# Requirements for Industrial Cabling Supporting Gigabit Applications for Control

A Study of Noise

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# Abstract

***This paper is the result of over 700 man hours of cable measurements, noise testing and analysis resulting in defining cabling parameters supporting 1Gig cabling requirements for harsh industrial environments.***

***In the early 2000 a study was performed by several ODVA member companies. The goal of this study was to define the requirements for 10/100mb/s twisted pair cabling for industrial environments.  This eventually resulted in the creation of national and international standards defining parameters for cabling used on the factory floor and industrial machine areas.  Once again with the need for additional bandwidth we find the need to define the parameters required to support of 1gig data rates on 4 pair industrial cabling.***

***This paper will discuss the approach used, the testing, analysis and the results of the study.  The testing, is based on standardized transmission line testing techniques and environmental noise testing as defined by ISO/IEC and IEC 61000 standards.  In addition this paper will discuss the impact of the new limits to the parameters from a technical perspective.  Since industrial cabling is the subject to national and international standards this paper will briefly cover the approach to standardization, including the EtherNet/IP Specification. The paper will conclude with a complete set of cabling component specifications defining the communications channel supporting robust data communications for control applications.***

# Purpose

***The purpose of this project is to determine the required cable performance needed to support 1000 Base-TX for industrial control applications. This study and white paper does not consider applications using office grade cabling in office (MICE 1) environments. This report documents the tests, test results and conclusions of cable transmission and EMC testing. Both unshielded and shielded cables were considered and evaluated. In the case of shielded cables additional testing is performed to determine the shielding effectiveness since it is expected that shielding has a positive impact on cable's noise rejection.***

***The foundation of this project is based on examining the performance of off-the-shelf cables and engineering samples designed for both office and industrial applications. The design of the cabling targeted for Industrial applications must be carefully considered where the environments are MICE - E 2 and MICE - E3.***

# Background

- Ethernet and Fast Ethernet (10/100Mb/s) cabling study 1999/2000
  - RL and TCL/ELTCTL was the focus
  - 2006 Industrial Focused Standards recognized the need and applied specs to cabling
  - Driven by ODVA
    - ISO/IEC 24702 and
    - ANSI/TIA 1005 Was Created
  - ISO/IEC specified TCL and ELTCTL in terms of MICE Classifications under "E" Electromagnetic Noise.
  - The TCL and ELTCTL values were not optimal for industrial cabling based on IEC 61000 Testing and limits.

# ISO/IEC 24702 -- ANSI TIA 1005 – IEC 61918

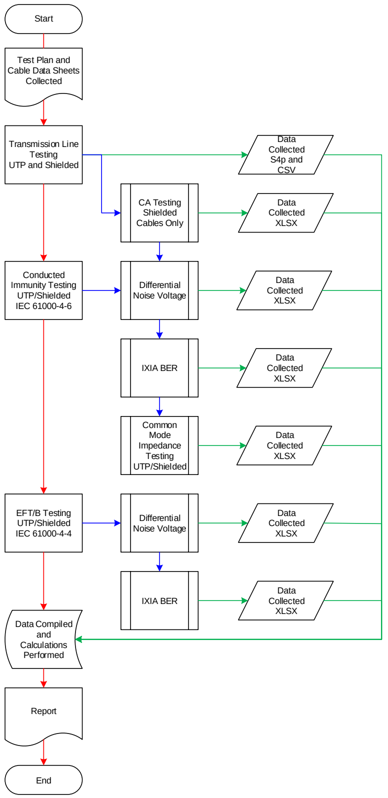
TCL for Class D and Class E Channels

| Class | Frequency MHz | Environmental classification | | |
|---|---|---|---|---|
| | | $E_1$ | $E_2$ | $E_3$ |
| | | Minimum TCL dB | | |
| D | $1 \leq f \leq 30$ | $53 - 15 \times \lg f$ , 40 max | $63 - 15 \times \lg f$ , 40 max | $73 - 15 \times \lg f$ , 40 max |
| | $30 \leq f \leq 100$ | $60{,}4 - 20 \times \lg f$ | $70{,}4 - 20 \times \lg f$ | $80{,}4 - 20 \times \lg f$ |
| E | $1 \leq f \leq 30$ | $53 - 15 \times \lg f$ | $63 - 15 \times \lg f$ , 40 max | $73 - 15 \times \lg f$ , 40 max |
| | $30 \leq f \leq 250$ | $60{,}4 - 20 \times \lg f$ | $70{,}4 - 20 \times \lg f$ | $80{,}4 - 20 \times \lg f$ |

ELTCTL for Class D and Class E Channels

| Class | Frequency MHz | Environmental classification | | |
|---|---|---|---|---|
| | | $E_1$ | $E_2$ | $E_3$ |
| | | Minimum ELTCTL (dB) | | |
| D, E and F | $1 \leq f \leq 30$ | $30 - 20 \times \lg f$ . | $40 - 20 \times \lg f$ | $50 - 20 \times \lg f$ , 40 max. |

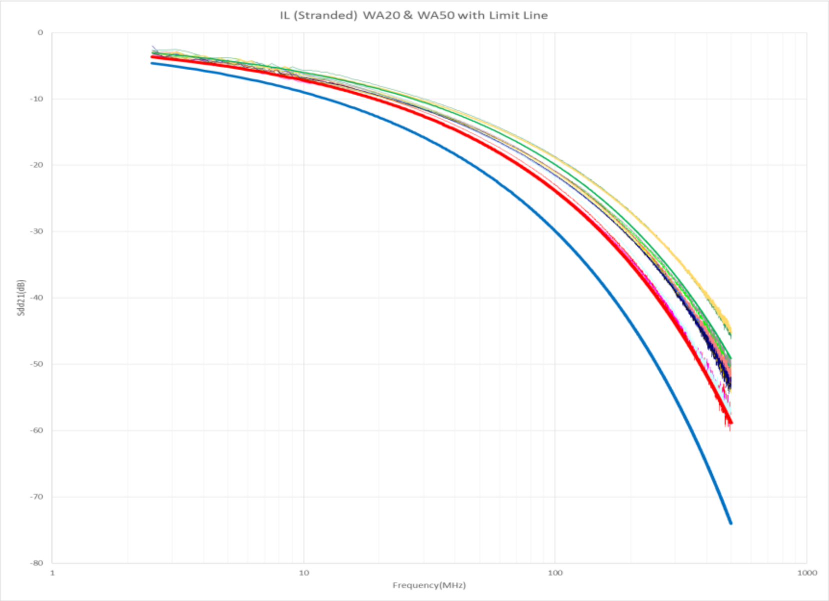
- A presentation describing the test methods and results has been circulated to the EtherNet/IP Physical Layer SIG, TIA TR42.9, ISO/IEC and IEC.
  - Described what was tested (30 cables 12 UTP and 18 Screened)
  - Mixture of solid and stranded designs UTP(4 stranded/8 solid), Screened (13 Stranded/5 Solid).
  - Tests Performed
  - Methods for how the cables were tested
  - Results of the Tests
  - Results, Channel Recommendations for TCL and ELTCTL

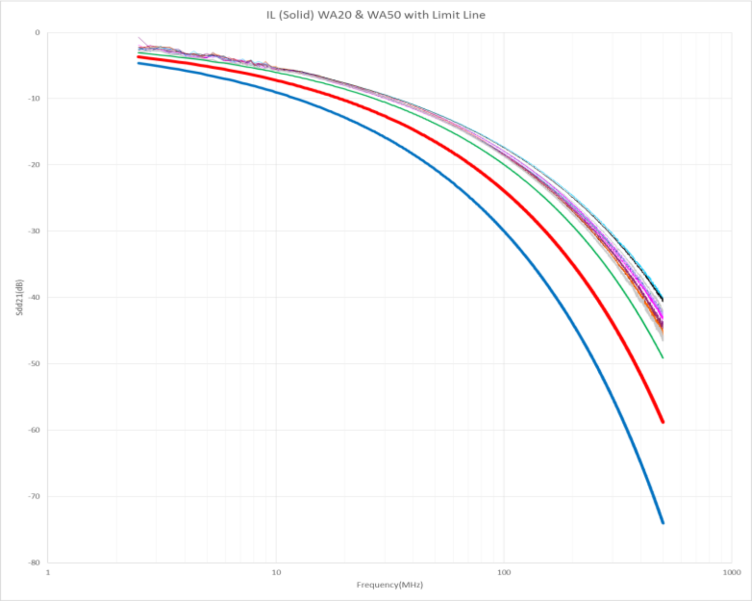



# 1Gigabite Industrial Project Work Flow

# Automation

- All Cable Tests were Automated using HP VEE
  - Data Collection was saved in S4P, CSV and XLSX formats
- Visual Basic was used for Data Import, Graphing
- Excel was Used for Trending
- Mathcad and Excel was Used for Calculations

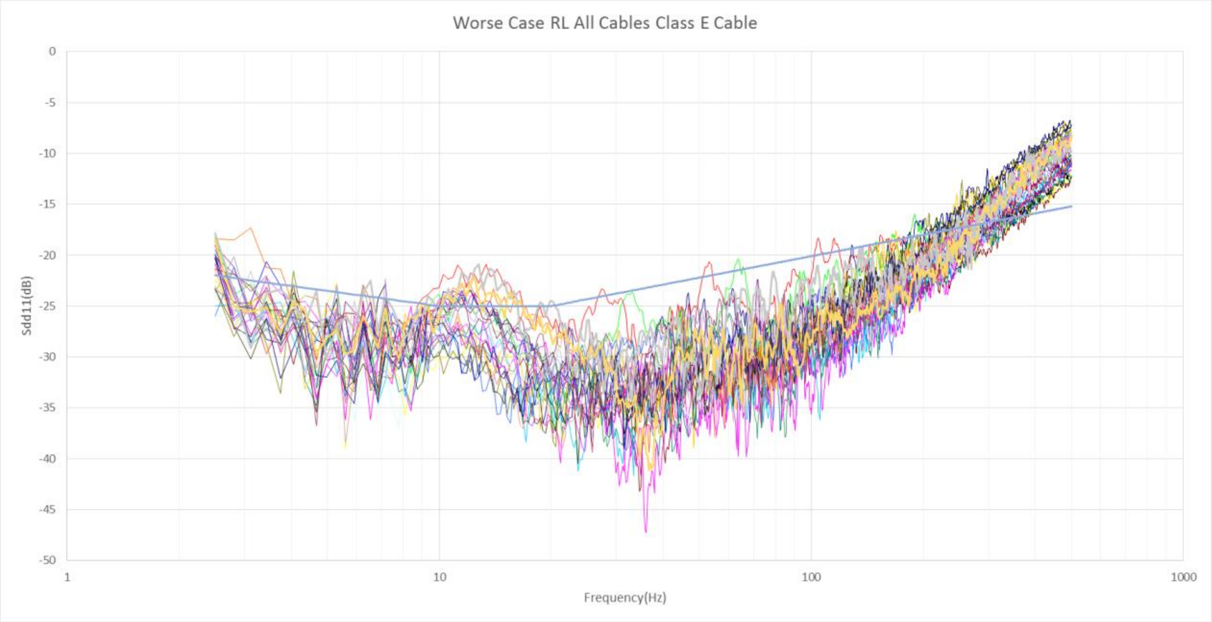



# Insertion Loss of Samples Stranded and Solid

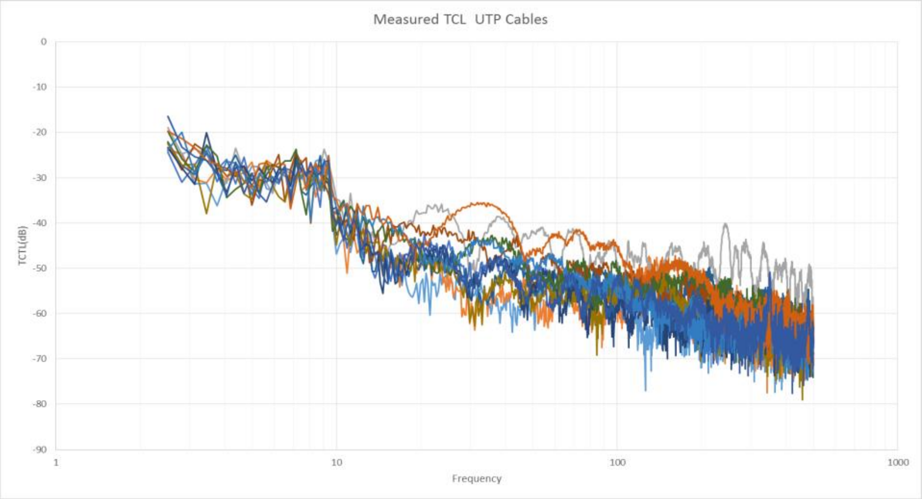
Sdd21Cable(PR1, PR2, PR3, PR4)-‘Sdd21(Fixture)

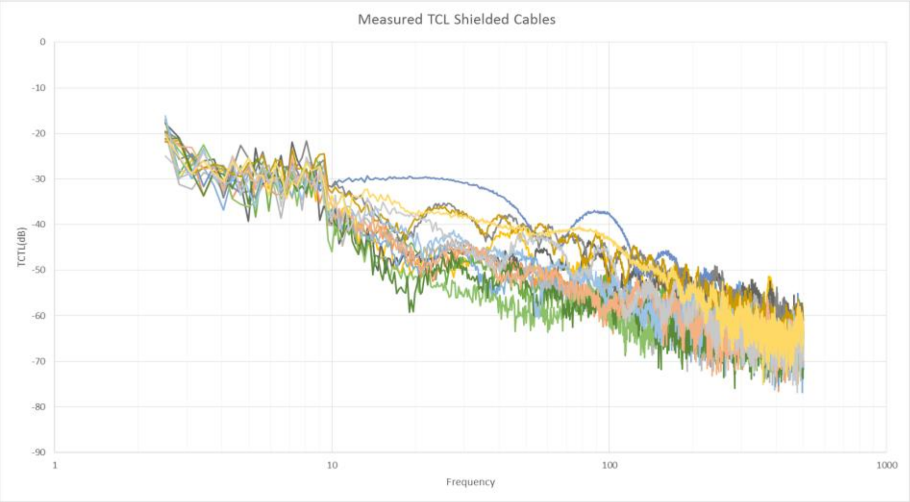
The maximum IL for any of the 4 pairs was used. The fixture IL was removed




# Return Loss

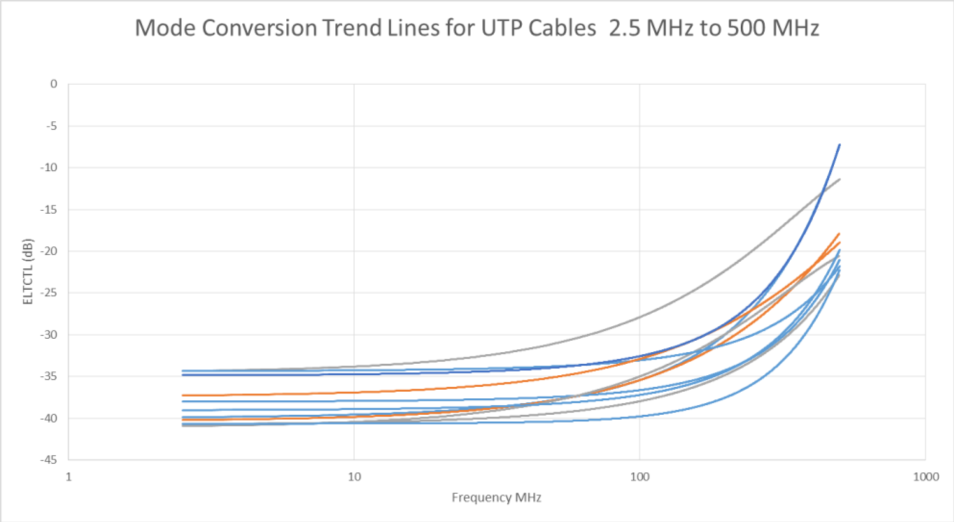
Worst Case RL was Graphed for any Given Pair

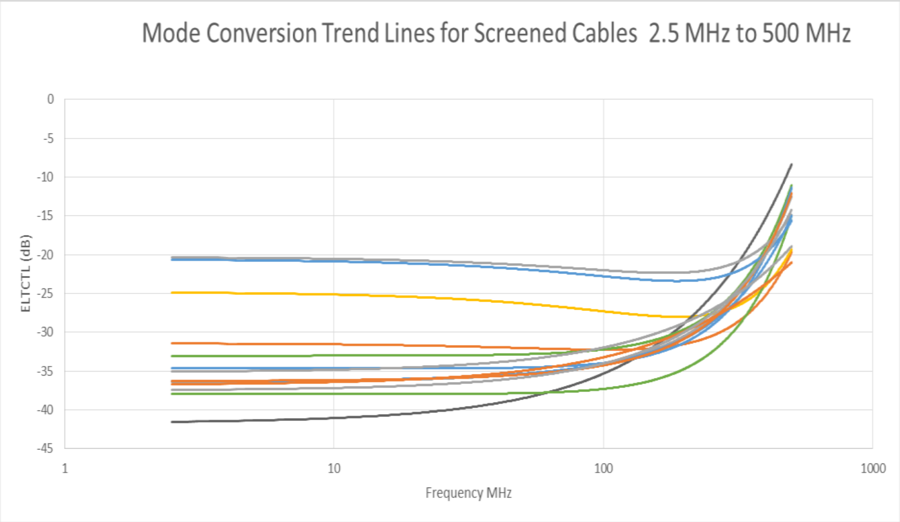



# TCL Maximum UTP and Screened

SCD21Max(PR1, PR2, PR3, PR4)




# Measured Balance TCL

SCD21max(PR1, PR2, PR3, PR4)-[Sdd21max(PR1, PR2, PR3, PR4)-Sdd21(fixture)]

The balance was graphed from the data and equations above. Trend lines created and equations extracted.

# Close Look at Measured TCL and Differential Noise

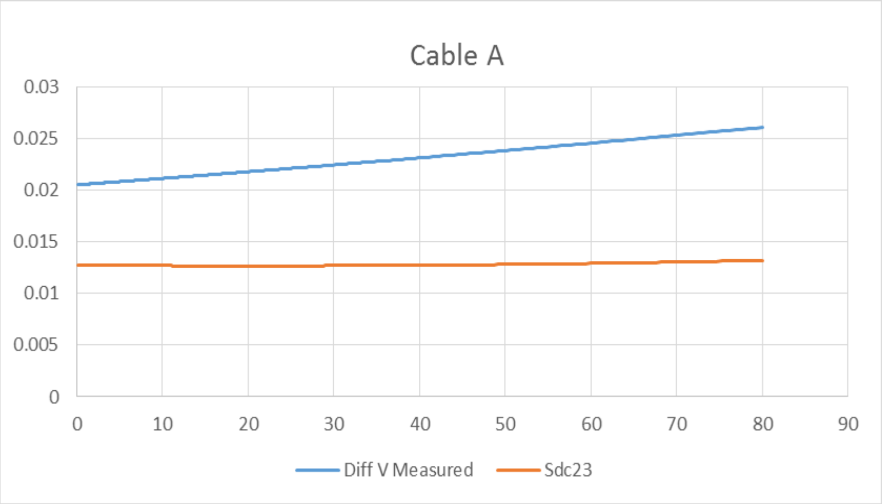
- The Measured Sdc21 was converted to a ratio of polynomial equivalent
- The measured Vn-Differential and trended to a equivalent equation
  - Graphed for comparison and analysis

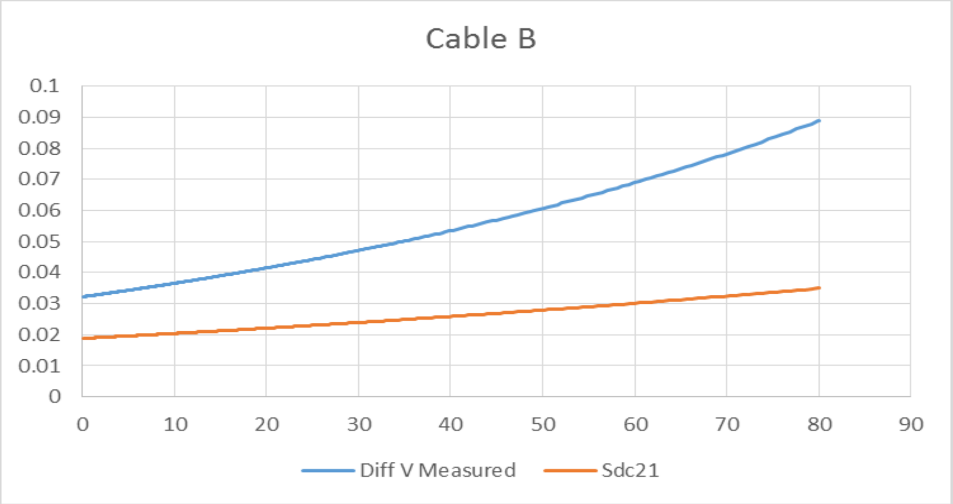
$$Scd21\_Ratio = 10^{\left(\frac{Scd21(f)}{20}\right)}$$

$$Vn\_Diff = Vn\_CM \cdot Scd21\_Ratio$$

As a function of frequency

As a function of frequency and balance



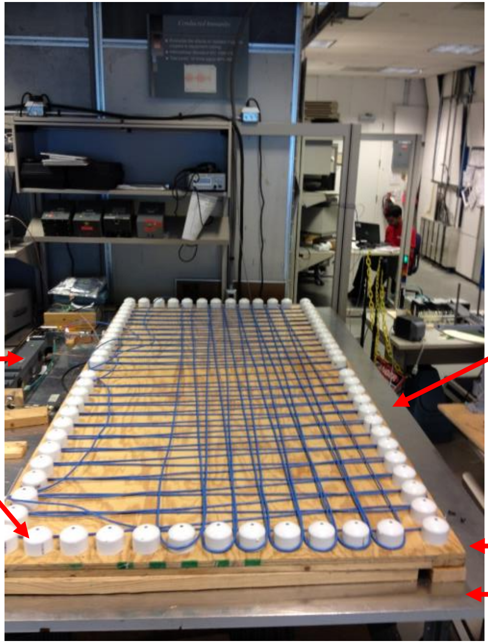

# Balance and Differential Noise Conversion

Sdc21 performance is seen in the cable's mode conversion

When the cable has poor balance the CM→Diff noise conversion is high

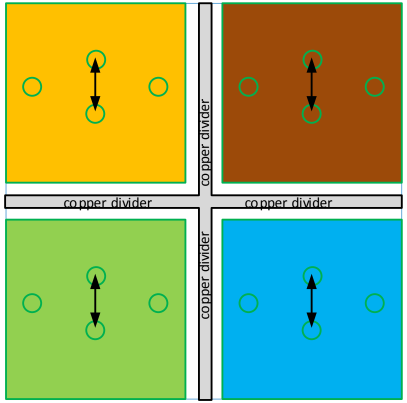
# Conducted Immunity

- In accordance with IEC 61000-4-6
  - Cable Test Fixture
    - Controlled impedance to the GRP
    - Low cross coupling
    - PVC Cones Protect Bend Radius



# Conducted Immunity Cable Termination

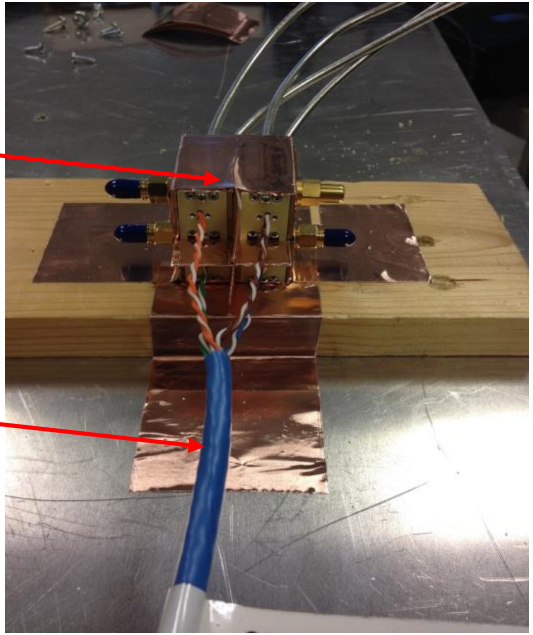
- Cables Terminated into Industrial Rated Plug at NE for BER Testing
- Cables Terminated into BALUNs for Vn Diff measurements.




4X BALUNs BH 040-229

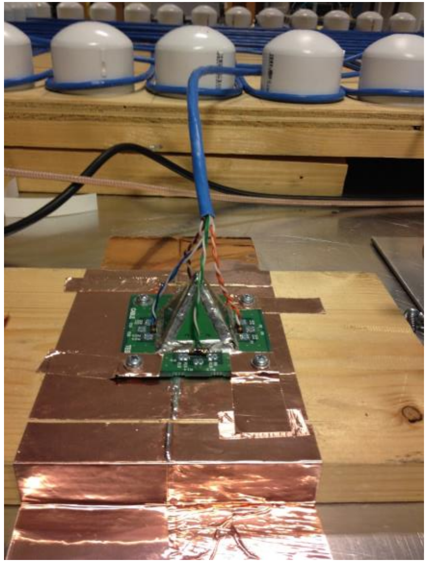
CUT

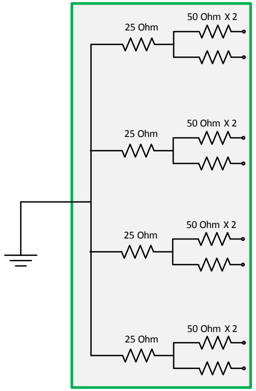
BALUNs directly connected to GRP via Copper Tape

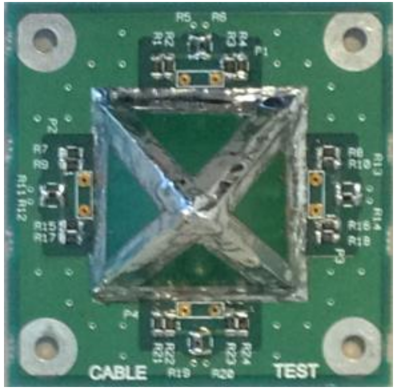


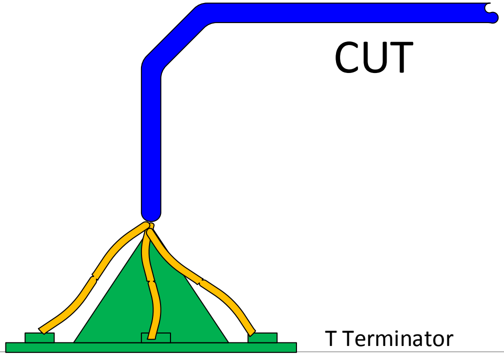
# Cable Termination FE

- Cables Terminated at CM and Diff Impedance



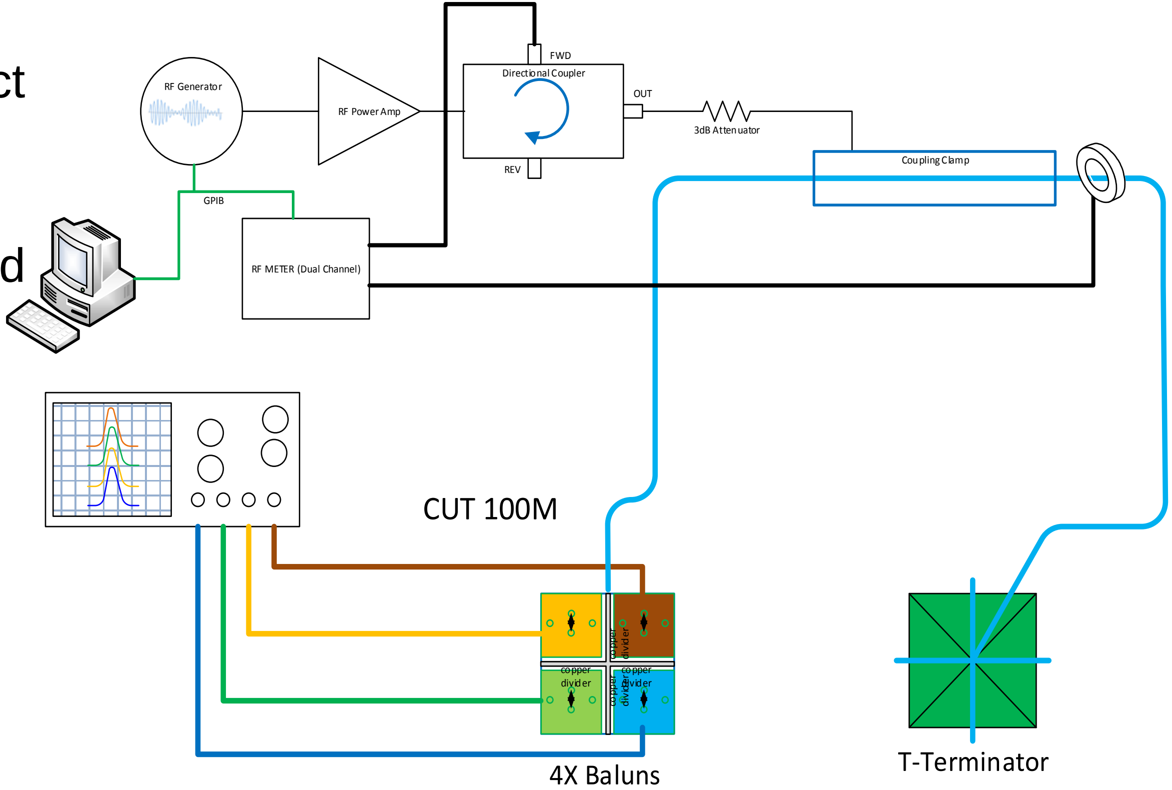


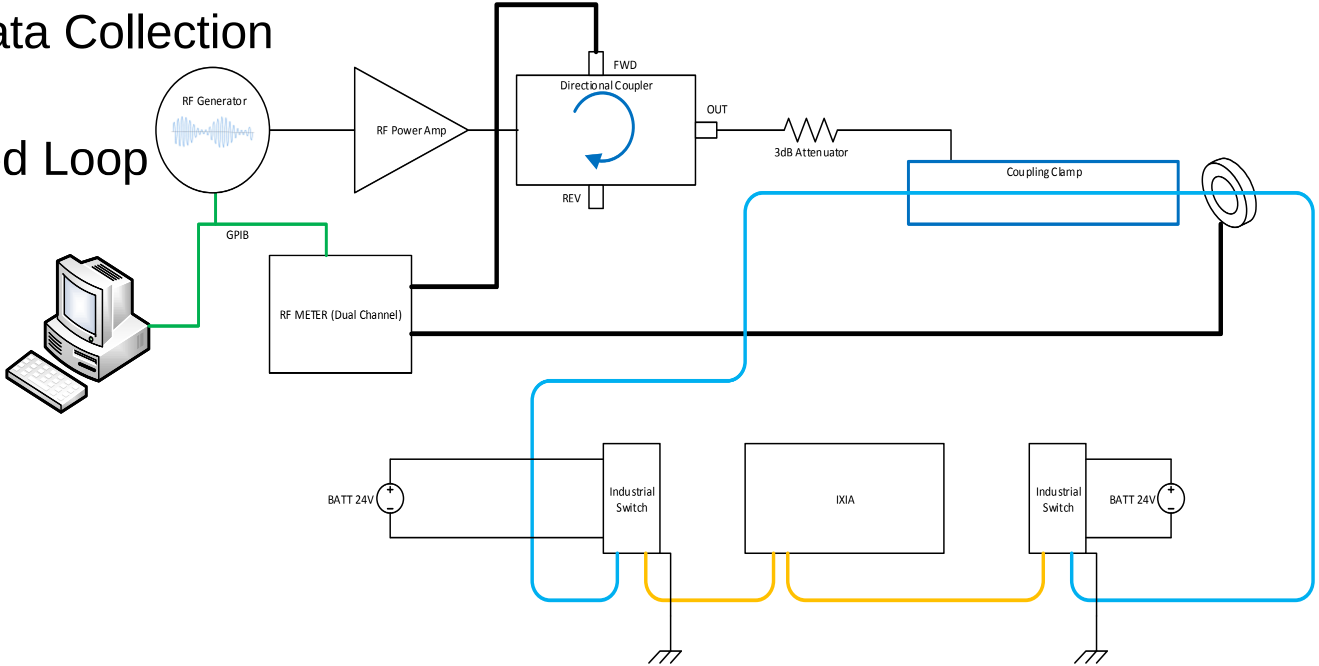
# IEC Bench Setup, Differential Noise Testing

- 12G scope was used to collect Vn_diff
- Bench Control and Data Collection was fully Automated
- Vn Applied was Closed Loop Controlled



# IEC Bench Setup, BER Testing

- Ixia was Used for BER Statistics
- Bench Control and Data Collection was Fully Automated
- Vn Applied was Closed Loop Controlled

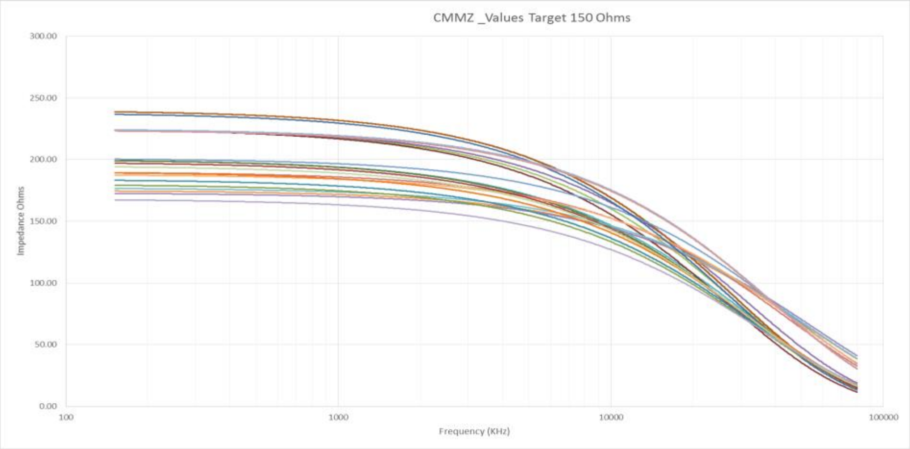


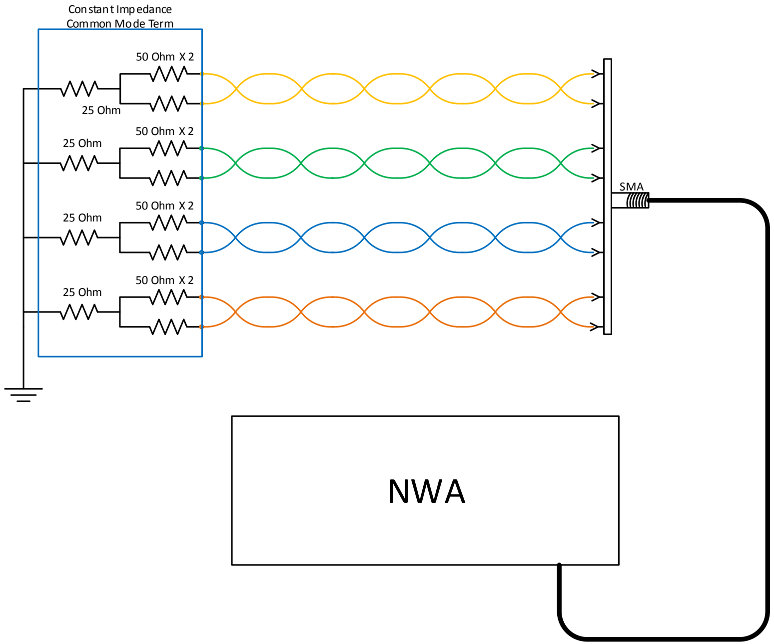

Port 1 PBRS Bit Errors
Port 2 PBRS Bit Errors
Port 1 Error Ratio
Port 2 Error Ratio

$$Re := |magnitude| \cdot \cos(phase)$$

$$Im := |magnitude| \cdot \sin(phase)$$

$$Zcmm := \sqrt{Re^2 + Im^2}$$



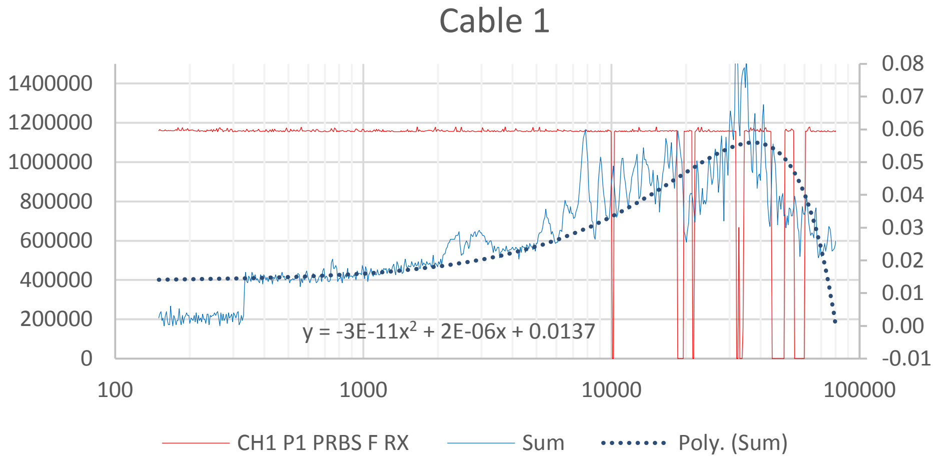

# The Common Mode Impedance was Measured

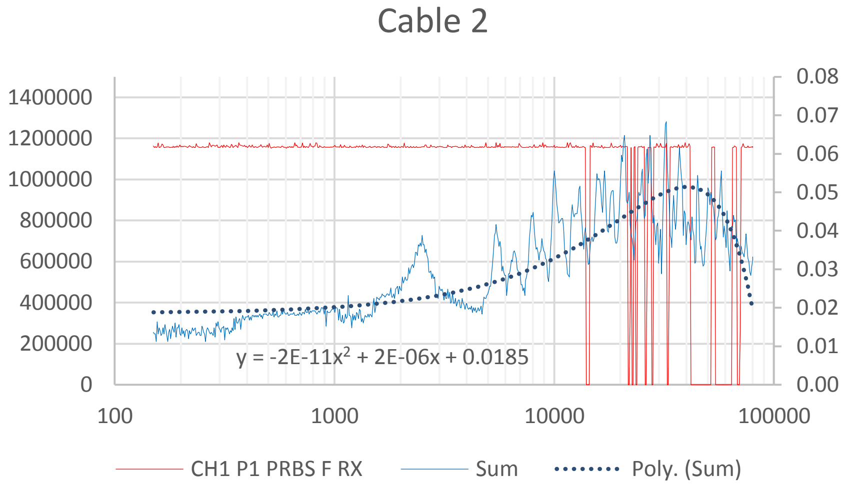
The common Mode Impedance was used to determine the magnitude of the common mode noise applied.

# Vn_CM Applied

- The Applied CM Noise Voltage is a function of the Probe CFs and the Common Mode Impedance Between the GRP and the Cable 10CM off the Bench.

$$V_{applied} = 10^{\left(\frac{20 \cdot \log\left(ProbeV_{mv} \cdot 1000\right) - CF - 120}{20}\right)} \cdot Zcm$$

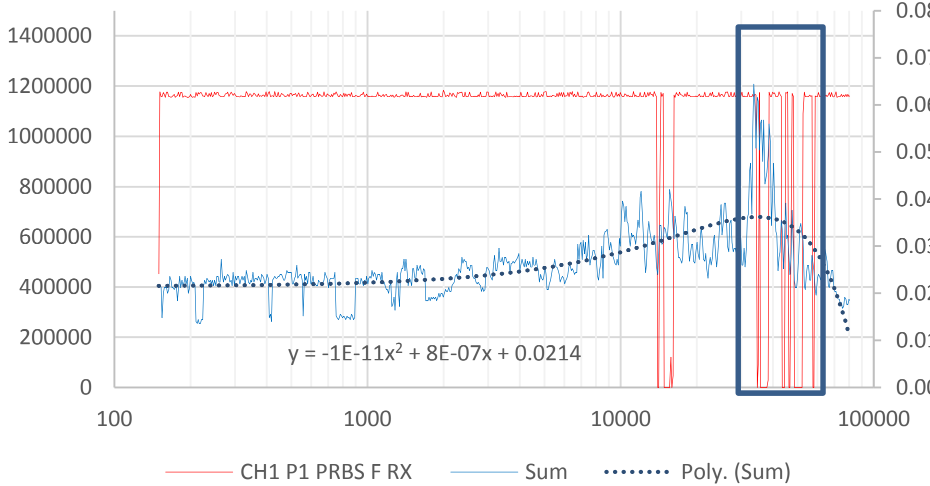


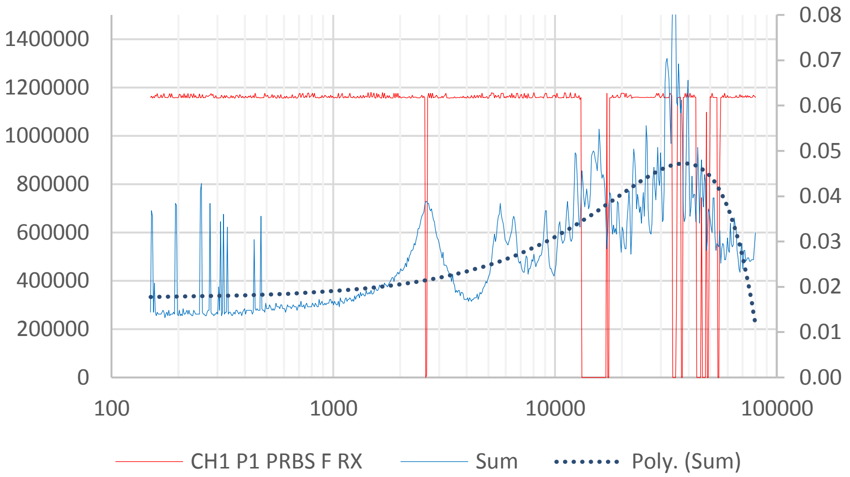

# BER Vs Differential Voltage (UTP)

Two graphs show that when the mode conversion increases the error rates follow. Noise above 40mV causes a sharp increase in errors.

Cable 3

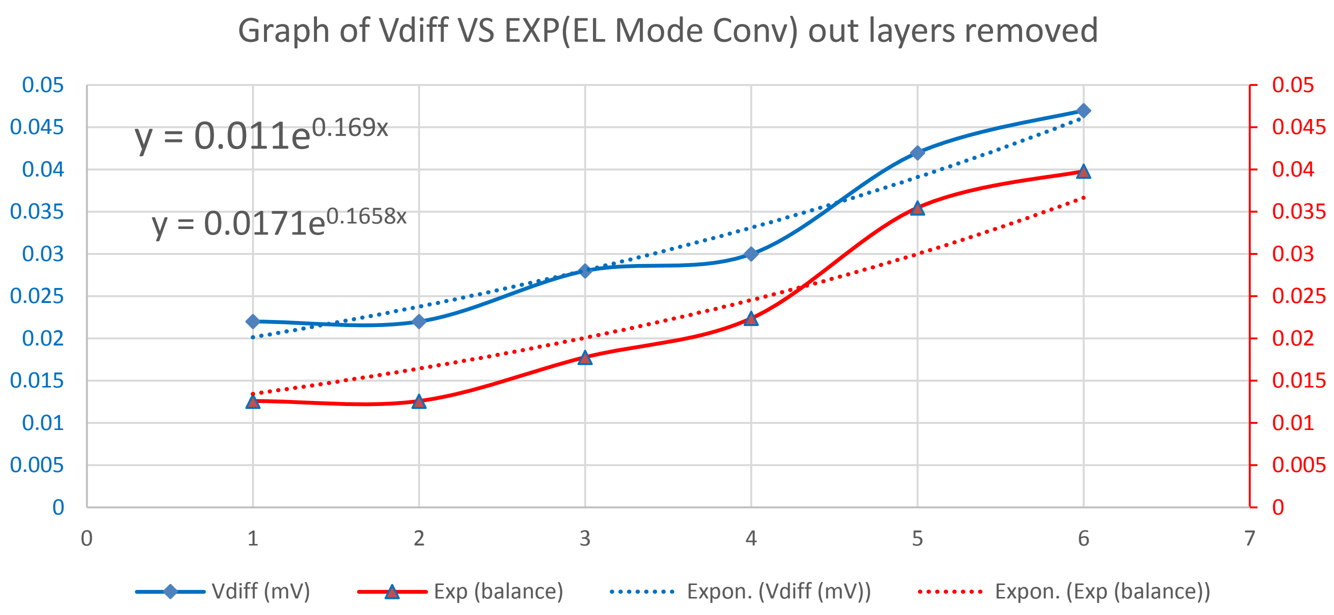



Cable 4




# BER and Mode Conversion Correlation

The UTP Cable Samples show a direct correlation between BER and Vn Diff




$$\mathrm{Exp(Balance)} = 10^{\left(\frac{\mathrm{Balance}_{dB}}{20}\right)}$$

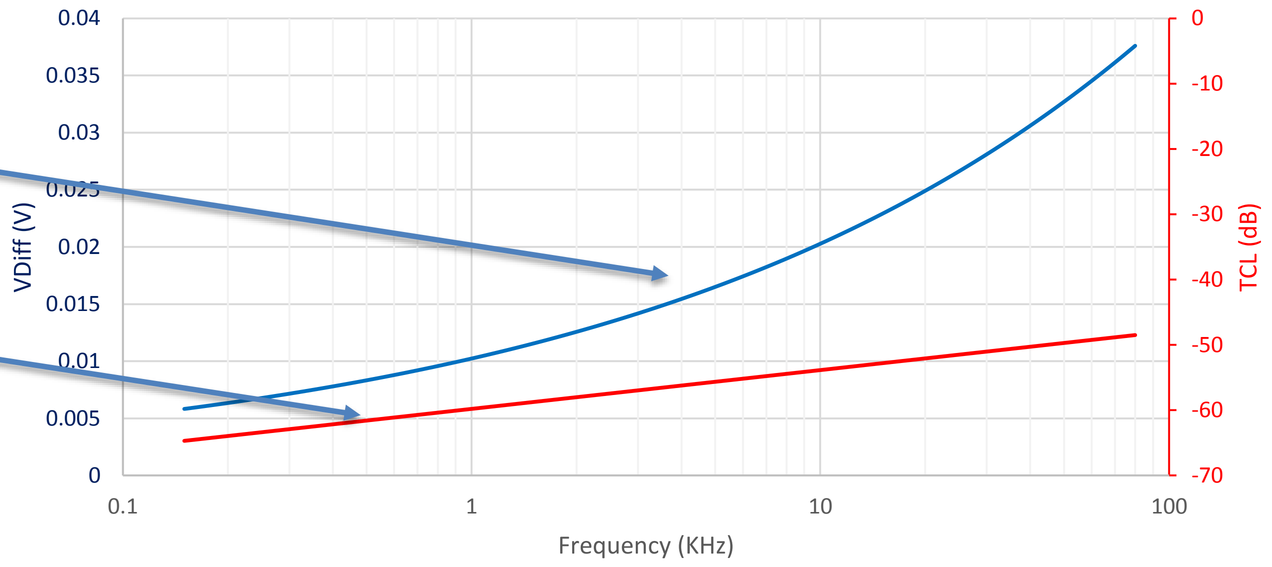
Balance as Measured Scd21

# Analysis of Vn Diff and EL Mode Conversion (UTP)

Blue Trace Vn Differential
Red Trace TCL Conversion Ratio According to the Equation above
Traces show that there is a correlation between Cable balance and mode conversion in the cable.

$$Vn\_Diff = VnApplied \cdot 10^{\left(\frac{ELTCTL_{dB}}{20}\right)}$$

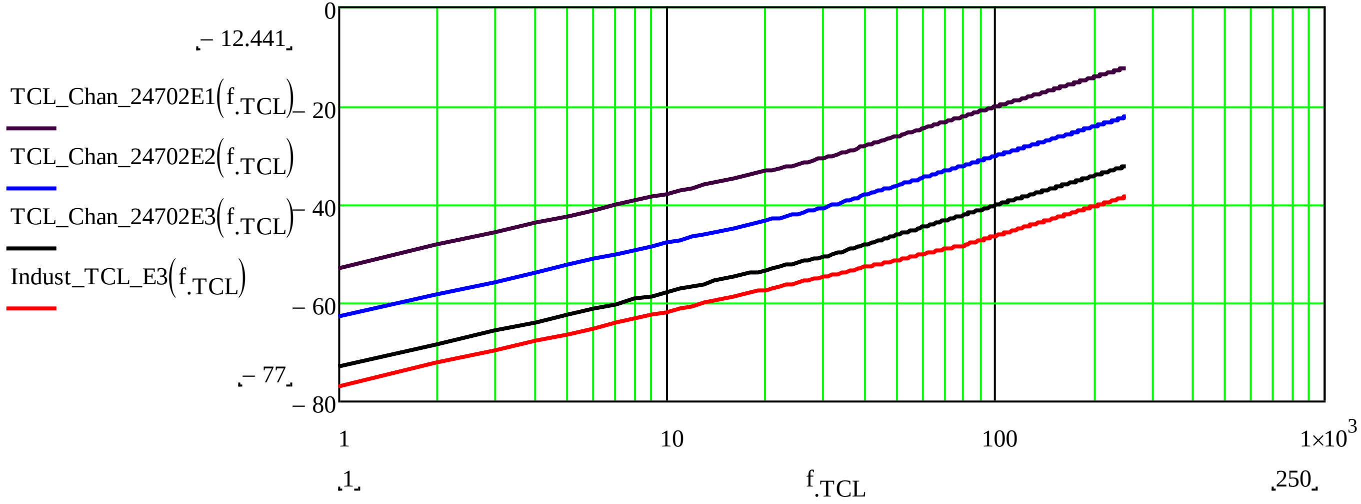
TCL = -59.8+5.9393*log(f)




# Channel TCL

Limit line for Channel TCL and Calculated Vn Diff at 10V RMS applied

Note over 40 MV we see a sharp increase in BER



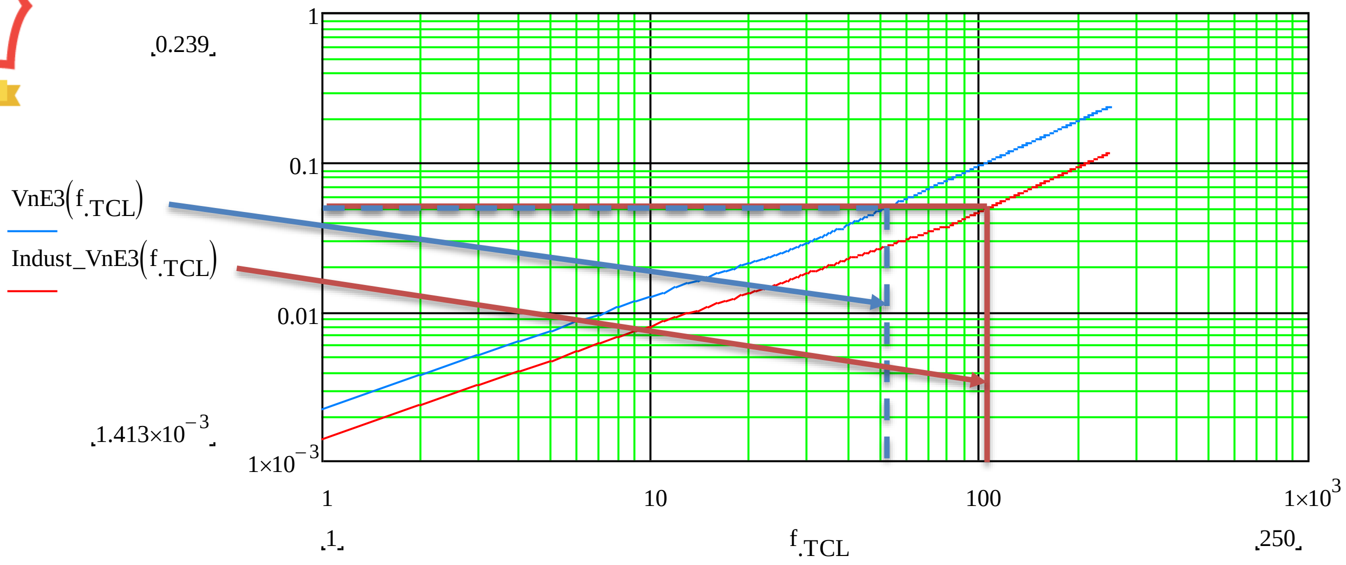

# Industrial Channel TCL E3 Comparison to ISO/IEC 24702

$$\text{Indust\_TCL\_E3(fChan)} := \begin{cases} y \leftarrow -\left(\left(MICE_{6,0} - 15\cdot\log(\text{fChan})\right)\right) & \text{if fChan} < 80 \\ y \leftarrow -\left(\left(MICE_{6,1} - 20\cdot\log(\text{fChan})\right)\right) & \text{otherwise} \end{cases}$$

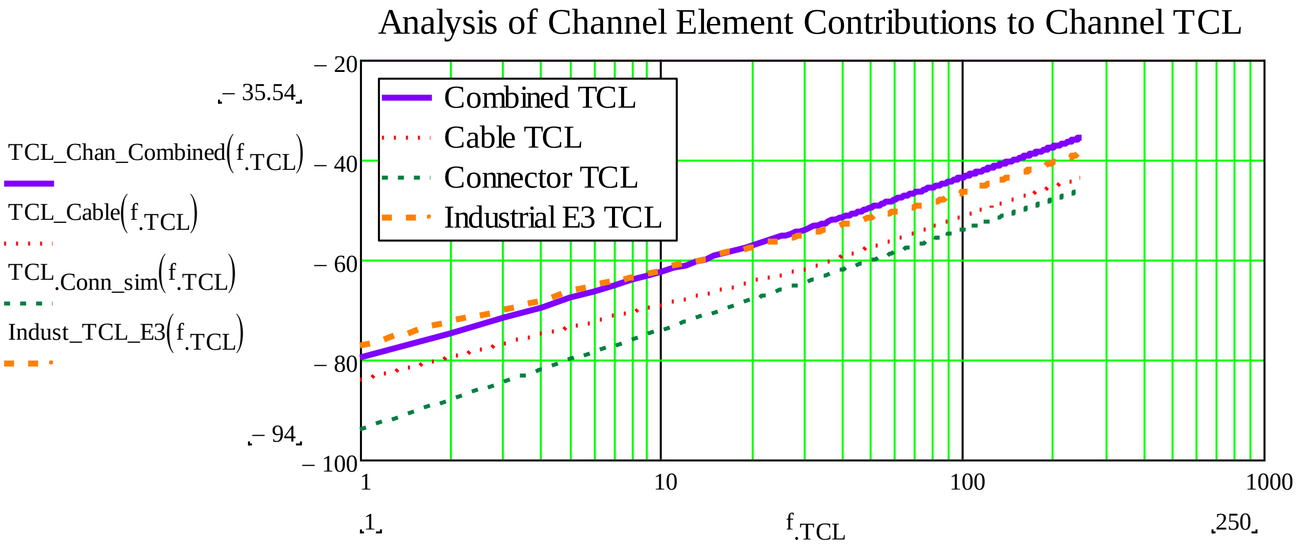
$\text{fChan} := 1, 2 .. 250$

$MICE_{6,0} = 77$

$MICE_{6,1} = 86.6$




# Comparison of Vn Diff Comparison between ISO/IEC 24702 E3 TCL and Recommended Industrial E3 TCL



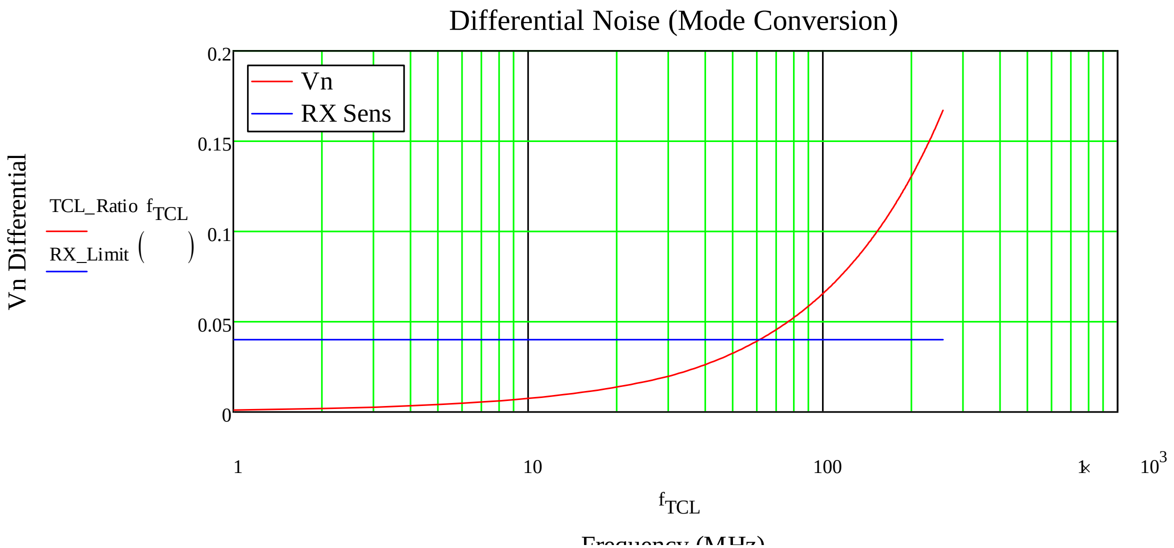

$$TCL\_Chan\_Combined(f_{TCL}) := 20\log\left[10^{\frac{(TCL\_Cable(f_{TCL}))}{20}} + n\_conn \cdot 10^{\frac{(TCL_{Conn\_sim}(f_{TCL}))}{20}}\right]$$

# Individual Contribution of Connectors, Cables to the Total TCL

Connector and Cable TCL’s adjusted to meet the Industrial E3 TCL

# Differential Noise

- Predicted Channel Differential Noise 2 Connectors 10V CM



# TCL Equations of Limit Lines

- Component and Channel Equations

$$\text{TCL\_Cable}(f_{TCL}) := \left| \begin{array}{l} y \leftarrow \left| \begin{array}{ll} -(\text{TCL\_Ancor} - 15 \cdot \log(f_{TCL})) & \text{if } f_{TCL} < 30 \\ -[(\text{TCL\_Ancor} + 7.4) - 20 \cdot \log(f_{TCL})] & \text{otherwise} \end{array} \right. \quad \text{if } \left| \begin{array}{ll} -(\text{TCL\_Ancor} - 15 \cdot \log(f_{TCL})) & \text{if } f_{TCL} < 30 \\ -[(\text{TCL\_Ancor} + 7.4) - 20 \cdot \log(f_{TCL})] & \text{otherwise} \end{array} \right. > \text{TCL\_Limit} \\ y \leftarrow \text{TCL\_Limit} \quad \text{otherwise} \end{array} \right.$$

New Values for Cable TCL

$$\text{TCL}_{\text{Conn\_sim}}(f_{comp}) := \left| \begin{array}{ll} -(\text{TCL\_Conn}_{\text{Ancor}} - 20 \cdot \log(f_{comp})) & \text{if } -(\text{TCL\_Conn}_{\text{Ancor}} - 20 \cdot \log(f_{comp})) > \text{TCL\_Limit}_{\text{conn}} \\ \text{TCL\_Limit}_{\text{conn}} & \text{otherwise} \end{array} \right.$$

New Values for Connector TCL

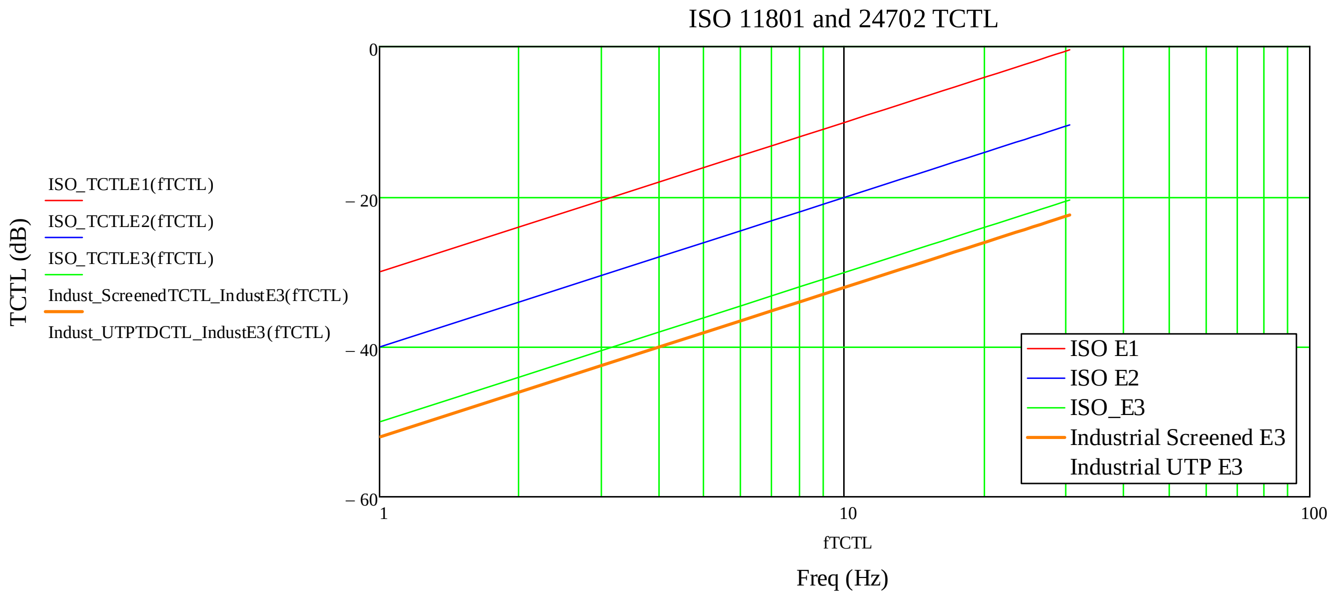
$$\text{TCL\_Chan\_Combined}(f_{TCL}) := 20 \log\left[ 10^{\frac{(\text{TCL\_Cable}(f_{TCL}))}{20}} + \text{n\_conn} \cdot \left[ 10^{\frac{(\text{TCL}_{\text{Conn\_sim}}(f_{TCL}))}{20}} \right] \right]$$

Calculated Combined TCL for 2 Connectors

Since a RJ45 connector is inherently unbalanced and there are 4 connections, they are the highest contributor to the poor TCL. Reducing the number of connectors and increasing the anchor helps to equal out the contribution between the cable and the connectors in the channel

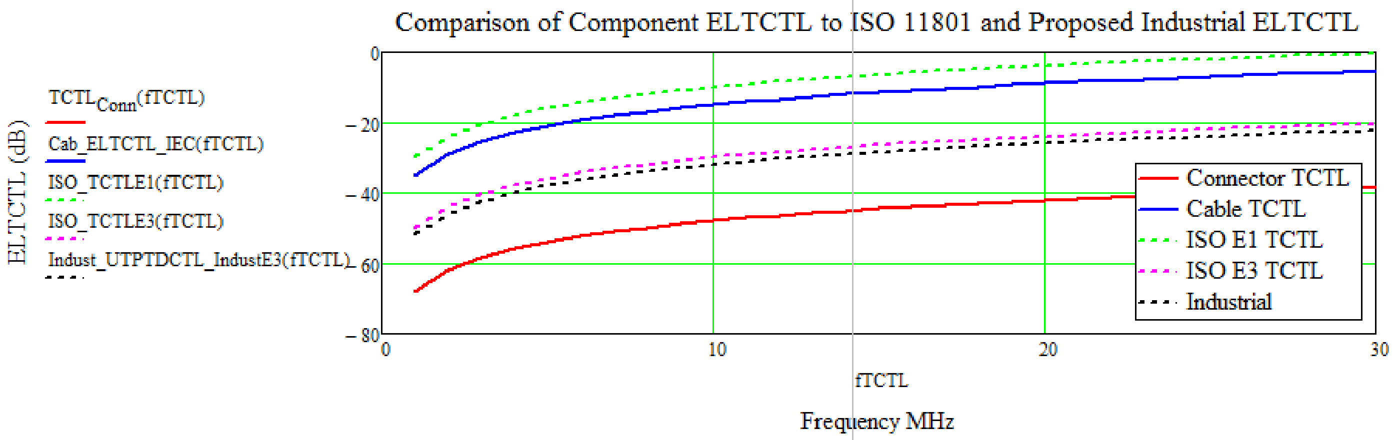
# ELTCTL

- Proposed Channel ELTCTL for UTP and Screened are the Same



# Limits for E3 Channel and Components

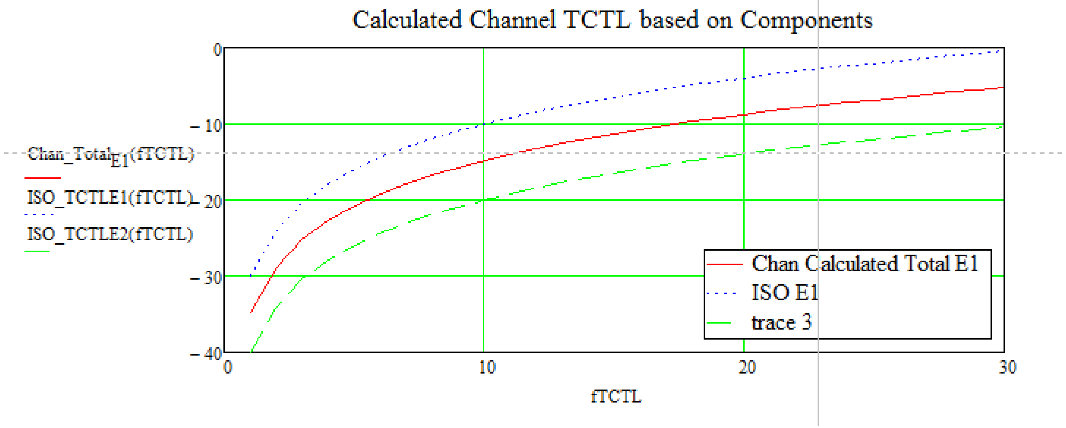
- Cable ELTCTL is the limiting Factor



# Component/Channel Disparity

- The mathematical model of the components falls in between E1 and E2 of the Channel ELTCTL

$$Chan\_Total_{E1}(fTCTL) := 20 \cdot \log\left[10^{\left(\frac{Cab\_ELTCTL\_IEC(fTCTL)}{20}\right)} + 10^{\left(\frac{TCTL_{Conn}(fTCTL)}{20}\right)}\right]$$

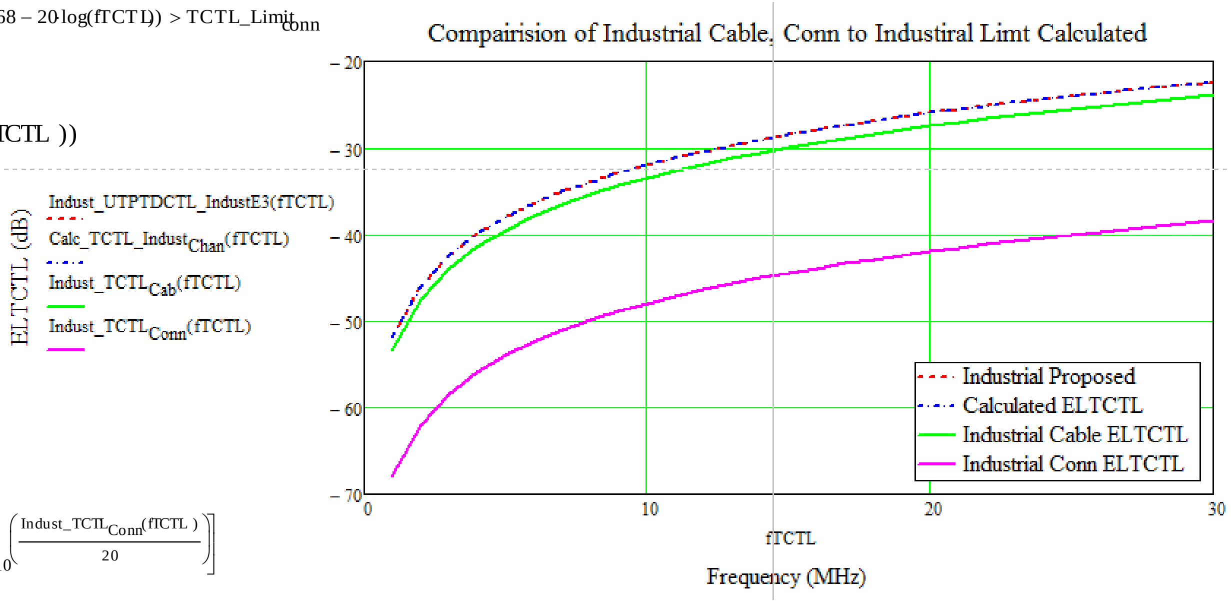


# Proposed Component Limits for ELTCTL

- The New Component Values Combined Meet the targeted Channel ELCTCL for E3 as Modified

$$Indust\_TCTL_{Conn}(fTCTL) := \begin{cases} -(68 - 20 \cdot \log(fTCTL)) & \text{if } -(68 - 20 \cdot \log(fTCTL)) > TCTL\_Limit_{conn} \\ TCTL\_Limit_{conn} & \text{otherwise} \end{cases}$$

$$Indust\_TCTL_{Cab}(fTCTL) := -(53.5 - 20 \cdot \log(fTCTL))$$



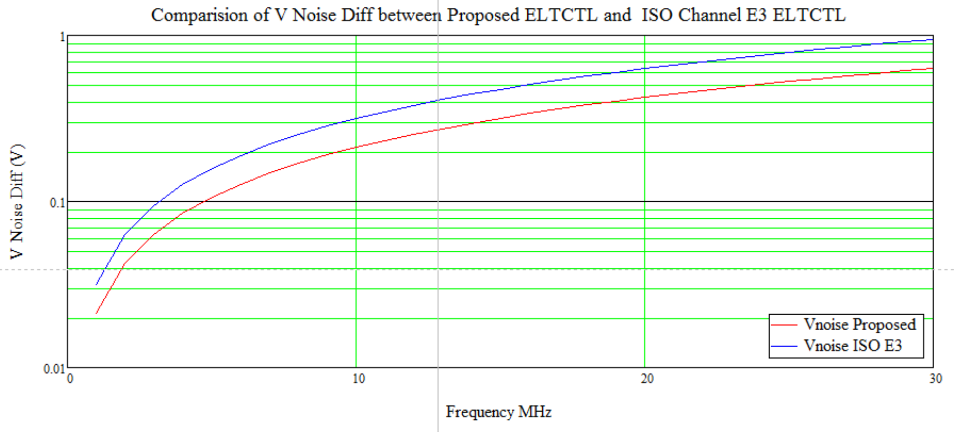

$$Calc\_TCTL\_Indust_{Chan}(fTCTL) := 20 \cdot \log\left[10^{\left(\frac{Indust\_TCTL_{Cab}(fTCTL)}{20}\right)} + 10^{\left(\frac{Indust\_TCTL_{Conn}(fTCTL)}{20}\right)}\right]$$

# Differential Noise Analysis for 10VCM

- Note Analysis still shows Differential Noise above 0.04V below 10MHz

$$Vn\_diff_{Chan\_ISO}(fTCTL) := Vn \cdot 10^{\left(\frac{ISO\_TCTLE3(fTCTL)}{20}\right)}$$

$$Vn\_diff_{Chan\_Proposed}(fTCTL) := Vn \cdot 10^{\left(\frac{Indust\_TCTL_{Cab}(fTCTL)}{20}\right)}$$



THANK YOU