Project: **WT-285**

Title: **Understanding the dual-slope effect in crosstalk (EL-FEXT)**

Source: Rob F.M. van den Brink
TNO, the Netherlands
Rob.vandenBrink@tno.nl

Date: July 25-28, 2016, Berlin

Distribution: **Metallic Transmission Group**

Abstract:

The goal of this contribution is to provide insights as to the cause of the dual slope effect in quad cables based on recent work in TNO. It contains the slides that were presented on 29-06-2016 to the yearly UFBB-Seminar in den Haag (the Netherlands). Further details can be found in our contribution bbf2016.686 in the form of a draft technical paper on the topic. This contribution is for information only. It supports our proposal in bbf2016.687 on a simplified EL-FEXT model covering that dual slope effect.

1 Background

One of the reasons why FEXT levels are getting so pronounced is that above a certain frequency the EL-FEXT increases with 40 dB/decade instead of the usual 20 dB/decade. This effect was raised in our ITU contribution of February 2012 [2] and called the “dual slope effect”. Since then the existence of that “dual slope” effect was confirmed by many others and observed in various different cables [3,4,5,6,7,8,9,10,11,12,13,14], and many other contributions thereafter.
So far the phenomenon was not well understood and resulted in a number of conjecture explanations [15] in both the Broadband Forum as in ITU-T. As a result it was not clear how to model that, and how the far end crosstalk changes with the loop length.

Recent studies at TNO have learned that the dual slope effect is caused by a combination of two independent phenomena’s: a first order and a second order crosstalk effect. Both effects can exist without the other, are completely independent from each other, and both scale differently with the cable length.

- The origin of the first order effect is well known [16, 17] and random in nature. Its magnitude in the EL-FEXT scales proportionally with the *root* of the cable length (in a statistical sense).
- The origin of the second order effect is deterministic in nature (assuming that the cable geometry is deterministic as well) and scales proportionally with the length.

The sum of both has a dual slope appearance and the break frequency between both slopes depends on the magnitude of each crosstalk effect.

This contribution is the covering letter to the slides of a presentation that TNO has recently held (July 29th, 2016) at the yearly UFBB-Seminar in den Haag (the Netherlands) about this topic. It is for information only and is to support our proposal in bbf2016.687 on a simplified EL-FEXT model covering this dual slope effect. Further details can be found in a paper we have written about this topic [1], and that has been attached to our contribution bbf2016.686 as well.

2 Summary

This contribution is provided for information, but with the goal of improving the collection of cable modelling techniques brought together in TR-285.

3 References

[1] Rob F.M. van den Brink, "*Modelling the dual-slope behavior of EL-FEXT in twisted-pair quad cables"* Submitted in January 2016 to IEEE for possible publication, revised on May 2016 and still under review at the time of writing.

[2] TNO (Rob van den Brink, Bas van den Heuvel), *"Dual slope behavior of EL-FEXT",* contribution 2012-02-4A-038 to ITU-T-SG15/Q4, Feb 2012.

[3] Brink, "*Far-End crosstalk in twisted pair cabling: measurements and modeling*", TNO Contribution 11RV-022, ITU-T SG15/Q4, Nov 2011.

[4] Eriksson, Berg, Lu; "*Equal Length FEXT measurements on PE05 cable*", Ericsson Contribution 11RV-054R1, ITU-T SG15/Q4, Richmond, November 2011.

[5] Huawei, "*Equal-Length FEXT Measurements on PE05 Cable*", Huawei Contribution COM 15 - C 1864, ITU-T SG15/Q4, November 2011.

[6] Bruyssel, Maes "Dual *slope behaviour of EL-FEXT*", ALU Contribution 2012-06-4A-033, ITU-T SG15/Q4, May 2012.

[7] Humphrey, "*On dual slope FEXT observations*", BT Contribution 2012-05-4A-021, ITU-T SG15/Q4, May 2012.

[8] Humphrey, Morsman, "*FEXT cable measurements*", BT Contribution 2012-05-4A-025, ITU-T SG15/Q4, May 2012.

[9] Muggenthaler, Tudziers; "*EL-FEXT Analysis*", DT Contribution 2012-06-4A-041, ITU-T SG15/Q4, May 2012.

[10] Bongard, "*Dual slope ELFEXT behaviour on Swiss cables*", Swisscom contribution 2013-01-Q4-042, ITU-T SG15/Q4, Feb 2013.

[11] Kozarev, Strobel, Leimer, Muggenthaler, "*Modeling of Twisted-Pair Quad Cables for MIMO Applications*" Lantiq/DT Contribution bbf2014.467, BroadbandForum, june 2014 (updated from bbf2014.377 and bbf2014.117).

[12] Heuvel, Trommelen, Brink, "*G.fast: Preliminary analysis of the transfer characteristics of the 104 m KPN Access cable*", TNO Contribution 2013-03-Q4-026, March 2013.

[13] Heuvel, "*G.vector: High in-quad crosstalk coupling in older cables*", TNO Contribution 2015-10-Q4-024, ITU-T SG15/Q4, Oct 2015.

[14] Heuvel, "*G.vector: High crosstalk coupling in older cables – Measurements on GPLK01",* TNO Contribution 2015-11-Q4-028, ITU-T SG15/Q4, Dec 2015.

[15] Schneider, Kerpez, Starr, Sorbara "*Transfer Functions, Input Impedance and Noise Models for the Loop End*", Cosigned contribution bbf2014.066.00, BroadbandForum, March 2014.

[16] *Transmission systems for communications*. Bell Telephone Labs, 1971, 4th edition.

[17] ETSI TR 101 830-2, Spectral Management on metallic access networks, Part 2: Technical methods for performance evaluations, revision V1.2.1, 2008.

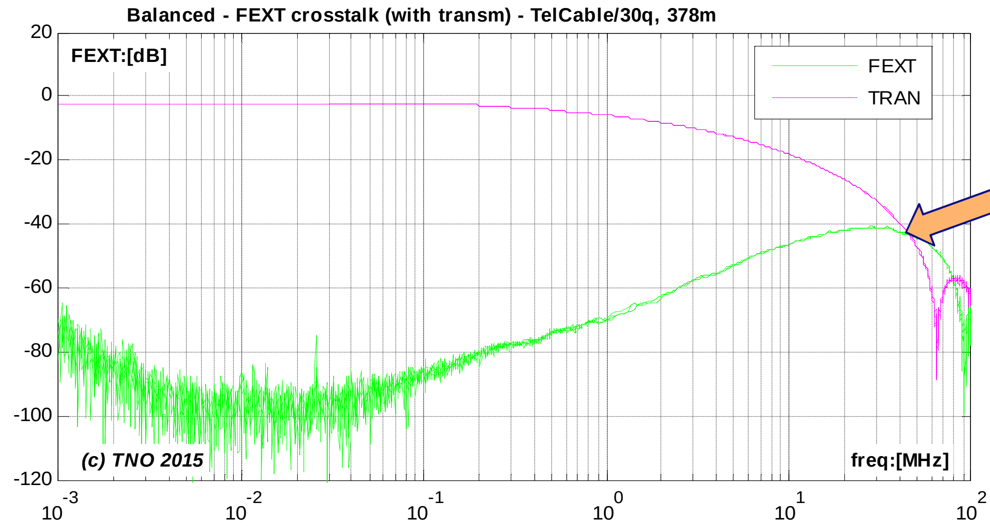
Understanding the dual-slope effect in crosstalk (EL-FEXT)

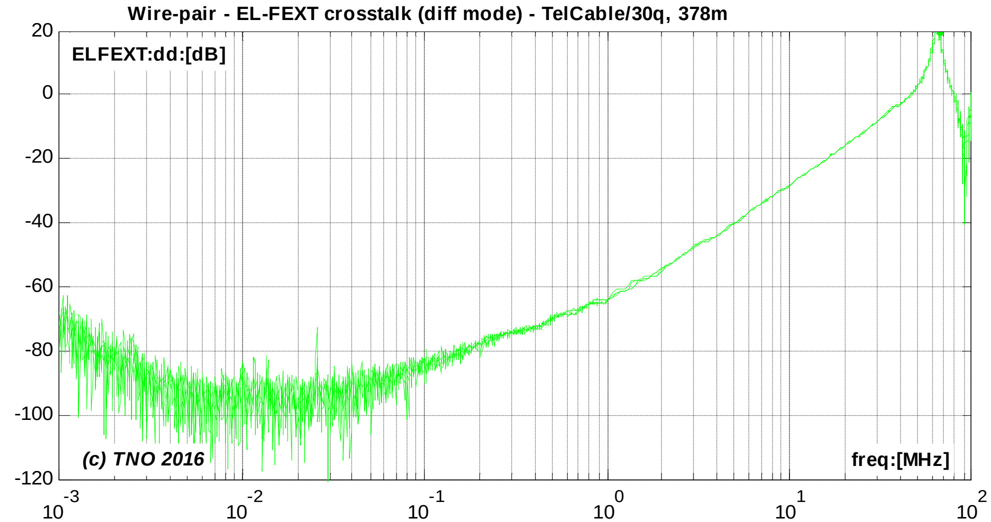
What causes this second order crosstalk effect in quad cables?

Rob F.M. van den Brink – TNO

1. FEXT crosstalk measurements in telephony cabling

An example: 30 quads, 378m, winded on a drum



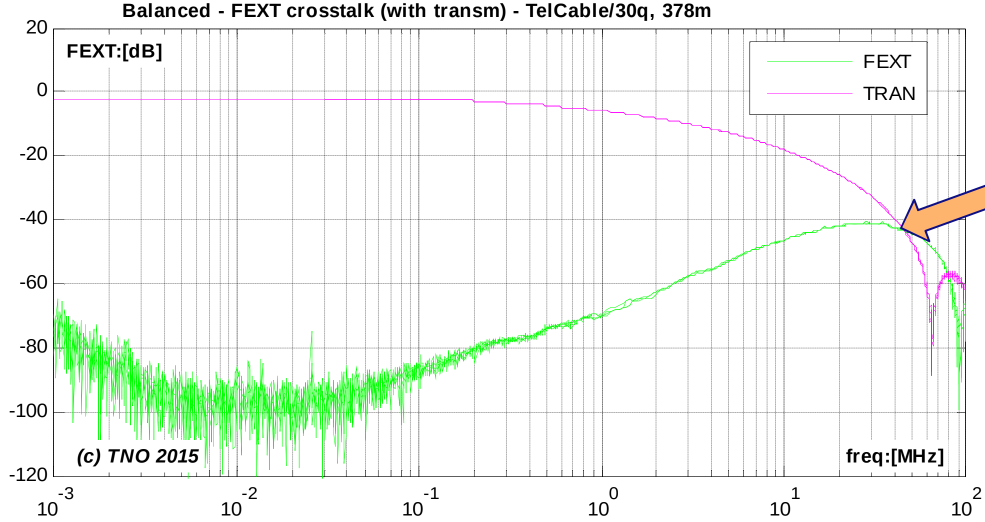


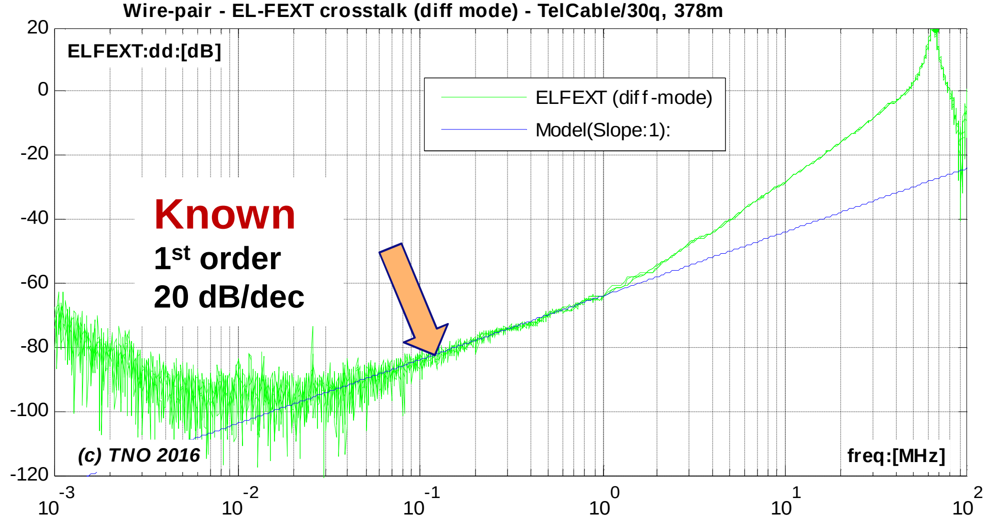
Crosstalk exceeds direct transmission

$$\textbf{EL-FEXT} = \frac{\textbf{FEXT (crosstalk)}}{\textbf{TRAN (signal)}}$$

1. FEXT crosstalk measurements in telephony cabling

An example: 30 quads, 378m, winded on a drum



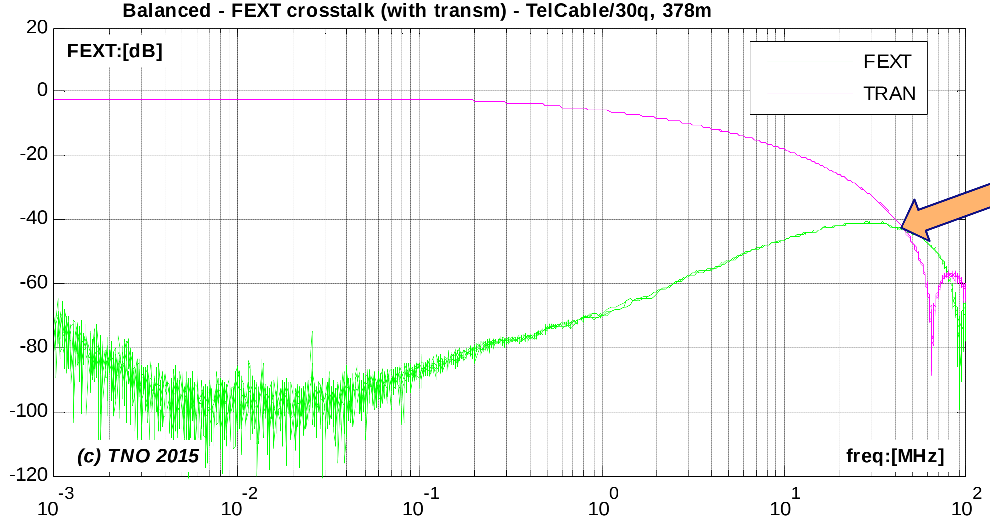


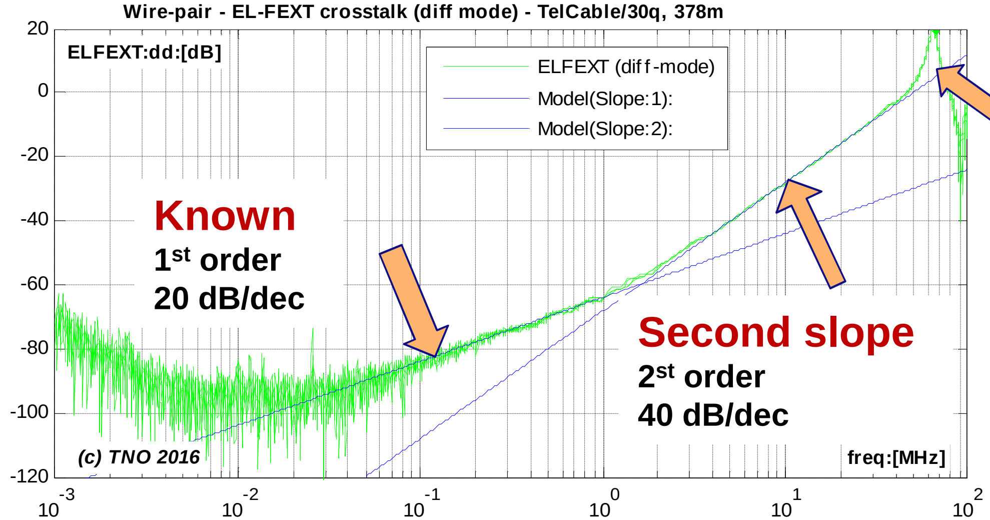
Crosstalk exceeds direct transmission

$$\text{EL-FEXT} = \frac{\text{FEXT (crosstalk)}}{\text{TRAN (signal)}}$$

1. FEXT crosstalk measurements in telephony cabling

An example: 30 quads, 378m, winded on a drum





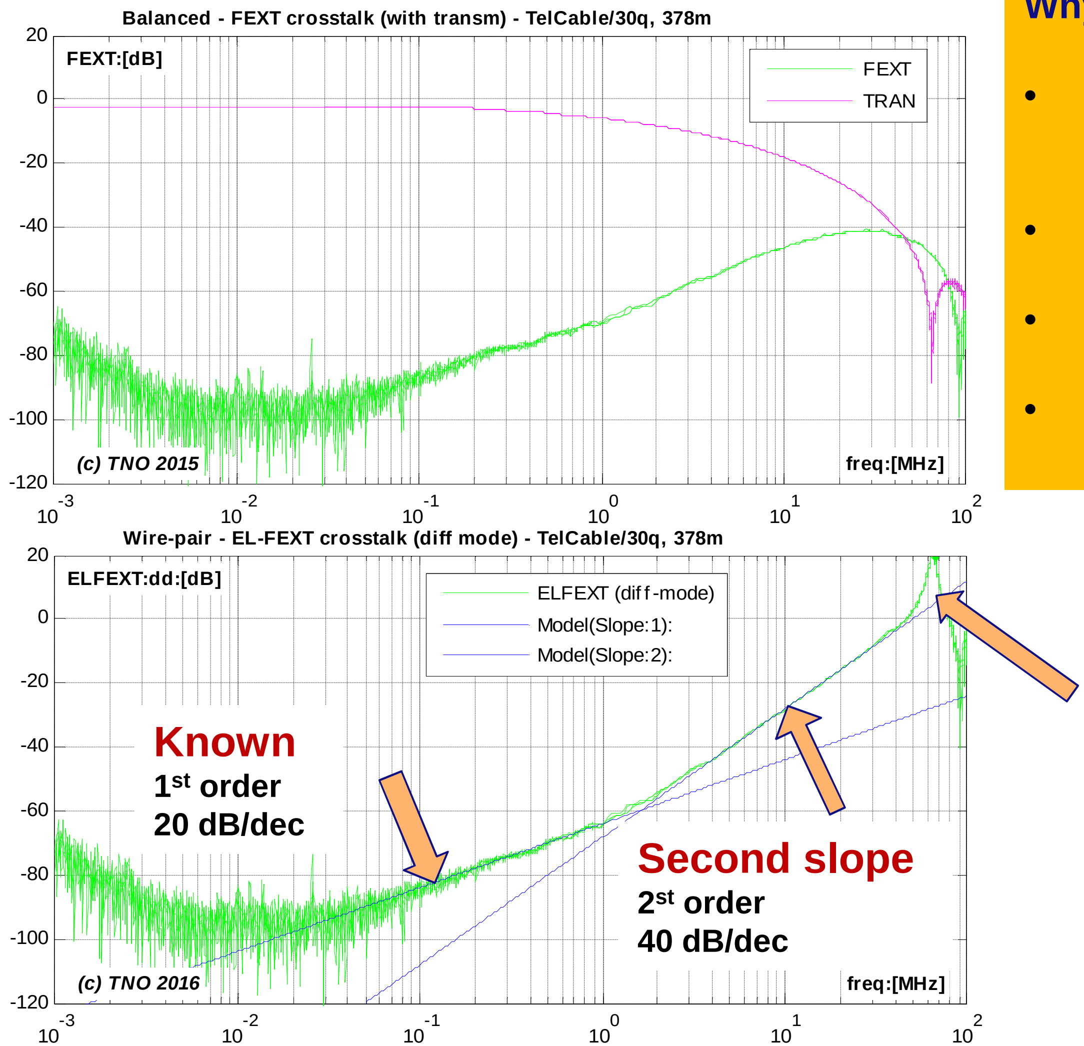
Crosstalk exceeds direct transmission

EL-FEXT > 0dB

$$\text{EL-FEXT} = \frac{\text{FEXT (crosstalk)}}{\text{TRAN (signal)}}$$

1. FEXT crosstalk measurements in telephony cabling

An example: 30 quads, 378m, winded on a drum



Why is 2nd order effect relevant for DSL?

- **Xtalk increases more rapidly with frequency**
- **VDSL/35b and G.fast suffer from it**
- **Dual slope effect not well understood**
- **Model needed for performance predictions**

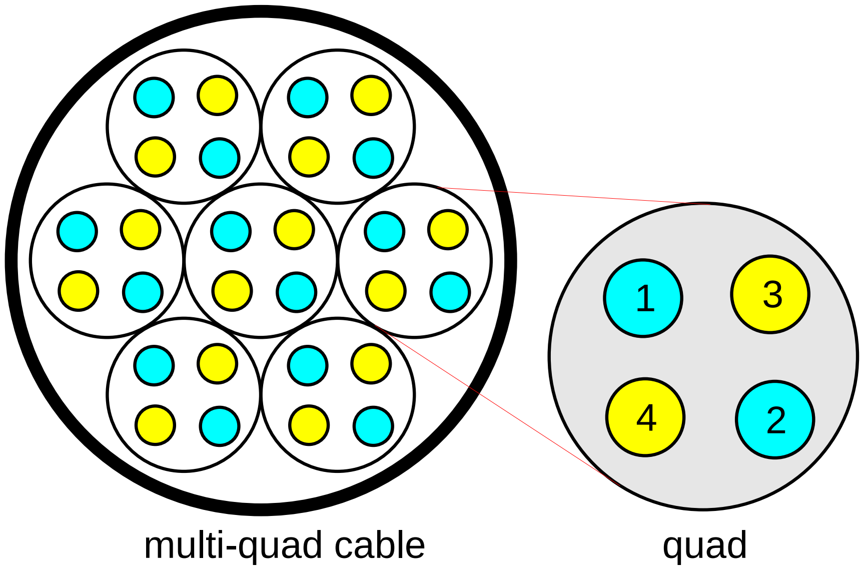
EL-FEXT > 0dB

Sudden increase of crosstalk (40 dB/decade) "dual slope effect"

1. FEXT crosstalk measurements in telephony cabling

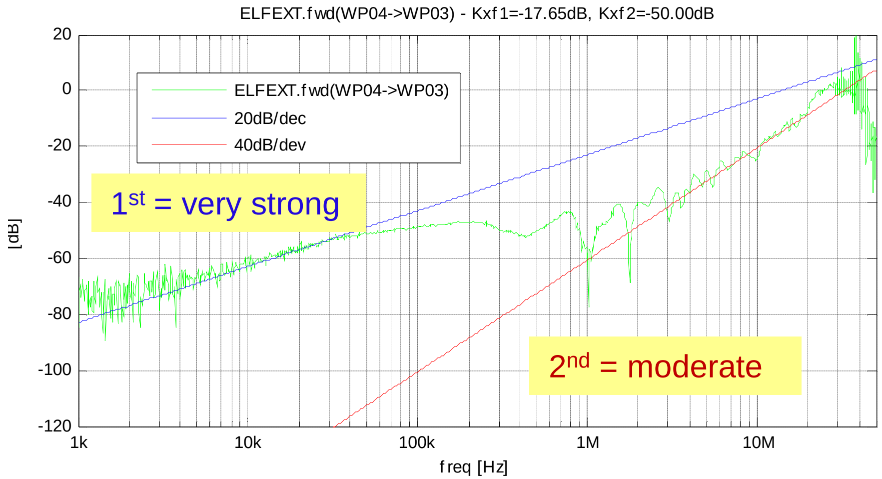
How behaves this dual-slope effect in other cables?

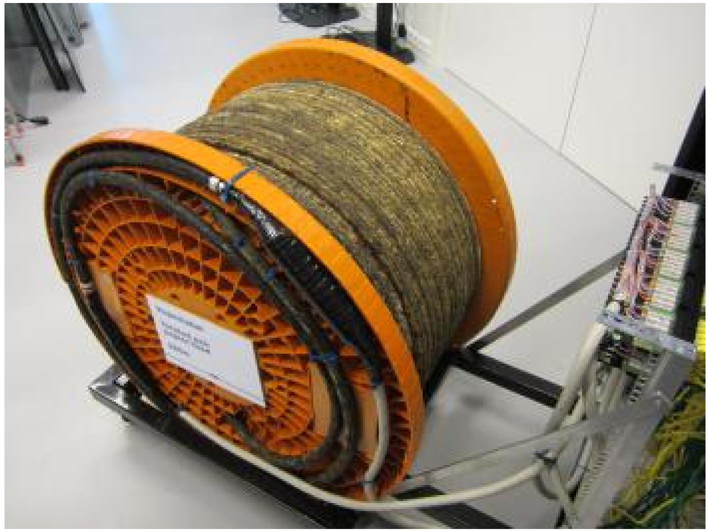
- 1st and 2nd order slopes are caused by independent mechanisms
- They scale differently with the cable length

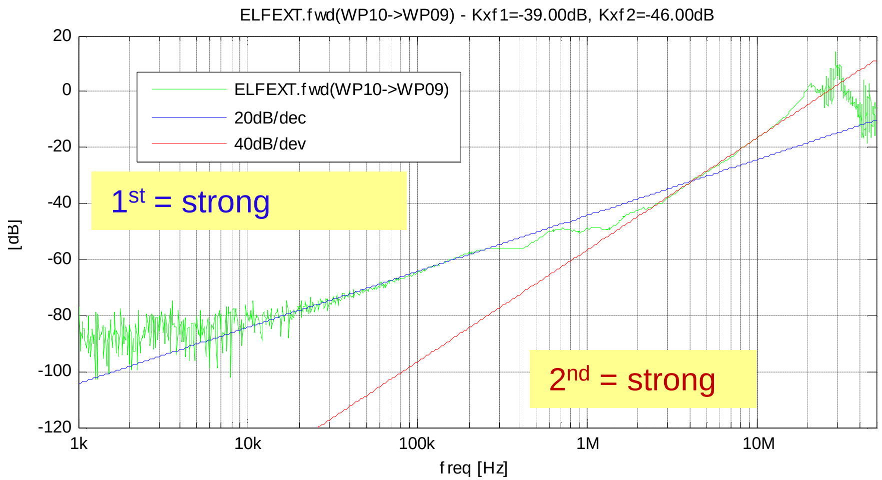


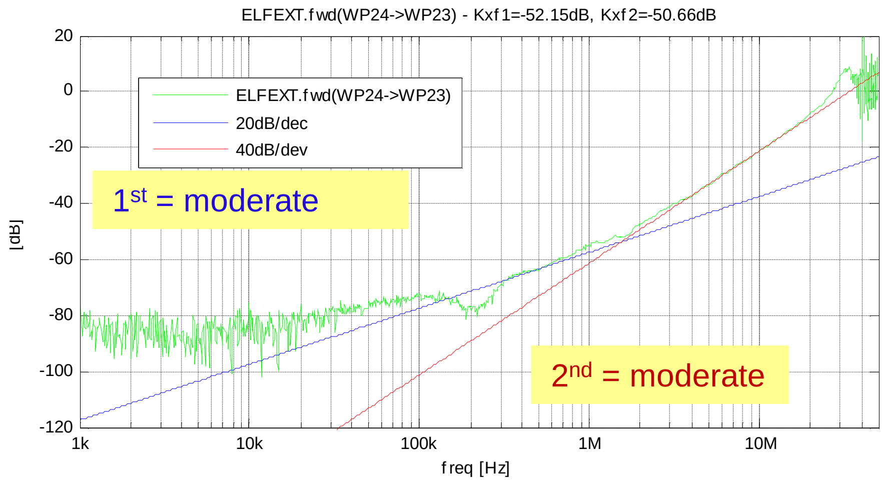
1. FEXT crosstalk measurements in telephony cabling

Other example: 280m, GPLK (paper insulated), drum, in-quad



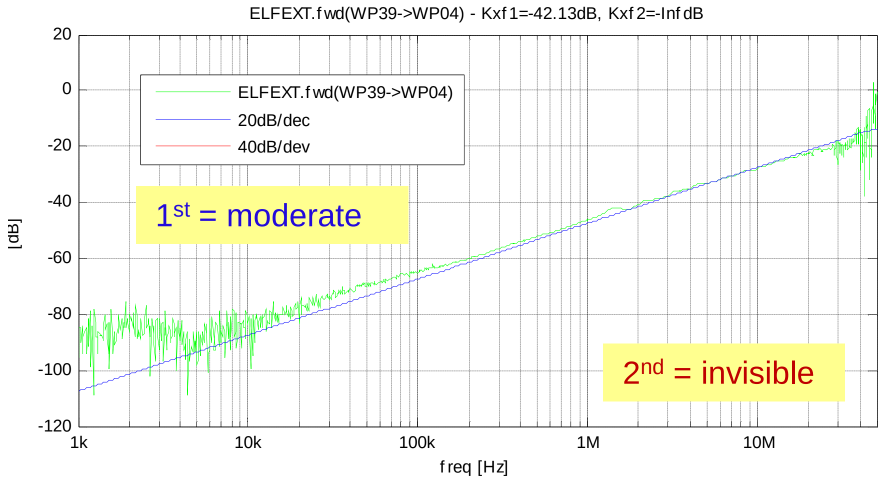


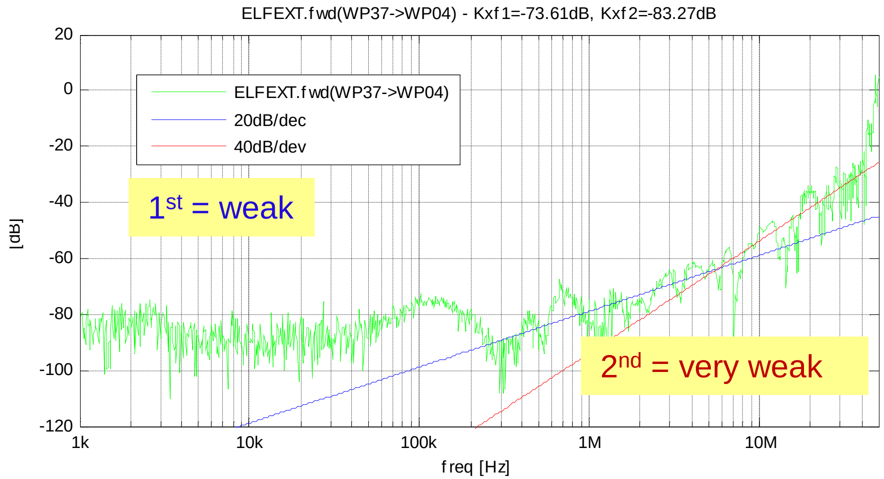


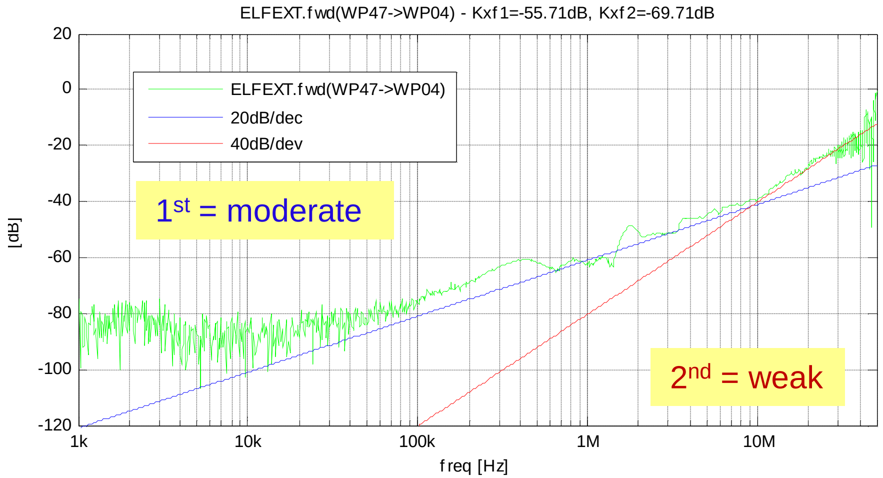


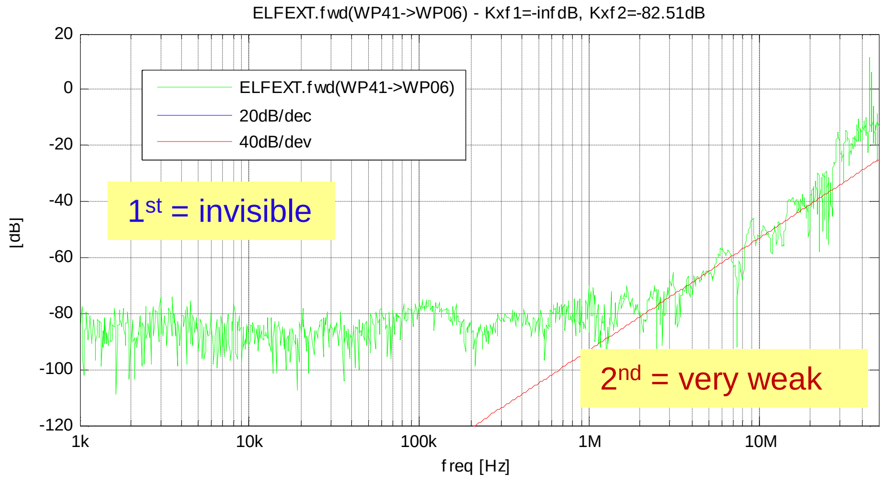
1. FEXT crosstalk measurements in telephony cabling

Other example: 280m, GPLK (paper insulated), drum: between quads









1. FEXT crosstalk measurements in telephony cabling

Summary of observations so far

	In-quad	Between quads
1st order crosstalk	Moderate **à** very strong	Invisible **à** moderate
2nd order crosstalk	Moderate **à** strong	Invisible **à** weak

Observations so far:

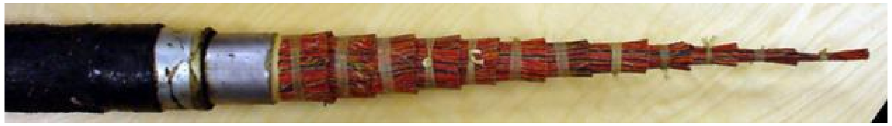
- Crosstalk with mix of 1st and 2nd order effect
- Crosstalk with 1st order only (*2nd order invisible*)
- Crosstalk with 2nd order only (*1st order invisible*)
- 2nd order effect observed in both in-quad and between quads
- In-quad crosstalk more pronounced

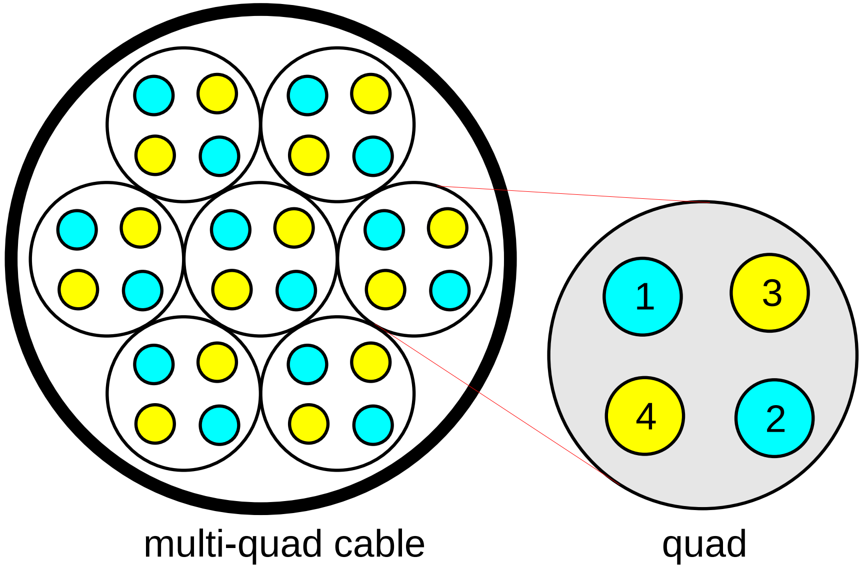
  à Dual slope more visible

  à Lets focus on in-quad crosstalk to gain understanding

2. Understanding the cause of crosstalk

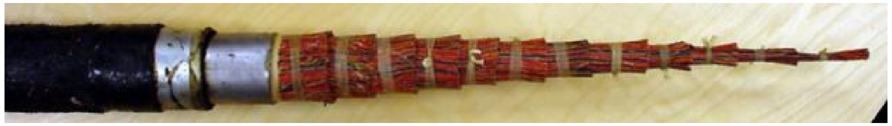
Cause of the first order effect (well known)

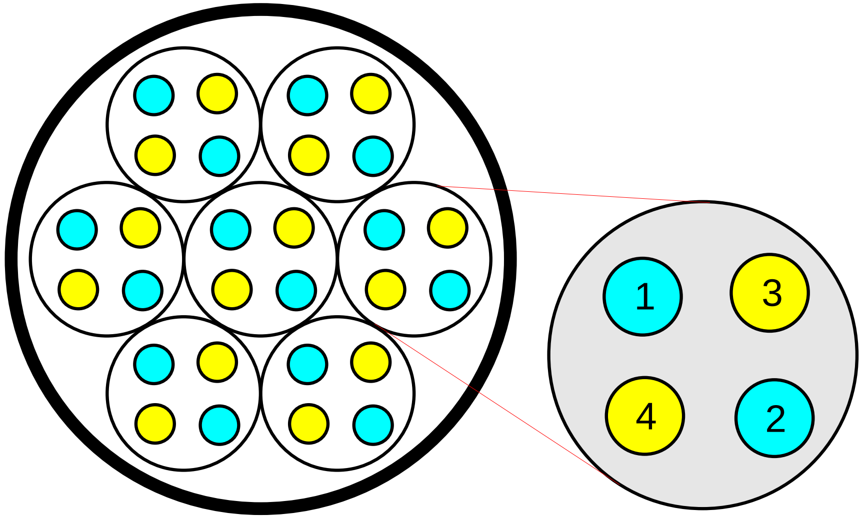




2. Understanding the cause of crosstalk

Cause of the first order effect (well known)

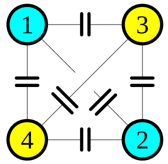




multi-quad cable

quad

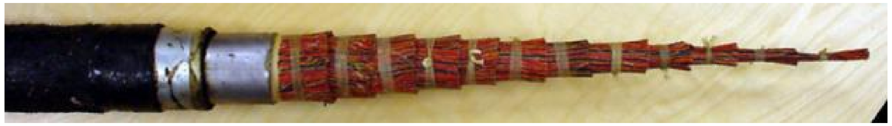
perfect square
capacitive balance
no crosstalk

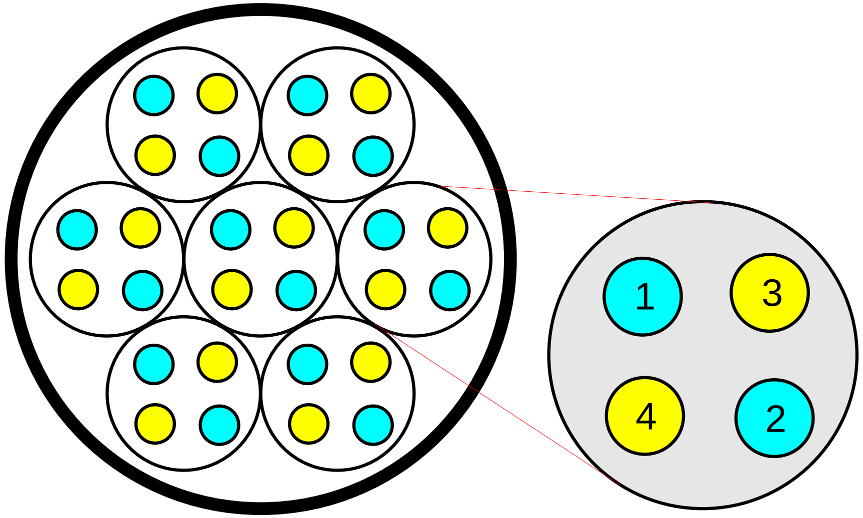


circuit equivalent

2. Understanding the cause of crosstalk

Cause of the first order effect (well known)





multi-quad cable

quad

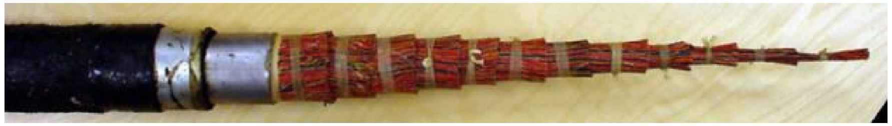
perfect square
capacitive balance
no crosstalk

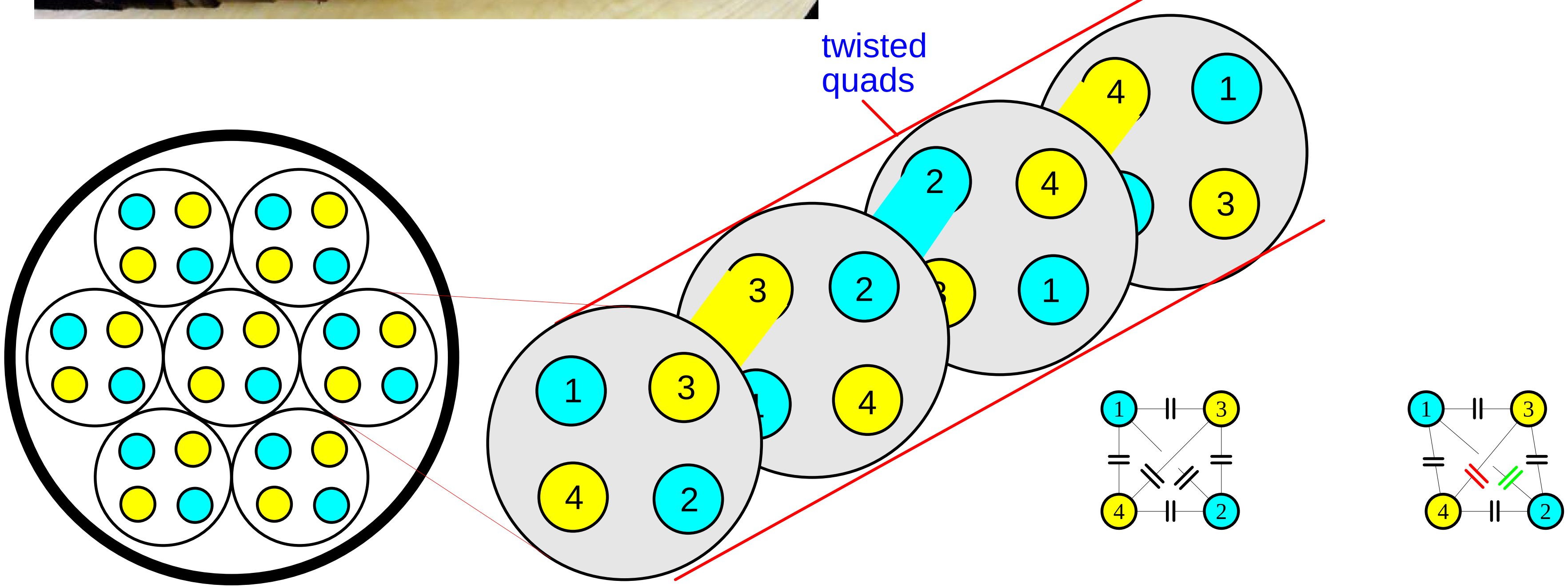
random variations
small unbalance
crosstalk

circuit equivalent

2. Understanding the cause of crosstalk

Cause of the first order effect (well known)





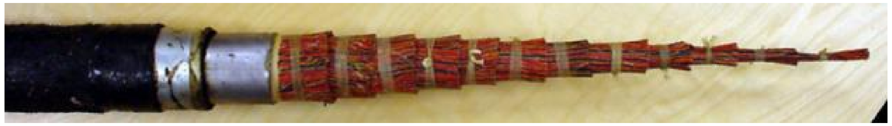
multi-quad cable quad circuit equivalent

Twisting can reduce crosstalk

- Does not reduce 1st order effect within a quad
- Reduces 1st order crosstalk between different quads
- Different quads should have different twist lengths

2. Understanding the cause of crosstalk

Cause of the first order effect (well known)



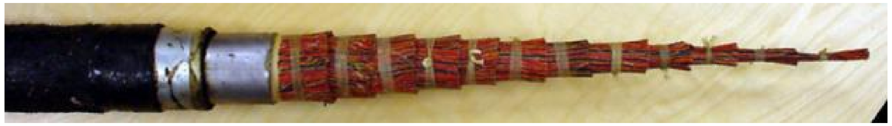
First order effect of EL-FEXT (well known):

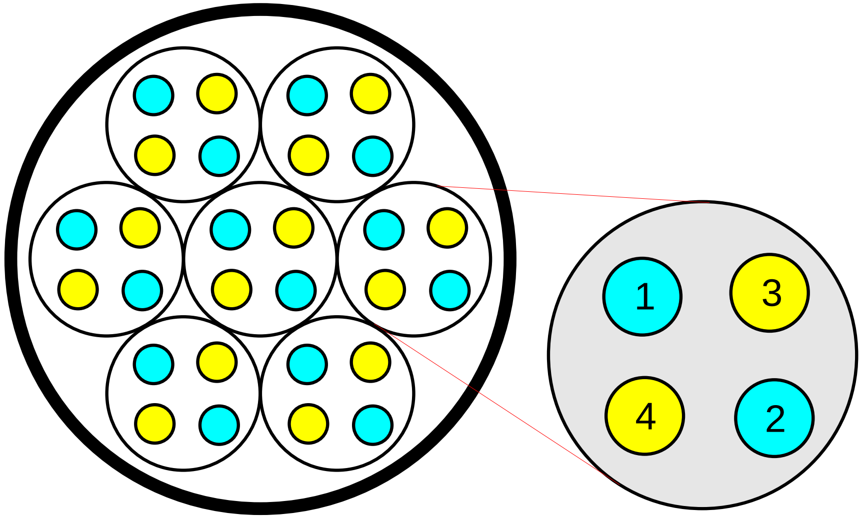
- Random perturbation of balance by imperfect geometry
- Scales proportionally with frequency (20 dB/decade)
- Scales with the root of the cable length (√L)

Bell technical staff, *Transmission Systems for Communications,* Bell Telephone Laboratories, 1969 (1st ed 1954)

2. Understanding the cause of crosstalk

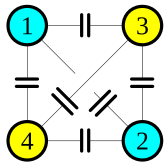
Cause of the second order effect





multi-quad cable

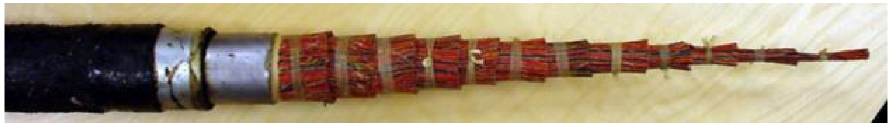
quad

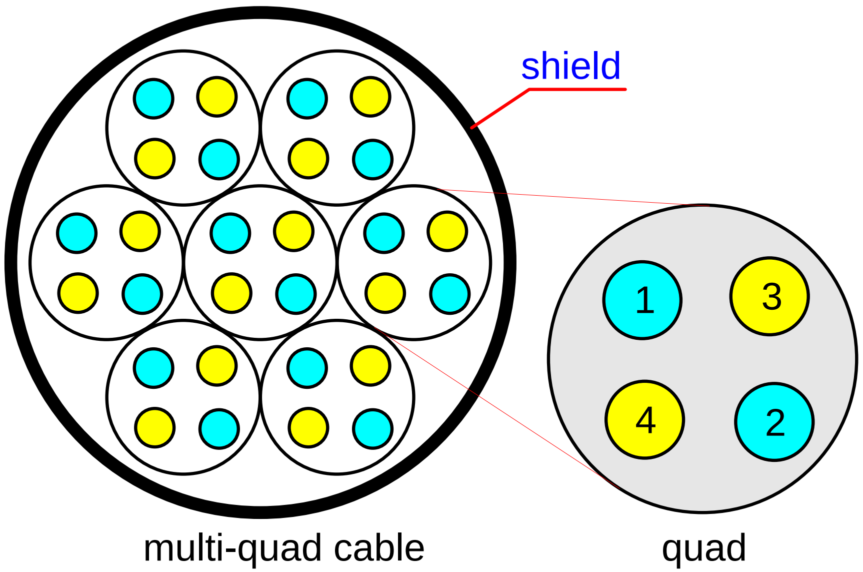


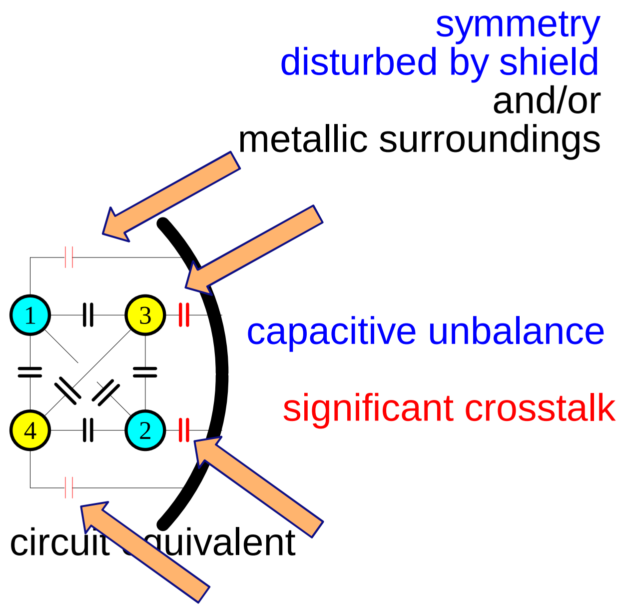
circuit equivalent

2. Understanding the cause of crosstalk

Cause of the second order effect

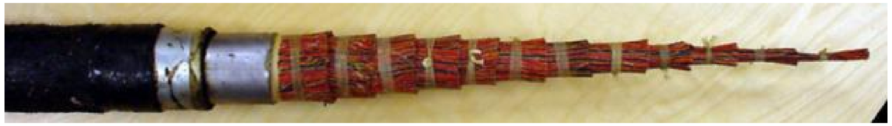


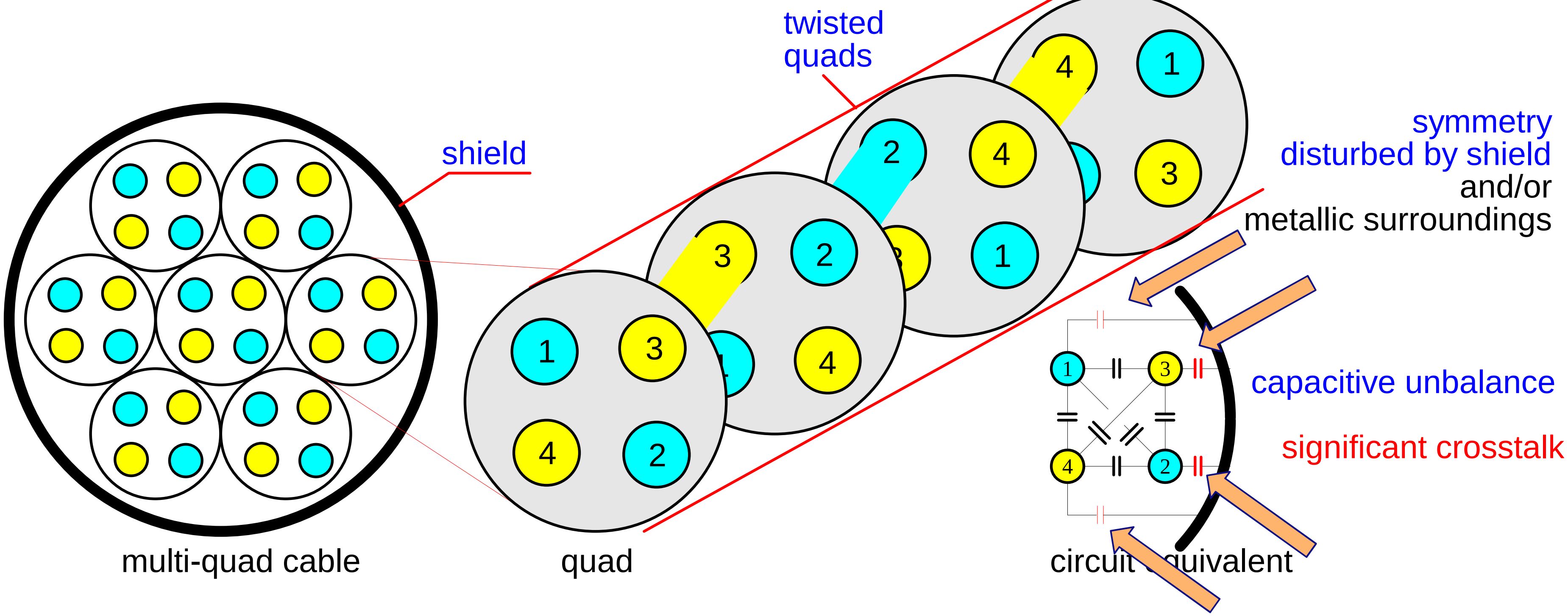




2. Understanding the cause of crosstalk

Cause of the second order effect

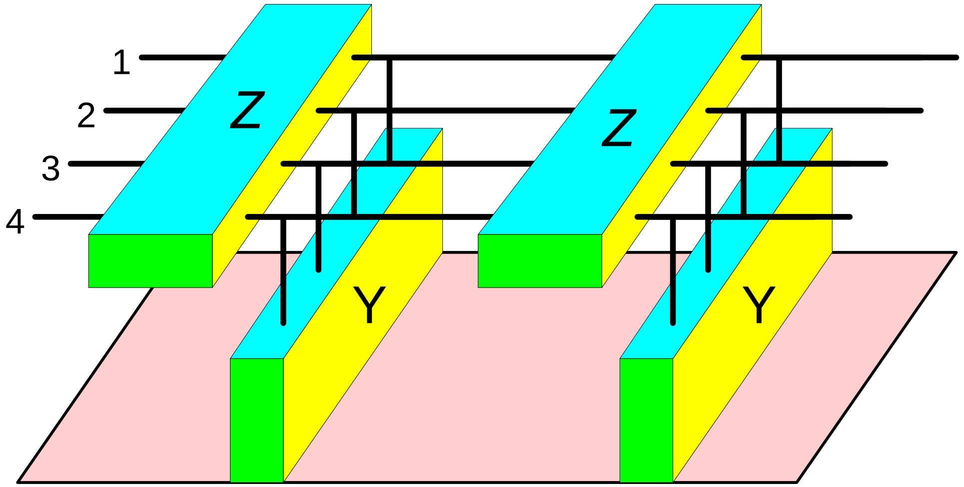




Twisting a quad restores capacitive balance only on *average*
Significant crosstalk reduction within the quad à residual crosstalk
Tighter twisting of a quad à lowers residual crosstalk (= 2nd order effect)

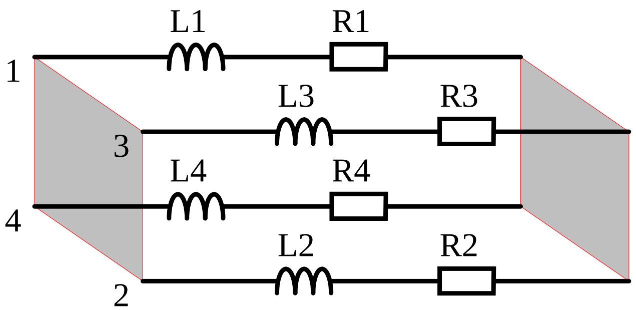
3. Brute force modelling crosstalk within a quad

Four wires and a shield = eight port

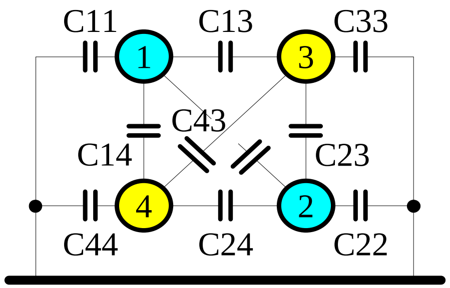


$$\frac{\partial}{\partial z}\mathbf{U}(z) = -\mathbf{Z}_s \cdot \mathbf{I}(z)$$

$$\frac{\partial}{\partial z}\mathbf{I}(z) = -\mathbf{Y}_p \cdot \mathbf{U}(z)$$



Z

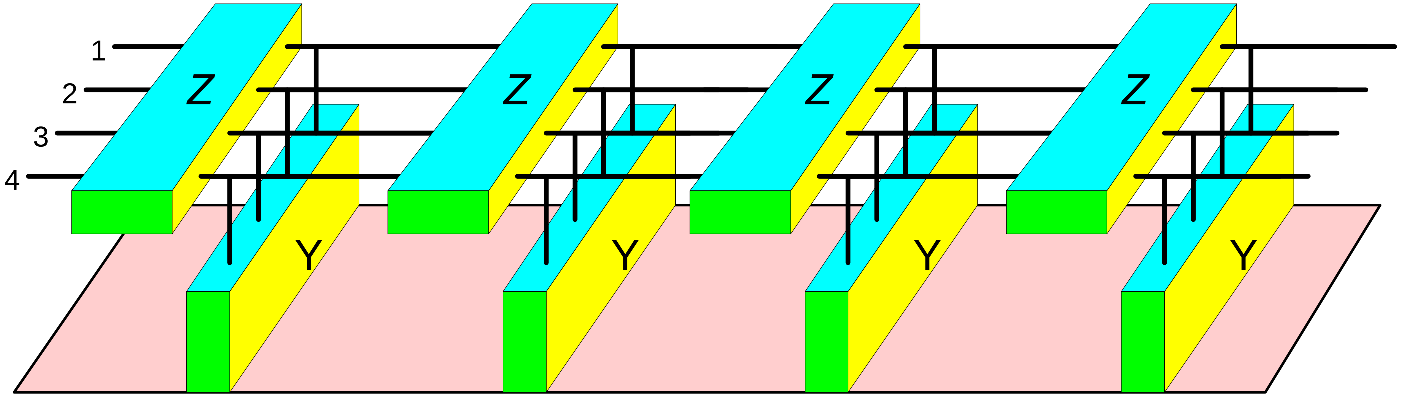


Y

Clayton R. Paul, *Analysis of multiconductor transmission lines,* IEEE press, 2008

3. Brute force modelling crosstalk within a quad

"Infinite" cascade **à** eight port cable model

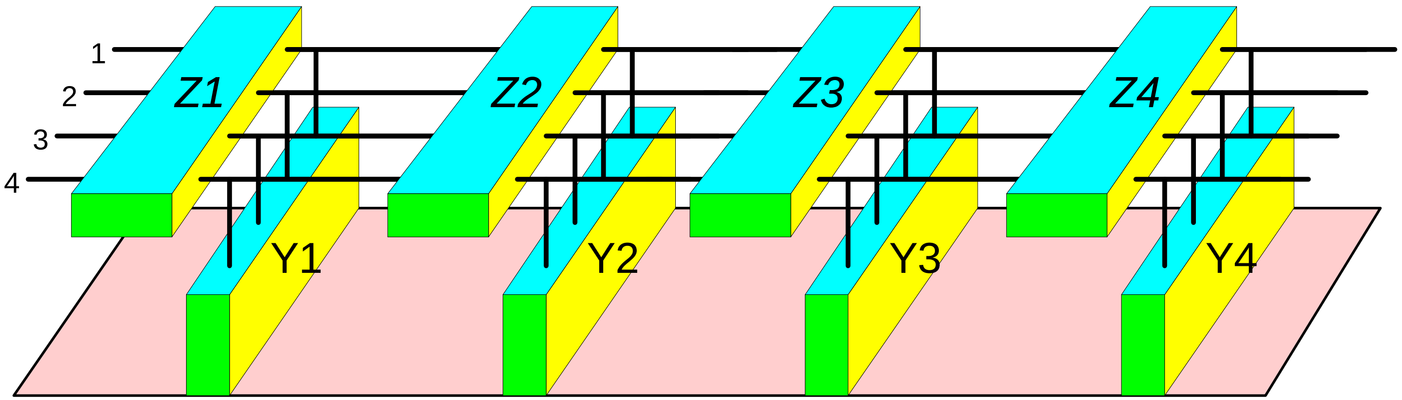


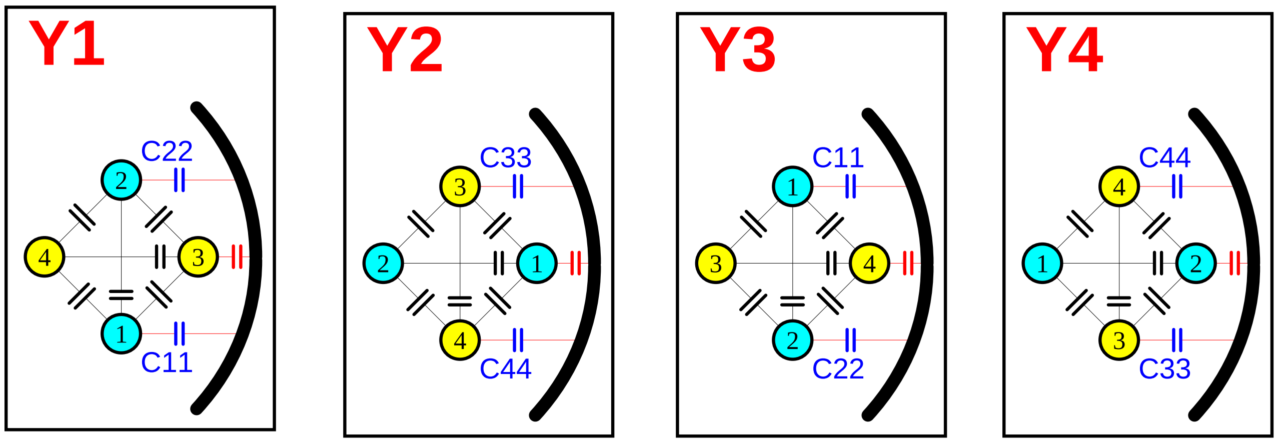
With only 9 values (for R,L,C) you can do a very good cable simulation ……

…. but the dual slope effect will not be visible

3. Brute force modelling crosstalk within a quad

"Infinite" cascade **à** eight port cable model **à** adding a twist





Cascade of piecewise uniform segments can add the twist to the cable

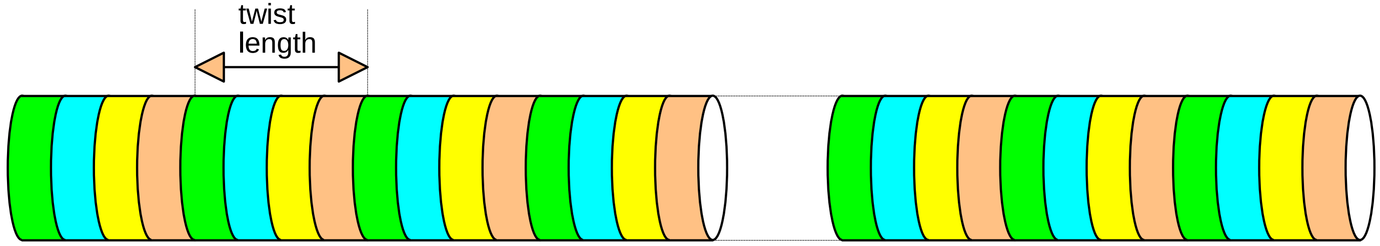
4 sections/twist ?
16 sections/twist ?
64 sections/twist ?

Y1	Y2	Y3	Y4
C11=Cc	C11=Cc+dC	C11=Cc	C11=Cc-dC
C22=Cc	C22=Cc-dC	C22=Cc	C22=Cc+dC
C33=Cc+dC	C33=Cc	C33=Cc-dC	C33=Cc
C44=Cc-dC	C44=Cc	C44=Cc+dC	C44=Cc

$$C_{11} = C_c / (1 + \Delta_c \cdot \sin(2p \cdot k/n \cdot \Delta L))$$
$$C_{22} = C_c / (1 - \Delta_c \cdot \sin(2p \cdot k/n \cdot \Delta L))$$
$$C_{33} = C_c / (1 + \Delta_c \cdot \cos(2p \cdot k/n \cdot \Delta L))$$
$$C_{44} = C_c / (1 - \Delta_c \cdot \cos(2p \cdot k/n \cdot \Delta L))$$

3. Brute force modelling crosstalk within a quad

"Infinite" cascade à eight port cable model



Twist length = 3 cm
Cable length = 300m
Model with 4 segments per twist

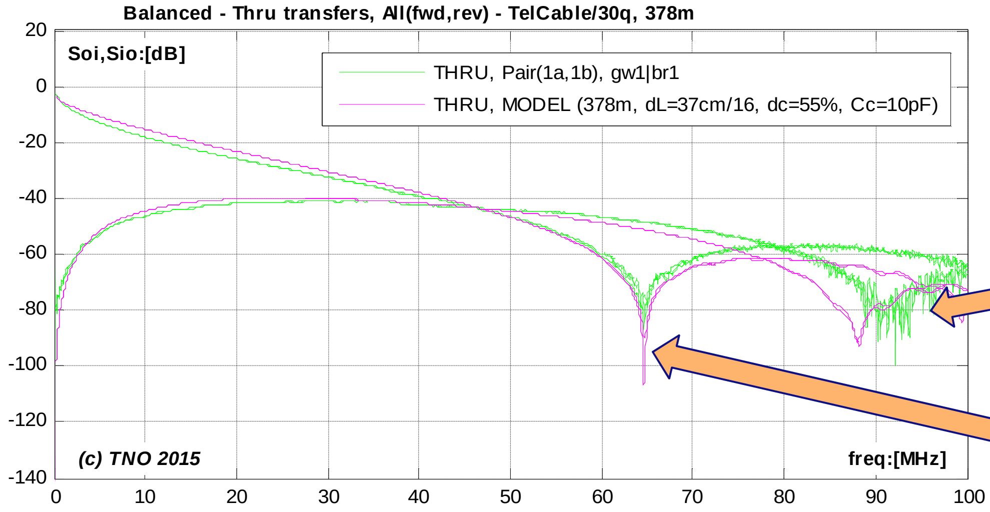
à 10000 twists in a cable
à 40000 segments in a cable
à And they all should go in the cascade

That was the theory,

But is it also realistic,
and is it good enough?

3. Brute force modelling crosstalk within a quad

Match between model and measurement



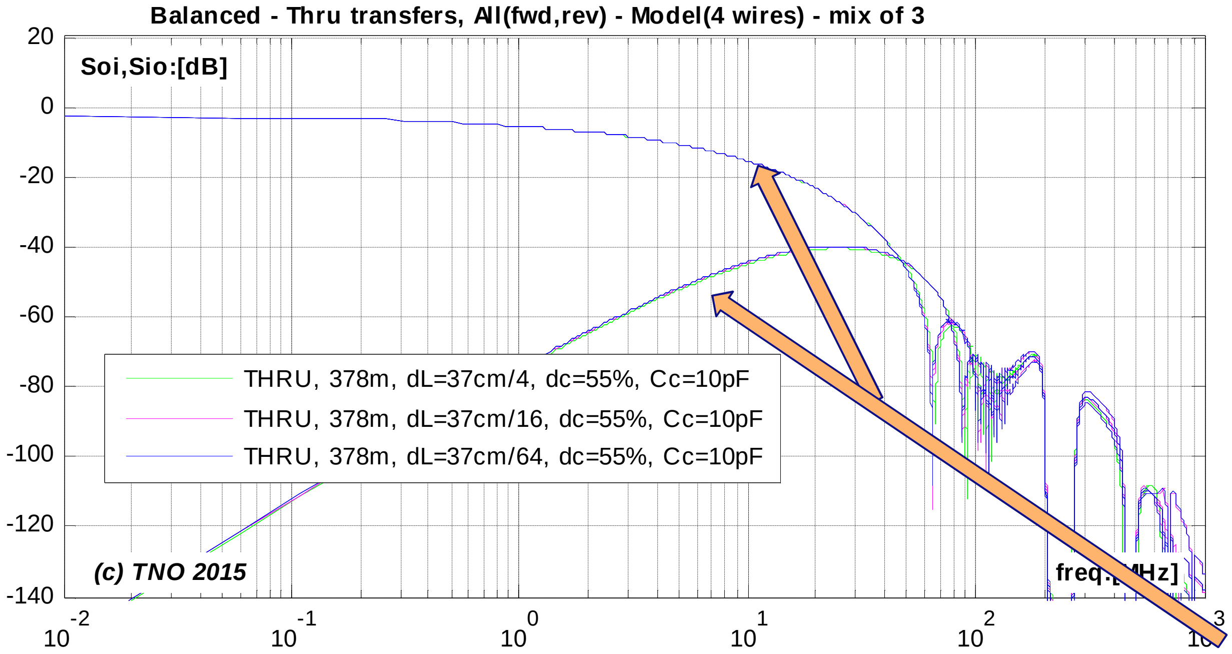
Very good match between model and measurement

This error is because we ignored that insulator has a frequency dependency

Even the dip is well modelled

3. Brute force modelling crosstalk within a quad

How many segments per twist are needed for a good match?



Three different simulation runs …

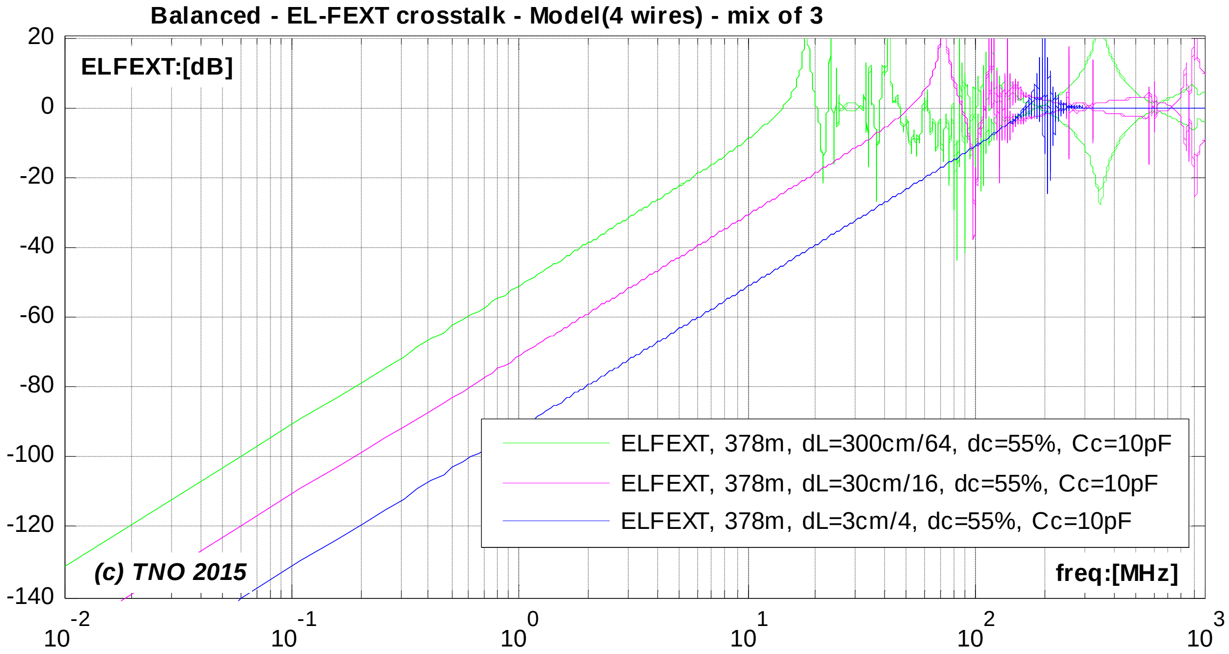
With different segments/twist
- **4 segments/twist**
- **16 segments/twist**
- **64 segments/twist**

You cannot see the difference!

4 segments/twist appears to be enough!

3. Brute force modelling crosstalk within a quad

Dual slope effect, as a function of the twist length



Three different simulation runs

With different twist lengths

300 cm

30 cm

3 cm

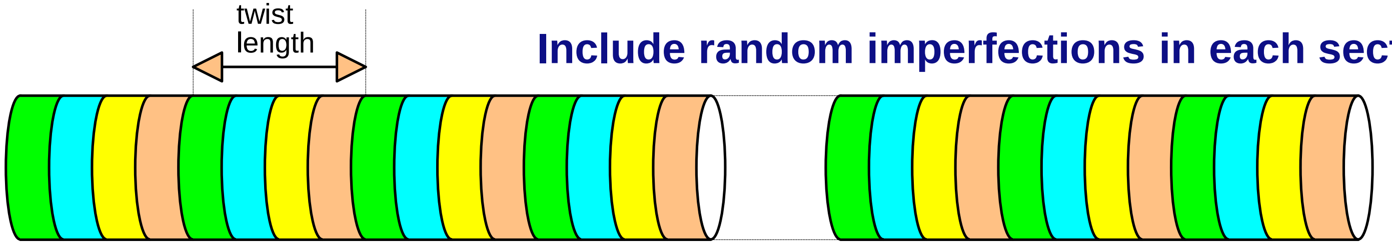
EL-FEXT has 40 dB slope (second order effect)
Even when all random perturbations (first order effect) is absent

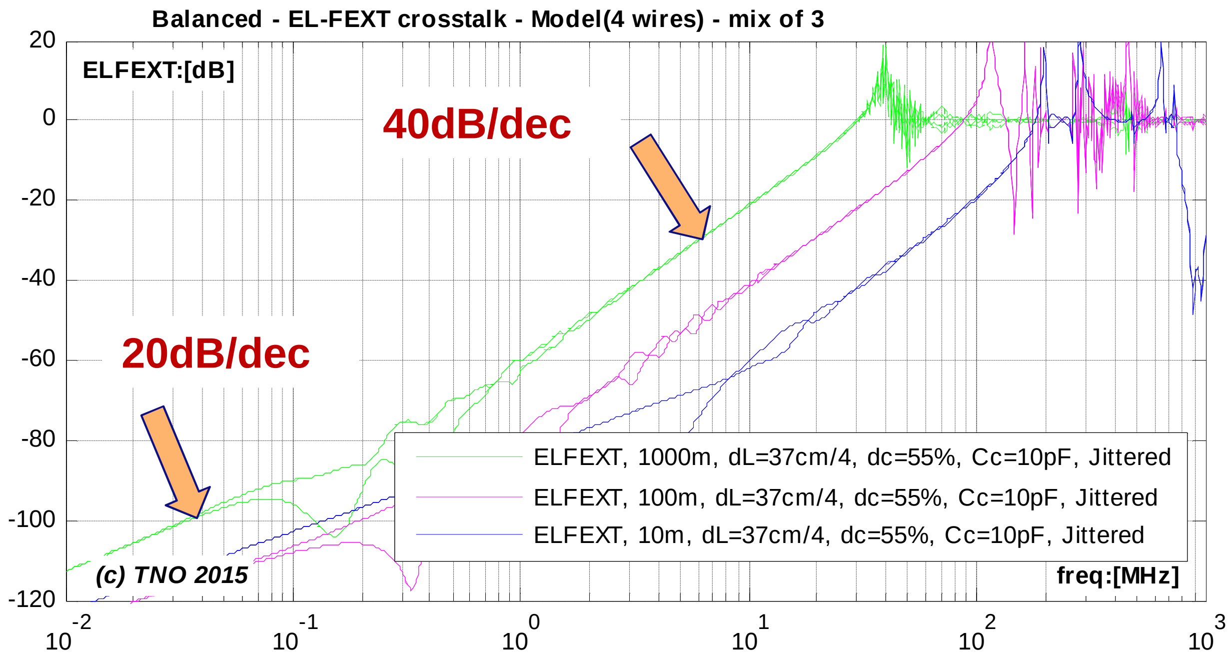
An decrease of the twist length by a factor 10 …
… decreases the EL-FEXT by 20 dB (second order effect)

3. Brute force modelling crosstalk within a quad

Fair prediction as function of frequency and cable length
for both the first ***and*** second order effects!

Include random imperfections in each section as well





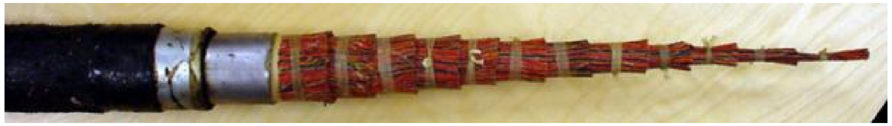
Three different simulation runs

Changing the loop length

10m
100m
1000m

3. Brute force modelling crosstalk within a quad

Cause of the first and second order effect (well known)



First order effect of EL-FEXT (well known):

- Random perturbation of balance by imperfect geometry
- Scales proportionally with frequency (20 dB/decade)
- Scales with the root of the cable length ($\sqrt{L}$)
  (*only on a statistical sense*)

Second order effect of EL-FEXT

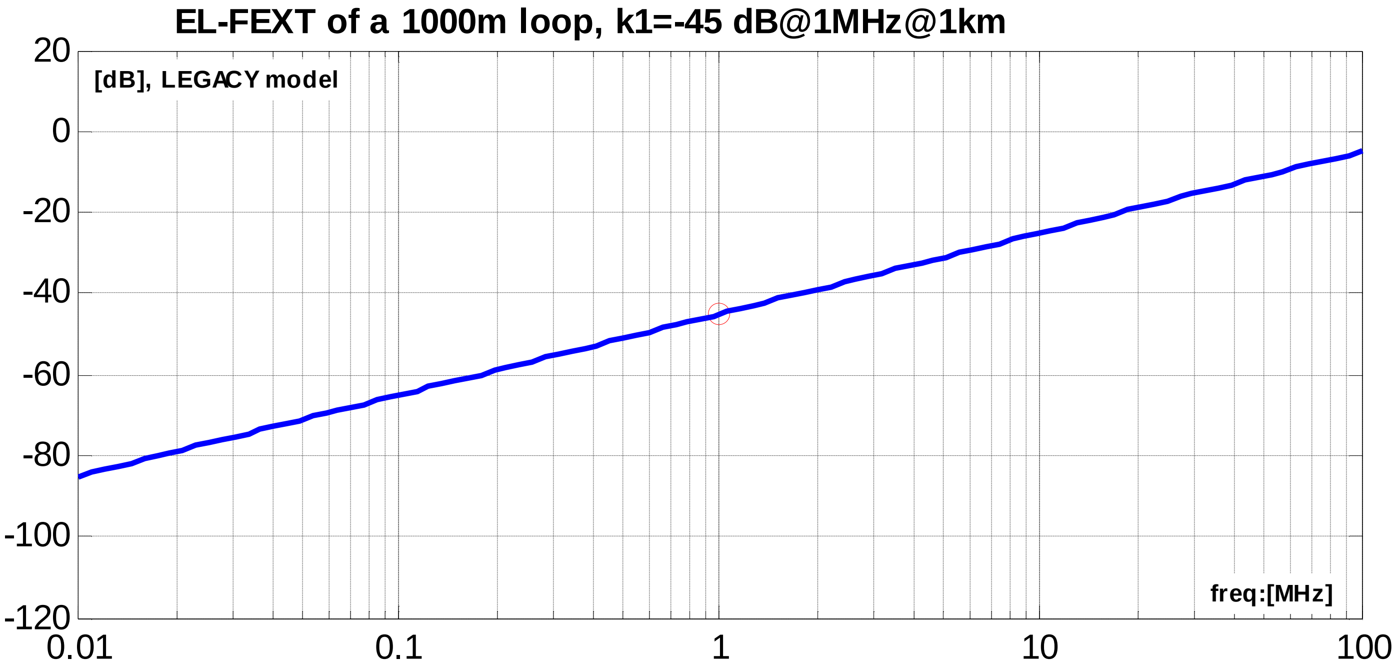
- Deterministic perturbation of balance by metallic surroundings
- Scales proportionally with square of frequency (40 dB/decade)
- Scales with the cable length (L)

4. Simplifying the system model on EL-FEXT

Fair prediction as function of frequency and cable length

Legacy system model for EL-FEXT (first order only, ETSI TR 101 830-2)

- **First order slope of 20 dB/decade**
- **Scales with the root of cable length**
- **No second order slope**
- **Infinite high EL-FEXT at high frequencies**

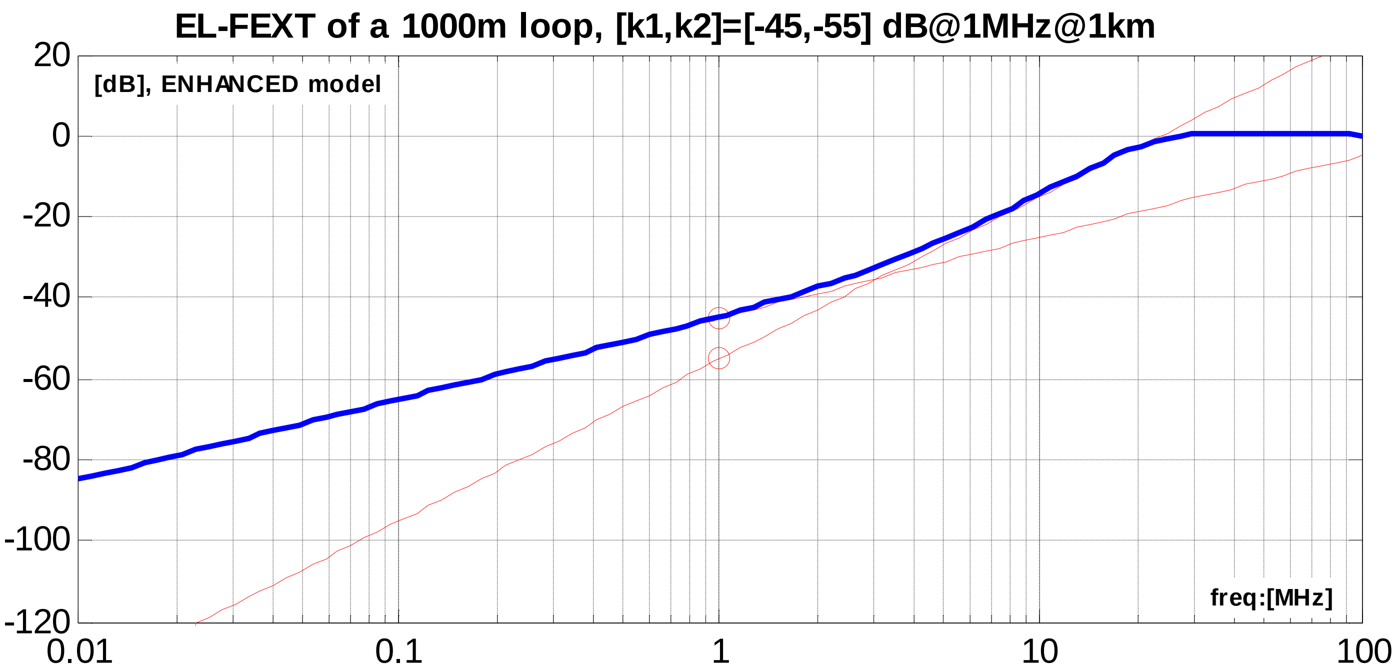


4. Simplifying the system model on EL-FEXT

Fair prediction as function of frequency and cable length

<u>Enhanced system model</u> for EL-FEXT (first + second order)

- **First order slope of 20 dB/decade**
- **Second order slope of 40 dB/decade**
- **Does not exceed 0dB for high frequencies**
- **First order slope scales with the root of cable length**
- **Second order slope scales linear with the cable length**

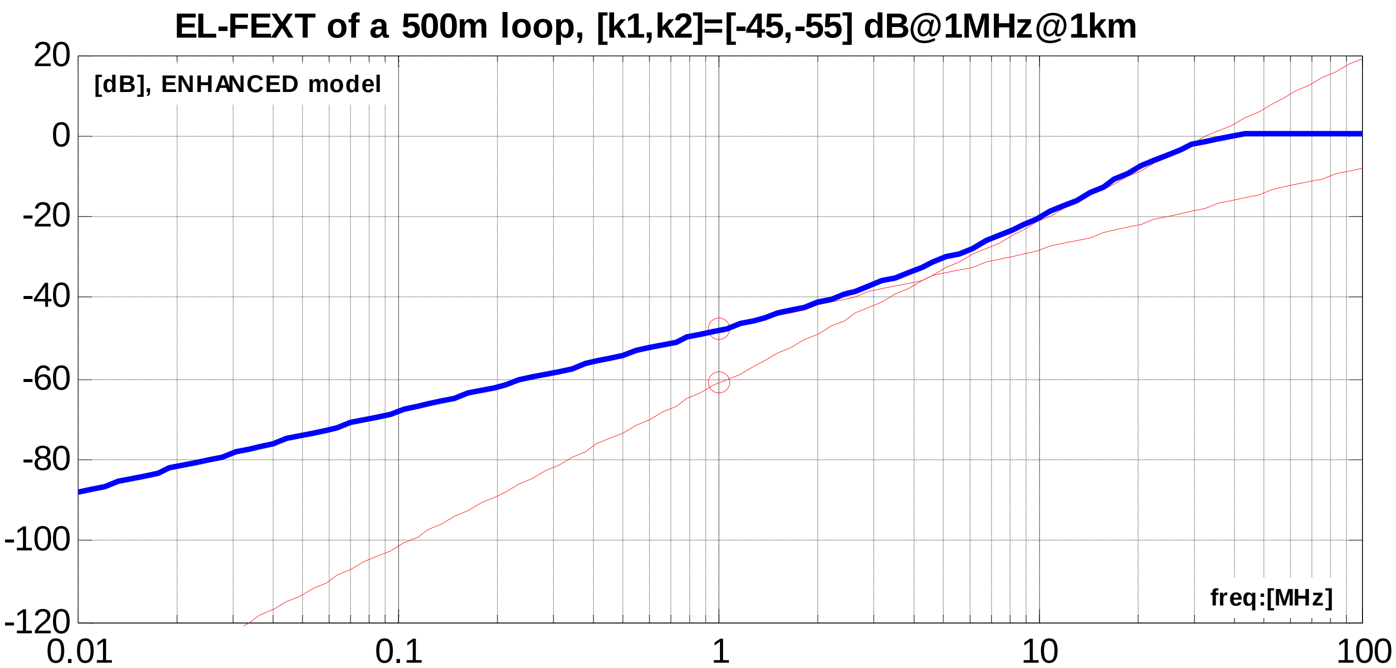


4. Simplifying the system model on EL-FEXT

Fair prediction as function of frequency and cable length

Enhanced system model for EL-FEXT (first + second order)

- **First order slope of 20 dB/decade**
- **Second order slope of 40 dB/decade**
- **Does not exceed 0dB for high frequencies**
- **First order slope scales with the root of cable length**
- **Second order slope scales linear with the cable length**

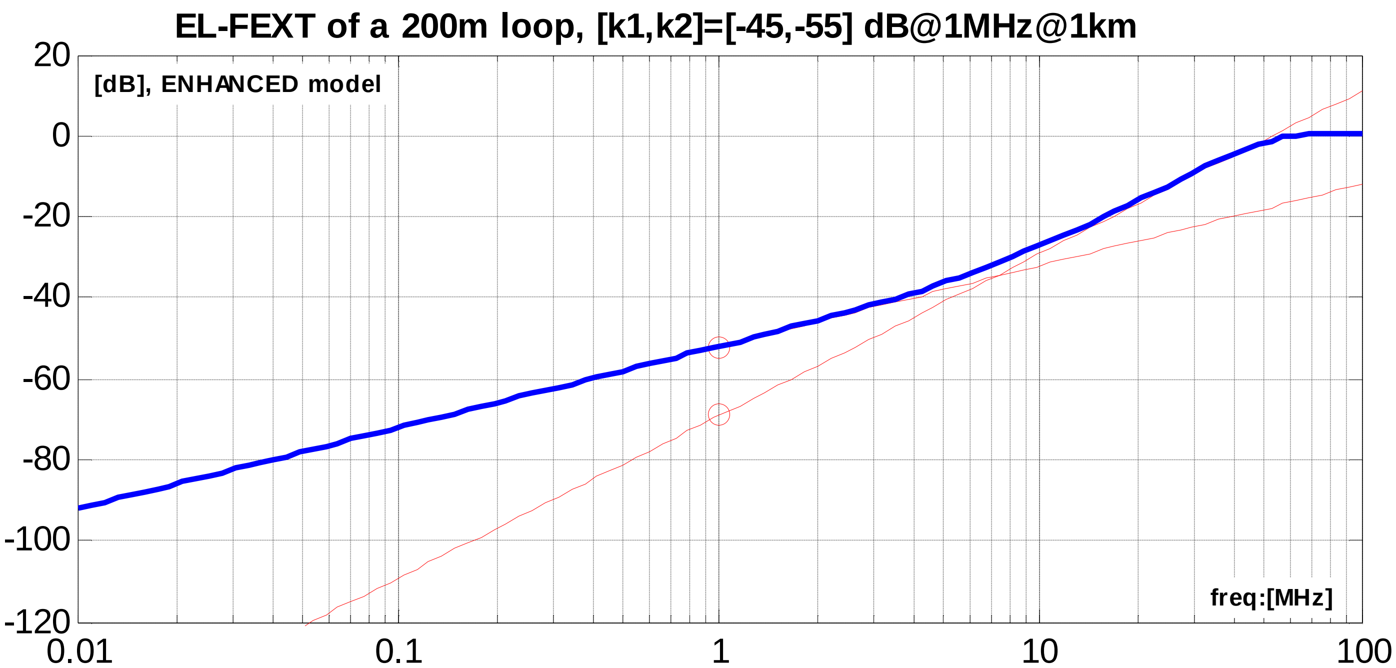


4. Simplifying the system model on EL-FEXT

Fair prediction as function of frequency and cable length

<u>Enhanced system model</u> for EL-FEXT (first + second order)

- **First order slope of 20 dB/decade**
- **Second order slope of 40 dB/decade**
- **Does not exceed 0dB for high frequencies**
- **First order slope scales with the root of cable length**
- **Second order slope scales linear with the cable length**

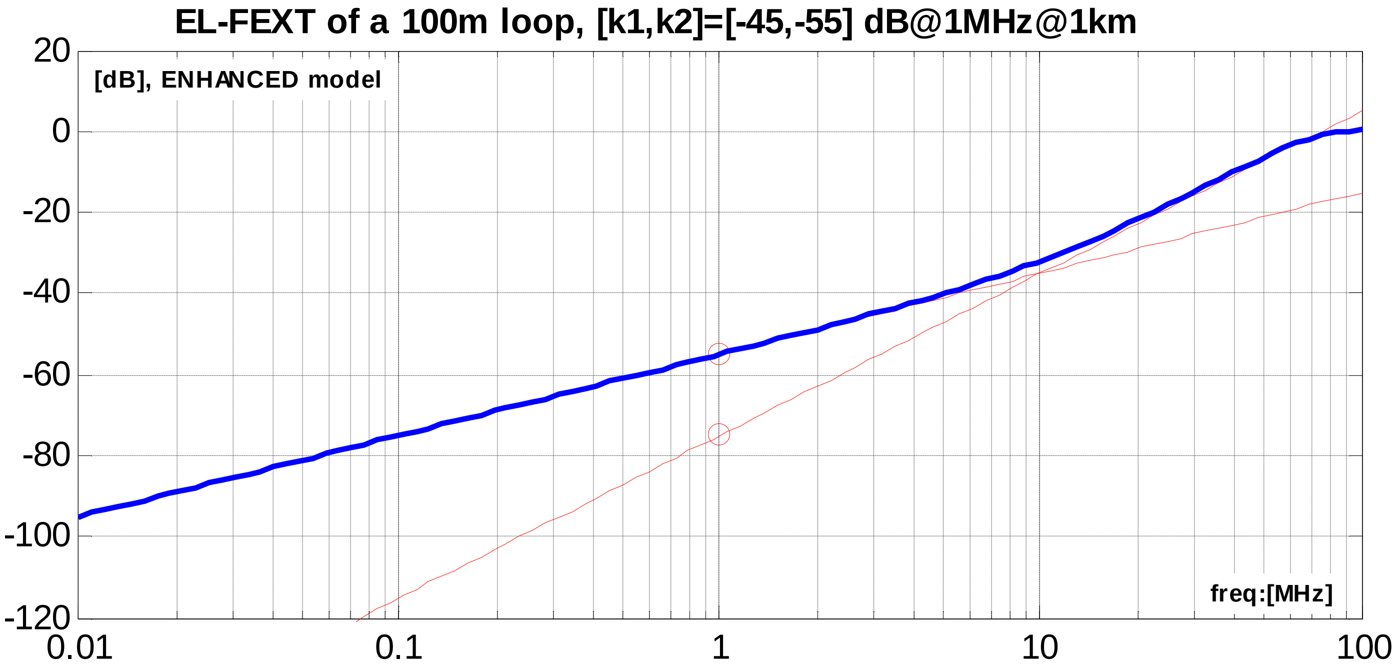


4. Simplifying the system model on EL-FEXT

Fair prediction as function of frequency and cable length

<u>Enhanced system model</u> for EL-FEXT (first + second order)

- **First order slope of 20 dB/decade**
- **Second order slope of 40 dB/decade**
- **Does not exceed 0dB for high frequencies**
- **First order slope scales with the root of cable length**
- **Second order slope scales linear with the cable length**

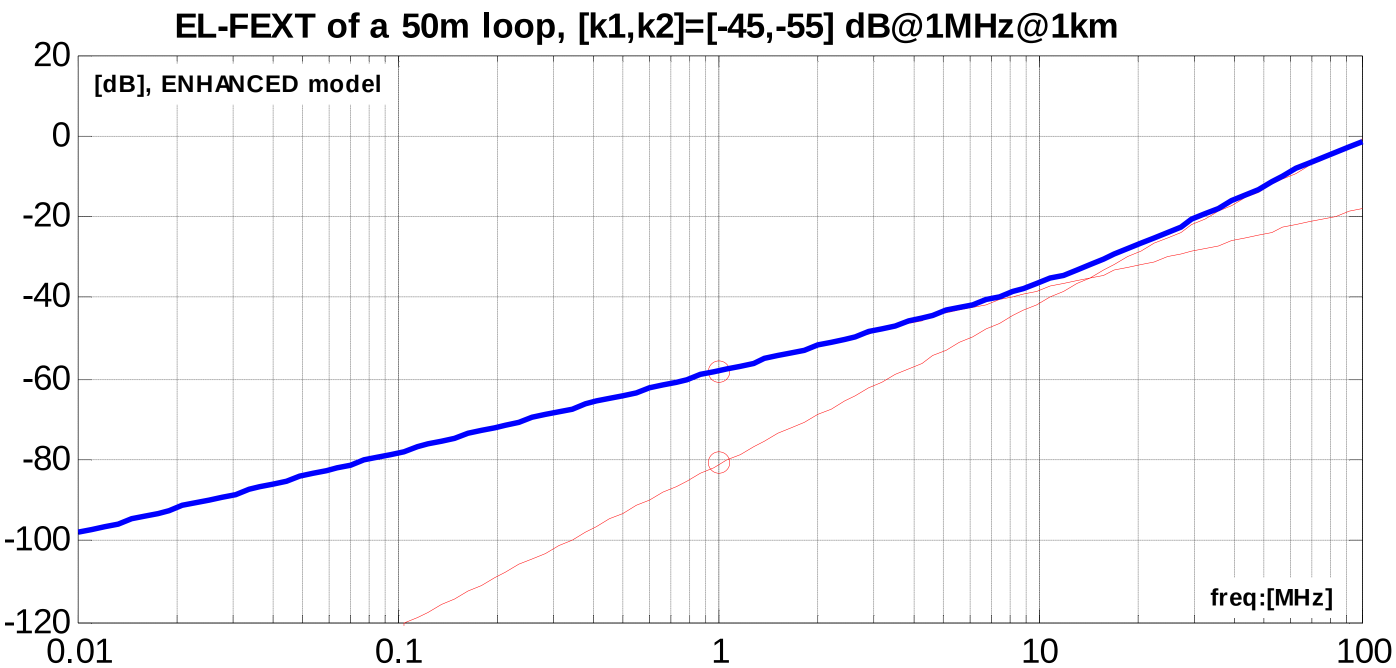


4. Simplifying the system model on EL-FEXT

Fair prediction as function of frequency and cable length

<u>Enhanced system model</u> for EL-FEXT (first + second order)

- **First order slope of 20 dB/decade**
- **Second order slope of 40 dB/decade**
- **Does not exceed 0dB for high frequencies**
- **First order slope scales with the root of cable length**
- **Second order slope scales linear with the cable length**

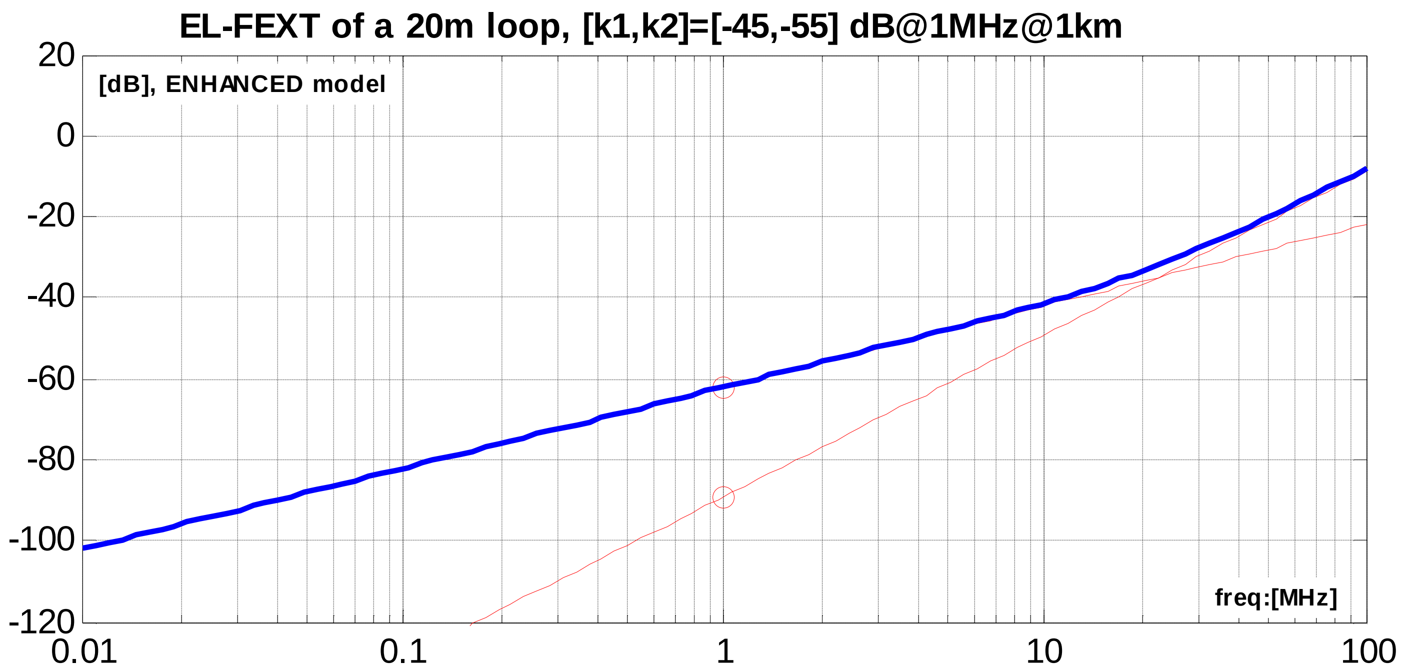


4. Simplifying the system model on EL-FEXT

Fair prediction as function of frequency and cable length

<u>Enhanced system model</u> for EL-FEXT (first + second order)

- **First order slope of 20 dB/decade**
- **Second order slope of 40 dB/decade**
- **Does not exceed 0dB for high frequencies**
- **First order slope scales with the root of cable length**
- **Second order slope scales linear with the cable length**

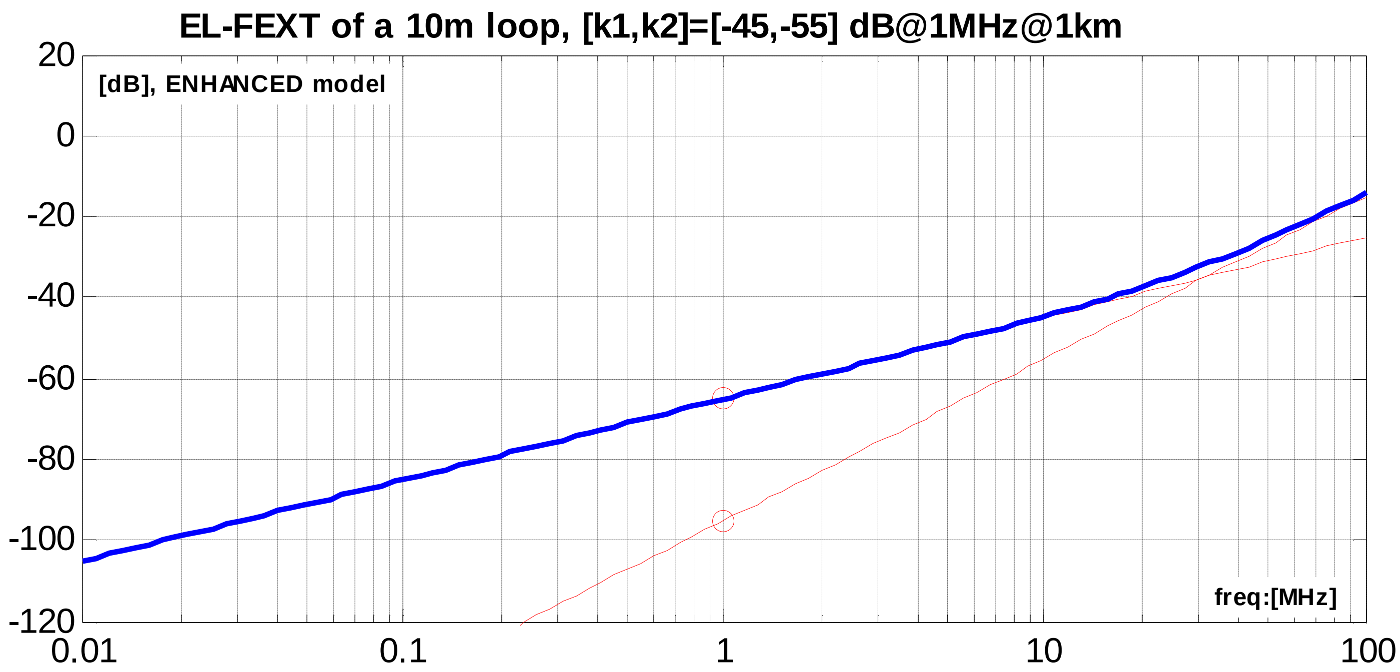


4. Simplifying the system model on EL-FEXT

Fair prediction as function of frequency and cable length

Enhanced system model for EL-FEXT (first + second order)

- **First order slope of 20 dB/decade**
- **Second order slope of 40 dB/decade**
- **Does not exceed 0dB for high frequencies**
- **First order slope scales with the root of cable length**
- **Second order slope scales linear with the cable length**



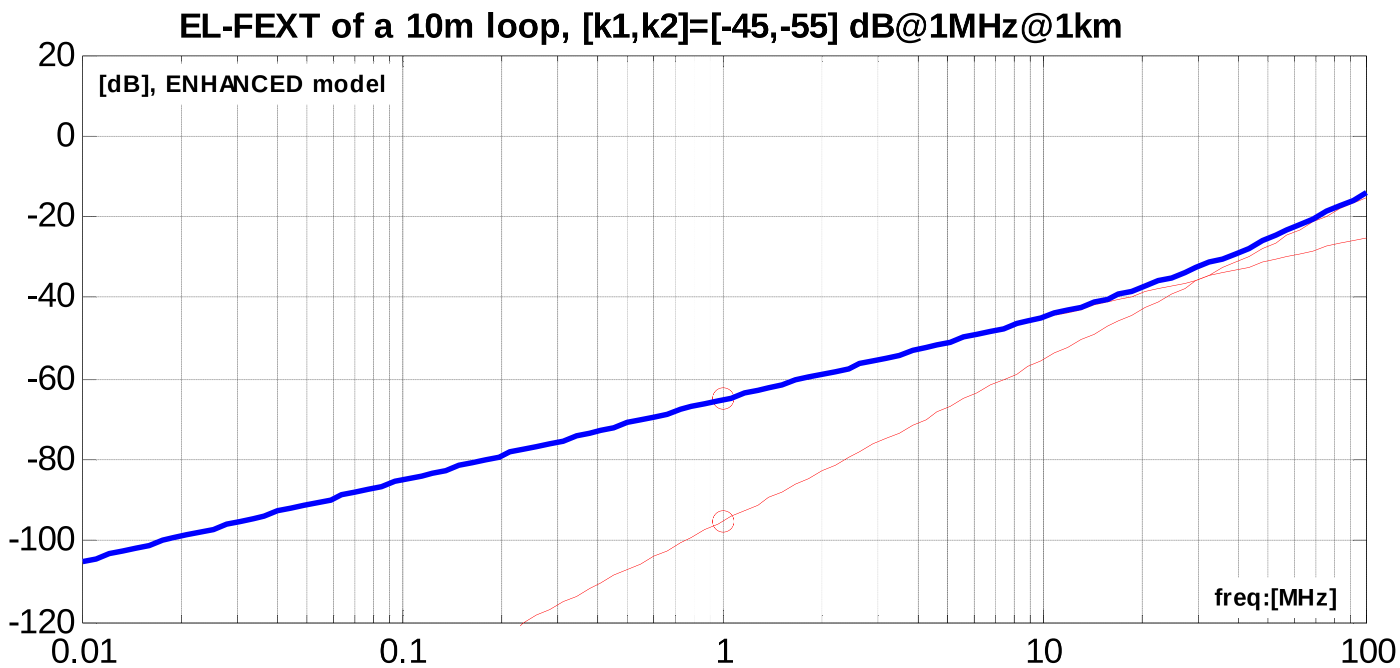
4. Simplifying the system model on EL-FEXT

Fair prediction as function of frequency and cable length

<u>Enhanced system model</u> for EL-FEXT (first + second order)

- **First order slope of 20 dB/decade**
- **Second order slope of 40 dB/decade**
- **Does not exceed 0dB for high frequencies**
- **First order slope scales with the root of cable length**
- **Second order slope scales linear with the cable length**

A second order high-pass filter curve meets all these requirements



4. Simplifying the system model on EL-FEXT

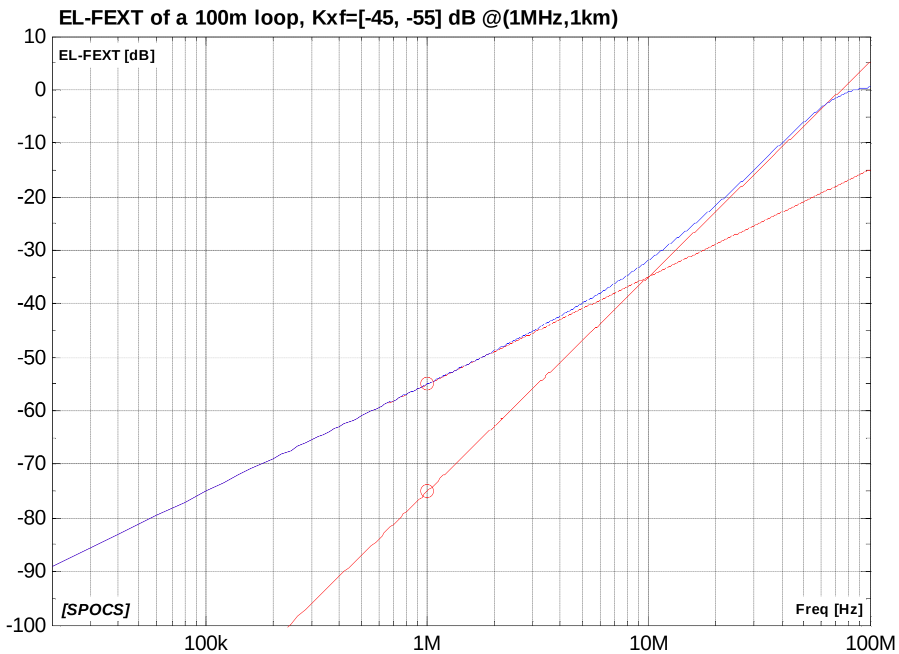
Fair prediction as function of frequency and cable length

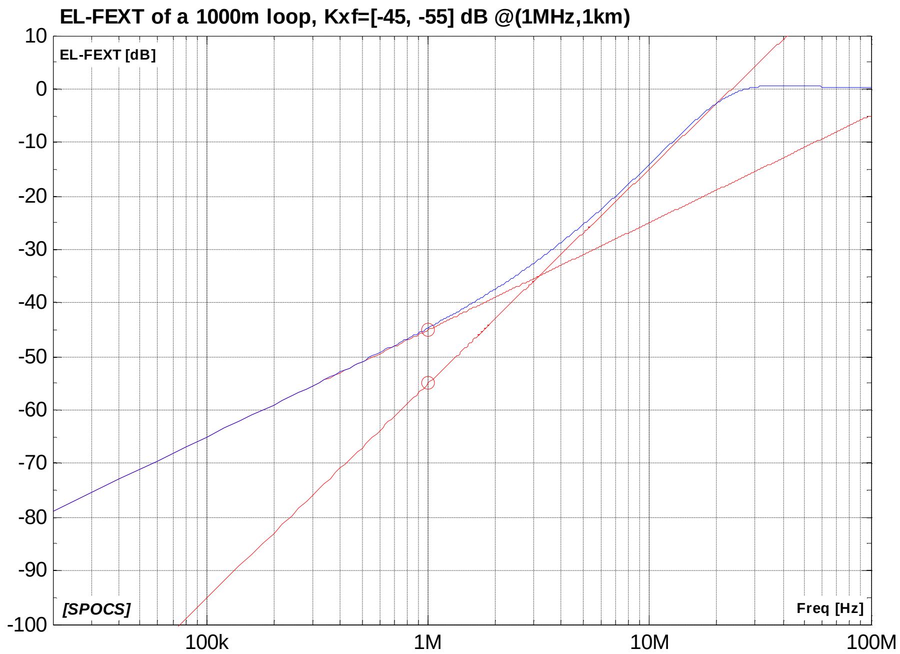
Enhanced model for EL-FEXT (first + second order)

$$H_{ELFEXT}(jw, L) = \left\| \frac{k_1(L)\cdot\left(\frac{jw}{w_0}\right) + k_2(L)\cdot\left(\frac{jw}{w_0}\right)^2}{1 + \left(k_1(L) + \sqrt{k_2(L)}\right)\cdot\left(\frac{jw}{w_0}\right) + k_2(L)\cdot\left(\frac{jw}{w_0}\right)^2} \right\|$$

e.g.
K_{XF1} = -45dB (@1MHz, 1km)
K_{XF2} = -55dB (@1MHz, 1km)

where $k_1(L) = K_{XF1}\cdot\sqrt{(L/L_0)}$, and $k_2(L) = K_{XF2}\cdot(L/L_0)$





5. Conclusions

Discussed the dual slope effect in crosstalk (EL-FEXT)

- EL-FEXT increases more rapidly at higher frequencies (40 dB/decade):
  - Dual slope effect in EL-FEXT raised in ITU, *Feb 2012* (2012-04-4A-038)
  - Confirmed by many measurements in different labs.
  - Has an impact on both G.fast and VDSL performance (above a few MHz)
  - Vector engines should cope with it.

- Achieved a good understanding on the origin of this effect:
  - Derived via an advanced brute force multi-port model of a cable (L,C,R)
  - 2nd order effect due to *deterministic* interaction of twist in quads and their metallic surroundings
  - 1st order effect due to *random* perturbation in geometry
  - Both effects are independent from each other
  - Both effects scale differently with cable length
  - Details in IEEE paper (submitted in Jan & May 2016)


Modeling the dual-slope behavior of in-quad EL-FEXT in twisted pair quad cables

- Proposed a simple FEXT model for performance simulations:
  - Simple extension to legacy crosstalk model (ETSI)
  - Handles magnitude (both slopes) and length scaling quite well
  - Convenient for performance simulations on VDSL & G.fast
  - Contributed to ITU, *April 2016* (2016-04-Q4-021), recommended for BBF TR-285

"Dual slope" effect in EL-FEXT is now well understood