PHY PMA electrical specs baseline proposal for 803.an

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Basic Approach taken

- In 1000BASE-T PMA electrical specs are addressed by:
  - **Transmit waveform test**
    - Transmit droop test
  - **Transmit distortion test**
  - **Transmit jitter test**
    - Master mode
    - Slave mode
  - **MDI impedance balance test**
  - **MDI Common mode output voltage test**
- To get more complete PMA electrical specs for 10GBASE-T, the following must be specified
  - **Modulation, if PAM, how many levels?**
  - **Symbol rate – current proposals range from 810MHz to 1000MHz**
  - **Filtering of the Transmitter – digital and analog**
  - **Peak to peak transmit voltage at the MDI port**

Transmit waveform and peak voltage test

- – **Modeled after Test Mode 1 and 4 in 1000BASE-T**
- – **PHY transmits the specified sequence of PAM data symbols, similar as in Gigabit Ethernet standard, 40.6.1.1.2.**
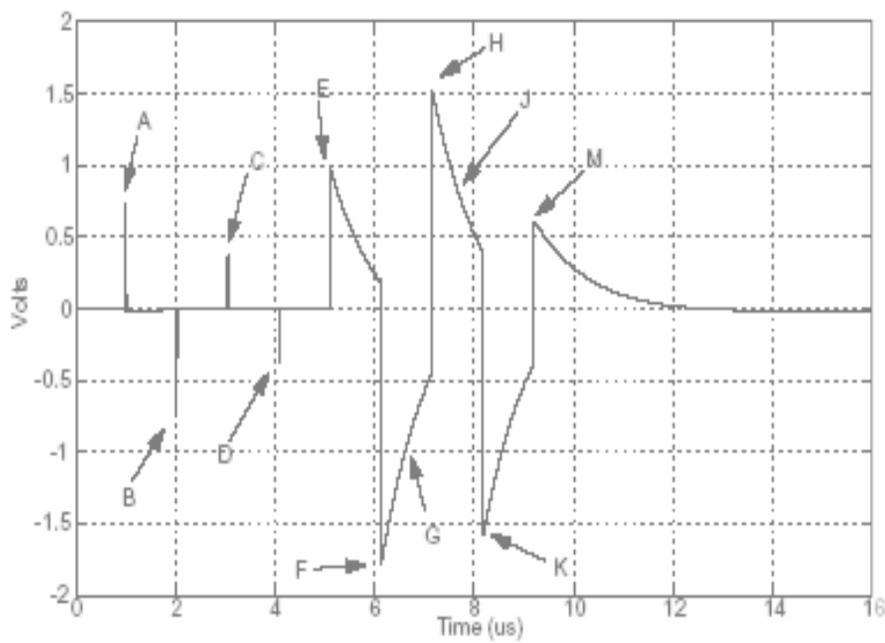- – **Example outputs in test modes 1 and 4 in 1000BASE-T :**

Figure 40–19—Example of transmitter test mode 1 waveform (1 cycle)
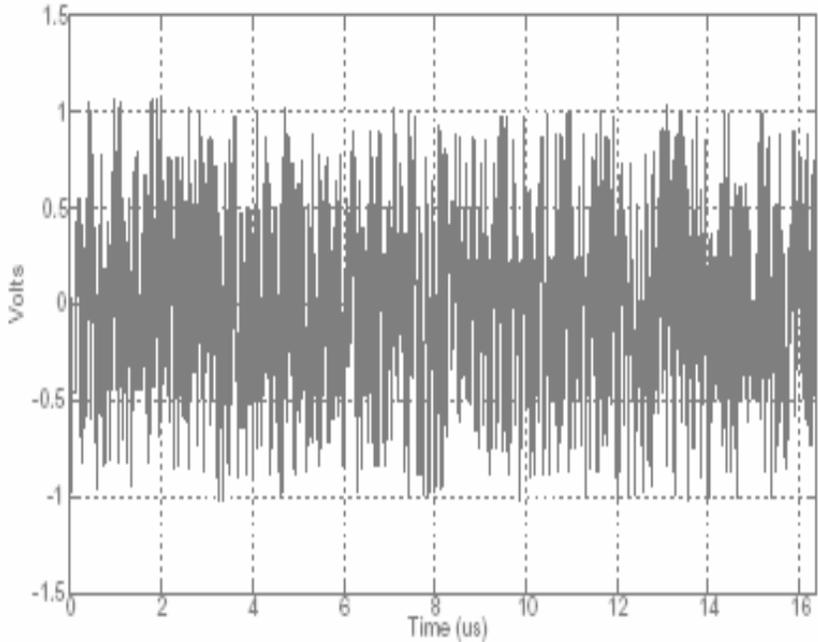
Figure 40–21—Example of Transmitter Test Mode 4 waveform (1 cycle)

Key specs in the waveform test mode

- Voltage level at the MDI for a totally random pattern through the transmitter, modeled after the test mode 4 of 1000BASE-T (primarily for excluding Baseline Wander) = 2V peak to peak differential.
  - Should take into account the transformer insertion loss, as transformer is a part of the transmitter.

- Level accuracy proposal, in test mode 1 = +/- 0.44dB (~ +/- 5%) instead of +/- 0.83dB (~ +/- 10%) in 1000BASE-T
  - » 10GBASE-T requires more predictable voltage levels, so as to not reduce already low system margin.

- Level matching accuracy of the PAM symbols in test mode 1 = +/- 1% as in 1000BASE-T.
  - » Same as in 1000BASE-T, clause 40.6.1.2.1

Transmitter droop test

- Depends primarily on the transformer high pass pole.
  - Backward compatibility to Gigabit requires lower than 100kHz high pass pole (informative rather than normative)
- 128 identical symbols sent for the droop test (<160ns for Fs>800MHz)
- Maximum droop defined over 64 symbol periods (<80ns for Fs > 800MHz)= 5.5%
  - 1000BASE-T defined maximum droop over 64 symbols as ~27% for Fs=125MHz
  - Reduces the overhead of design on transmitter and receiver due to baseline wander to much lower than 1000BASE-T.
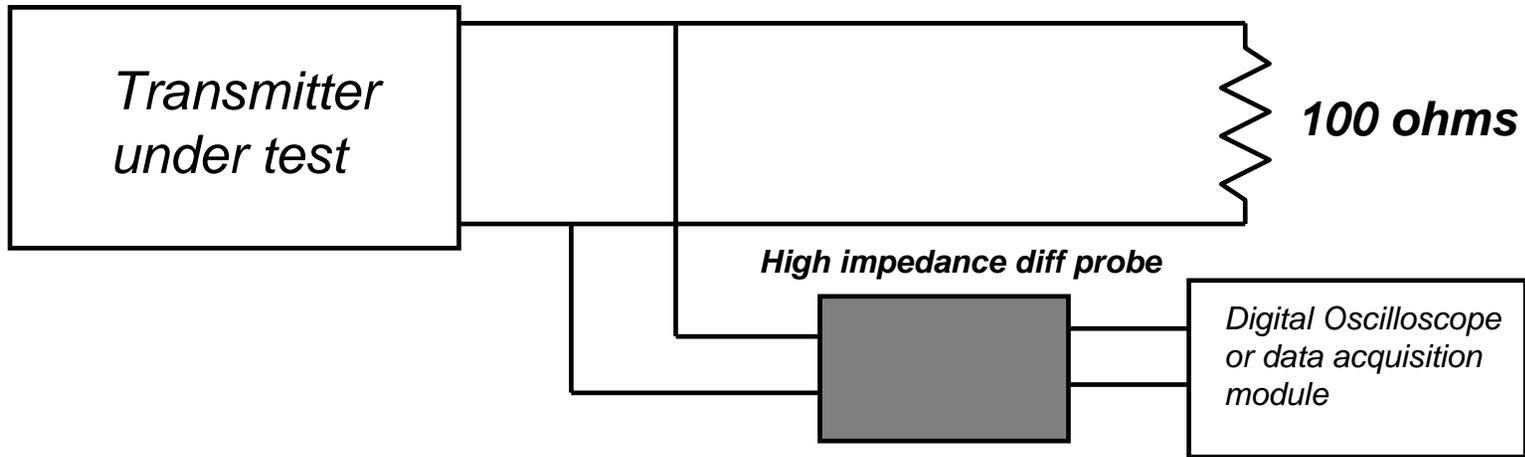
For defining waveform template

- Filter assumptions specified as information to create the templates, only templates being normative.

- Analog filter assumptions proposal:
  - **A two (or more) pole continuous time filter will exist**
    - One pole comes from the transformer
    - One from the output capacitance of the transmitter (bond-wire inductance and output impedance of the transmitter)
  - **Proposal: -3dB frequency varying from fs/2 to ¾ fs, fs being the sampling rate.**

- Single pole continuous time high pass filter with pole ≤ 100kHz to model the lower -3dB frequency of the transformer.
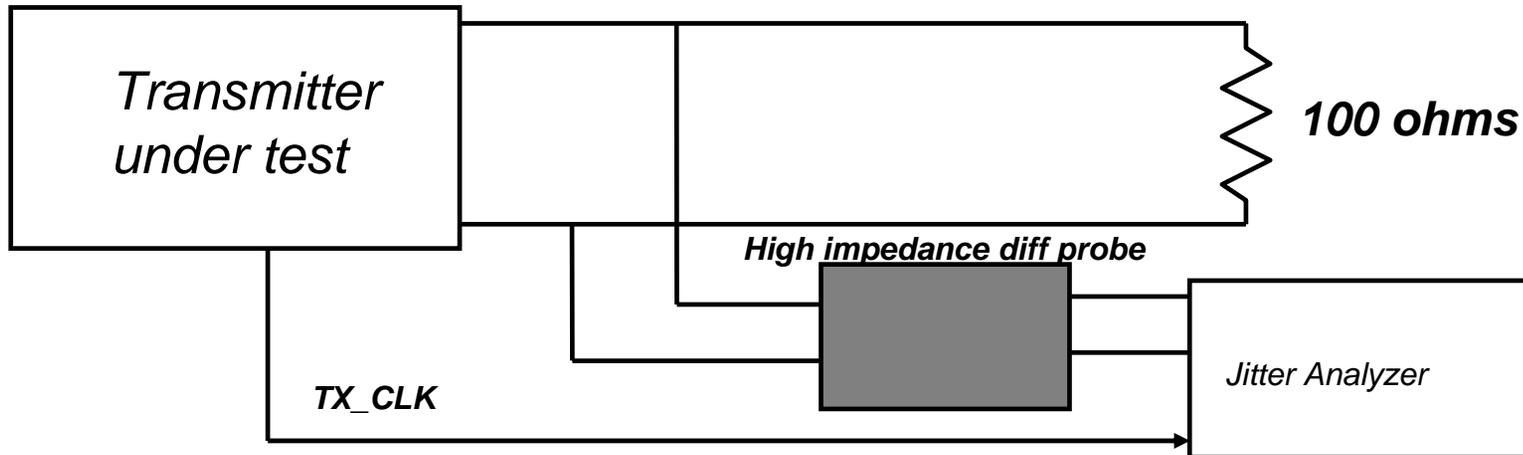
Jitter test modes and spec.

- Test setup similar to 1000BASE-T test mode 2 and 3 where the transmitter sends alternating +M,-M symbols timed from a clock with frequency Fs +/-0.01% in the MASTER and SLAVE timing mode respectively.

- In 1000BASE-T: Peak to peak jitter of the differential signal at the MDI w.r.t. TX_CLK called J_{txout} , wherein TX_CLK is the transmitter output clock.

- Jitter on TX_CLK filtered w.r.t. a high pass filter with pole of ~5kHz in Master device and 32kHz in the slave device in 1000BASE-T.
  - **1000BASE-T specification for filtered jitter plus J_{txout} was 300ps for Master mode (test mode 2) and 400ps more than the Master in Slave mode (test mode 3)**

- In 10GBASE-T, peak to peak value of the jitter on the differential signal at the MDI and on the TX_CLK, to be less than 30ps peak to peak.
  - **The peak-to-peak value of jitter measured over 10^6 clock edges (~ +/- 5σ)**
  - **Measurement was done over 10^5 clock edges in 1000BASE-T**

Test fixture for waveform/jitter tests

Transmitter under test

100 ohms

High impedance diff probe

Digital Oscilloscope or data acquisition module

Test Fixture 1:Transmitter test fixture for template and waveform measurement

Transmitter under test

100 ohms

High impedance diff probe

Jitter Analyzer

TX_CLK

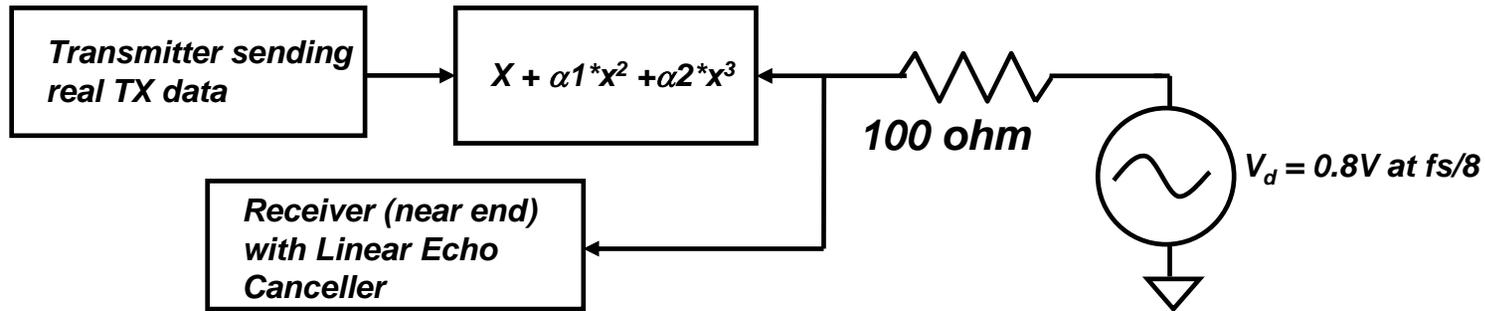**Test Fixture 2: Transmitter test fixture for jitter measurement**

TX nonlinearity modeling and measurement

| Transmitter sending real TX data | → | $X + \alpha 1 * x^2 + \alpha 2 * x^3$ | → | Channel | ← | $X + \alpha 1 * x^2 + \alpha 2 * x^3$ | ← | Transmitter (far end) |

Receiver (near end) with Linear Echo canceller

Receiver (far end) with Linear Echo canceller
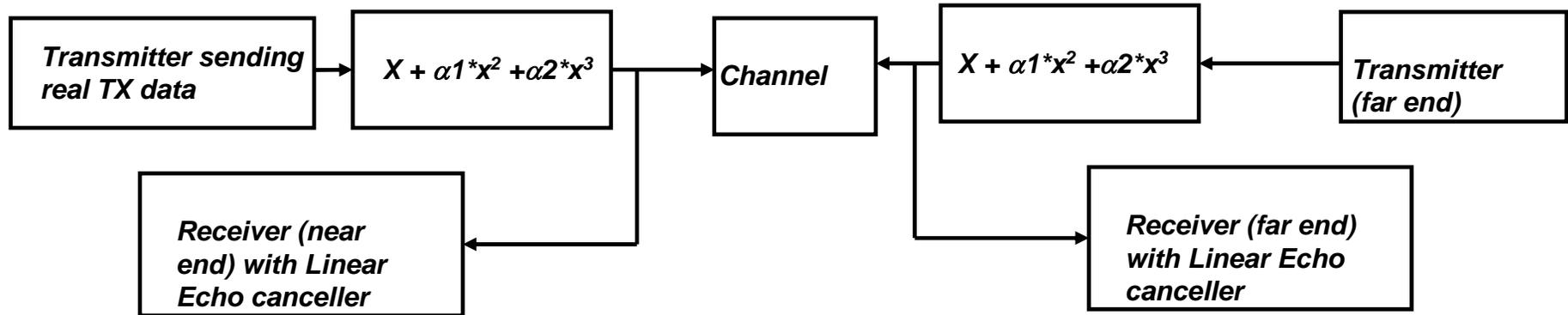
- Nonlinearity of the far end and local transmitter modeled the same.

- Only second and third order nonlinearity modeled.

- Second order nonlinearity due to differential nature of circuits will be much lower than third order in actual practice.

- Determine the coefficients of transmit second and third order nonlinearity in a real system to meet 10G net rate.

- Nonlinearity/distortion spec tight due to the limited echo cancellation in the local receiver for a linear echo canceller.

TX nonlinearity time-domain modeling

```
┌──────────────────┐        ┌──────────────────┐                  
│ Transmitter sending │────▶│ X + α1*x² + α2*x³ │◀─────/\/\/\─────┐
│ real TX data        │      │                   │     100 ohm     │
└──────────────────┘        └──────────────────┘                 (~)  Vd = 0.8V at fs/8
         ┌──────────────────┐                                      │
         │ Receiver (near end) │◀─────────────────────────────────┘
         │ with Linear Echo    │
         │ Canceller           │
         └──────────────────┘
```

- **Far end transmitter and cable replaced with a sinusoidal disturber with series 100ohm impedance to produce similar rate of 10Gbps for same $\alpha1$ and $\alpha2$ as determined in previous slide.**

- **Determine amplitude V_d and frequency to have similar effect on capacity and net rate as the real far end signal.**

   - **V_d determined to be 0.8V peak to peak differential so that at MDI it corresponds to 0.4V peak to peak differential, and average frequency of ~fs/8.**

TX distortion time-domain measurement test setup

50 ohm

Transmitter under test

V_d

50 ohm

Digital Oscilloscope or data acquisition module

Post-Processing

High impedance diff probe
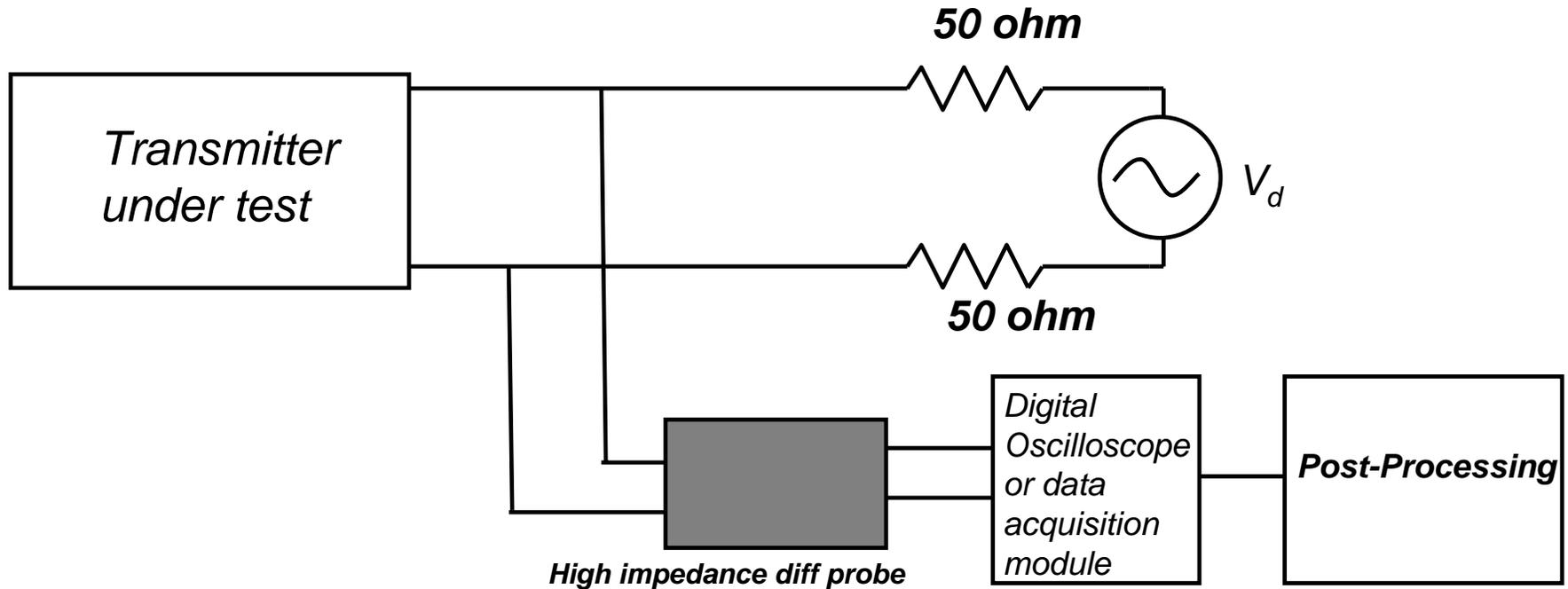
- **Purity of the signal source V_d such that all harmonics at least 75dB below fundamental.**

  - **Obtained by band pass/low pass filtering the output of a signal source.**

- **Post processing block removes the disturbing signal, by removing the best fit sine wave at the fundamental frequency of the disturber.**

- **Distortion spec captures also the device noise of the transmitter, which is equally important for own local receiver performance.**

Time-domain measurement challenges

- Availability of Oscilloscope and high impedance probe with low noise and low jitter.
  - **Example scope and probe: Agilent 54850 series and Infinimax probes with 25kohm impedance**
    - With averaging the noise might be acceptable, and by the available datasheets, the result almost 11-12 bit accurate.
  - **Low jitter: Scope jitter needs to be less than ~1ps rms.**
  - **Limited accuracy in time-domain measurement because of the resolution of the ADC generally in the measurement equipment.**
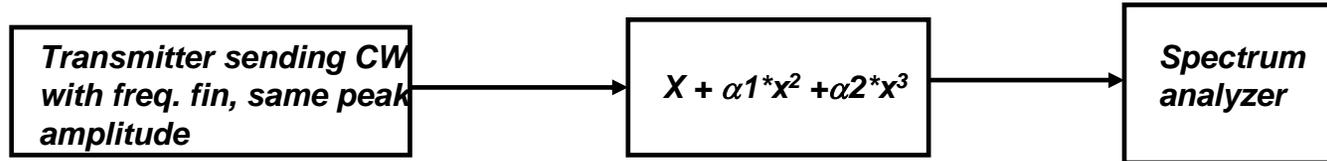   - Suitable equipment to be investigated.

Transmit time-domain distortion test

- Specified in presence of a disturber with 0.4V peak to peak differential amplitude, at a frequency of fs/8, with transmitter transmitting a sequence of 2047 symbols
  - **Number of symbols same as in 1000BASE-T**
  - **Disturber voltage reduced as justified in prior slide.**
- Peak distortion measured by sampling the differential output w.r.t. any arbitrary phase and processing a block of 2047 consecutive samples with the MATLAB code from Gigabit Ethernet modified to get to the required accuracy (modified from clause 40.6.1.2.4, IEEE std. 802.3-2002, section three)
  - **Removes sinusoidal disturber & does a minimum mean square error fit**
- Measured with test fixture 3, and processed through the MATLAB code, the peak distortion output of the code proposed to be less than TX_{dist} mV.

TX nonlinearity in frequency domain

```
┌─────────────────────┐      ┌──────────────────────┐      ┌──────────────┐
│ Transmitter sending │      │                      │      │  Spectrum    │
│ CW with freq. fin,  │ ───► │ X + α1*x² + α2*x³     │ ───► │  analyzer    │
│ same peak amplitude │      │                      │      │              │
└─────────────────────┘      └──────────────────────┘      └──────────────┘
```

- For same $\alpha 1$ and $\alpha 2$ as in Step 1, measure ratio of Signal power to net harmonic power.

- This was reported in slide 5 of presentation
http://www.ieee802.org/3/an/public/may04/gupta_1_0504.pdf

- Easier to measure than time-domain approach.

Frequency domain measurement of TX nonlinearity

- More availability of spectrum analyzers to capture the DAC output. If the pre-coder approach is taken, the transmitter can output a sine wave, and all the harmonics measured on the spectrum analyzer.
  - Scott Powell, Kevin Chan, Broadcom, Pvt. conversation
  - **Approximate Specs in this mode discussed in May meeting of 802.3an task force.** http://www.ieee802.org/3/an/public/may04/gupta_1_0504.pdf

- The transmit nonlinearity to be measured under the condition of
  - **a single tone sine wave of peak-peak amplitude of 2V, of frequencies ~ fs/16, fs/8, & fs/4 and measuring all the harmonics to be below the fundamental by (TX_{nonlin}) dB.**

    AND

  - **A two tone output with a peak to peak amplitude of 2V, the two tones being close to fs/2, with spacing less than 1MHz, and all the inter-modulation components being measured below the fundamental tones by at least (TX_{nonlin} + 2.5) dB.**

- Limitation:
  - **Does not accurately capture the device noise contribution of transmitter to un-cancelable echo.**

Distortion test for 10GBASE-T

- The measurement method of distortion to be either **one** of the previous tests, i.e.

    - either in the time domain through the test setup described in slide 11, and detailed in slide 12-13,

    - OR in the frequency domain specified and detailed in slide 14-15.

- **Observation**: Nonlinearity/distortion spec is tight due to the own local receiver performance.

    - Note: Nonlinearity/distortion spec could be specified as loose to meet the 10G performance of the far end device only.

    - In that case, risk of under-specifying and misleading a local transmitter design which may not meet 10G performance on local receiver, and break the link, even being spec compliant.

Distortion specification: Far end/Near end

- Because of reasoning in the last bullet point of last slide:
  - **Concept of** *normative spec/recommended* **spec to be mentioned in the standard (***Scott Powell, Broadcom, Pvt. Conversation***):**
- Specify
  - **a** *normative* **spec for** interoperability **of the far end receiver.**
  - **a** *recommended* **spec. for the near end receiver.**
- The numbers discussed in the initial proposals in the previous slides can be considered mainly for ***recommended*** specifications for near end receiver.
  - ***Recommended*** **specification can be TX$_{dist}$ ≤ 1.5mV, TX$_{nonlin}$ ~ 68dB.**
- Normative spec. to be met with respect to a frequency mask.
  - **At low frequency (≤ 25MHz), the linearity spec similar to the one proposed for recommended spec, as the TX nonlinearity appears similarly at both the far end and near end receiver.**
  - **For margin over different link segment lengths, initial proposal for parameter TX$_{nonlin}$ in the range of (65,70) dB for 0-25MHz, and roll of in the range of [(65,70)– 20*log10(f/25)] dB, f ≥ 25, f in MHz.**
  - **Exact values in the above equation TBD. (Theoretically linearity mask can even follow something close to IL curve)**
  - **Linearity measured w.r.t. the spectrum analyzer approach as detailed in slide 15.**
    - Sine wave outputs for frequency < fs/4, Two tone outputs for IM tests for high frequencies.
    - time domain measurement approach does not address frequency dependent nonlinearity spec.

MDI impedance balance

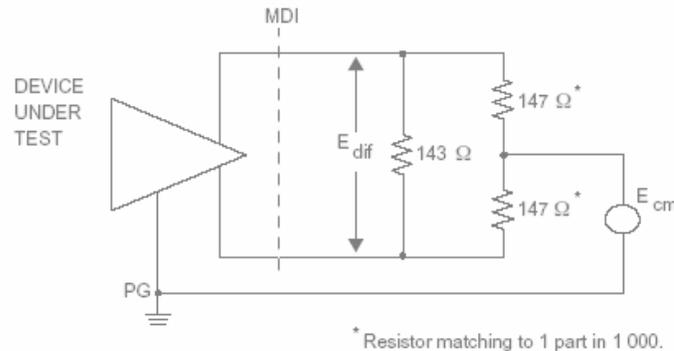- Specified in 1000BASE-T with the following test setup:

Figure 40–31—MDI impedance balance test circuit

- In 1000BASE-T, over a frequency range of 1-100MHz, the common mode-to-differential impedance balance of each channel of MDI, specified to exceed 34-19.2*log10(f/50) dB, f in MHz. The balance being defined as $20*\log10(E_{cm}/E_{diff})$

- In 10GBASE-T, the frequency range needed is 1-625MHz. The specification for common mode-to-differential balance for 10GBASE-T based on measurements as suggested in "Baseline Text for Clause 55.X MDI specifications", Terry Cobbs, Systimax, or TBD.

MDI common mode output voltage

- 1000BASE-T spec: Magnitude of the common mode output voltage V_{cmout}, on any transmit circuit, when measured as shown in the test setup shown below (reproduced from IEEE Std. 802.3, Clause 40.8.3.3, section three), shall be below 50mV peak to peak, when transmitting data.
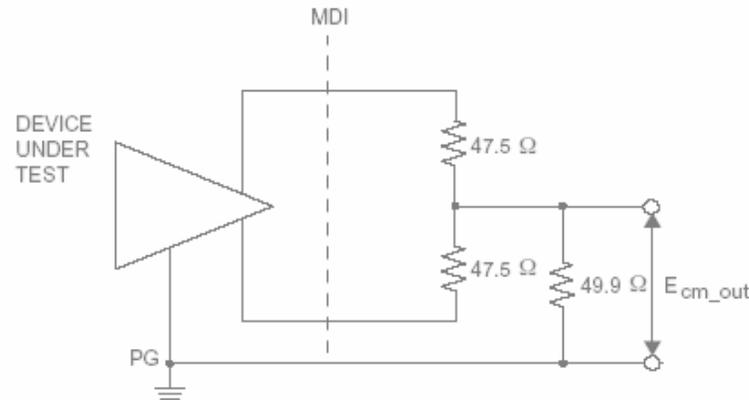

Figure 40–32—Common-mode output voltage test circuit

- Specification for 10GBASE-T to be kept TBD

Common mode noise rejection

- 1000BASE-T provided a common mode rejection test where you inject a common mode signal at any frequency from 1-250MHz through a cable clamp, with the output of the signal generator adjusted for a voltage of 1.414V peak on the oscilloscope.
  - **Cable clamp test specified in clause 40.6.1.3.3 and in Annex 40B of IEEE std 802.3.**
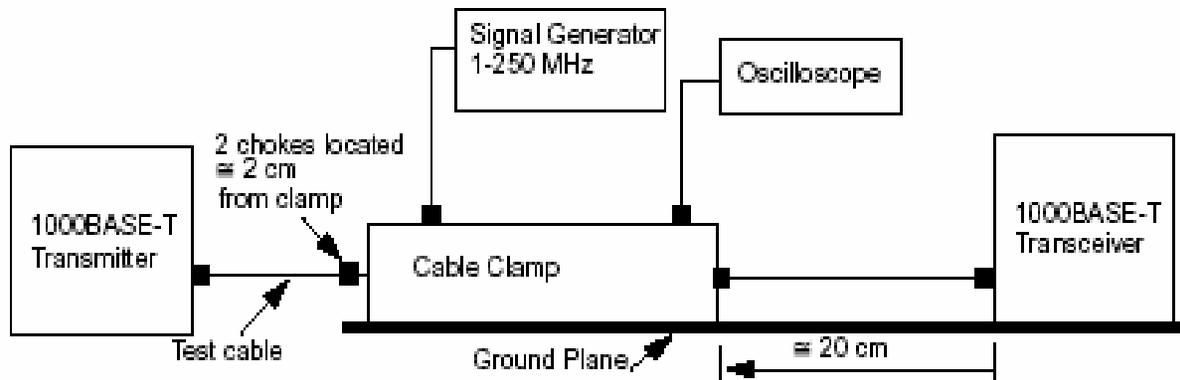
Figure 40–27—Receiver common-mode noise rejection test

10GBASE-T common mode rejection test

- Proposed changes to above for 10GBASE-T
  - **Increase frequency range: 1- 625MHz.**
  - **Common mode signal imposed on the 10GBASE-T device, should take into account the limited CMR of the transformer magnetic at high frequencies**
    - Pulse transformer CMR plots show 6dB/octave roll-off for frequencies greater than 100MHz.
  - **Recommendation:**
    - Cable clamp specification to be widened up-to 625MHz, and should be such that the common mode output signal at the receiver input should be
    - ≤ 2.8V for frequencies from 1-80MHz.
    - ≤ 2.8V*80/f for frequencies > 80MHz, f in MHz.
  - **Such applied voltage should be representative of real environment specified. To be determined by the following tests:**
    - For Europe for ITE including LAN products: EN55024
    - For central office equipment : GR1089 in the USA and EN300386 in EU

Alien Crosstalk Noise rejection

- Alien Crosstalk noise rejection test very important for qualification of the 10GBASE-T device.

- 1000BASE-T assumed ANEXT coupling transfer function was spectrally flat. 25mV peak to peak noise source imposed on the MDI using an external 100BASE-T transmitter coupled with a resistive divider.

Clause 40.8 TRANSMITTER | MDI | LINK SEGMENT AS DEFINED BY 40.7 (worst case) | MDI | RECEIVE DEVICE UNDER TEST

2000 Ω*

< 0.5m CAT 5 UTP

100 Ω

2000 Ω*

NOISE SOURCE (100BASE-TX COMPLIANT TRANSMITTER SENDING IDLE NONSYNCHRONOUS TO THE 1000BASE-T TRANSMITTER UNDER TEST)
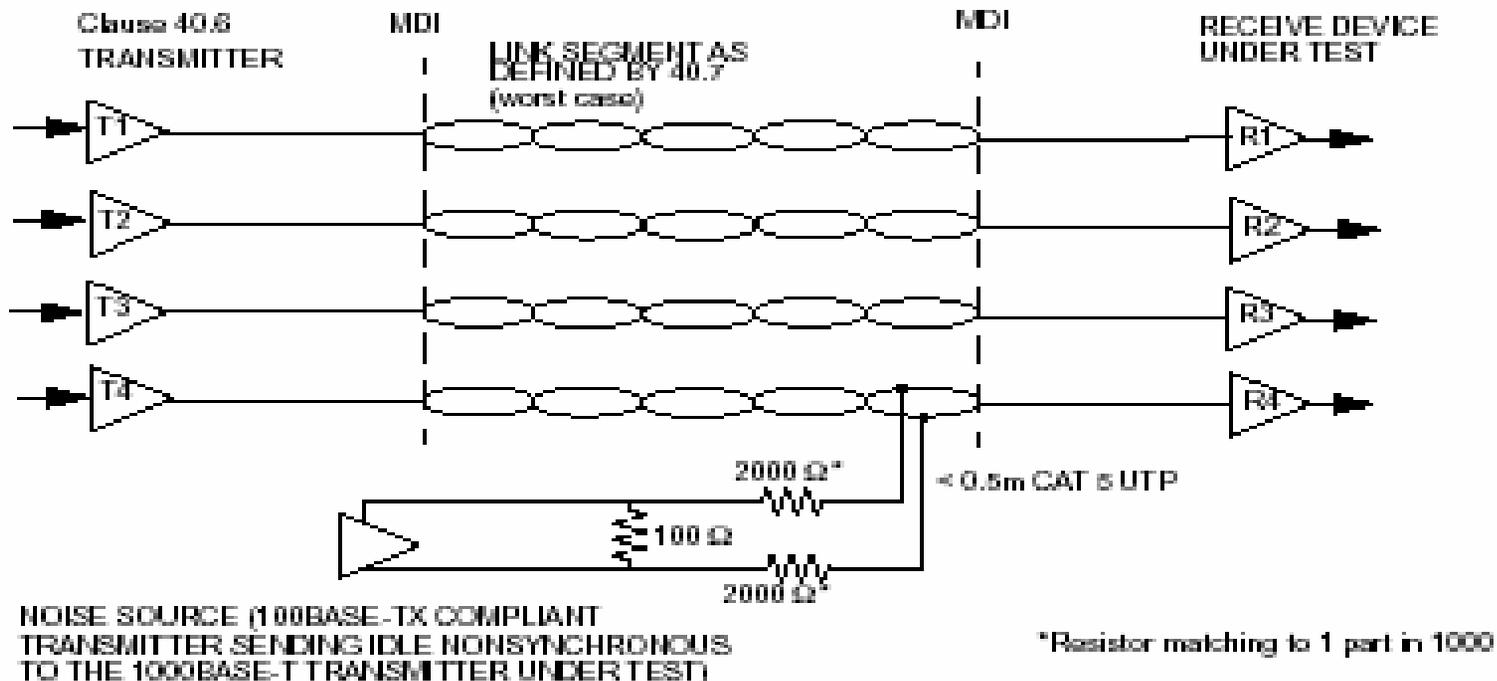
*Resistor matching to 1 part in 1000

Figure 40–28— Differential mode noise rejection test
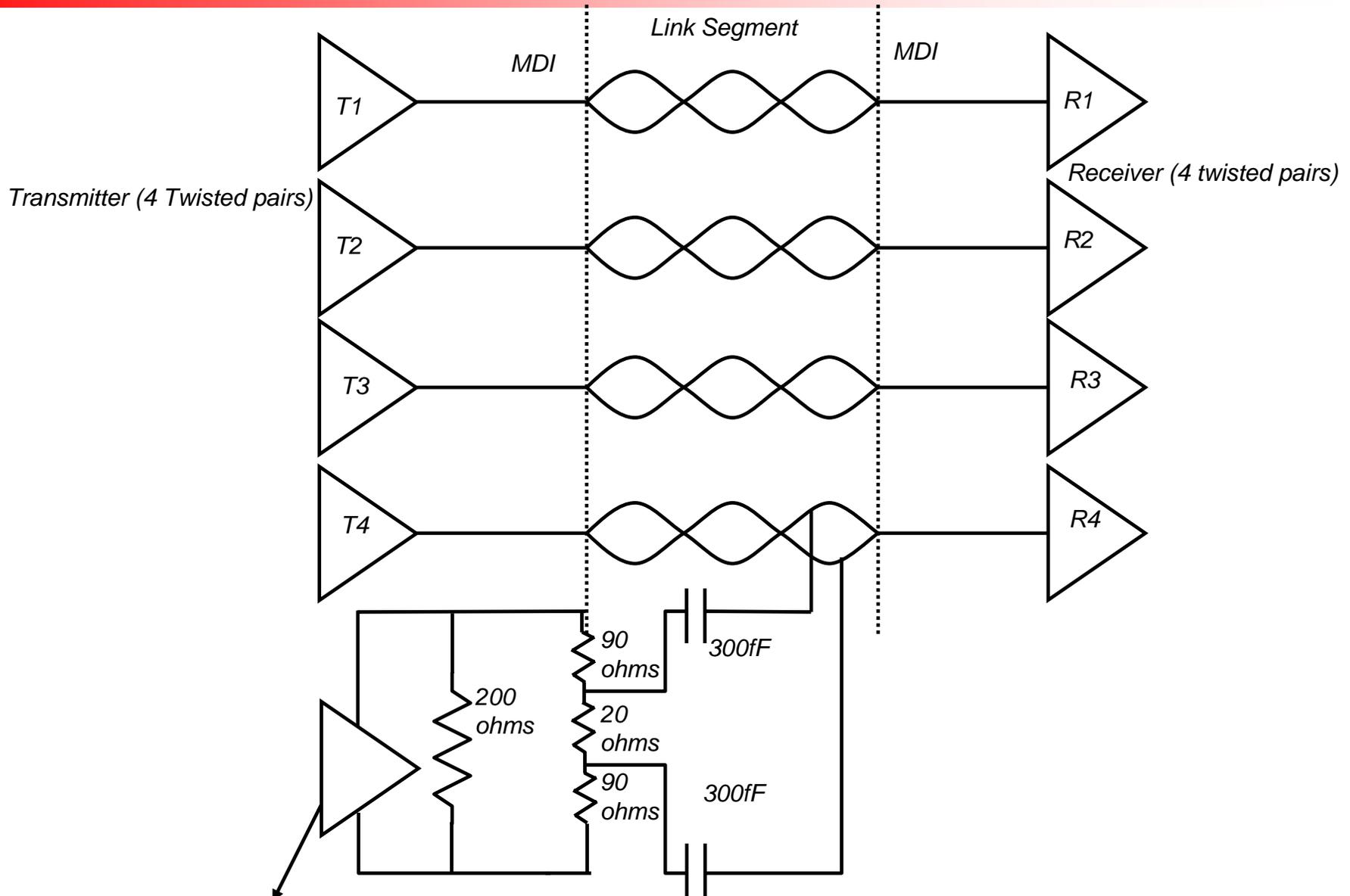
Alien Crosstalk Noise rejection proposal

- In 10GBASE-T, ANEXT test should be performed with some model of real ANEXT coupling built in the test.

- A real 10GBASE-T transmitter driving 100 ohm produces the Power Spectral Density of the transmitter.

- Alien crosstalk for 10GBASE-T, CAT6, channel model #3 is specified as:
  - **-64.5+15*log10(f/100), f in MHz for f > 100MHz.**
  - **-64.5+10*log10(f/100), f in MHz for f < 100MHz.**

- Alien crosstalk for 10GBASE-T, CAT6, channel model #2 (55m CAT6) is specified as:
  - **-49.5+15*log10(f/100), f in MHz for f > 100MHz.**
  - **-49.5+10*log10(f/100), f in MHz for f < 100MHz.**

- Need two different networks for reproducing test setup modeling the two different ANEXT channel models.
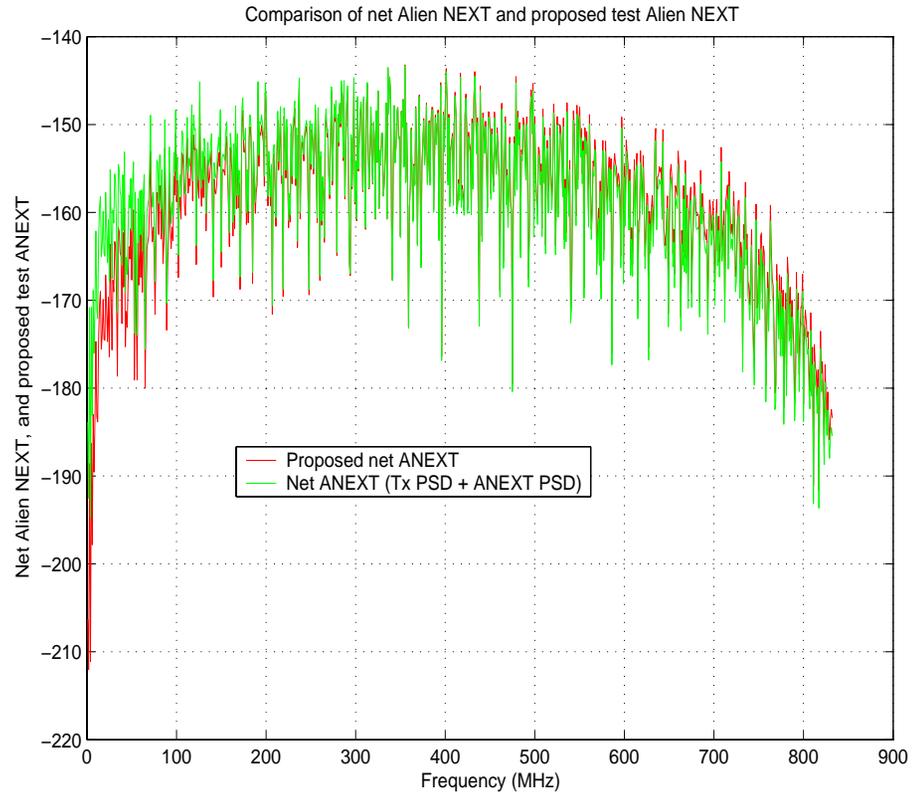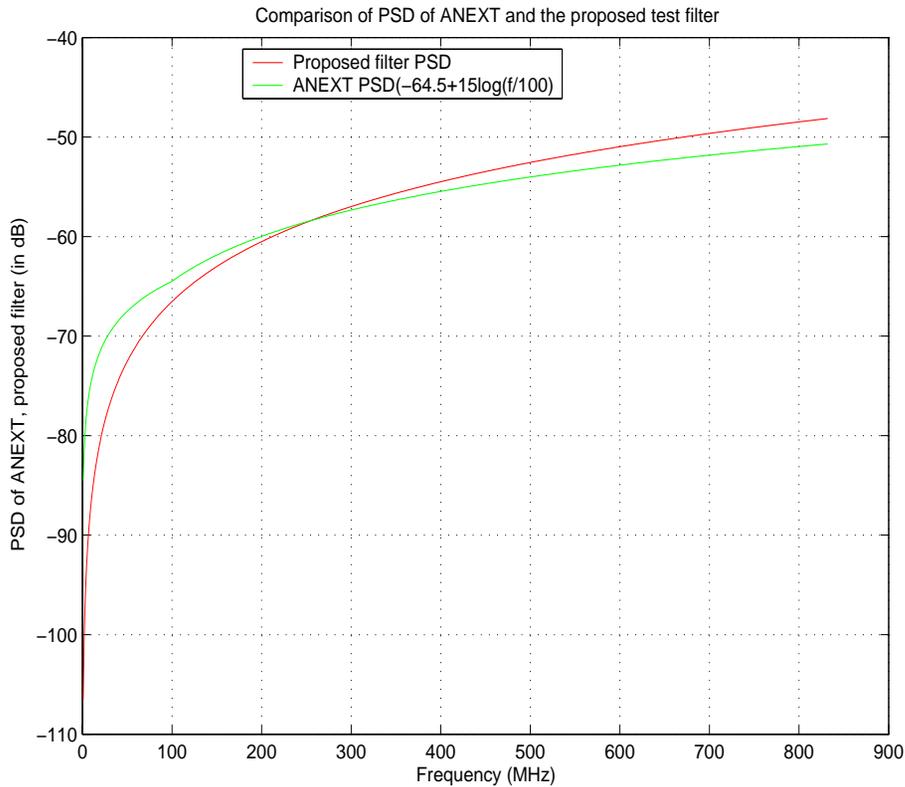
ANEXT noise rejection proposal

- The slope of 10*log10(f) or 15*log10(f) difficult to reproduce in a test setup (different than a single pole high pass filter)

- Channel model #3:

    - **An approximation to both the ANEXT voltage(~ 5mV peak to peak differential) and its spectral shape is obtained by passing the real PSD of a asynchronous 10GBASE-T transmitter through a 10:1 attenuator and a simple high pass filter.**

    - **Attenuator of 10:1 needed for reasonably large value of coupling capacitors as shown in next figure coupled from the network to the victim receiver (with differential impedance of 50ohm)**

- Channel model #2:

    - **2:1 attenuator used for similar order coupling capacitors to the victim receiver.**

- **Capacity and net rate achieved for the real ANEXT models in both Channel model #2 and #3 and the test network very close**

Proposed Alien Crosstalk noise rejection test setup (for Channel model #3, ANEXT=-64.5 + 15*log10(f/100))

Link Segment

MDI

MDI

T1

R1

Receiver (4 twisted pairs)

Transmitter (4 Twisted pairs)

T2

R2

T3

R3

T4

R4

90 ohms

300fF

200 ohms

20 ohms

90 ohms

300fF

Noise source: Independent 10GBASE-T transmitter sending PAM data asynchronous to the 10GBASE-T transmitter under test applied to each pair simultaneously.

ANEXT and proposed network's ANEXT (for Channel model #3, ANEXT=-64.5+15*log10(f/100))

Comparison of PSD of ANEXT and the proposed test filter

- Proposed filter PSD
- ANEXT PSD(−64.5+15log(f/100)

Comparison of net Alien NEXT and proposed test Alien NEXT

- Proposed net ANEXT
- Net ANEXT (Tx PSD + ANEXT PSD)

Proposed Alien Crosstalk noise rejection test setup (for Channel model #2, 55m Class E ANEXT=-49.5+15*log10(f/100))

Link Segment

MDI

MDI

T1

T2

T3

T4

R1

R2

R3

R4

Transmitter (4 Twisted pairs)

Receiver (4 twisted pairs)

50 ohms

350fF

200 ohms

100 ohms

50 ohms

350fF

Noise source: Independent 10GBASE-T transmitter sending PAM data asynchronous to the 10GBASE-T transmitter under test applied to each pair simultaneously.

ANEXT and proposed network's ANEXT (for Channel model #2, 55m Class E, ANEXT=-49.5+15*log10(f/100))

Comparison of PSD of ANEXT and the proposed test filter

Comparison of net Alien NEXT and proposed test Alien NEXT