10GBASE-T Tutorial

IEEE 802.3

Kauai, Hawaii

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Agenda

• Introduction, Cabling & Challenges -
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  CEO & CTO
  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

- Perceived Shannon
  - 10BASE-T

- Conventional Wisdom Shannon
  - 1000BASE-T
  - 10GBASE-T

- New Model Shannon
  - AFE+DSP
  - MIMO/Multiuser
  - Channel-Optimized

- 1 bit/s/Hz
  - Analog
    - Linear
  - >1 bit/s/Hz
    - Analog & Digital
      - Non-Linear

- >>1 bit/s/Hz
  - "Divide & Conquer"
    - DSP, Coded

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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

- Alien Crosstalk, EMI
- Far Echo
- Near Echo
- NEXT12
- NEXT13
- NEXT14
- FEXT12
- FEXT13
- FEXT14

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

Measured Pair-to-pair NEXT Coupling into Cat 5e Pair 1

![Graph showing measured pair-to-pair NEXT coupling into Cat 5e pair 1.](chart)

- **Frequency (MHz)**
- **Insertion gain (dB)**

- NEXT12
- NEXT13
- NEXT14
- Cat 5e limit
- Extended limit

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**Cat 5e Channel: FEXT**

Measured Pair-to-pair FEXT Coupling into Cat 5e Pair 1

![Graph showing Measured Pair-to-pair FEXT Coupling into Cat 5e Pair 1](image)

- **Frequency (MHz)**
- **Insertion gain (dB)**

**Lines in the Graph:**
- FEXT12
- FEXT13
- FEXT14
Cat 5e Power Sum Alien NEXT vs. Patch Panel Position

Single (4-pair cable) disturber, 40 meter length unbundled

Frequency (MHz) vs. Insertion gain (dB) chart showing differences between adjacent and non-adjacent connectors, as well as Cat 5e NEXT and Extended limits.
• >100 MHz on Cat 5e can meet FCC Class A

~12 dBm launch power limitation

Worst-Case Radiated Emissions at 3 Meters - Cat 5e UTP
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

Received Signal & Residual Noise Terms

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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

Bit Capacity

![Graph showing bit capacity vs frequency](image-url)
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

<table>
<thead>
<tr>
<th>1000BASE-T</th>
<th>Straw Man 10GBASE-T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multilevel coded PAM signaling (2-bits/symbol)</td>
<td>Multilevel coded PAM signaling (3-bits/symbol)</td>
</tr>
<tr>
<td>5-level with Trellis code across pairs</td>
<td>10-level with Trellis code across pairs</td>
</tr>
<tr>
<td>Full duplex echo-cancelled transmission</td>
<td>Full duplex echo-cancelled transmission</td>
</tr>
<tr>
<td>125 Mbaud, ~80 MHz used bandwidth</td>
<td>833 Mbaud, ~400 MHz used bandwidth</td>
</tr>
<tr>
<td>Moderate NEXT cancellation</td>
<td>High-Performance NEXT cancellation</td>
</tr>
<tr>
<td>No specified FEXT cancellation</td>
<td>High-Performance FEXT cancellation</td>
</tr>
</tbody>
</table>
PCS SER & BER Straw Man Goal

![Graph showing Slicer Input SNR (dB) vs. Coded PAM10 simulation SER, Coded PAM10 Theory SER, and Coded PAM10 Theory BER. The graph indicates a requirement of 25.3 dB for 1000BASE-T.]

1000BASE-T
Reqm't

25.3 dB
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

Diagram:

- FeedForward Equalizer
- Slicer
- Decision Feedback Equalizer

Graph:

Wireline Channel Impulse Response

Amplitude

Sample Number (1x)
Echo

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

\[ H_{\text{fext}} = H_{\text{elf}} \cdot H_{\text{chan}} \]
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
• Data recovery & Fext cancellation

• Multiuser Detector (MUD) of MIMO channel provides simultaneous data decisions & interference removal
Parallelizing FIRs

• One high rate N tap filter

\[ H(z) = H_0(z^2) + z^{-1}H_1(z^2) \]

• 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

Diagram showing the flow of signals from Tx to Rx through MAG, Cat 5e cable, ENFX, EQ, and finally to the output. The spectrum graph illustrates the equalized signal and residual ISI.
ISI Impairment - Symbol Stream

a) Rx Far End Signal  b) Slicer Input  Vs. time
Echo Impairment - After Cancellation

(a) Tx → MAG → Cat 5e cable → Rx

(b) MAG → Rx → ENFX → EQ → Output

Rx far end signal
Rx echo

Rx Echo
Cancelled Echo

Spectrum (dB)
Frequency

Rx far end signal
Rx echo

Spectrum (dB)
Frequency

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Echo Impairment - SNR @ Detector

- FFE scales to produce unit variance hard decisions
**NEXT Impairment - After Cancellation**

(a) Diagram showing signal flow from Tx to Rx through MAG, Cat 5e cable, RX, ENFX, and EQ.

(b) Graphs showing spectrum (dB) versus frequency for Rx far end signal and Rx Next(3) at different points.

- **Rx far end signal**
  - Frequency: $0 \times 10^8$ to $4.5 \times 10^8$
  - Spectrum: -140 dB to 20 dB

- **Rx Next(3)**
  - Frequency: $0 \times 10^8$ to $4.5 \times 10^8$
  - Spectrum: -140 dB to 20 dB

- **Cancelled Next(3)**
  - Frequency: $0 \times 10^8$ to $4.5 \times 10^8$
  - Spectrum: -140 dB to 20 dB
NEXT Impairment- SNR @ Detector

- FFE scales to produce unit variance hard decisions
FEXT Impairment - After Cancellation

(a) Cat 5e cable
(b) 

- Tx ➔ MAG
- R_x ➔ ENFX ➔ EQ ➔ f

Graphs showing spectrum in dB vs frequency for Rx (far end) and Rx FEXT(3) before and after cancellation.
FEXT Impairment - SNR @ Detector

- FFE scales to produce unit variance hard decisions

Diagram:

- TX to MAG
- Cat 5e cable
- MAG to RX
- RX to ENFX
- ENFX to EQ
- EQ to decision

Graph:

- Spectrum (dB) vs Frequency
- FEXT(3) @ Slicer
- Eq Signal
Total Slicer SNR

Equalized Signal

• FFE scales to produce unit variance hard decisions

Total Noise Power Goal (-25.3)

Total Noise

Spectrum (dB)

Frequency

x 10^8
Eye Diagram

Slicer input, including all noise sources vs. time

![Eye Diagram](image_url)
Sequenced Startup

\[ \text{N = ECHO/NEXT Canceller Convergence} \]
\[ \text{E = Equalizer Convergence} \]
\[ \text{F = FEXT Canceller Convergence} \]
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