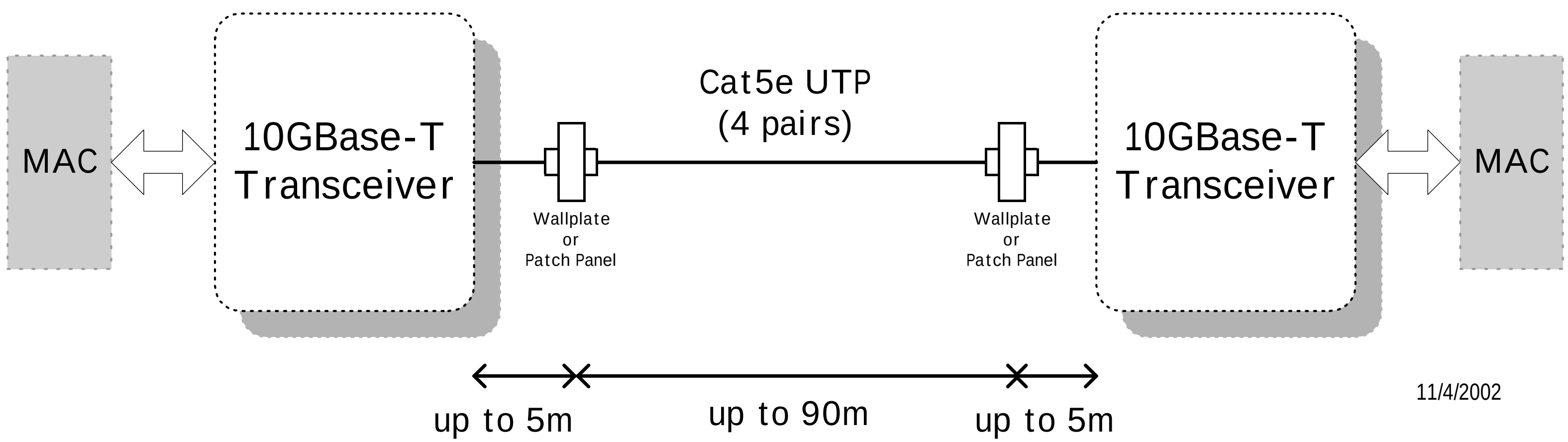
  Director, Systems Engr.

10G on UTP Possible or Not?

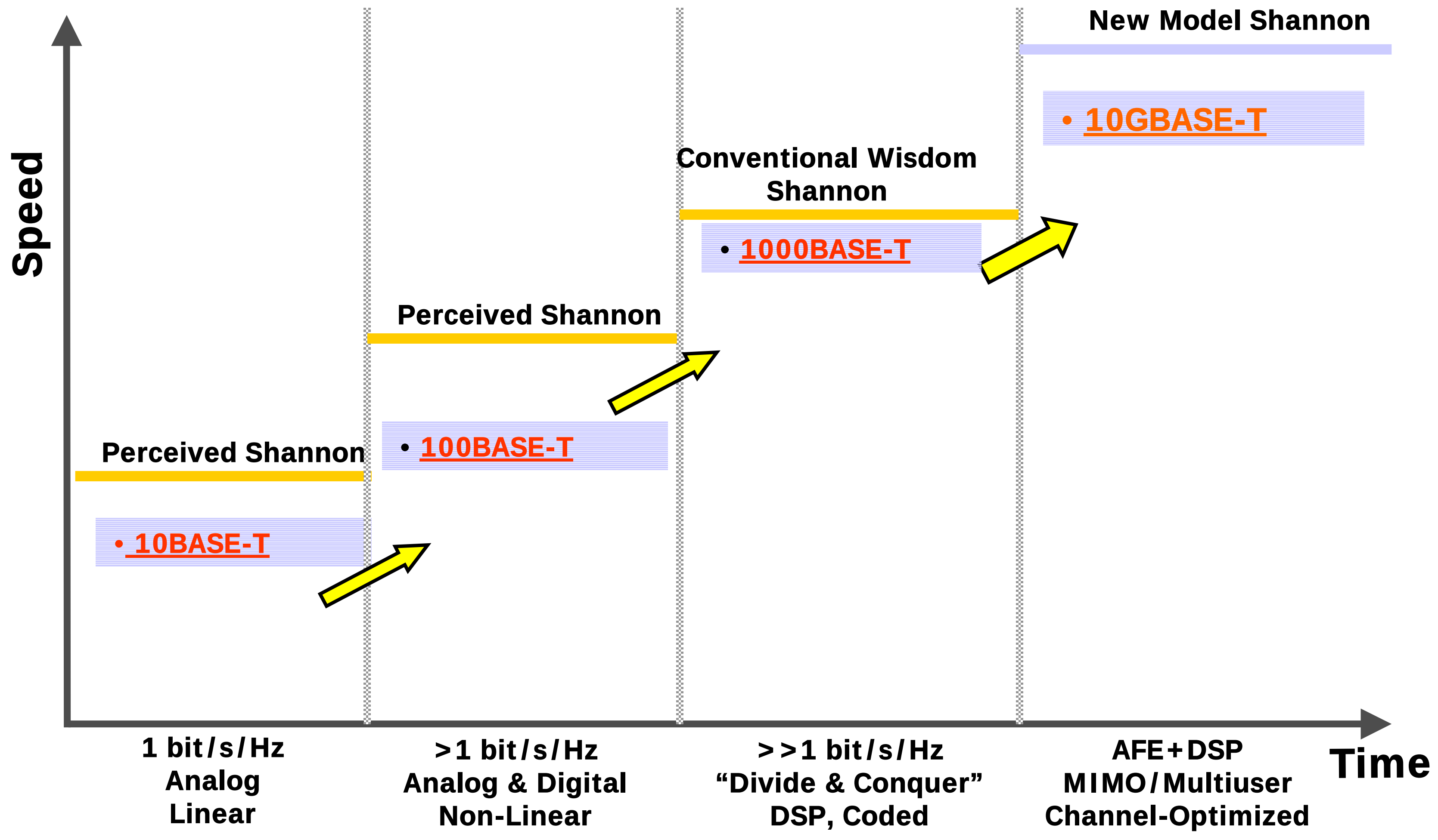
- The Problem
- Characterization vs. Specification
- Cabling & Impairments
- Limitations
- Capacity
  - How to pick the right bandwidth?
- Challenges

Applications Overview

- 10-Gb/s Ethernet connections </= 100m
- Utilize installed base of structured Cat 5e UTP
- Upgrade from 1000BASE-T



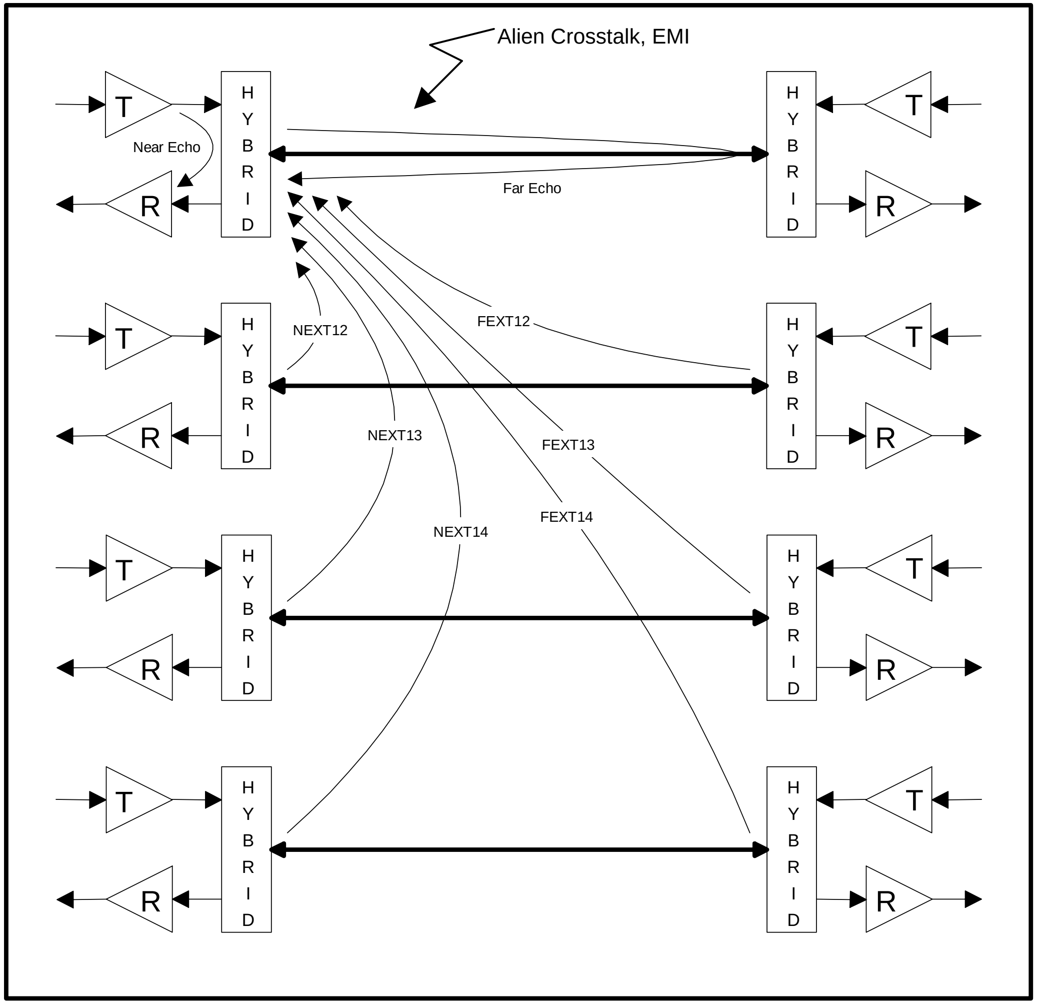
Ethernet Evolution



What Makes Shannon Limits?

- NOT modulation-specific
- Signal Attenuation (*assumed* usable bandwidth)
- *Assumed* irreducible noise sources
  - Background
  - Crosstalk
    - Crosstalk from other pairs in our sheath
    - Alien crosstalk – coming from other bundled 4-pair sheaths
  - Device noise from transceiver
- *Change the assumptions & change the limit!*
  - (to a point...)

Channel Impairments

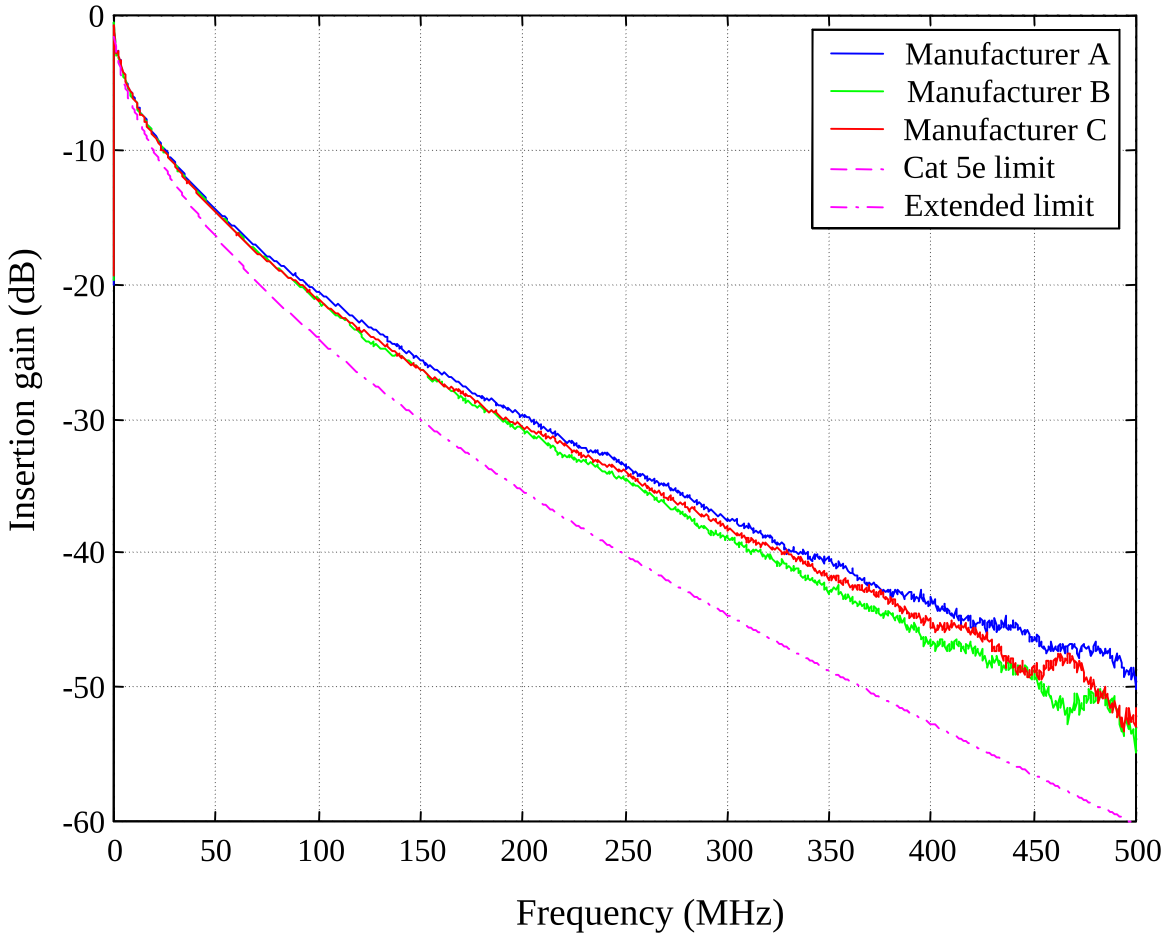


Characterization vs. Specification

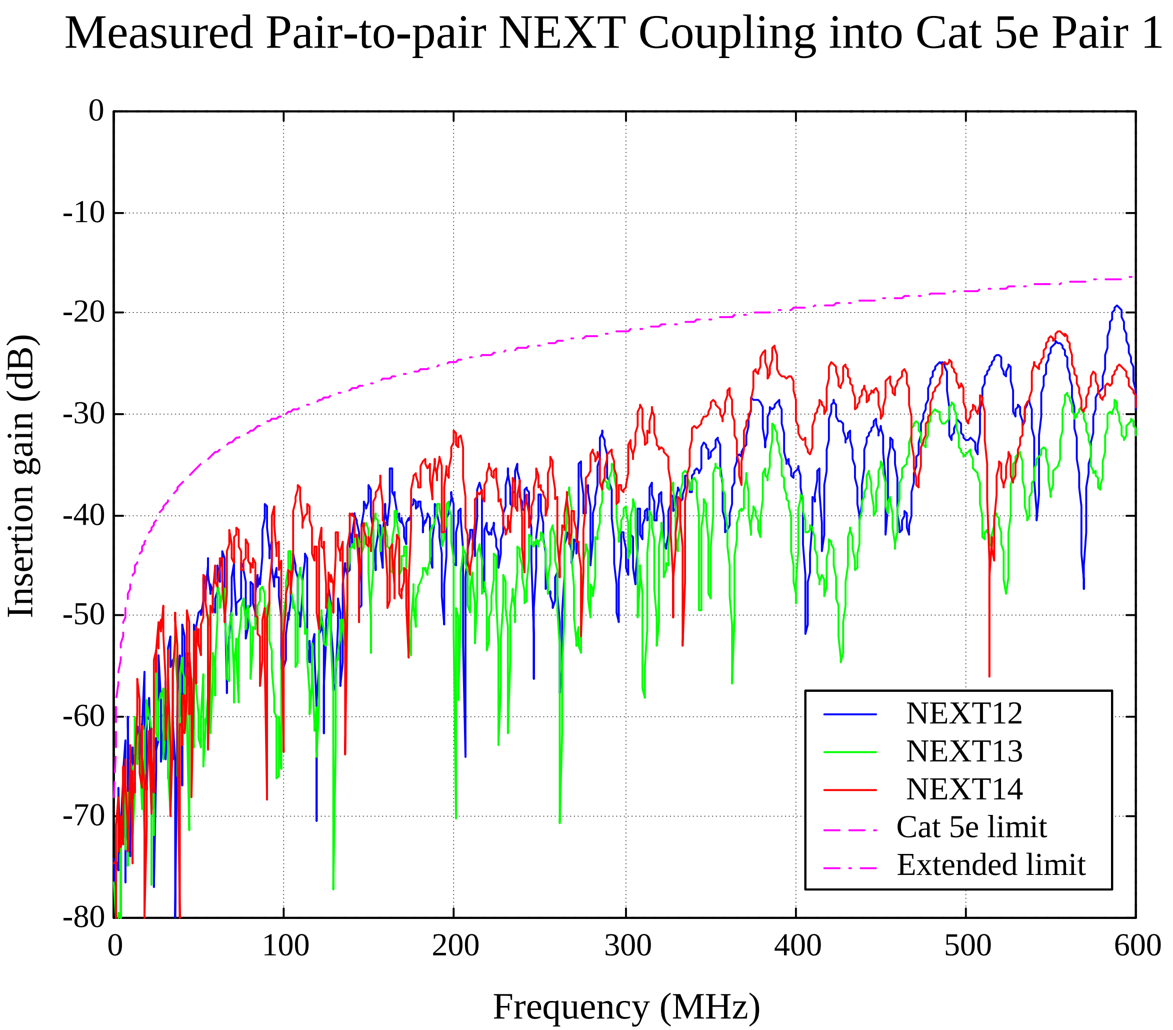
- Cat 5/5e cable must be high quality with minor structural variations to meet TIA-568 requirements
- 100 MHz (or 250 MHz) "limit" imposed by TIA qualification requirements
  - not the physical limitations of the cable
- Cable properties stable beyond 500 MHz
  - depends mainly on transmission line geometry and construction materials
- Minor structural variations and connector discontinuities affect channel transmission, but not catastrophically

Cat 5e Channel: Insertion Loss

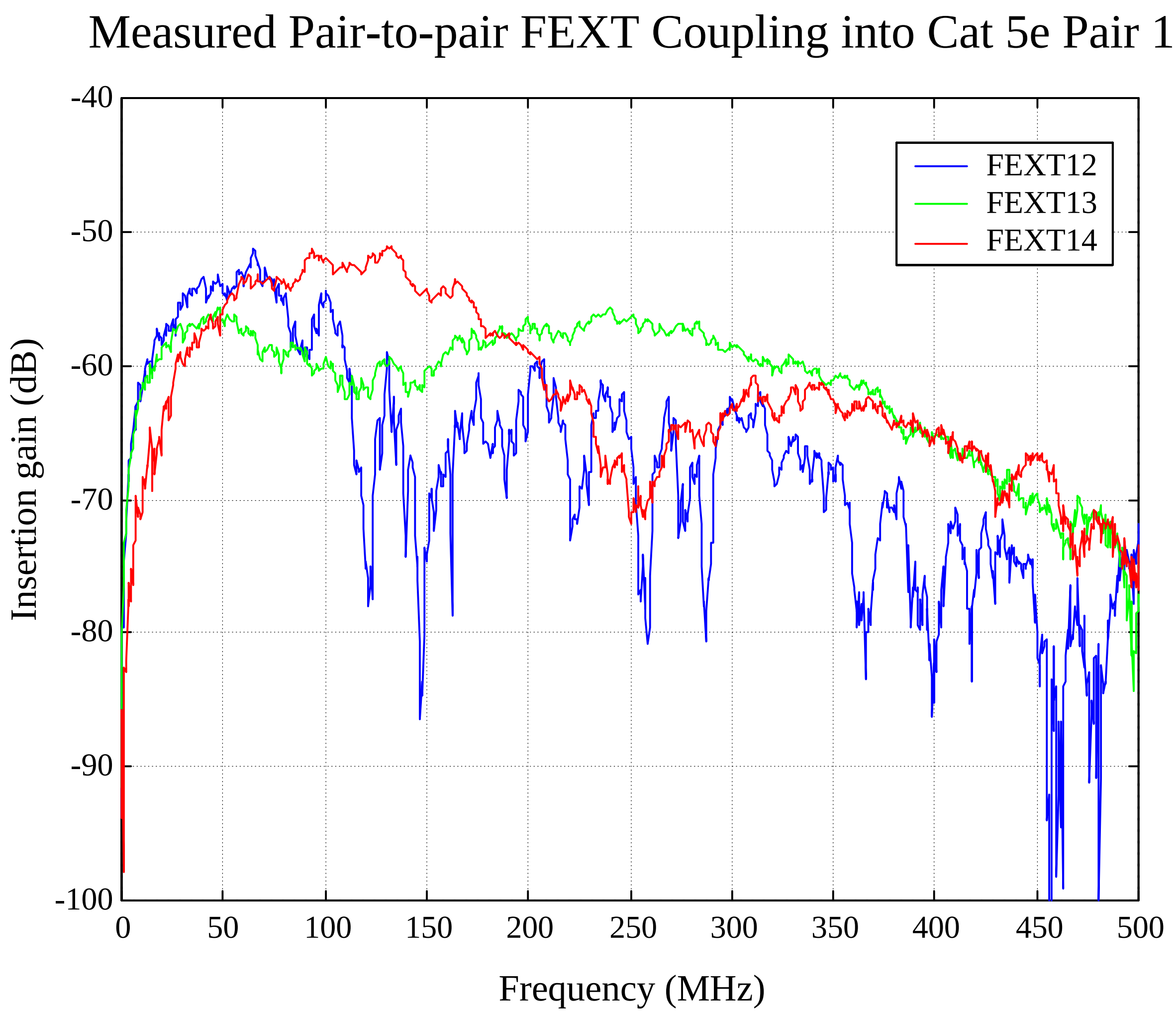
Measured Cat 5e 100 Meter Channel Insertion Gain at 20 C



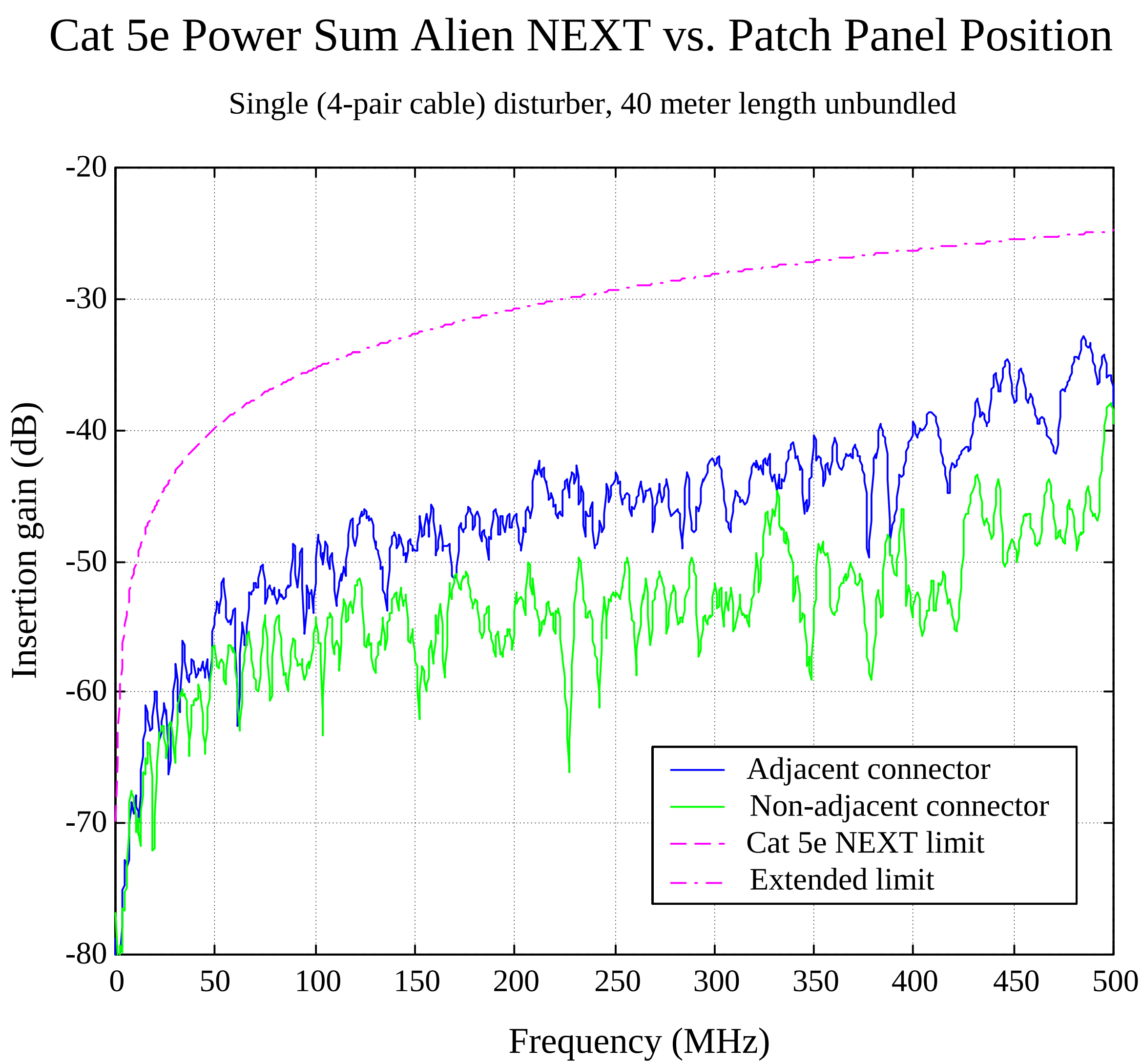
Cat 5e Channel: NEXT



Cat 5e Channel: FEXT



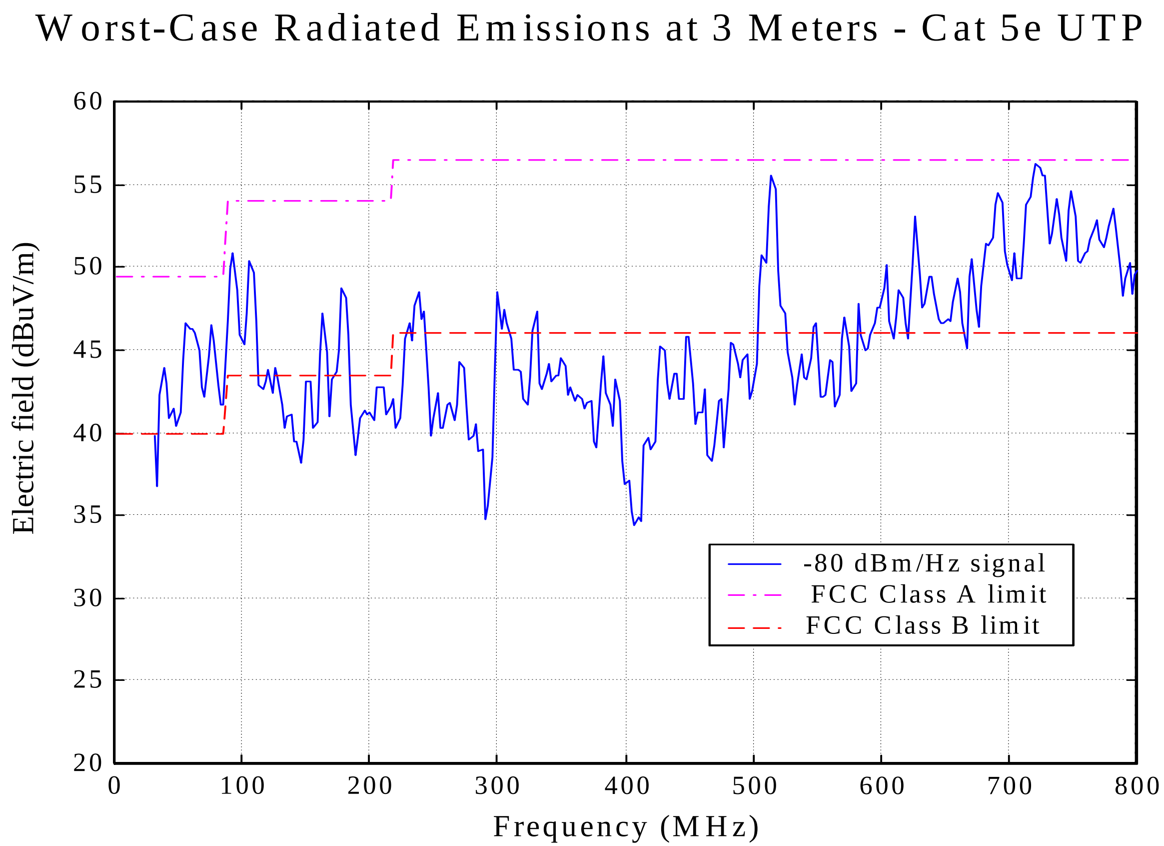
Alien NEXT



Cat 5e Power Sum Alien NEXT vs. Patch Panel Position
Single (4-pair cable) disturber, 40 meter length unbundled
-20
-30
-40
-50
-60
-70
-80
Insertion gain (dB)
0
50
100
150
200
250
300
350
400
450
500
Frequency (MHz)
Adjacent connector
Non-adjacent connector
Cat 5e NEXT limit
Extended limit

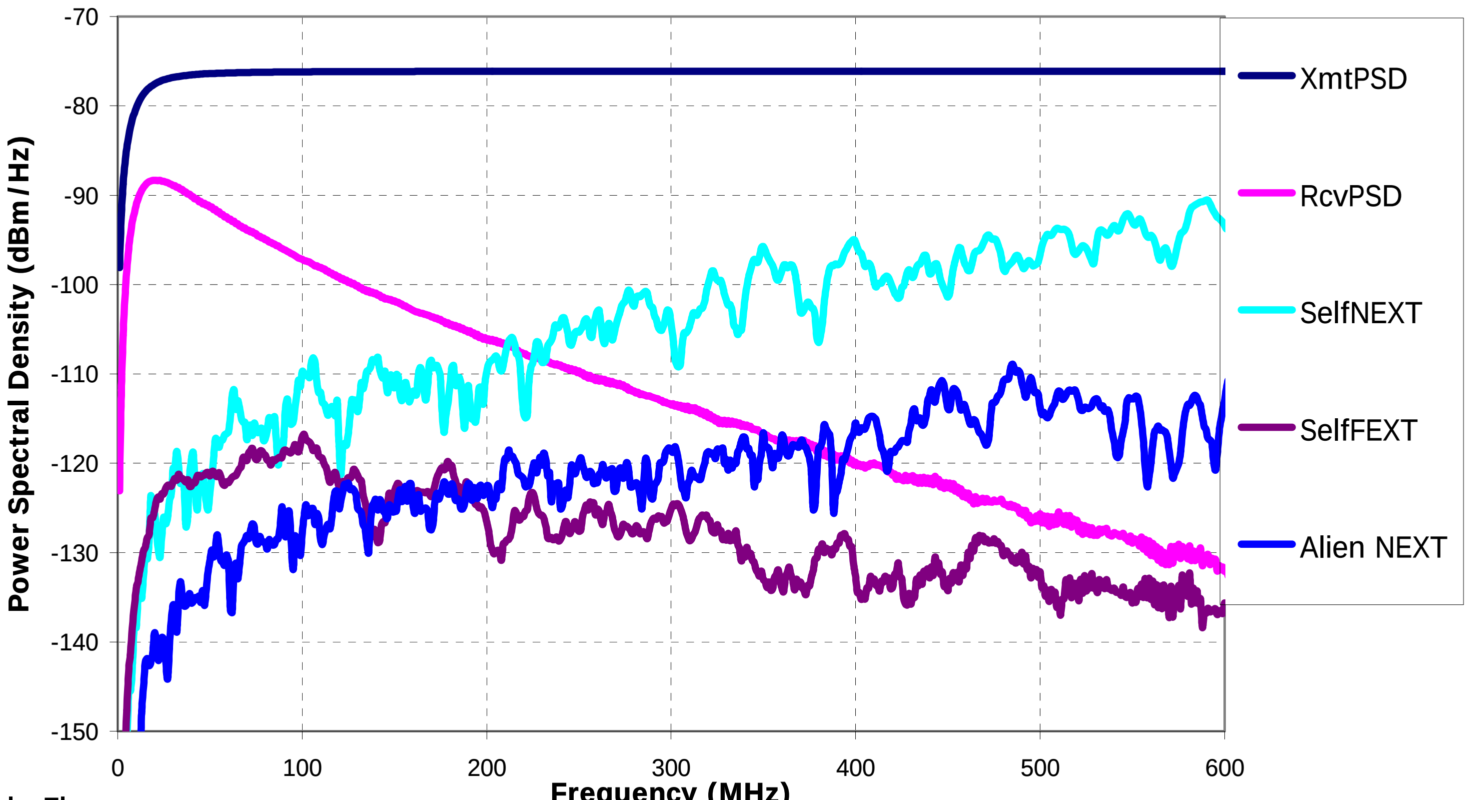
EMI - Emitted

- >100 MHz on Cat 5e can meet FCC Class A
  - ~12 dBm launch power limitation



Overall Environment

- Sources require significant cancellation
  - Extensions from 1000BASE-T
  - Significantly greater NEXT + FEXT + Equalization challenge

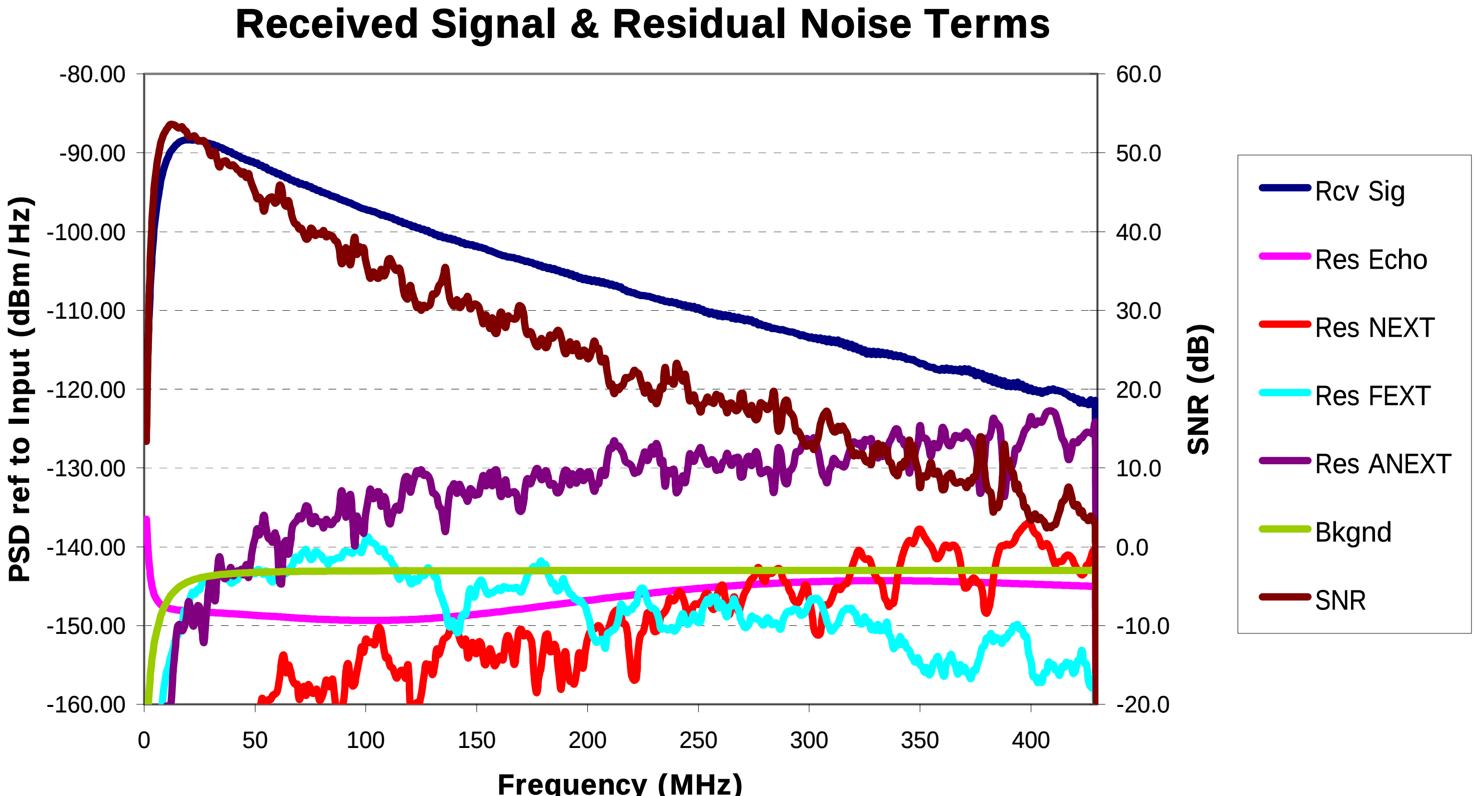


Strawman Improvements

- Baseline Requirements:

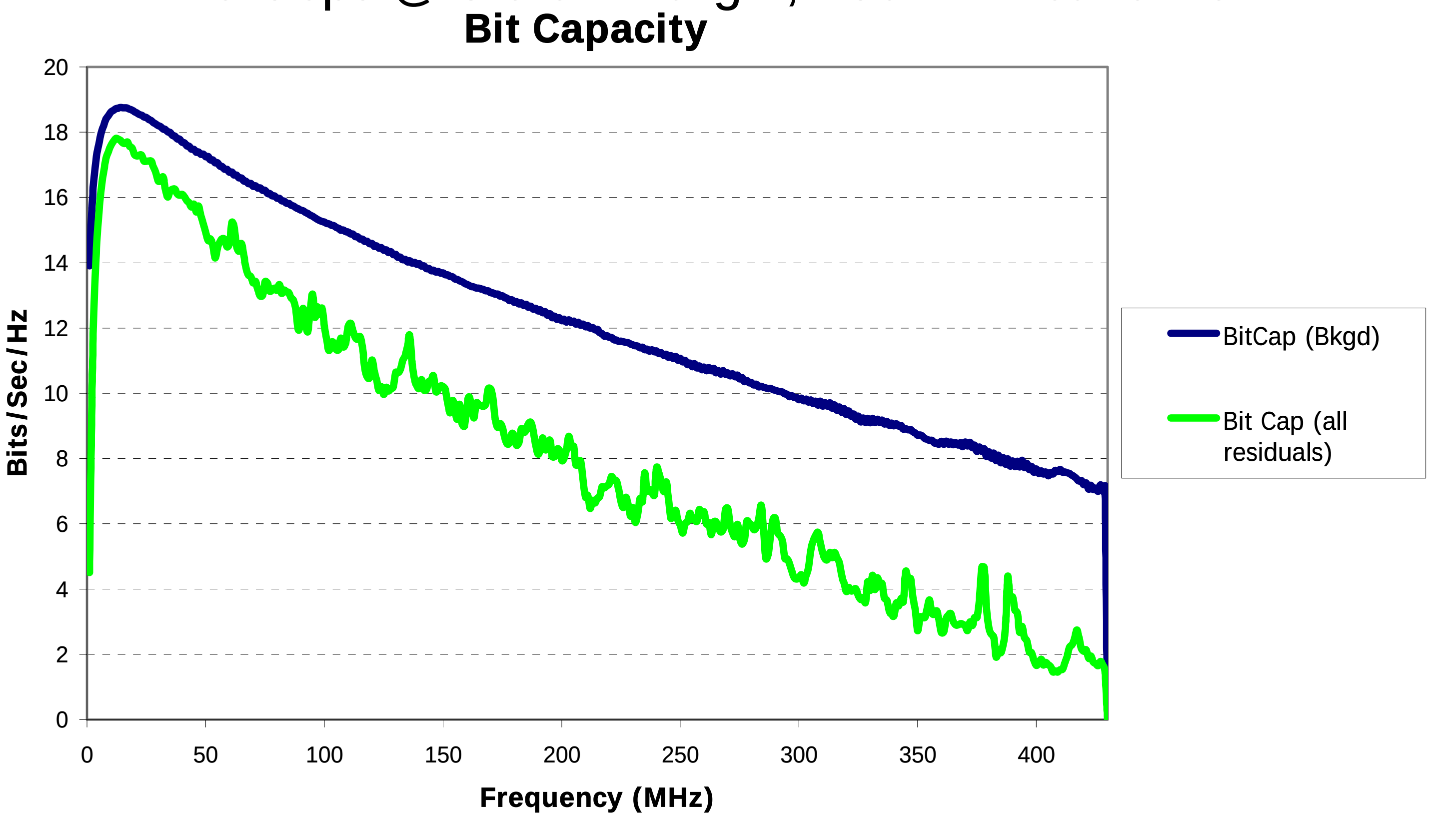
  ~40 dB Echo & NEXT Cancellation, ~20 dB FEXT Cancellation

  Alien NEXT suppression for crowded installations



Capacity

- 100m Cat 5e, with cancellers
  - 14.4 Gbps on 100m at 10dBm launch, 600 MHz
  - 10 Gbps @ 8.9 dB Margin, 430 MHz bandwidth



Conclusion:
It CAN be done, but HOW?

- Bandwidth required 400-500 MHz
- 40+ dB Echo & NEXT reduction
- 20+ dB FEXT reduction
- 10-12 dBm launch power
- > 8 bits (ENOB) signal processing
  - A/D performance, or analog noise performance if analog circuits used
- Shannon limits say “Not Impossible”, just hard!
  - It’s up to us engineers!

Realizing 10GBASE-T

- Addressing communication system challenges
- Modern signal processing algorithms
- Low power, high speed digital circuit design
- High linearity, wideband analog circuit design

Communication System Challenges

- High frequency multiple twisted pair media characterization
  - Line attenuation, NEXT, FEXT, Alien Xtalk & EMI
  - Cat 5e specification out to 100MHz
    - Sufficient for 1000BASE-T
  - Utilizing frequencies beyond cable's initial intended objective is not new
  - Case in point: xDSL
    - Installation designed for 20kHz max

- Measurements converted for use in system evaluation
  - No assumptions or short cuts taken
  - Scaled to worse case specifications (when they exist)

Line Code Selection

- Pulse Amplitude Modulation (PAM)
- Evolution Of 1000BASE-T
  - Builds on proven technology
- Lower AFE requirements
  - De-stressing an already stressed requirement
- Utilizing an optimal DFE achieves capacity

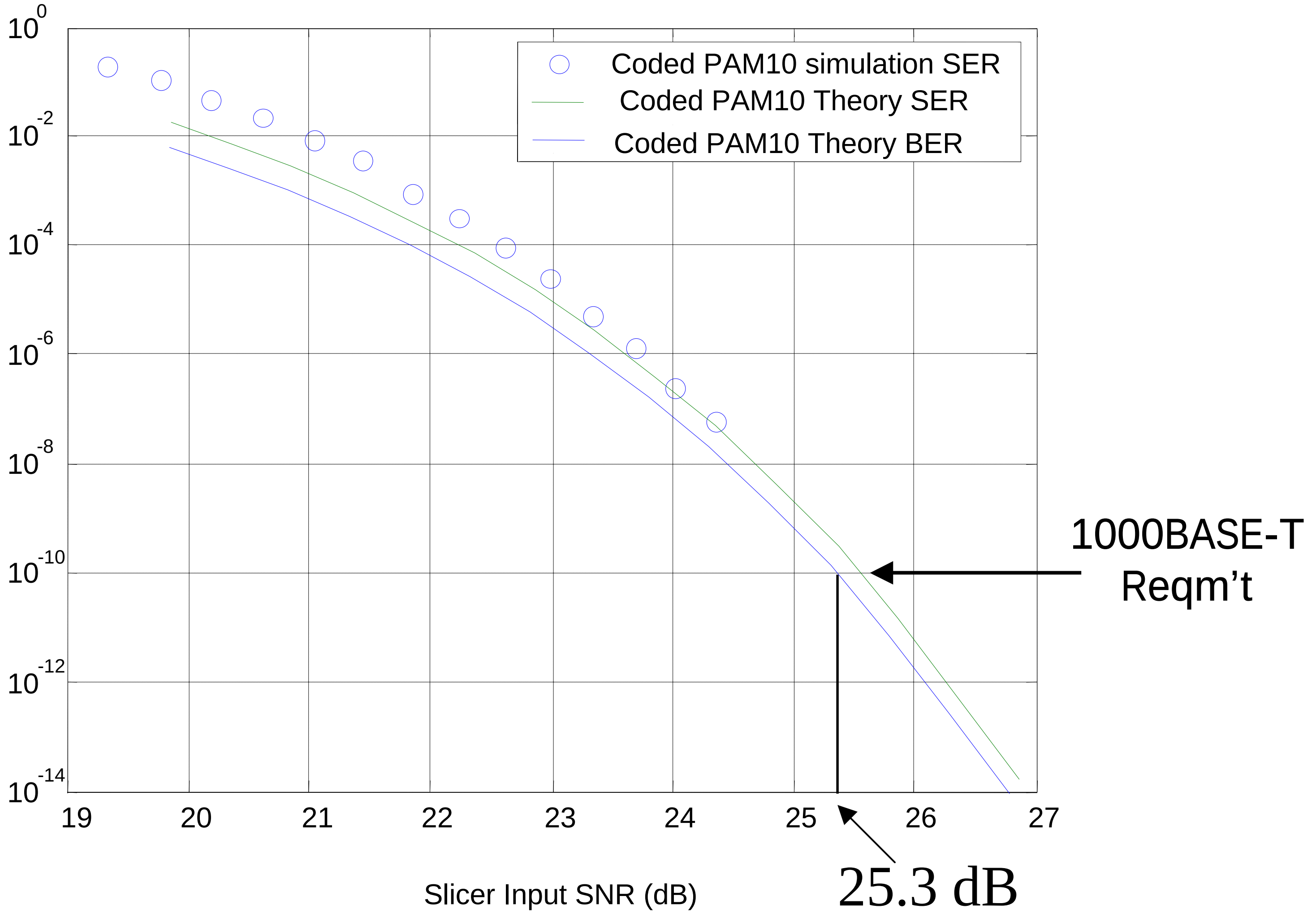
PAM-10 Coding

- Given the characteristics of the channel/disturbers, capacity is maximized with an analog bandwidth around 400MHz
- 10Gbps is achieved with a baud rate of 833MHz and 12 bits/baud or 3 bits/pair (4 pairs)
  - Minimum requirement of PAM8 for uncoded operation
- PAM9 may be sufficient for Ethernet control symbols
- PAM10 needed for both control and Trellis coding
- Extension of 1000BASE-T
  - 4D, 8-state Trellis code (one dimension per pair)
  - 6 dB coding gain relative to uncoded 10PAM

Comparison With 1000BASE-T

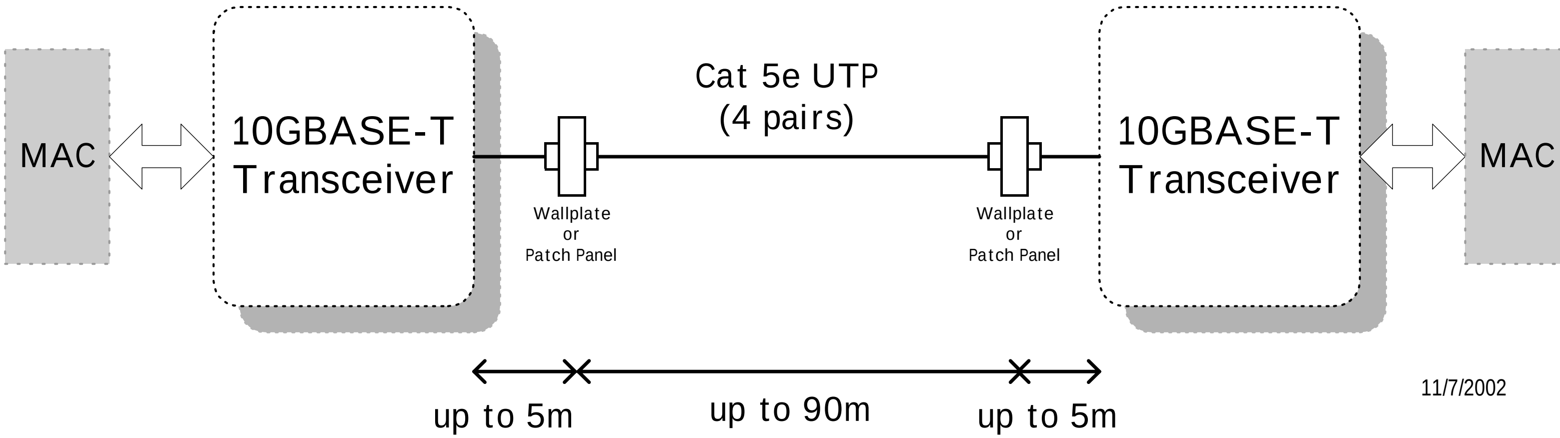
1000BASE-T	Straw Man 10GBASE-T
Multilevel coded PAM signaling (2-bits/symbol)	Multilevel coded PAM signaling (3-bits/symbol)
5-level with Trellis code across pairs	10-level with Trellis code across pairs
Full duplex echo-cancelled transmission	Full duplex echo-cancelled transmission
125 Mbaud, ~80 MHz used bandwidth	833 Mbaud, ~400 MHz used bandwidth
Moderate NEXT cancellation	High-Performance NEXT cancellation
No specified FEXT cancellation	High-Performance FEXT cancellation

PCS SER & BER Straw Man Goal



PMD Performance Straw Man Goal

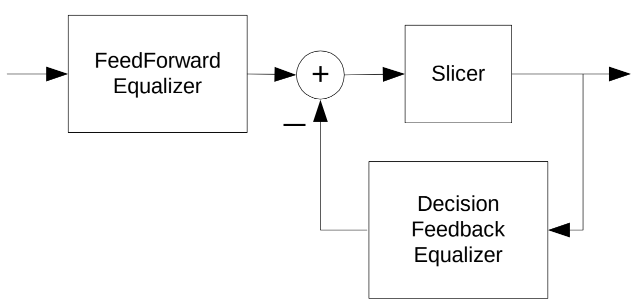
- TSB 67 Channel

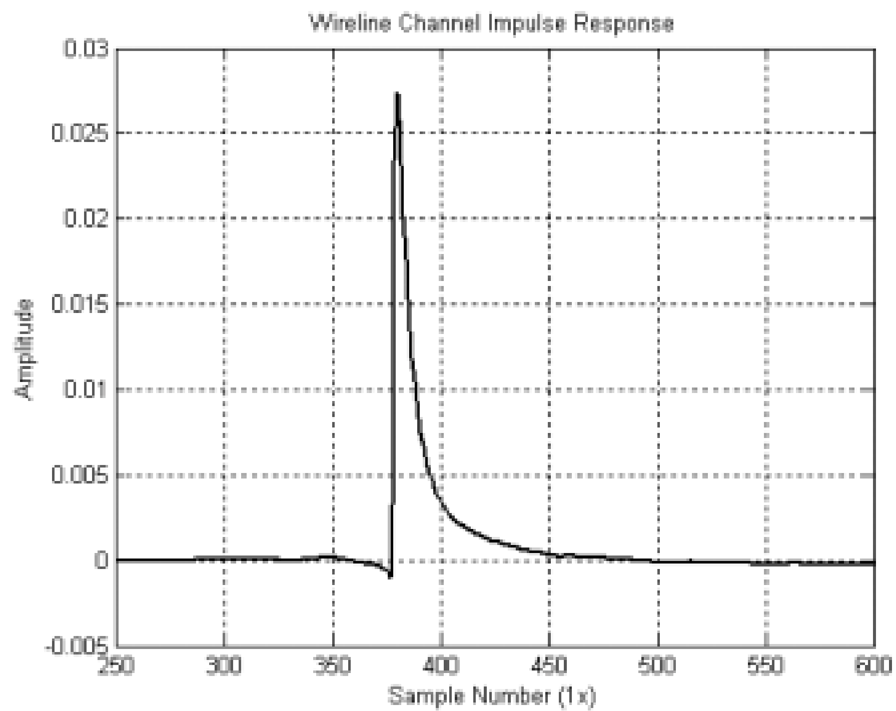


- Consider an aggregate slicer SNR of 25.3 dB with five dominating noise terms requires individually around 32 dB SNR

Channel Impairments- ISI

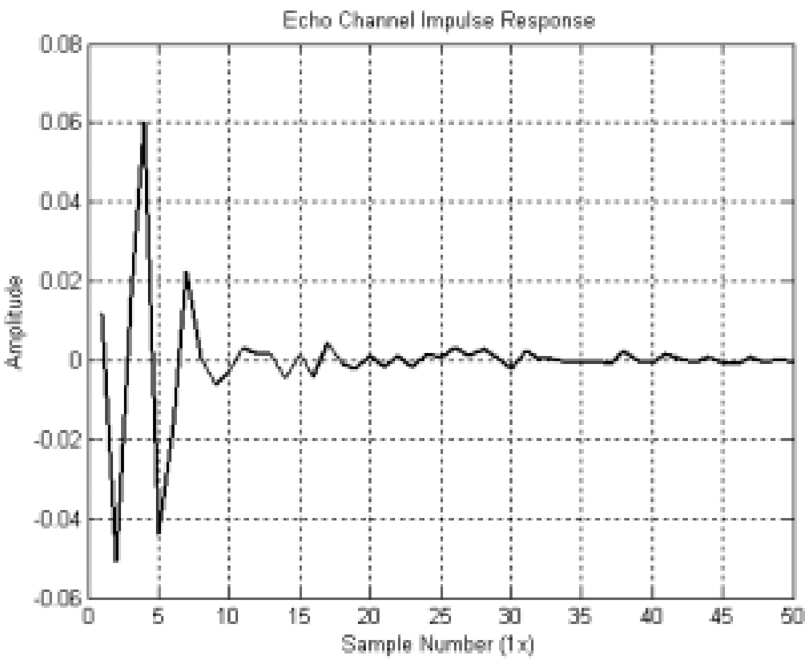
- Pre- & Post-Cursor Interference from limited Bandwidth
- Post-Cursor Dominates (>100 terms)
- Feedforward & Decision Feedback Equalization Solution





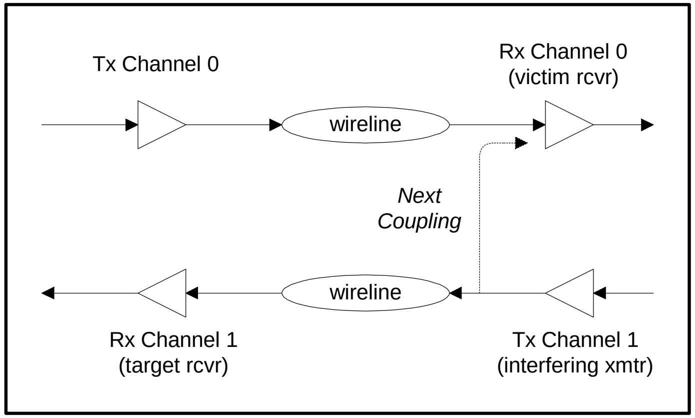
Echo

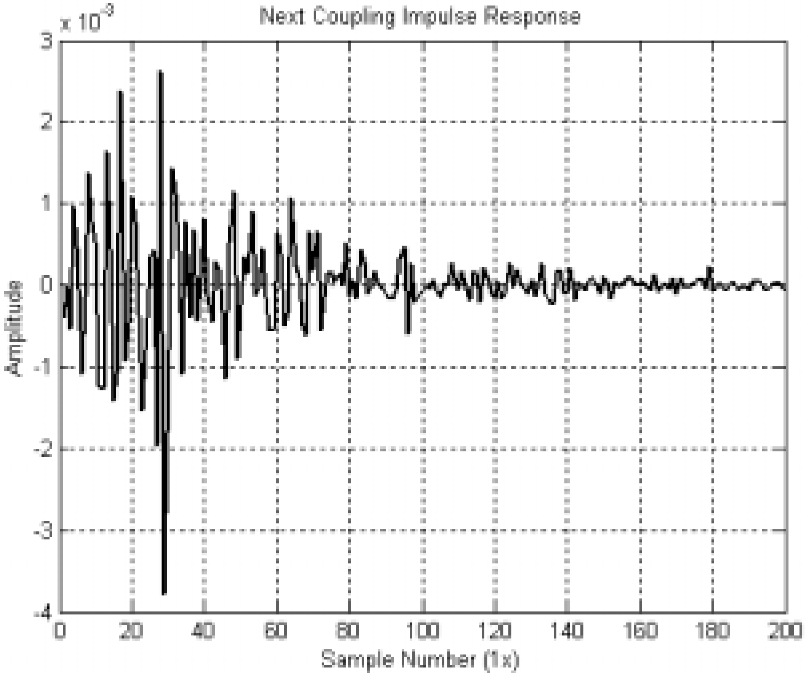
- Full duplex needed for limited BW
- Compromise hybrid for Tx/Rx isolation
- Impedance mismatches require residual echo cancellation
- > 40 dB rejection



NEXT

- High-level interference from transmitters
- Very long response time
- > 40dB NEXT cancellation

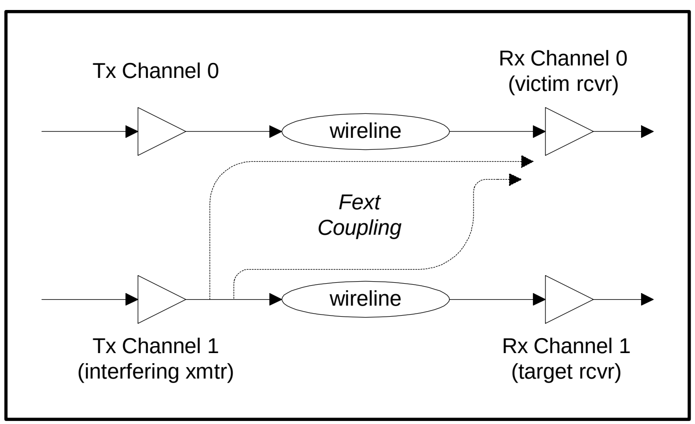


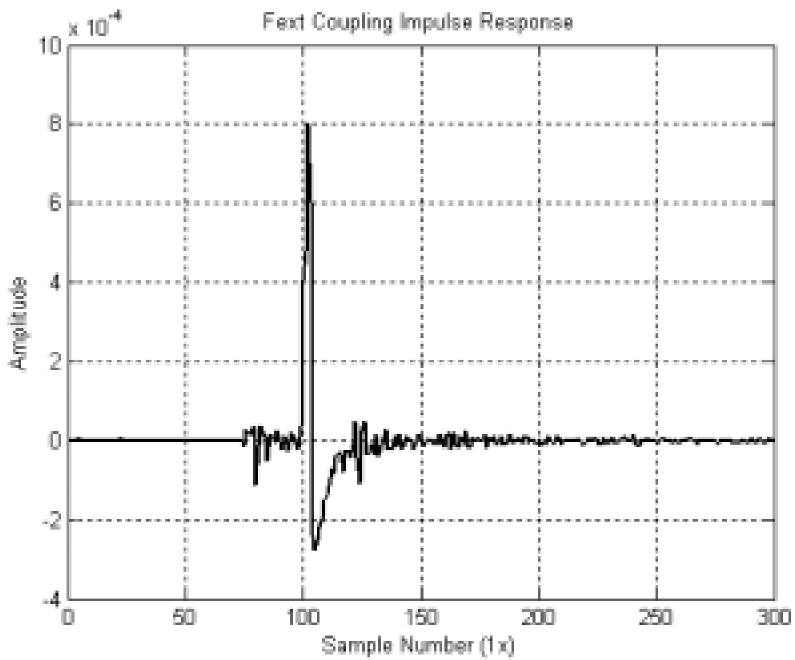


FEXT Impairment

- Pre- and post-cursor elements of interference
- Based on an equal-level FEXT (ELFEXT) model
- Uncompensated in 1000BASE-T
- Must be cancelled in 10GBASE-T
- > 20 dB cancellation

$$H_{fext} = H_{elf} \cdot H_{chan}$$



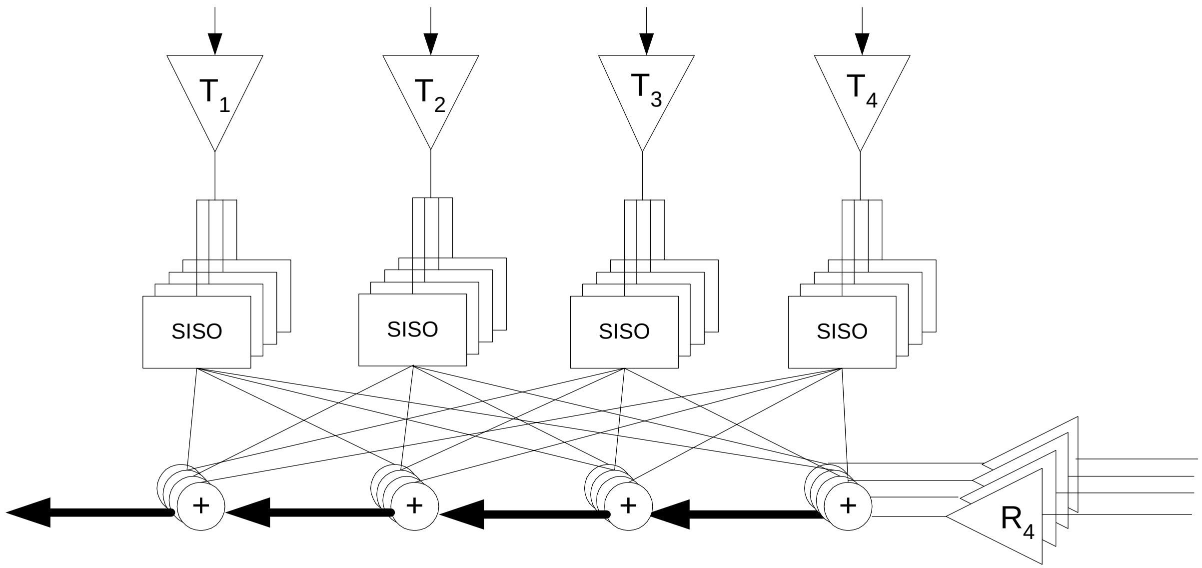


Challenging Implementation

- A new approach to problem solving needed to meet SNR requirement (>25.3 dB)
- Efficient reuse of resources in MIMO modeling
- Utilization of parallel structures

Traditional Signal Processing

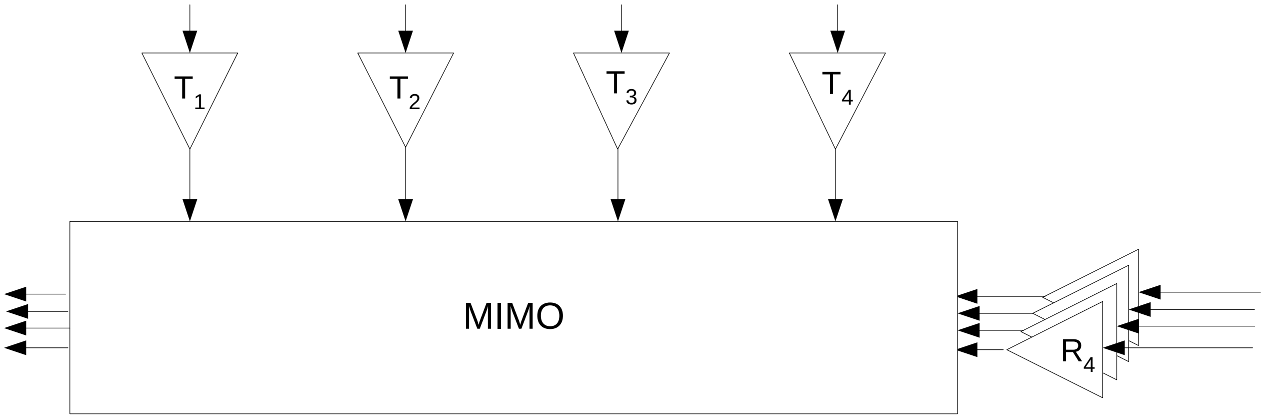
- Echo & NEXT cancellation



- 16 Single Input Single Output (SISO) processing elements (scalar filters)
- With canceller taps on the order of several hundred
  ➔ 10 Tera Operations (TOps)!

Modern Signal Processing

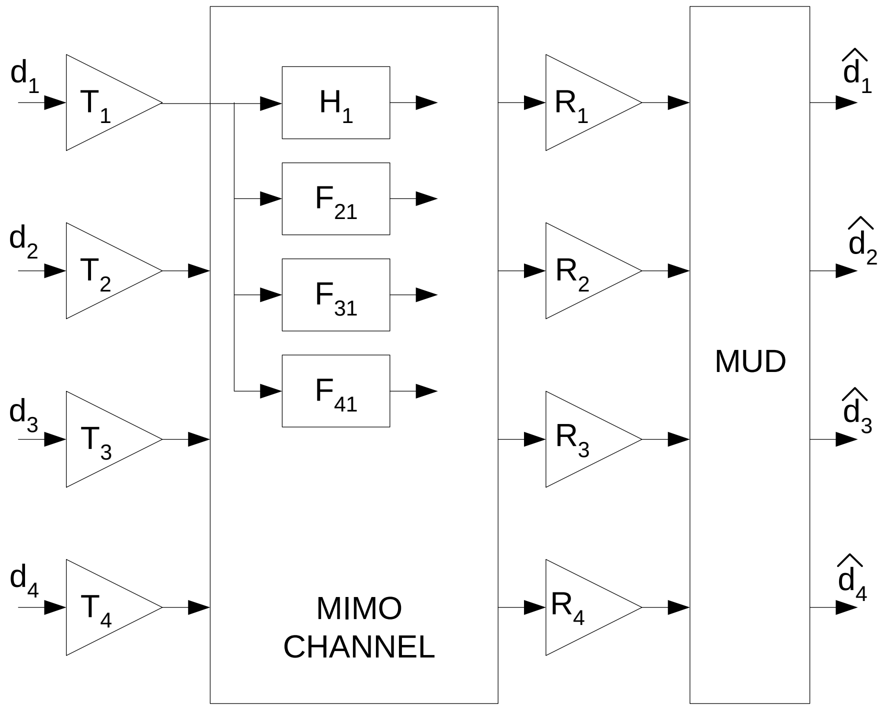
- Echo & NEXT Cancellation



- One Multiple Input Multiple Output (MIMO) processing element (matrix filter)
- Exploits correlation to reduce interference common to all received channels
- Enables massive reuse of computing resources

Modern Signal Processing

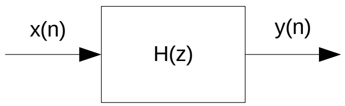
- Data recovery & Fext cancellation



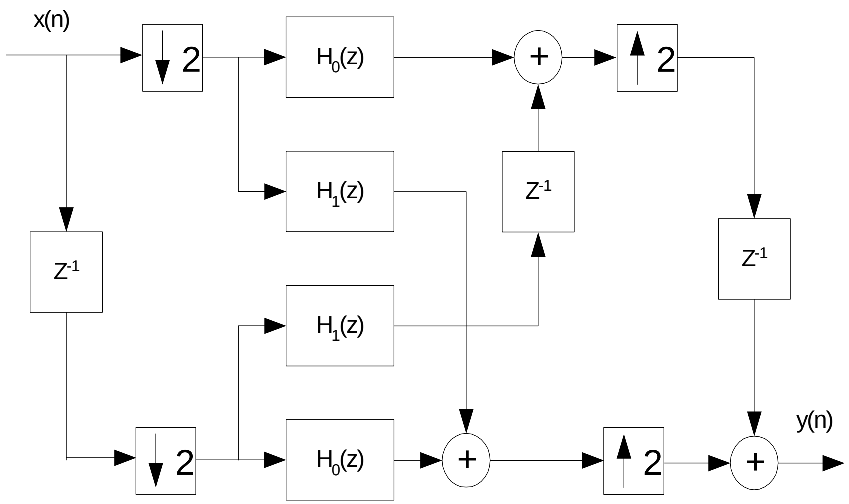
- Multiuser Detector (MUD) of MIMO channel provides simultaneous data decisions & interference removal

Parallelizing FIRs

- One high rate N tap filter

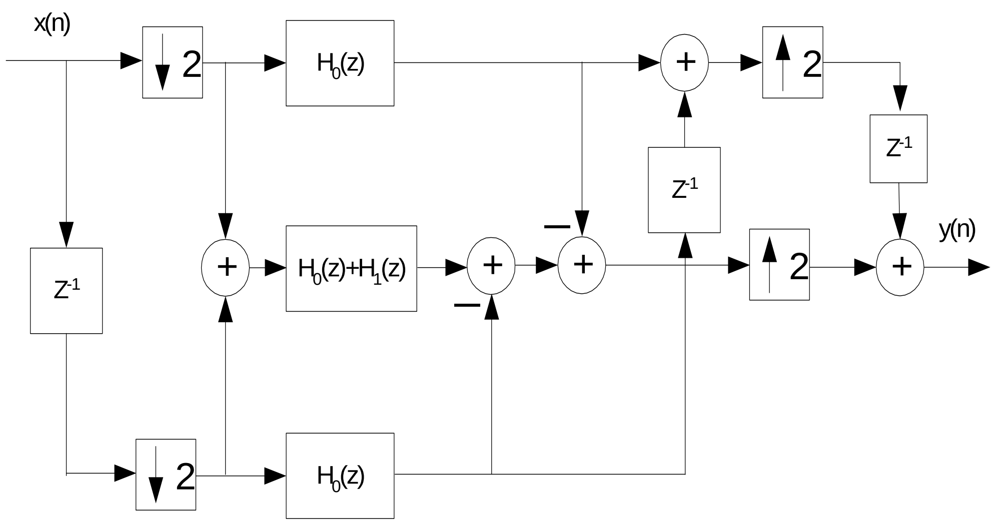


$$H(z) = H_0\left(z^2\right) + z^{-1} H_1(z^2)$$



- Good for clock limited or high speed applications
- Four half rate N/2 tap filters
- Equivalent number of operations per unit time

Efficient Parallelization



- Four filters reduced to three
- 25% improvement in efficiency
- Greater efficiency with greater parallelism

Digital Circuit Straw Man Goals

- Puts total DSP requirements at 1.5 Tera Operations (TOps)
- Quad 1000BASE-T requires 1.0 TOps

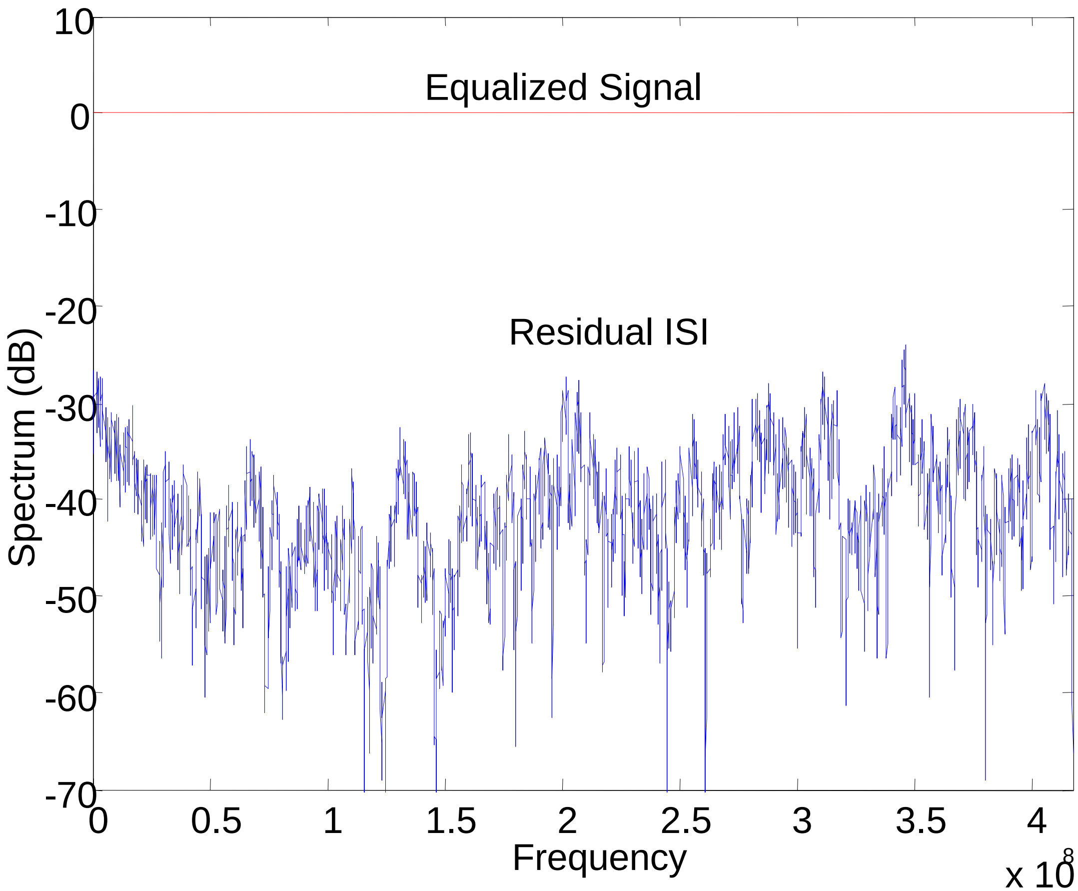
  → 150% increase in possible aggregation with 50% increase in complexity today!

- CMOS technology

Analog Circuit Straw Man Goals

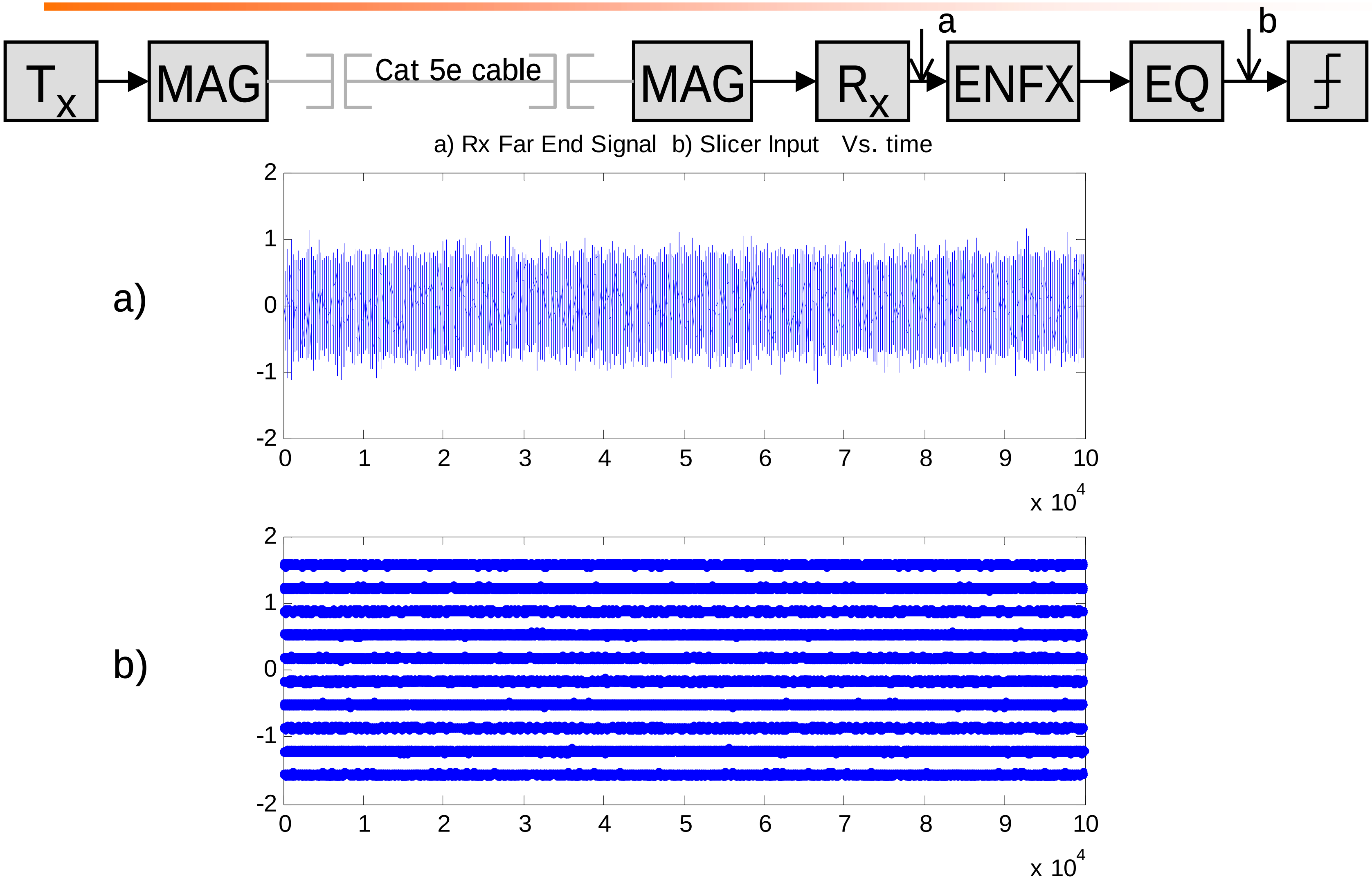
- Transmitter: DAC & Line driver
  - >40 dB Linearity
  - 450 MHz Bandwidth
- Receiver: Hybrid, LNA & ADC
  - >8 bits ENOB
  - 833 MSPS
- PLL & Clock recovery
  - 833 MHz
- CMOS technology

ISI Impairment- After Equalization

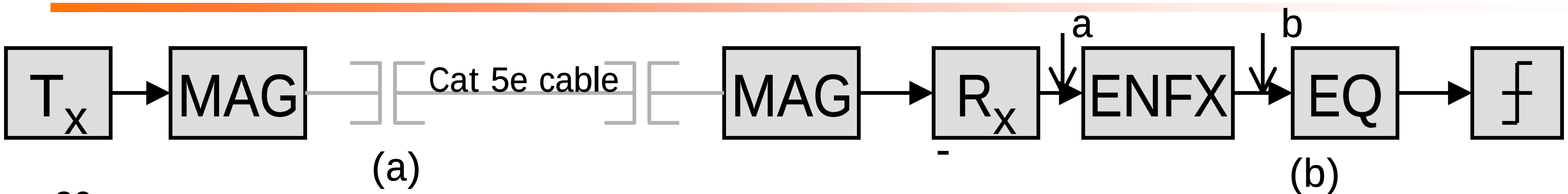


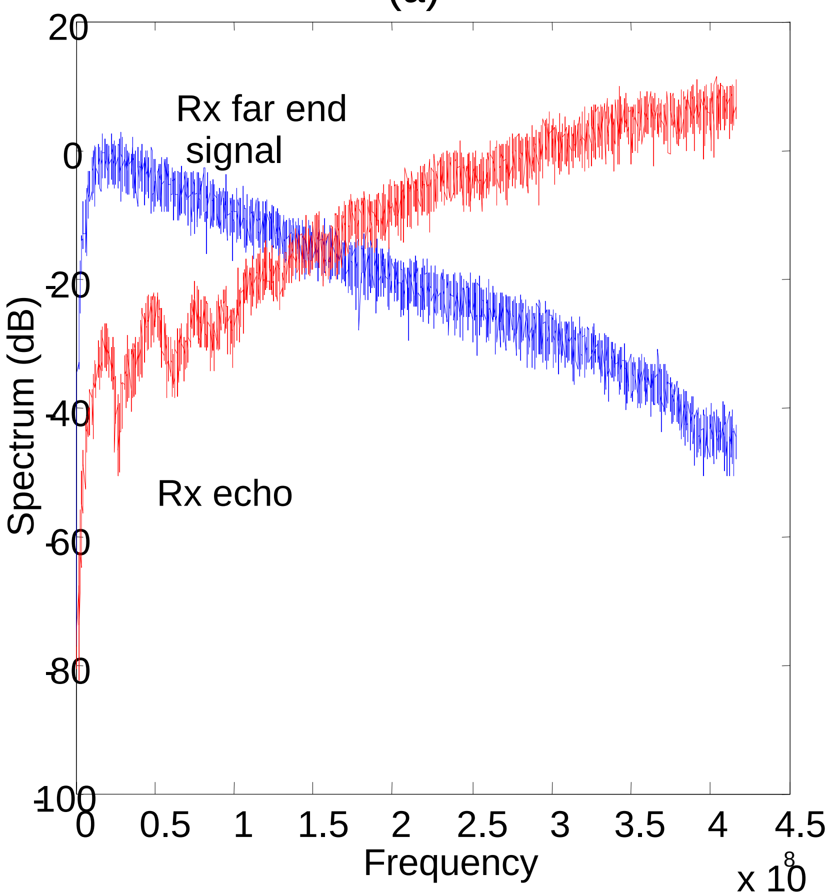
- FFE scales to produce unit variance hard decisions

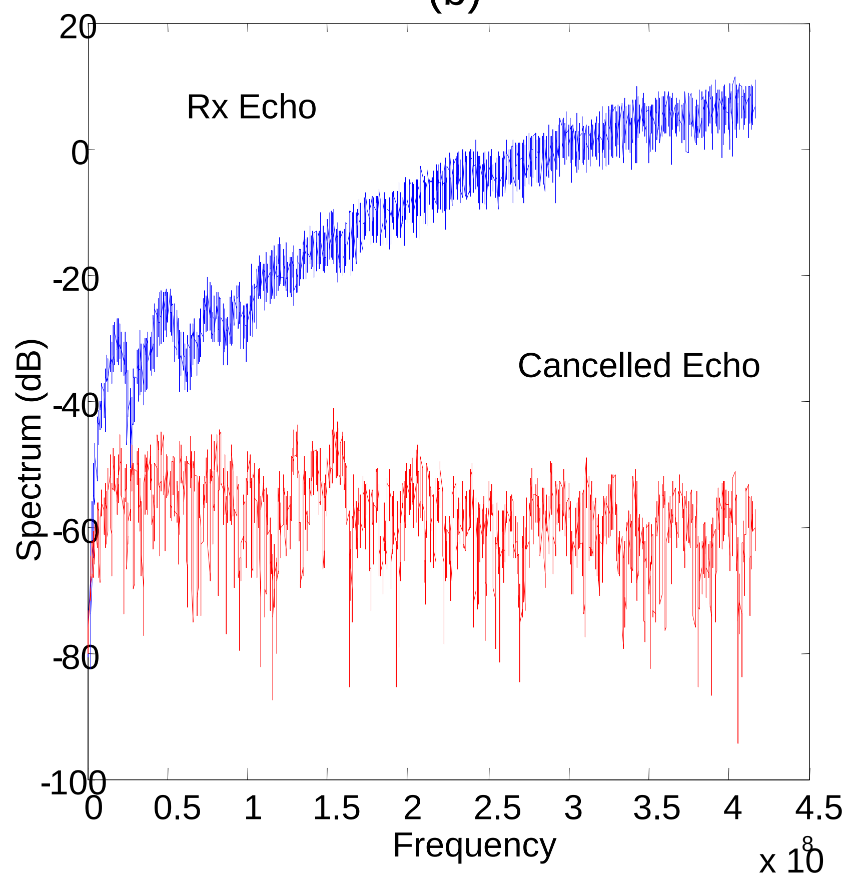
ISI Impairment- Symbol Stream



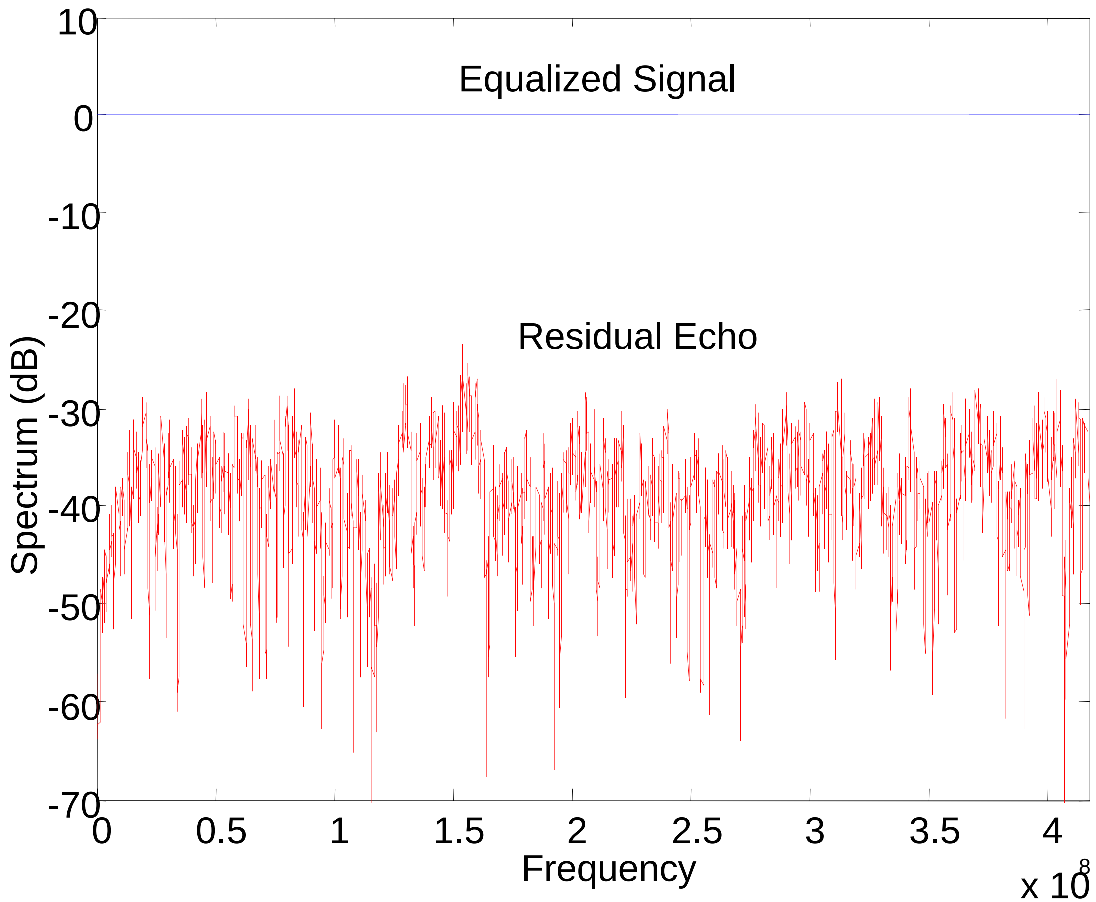
Echo Impairment- After Cancellation







Echo Impairment- SNR @ Detector



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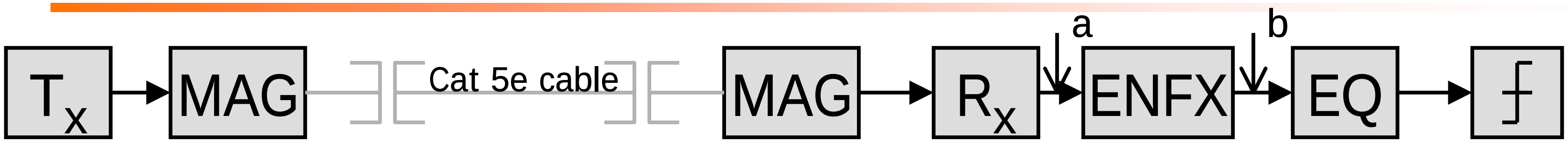
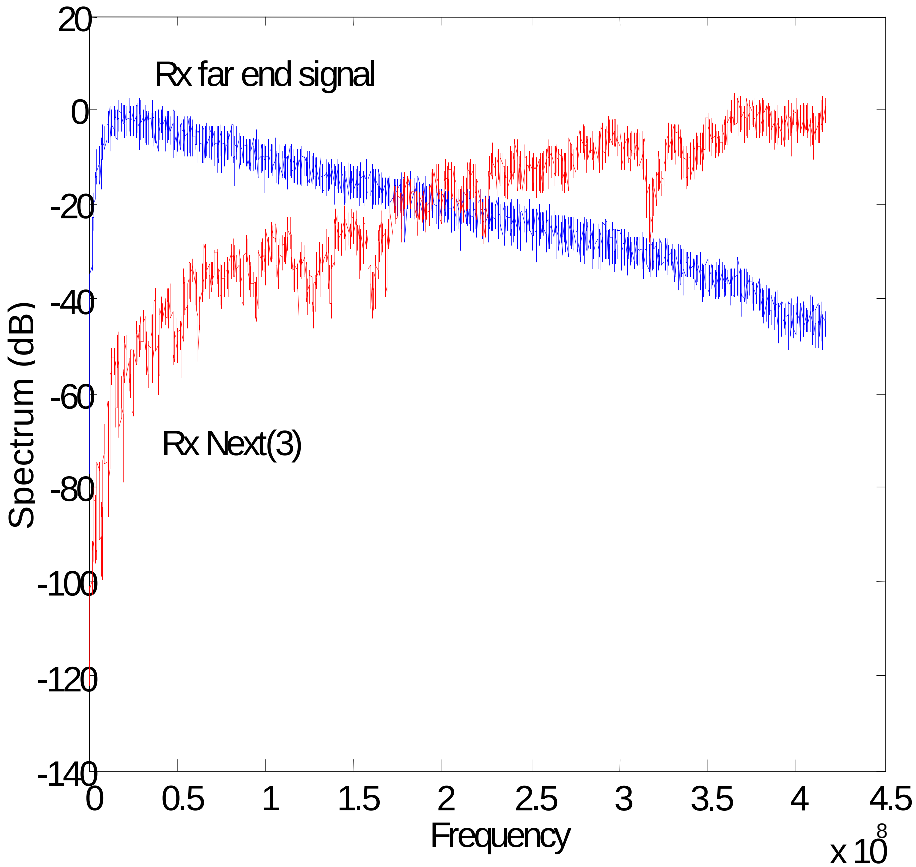
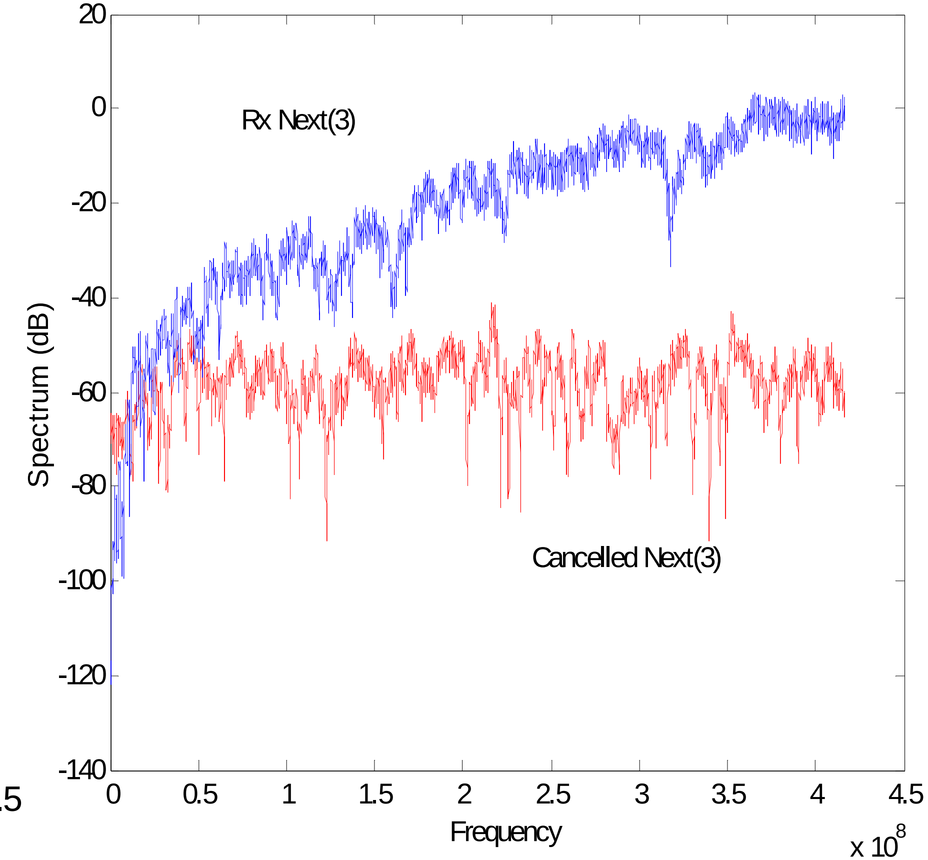
NEXT Impairment- After Cancellation



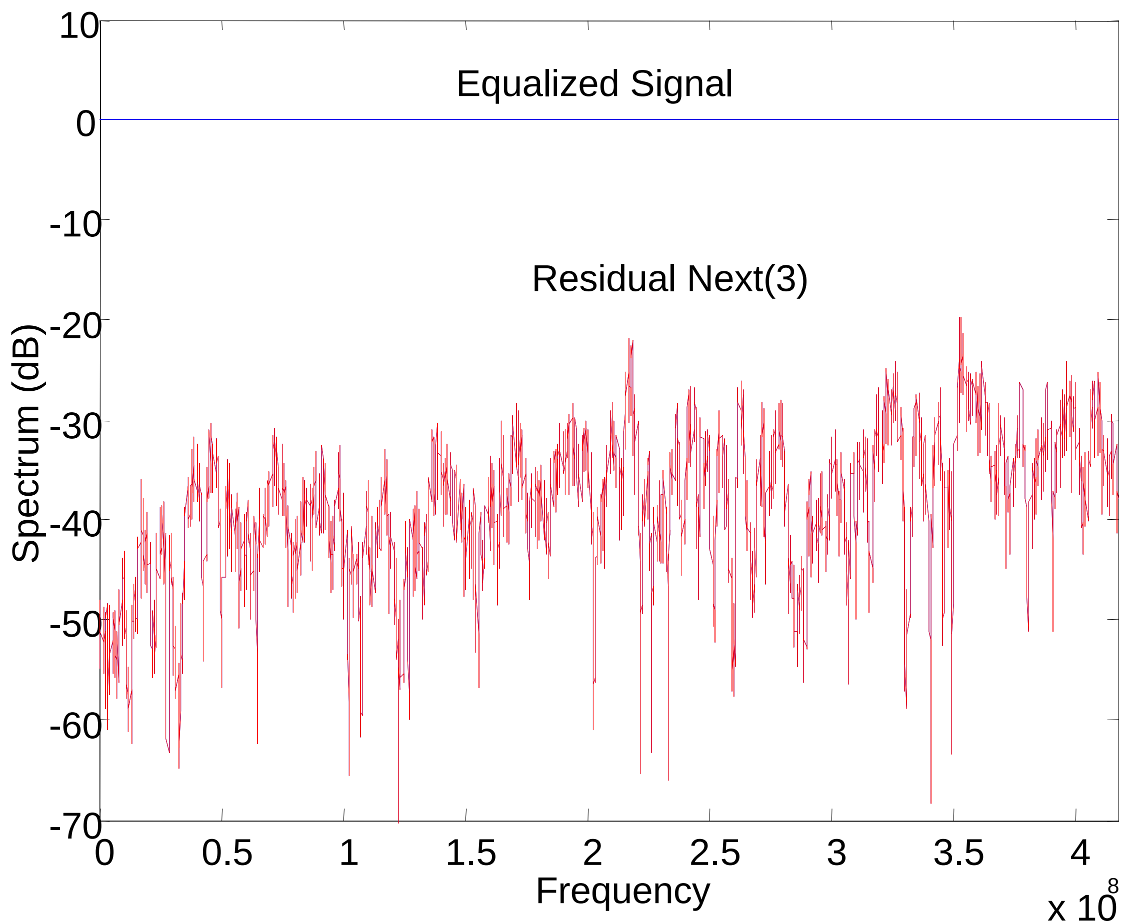
(a)



(b)

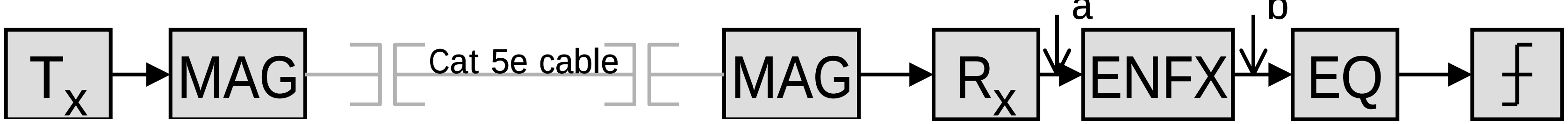


NEXT Impairment- SNR @ Detector



- FFE scales to produce unit variance hard decisions

FEXT Impairment- After Cancellation



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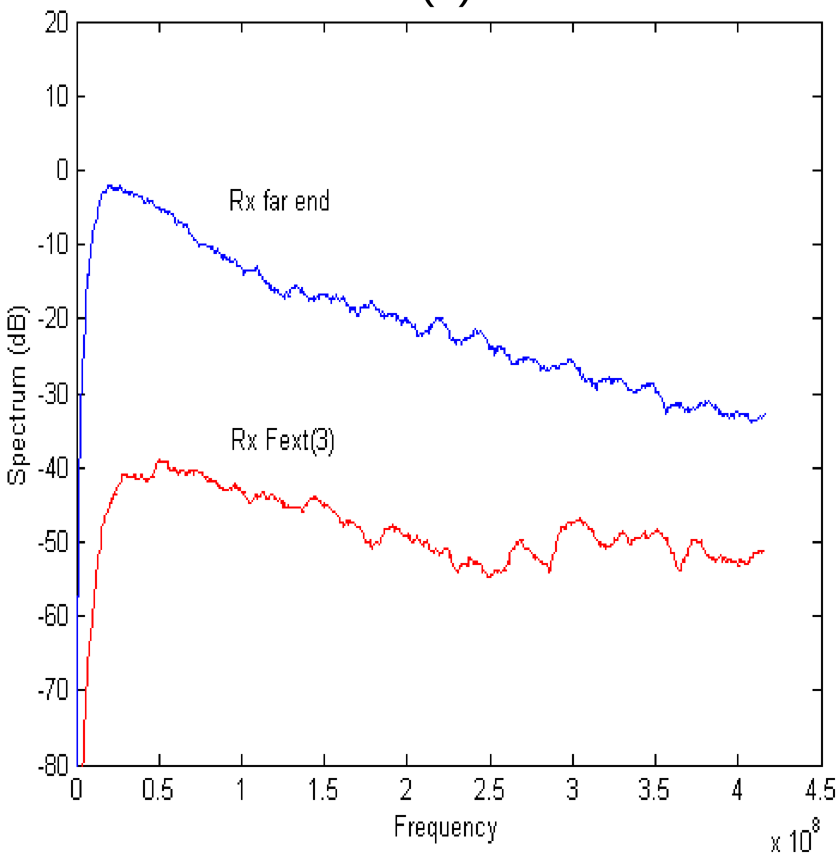

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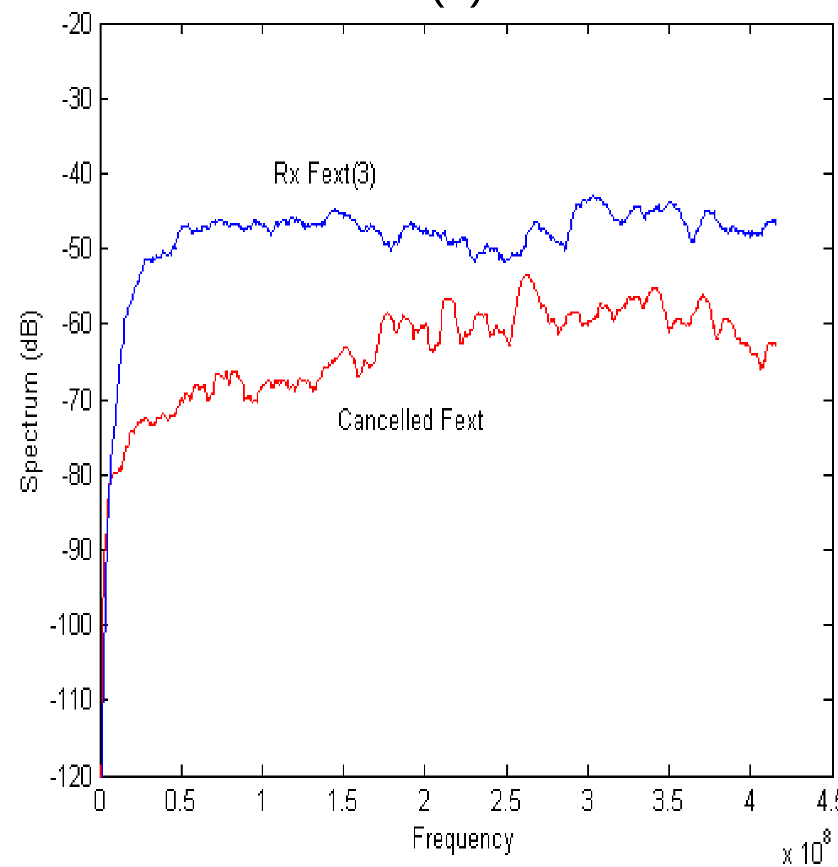
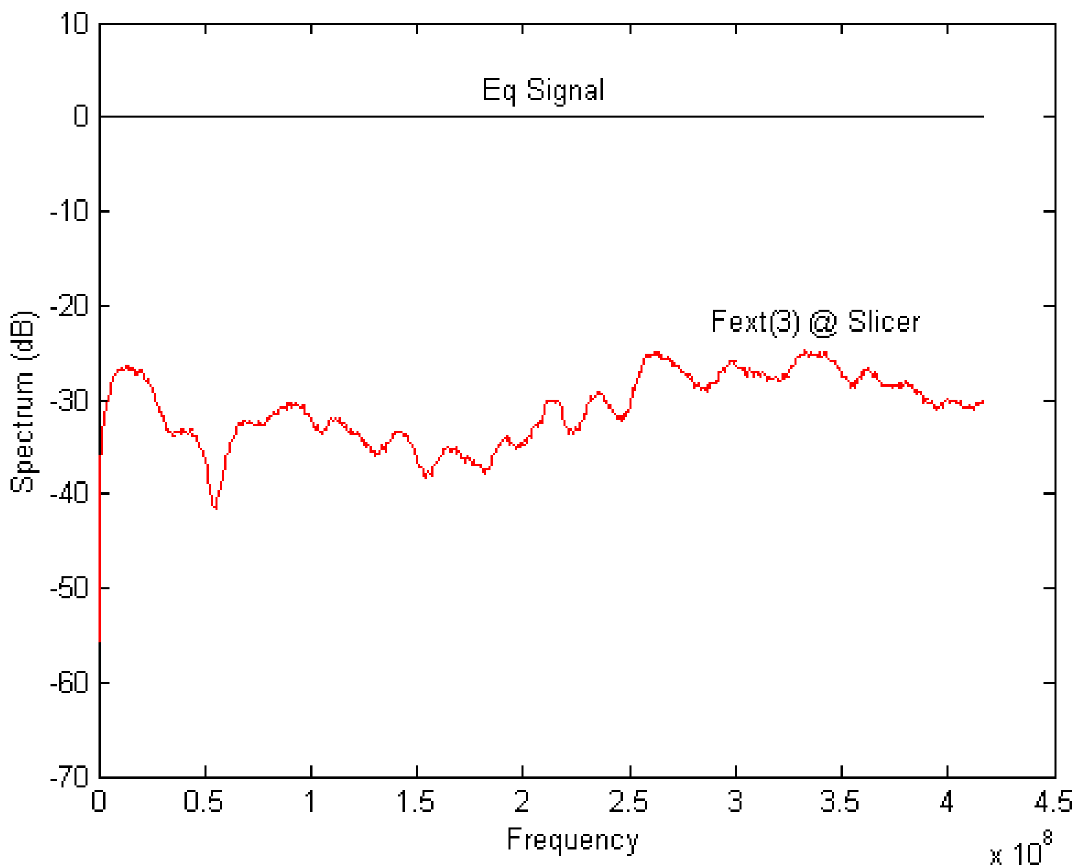
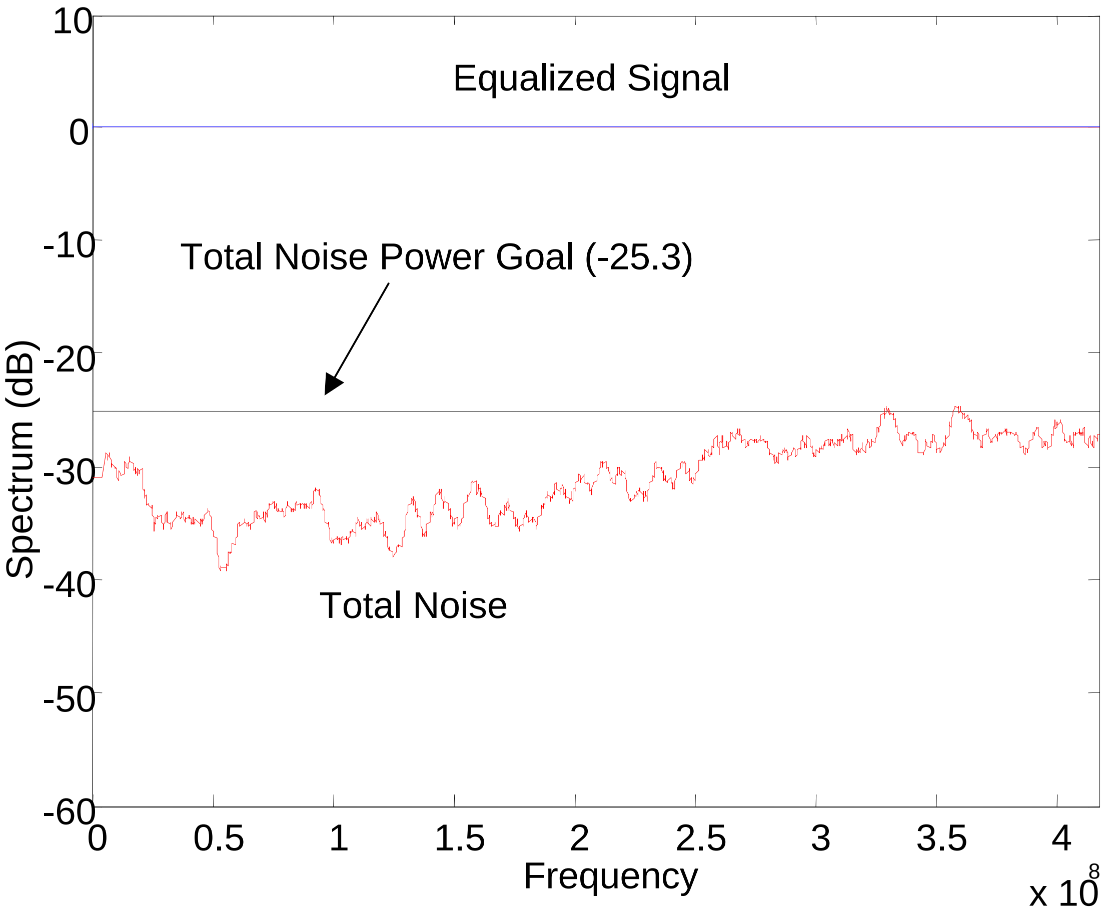


FEXT Impairment- SNR @ Detector



- FFE scales to produce unit variance hard decisions

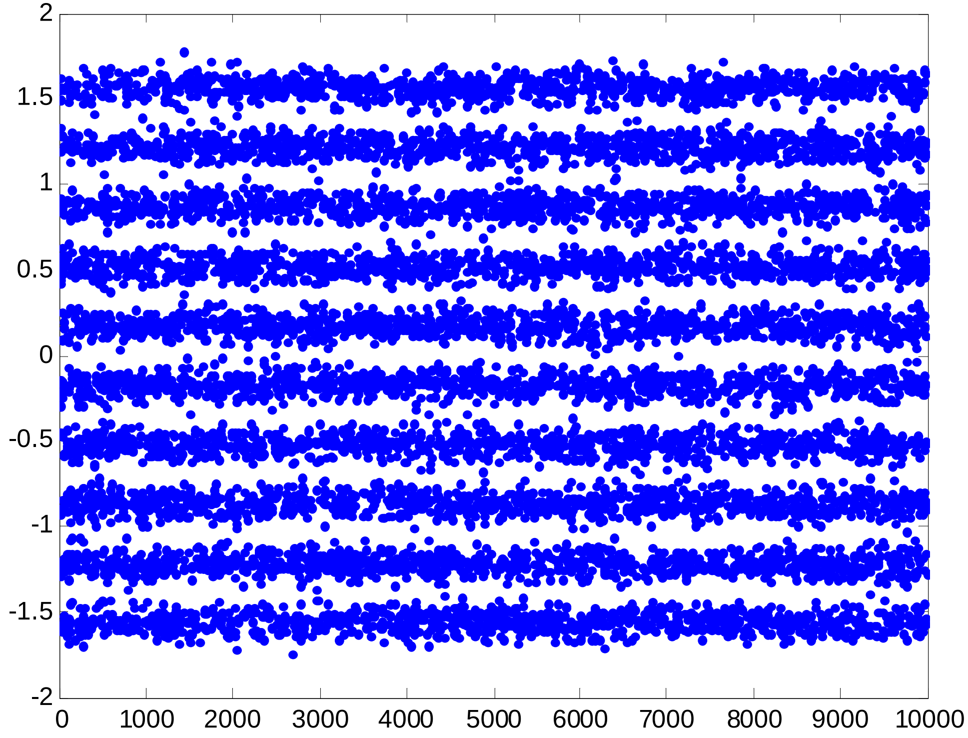
Total Slicer SNR



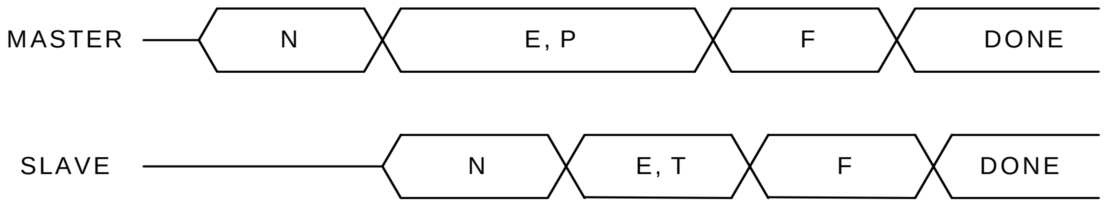
- FFE scales to produce unit variance hard decisions

Eye Diagram

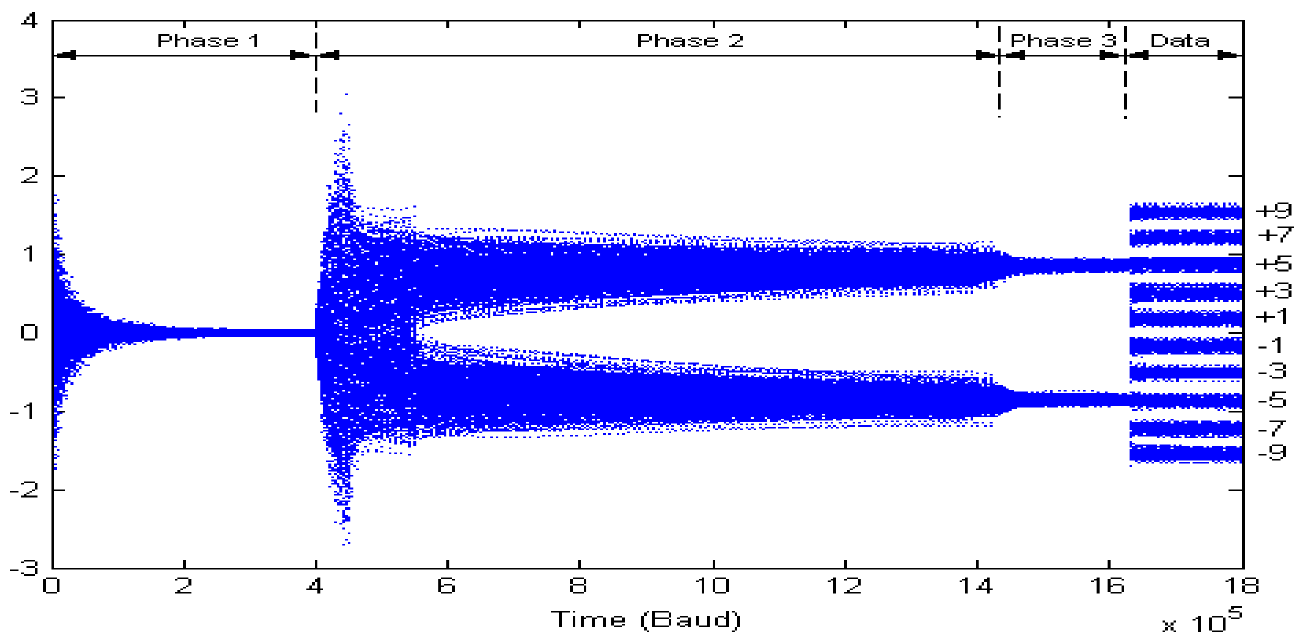
Slicer input, including all noise sources vs. time



Sequenced Startup



N = ECHO/NEXT Canceller Convergence
E = Equalizer Convergence
F = FEXT Canceller Convergence
T = Timing Acquisition
P = Phase Adjustment



Summary: Realizing 10GBASE-T

- Careful attention to media characterization beyond 100MHz
- Evolution of 1000BASE-T
- Modern signal processing methods
- Feasible CMOS realizations of digital & analog circuits
- Q&A