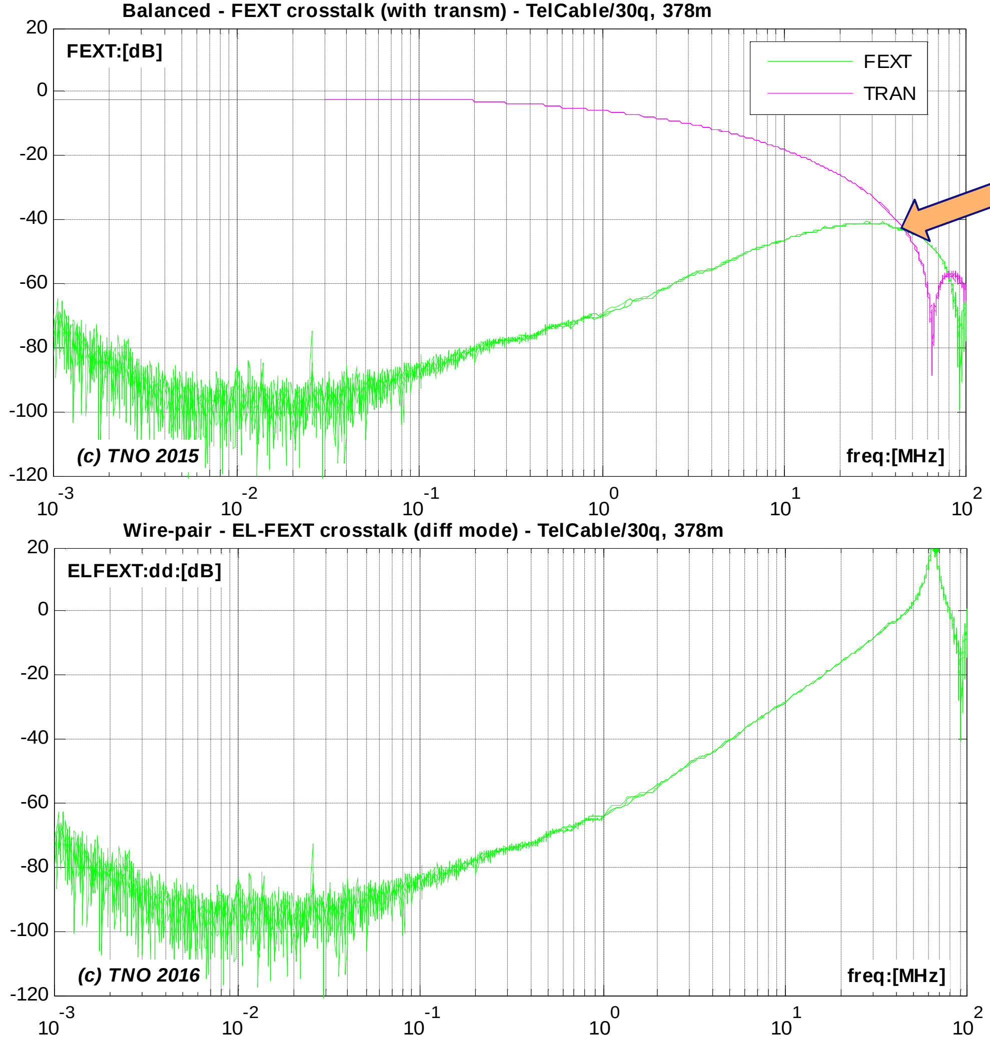
Understanding the dual-slope effect in crosstalk (EL-FEXT)

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

EL-FEXT = FEXT (crosstalk) / TRAN (signal)

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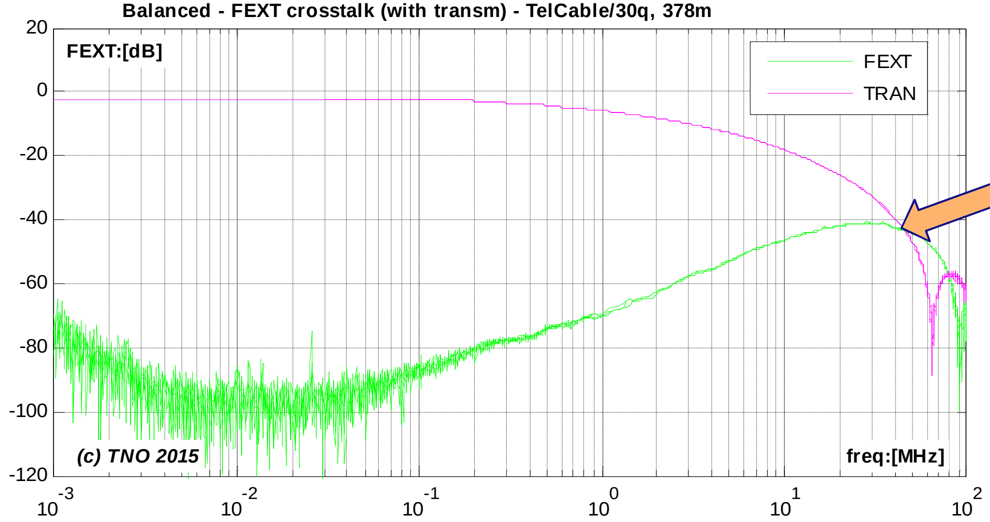

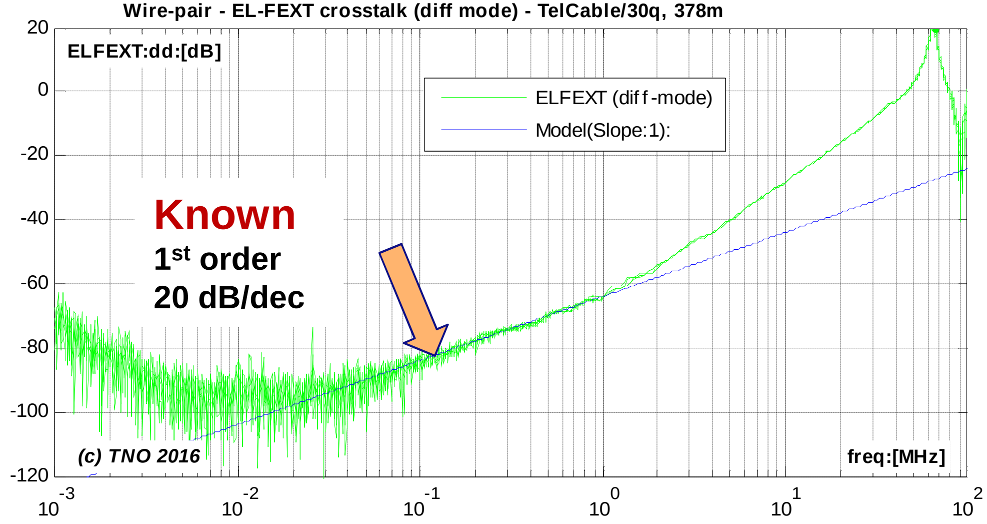

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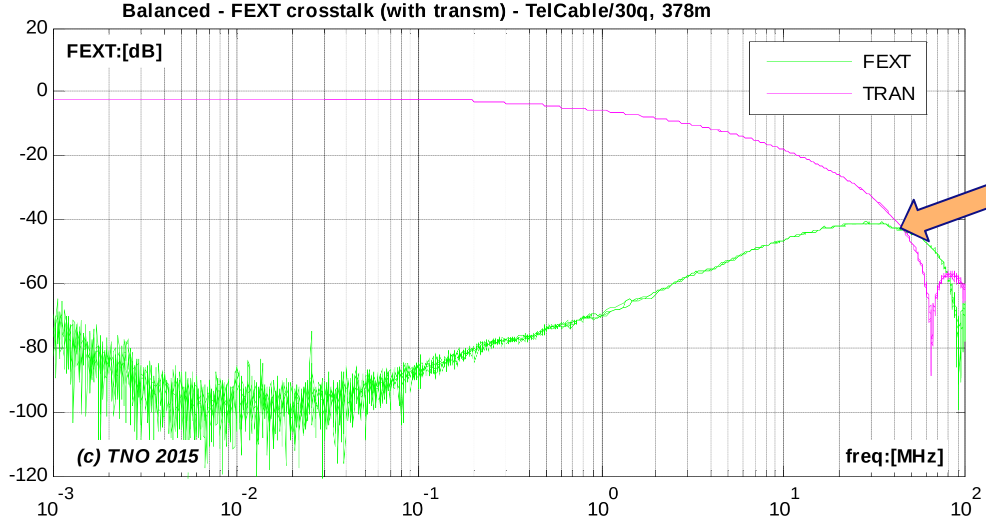

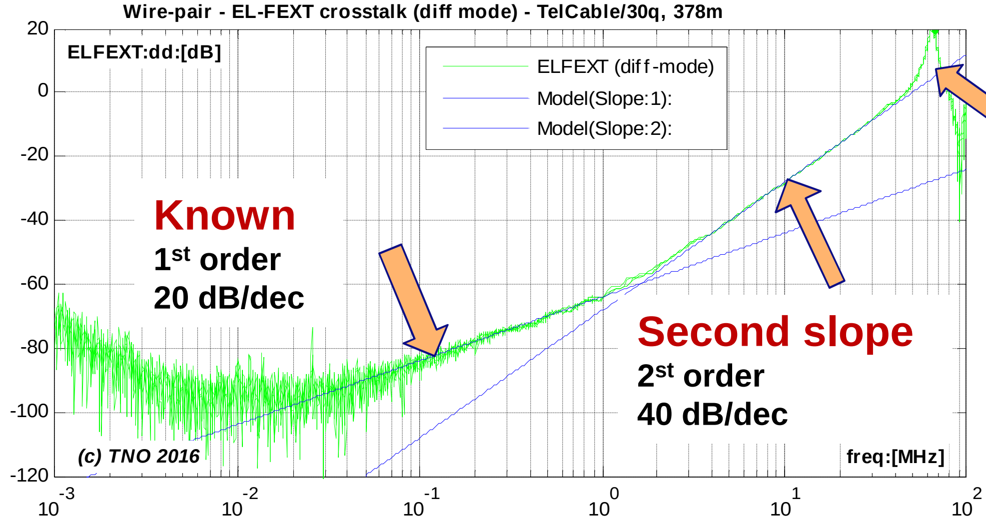

Crosstalk exceeds direct transmission

EL-FEXT > 0dB

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

1. FEXT crosstalk measurements in telephony cabling

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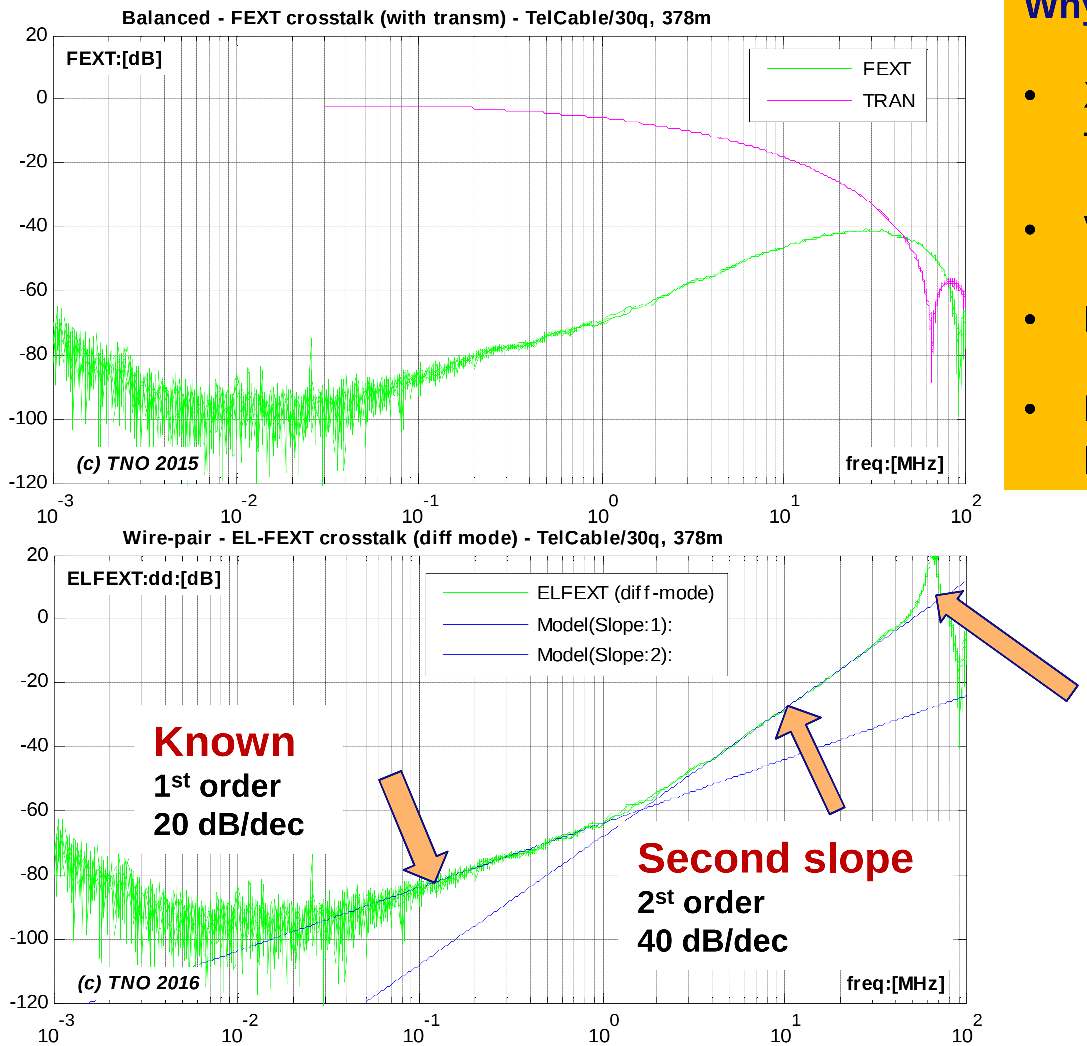


Why is 2^{nd} order effect relevant for DSL?

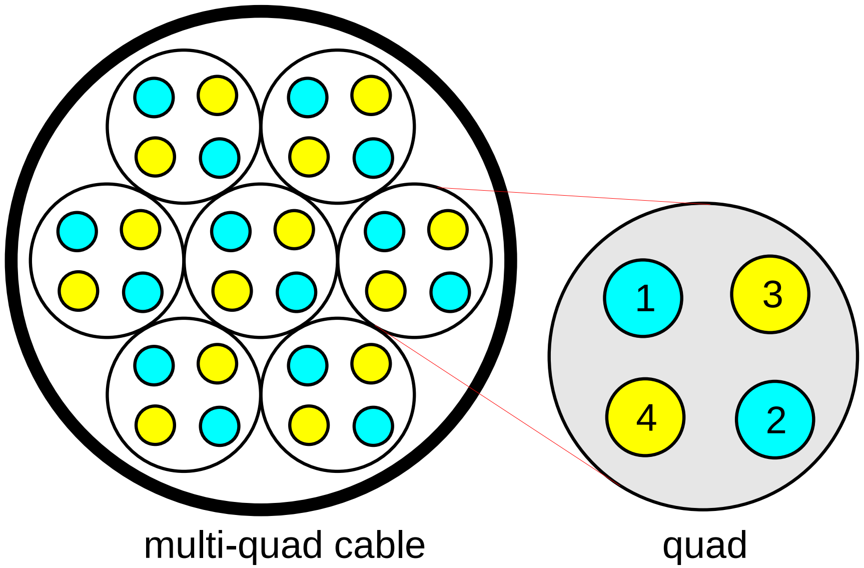
- **Xtalk increases more rapidly with frequency**
- **VDSL/35b and G.fast suffer from it**
- **Dual slope effect not well understood**
- **Model needed for performance predictions**

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

1. FEXT crosstalk measurements in telephony cabling

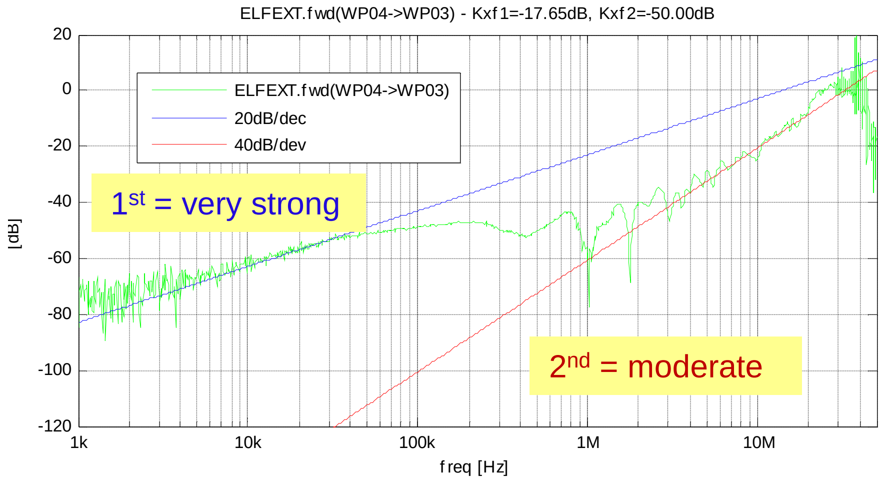
How behaves this dual-slope effect in other cables?

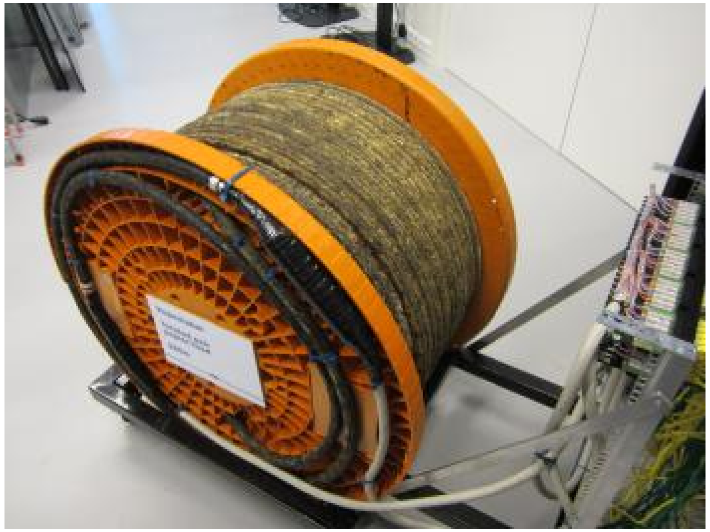
- 1st and 2nd order slopes are caused by independent mechanisms
- They scale differently with the cable length

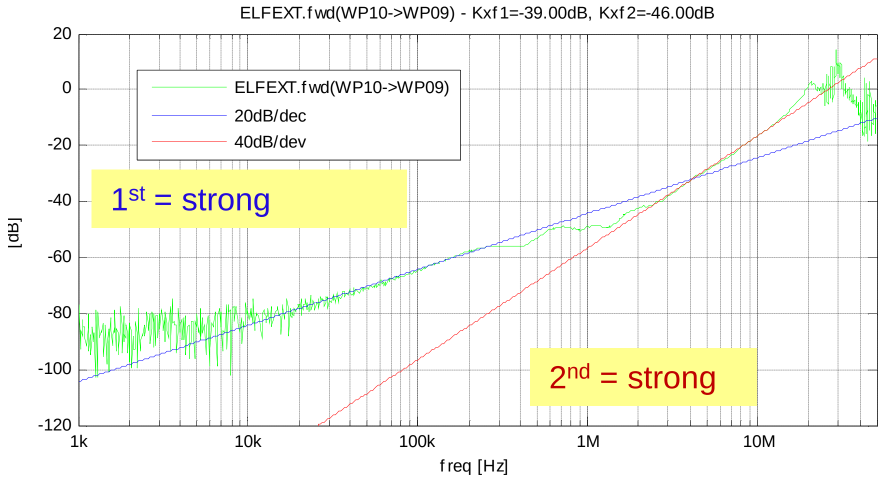


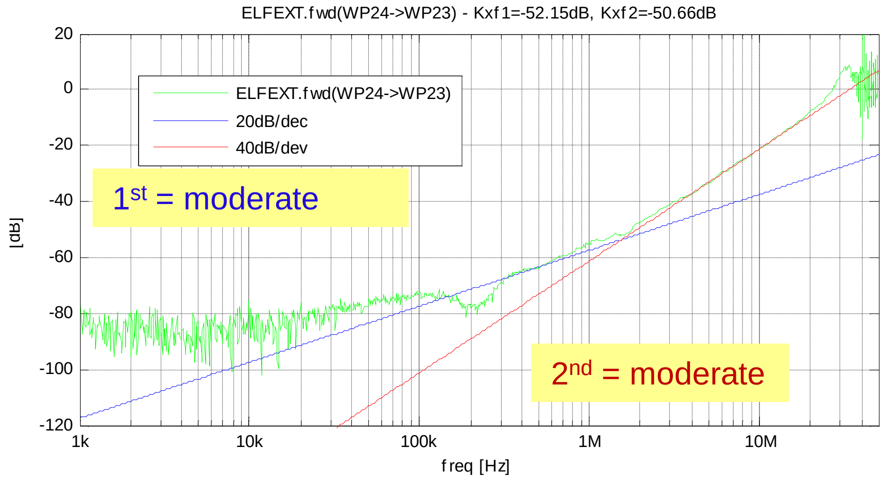
1. FEXT crosstalk measurements in telephony cabling

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



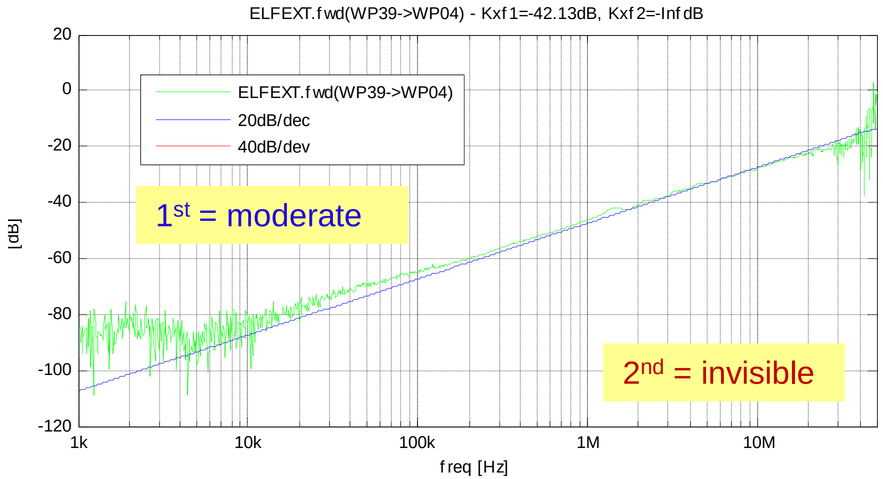


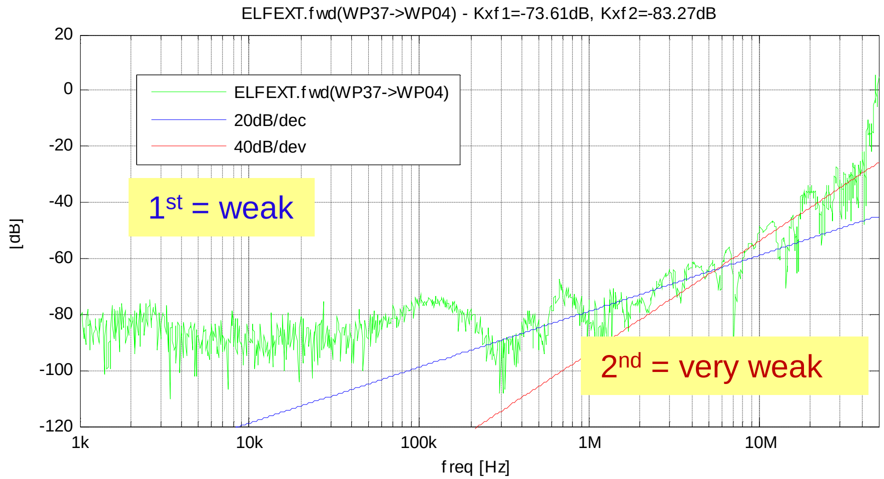


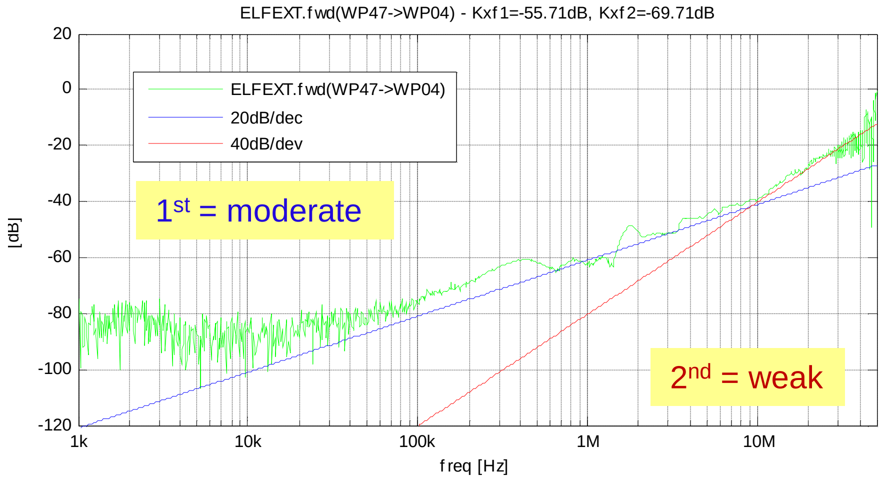


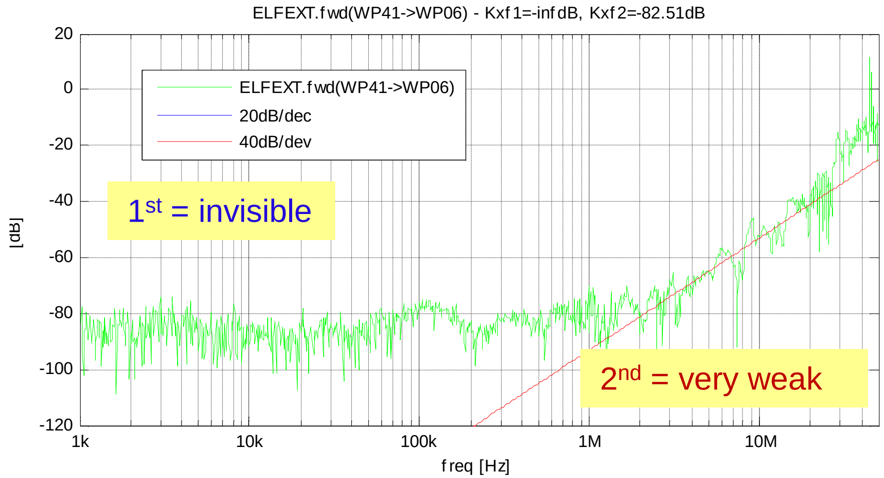
1. FEXT crosstalk measurements in telephony cabling

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:

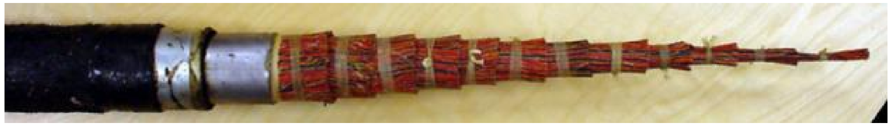
- Crosstalk with mix of 1st and 2nd order effect
- Crosstalk with 1st order only (*2nd order invisible*)
- Crosstalk with 2nd order only (*1st order invisible*)
- 2nd order effect observed in both in-quad and between quads
- In-quad crosstalk more pronounced

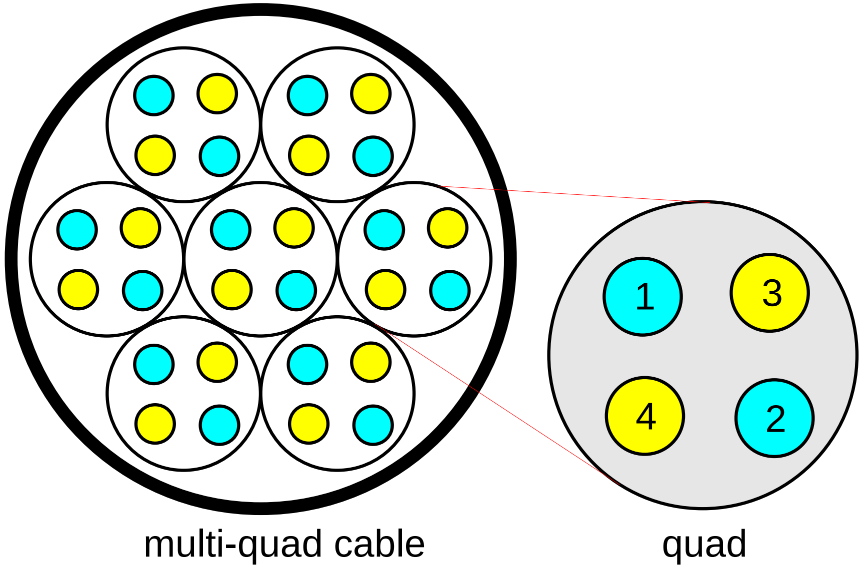
  à Dual slope more visible

  à Lets focus on in-quad crosstalk to gain understanding

2. Understanding the cause of crosstalk

Cause of the first order effect (well known)





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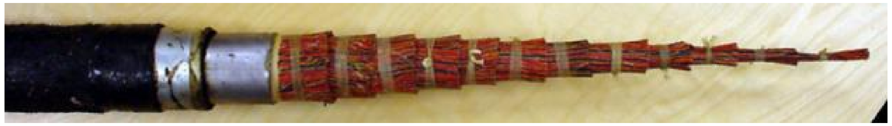
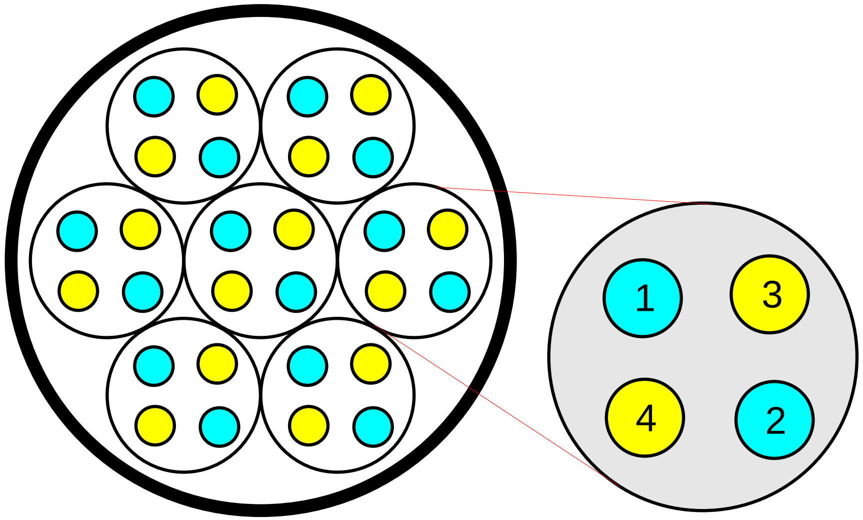
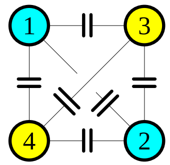




multi-quad cable   quad

perfect square
capacitive balance
no crosstalk



circuit equivalent

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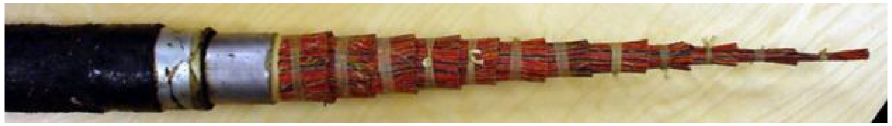

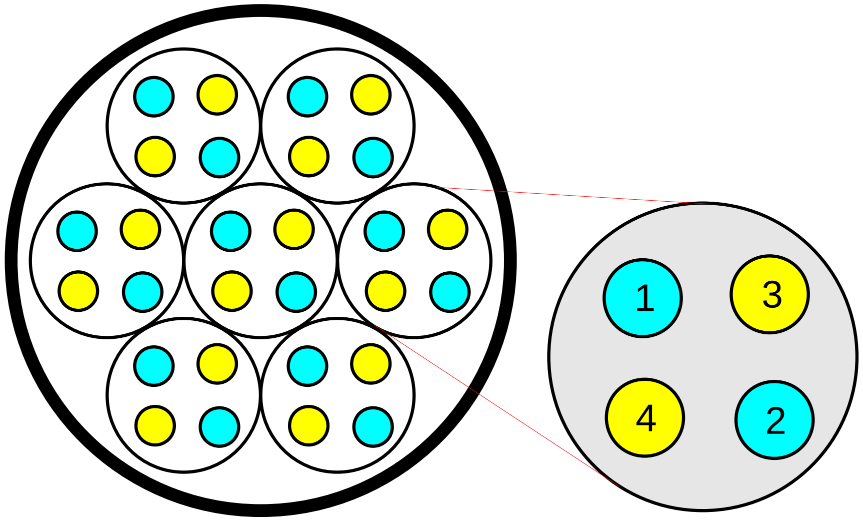

multi-quad cable quad

perfect square capacitive balance no crosstalk

random variations small unbalance crosstalk

circuit equivalent

2. Understanding the cause of crosstalk

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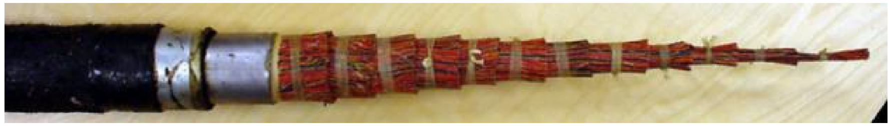
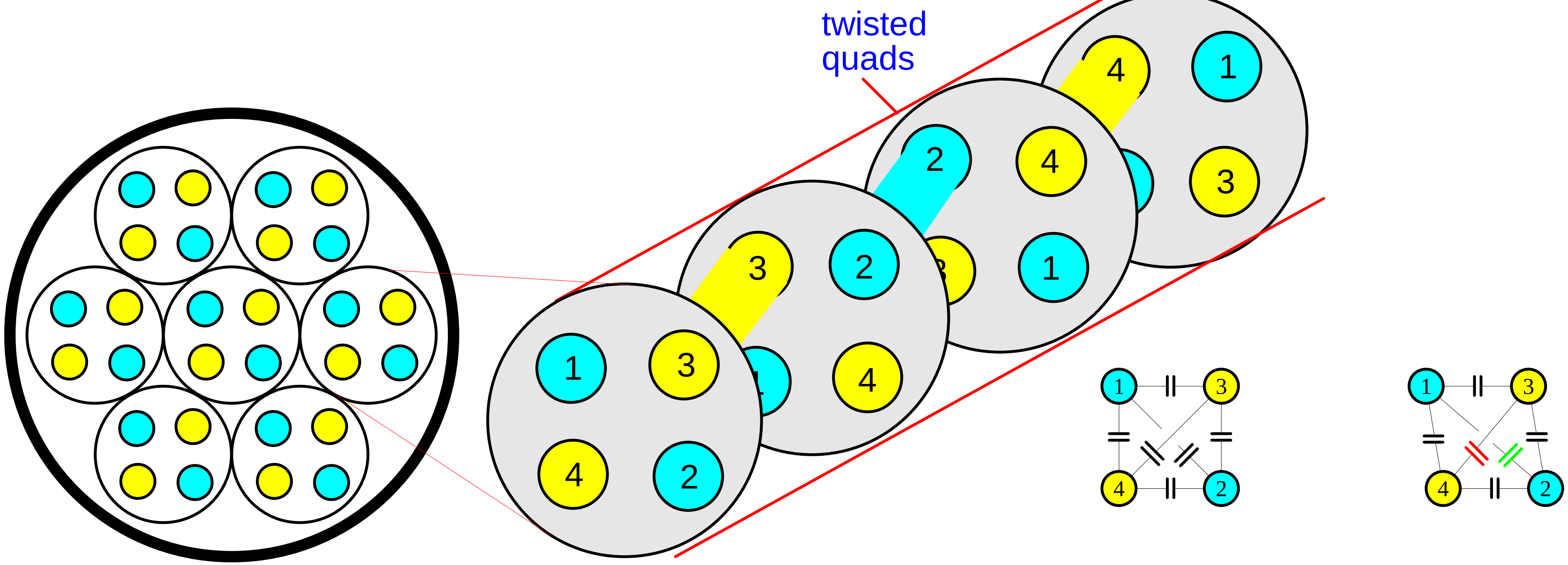




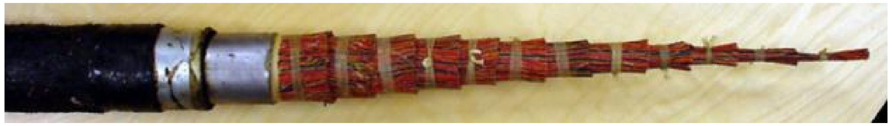
multi-quad cable quad circuit equivalent

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)



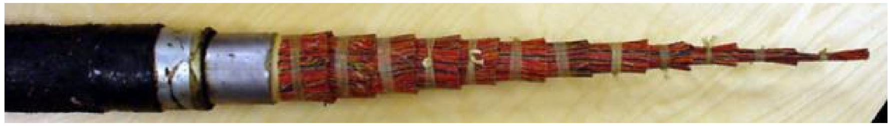
First order effect of EL-FEXT (well known):

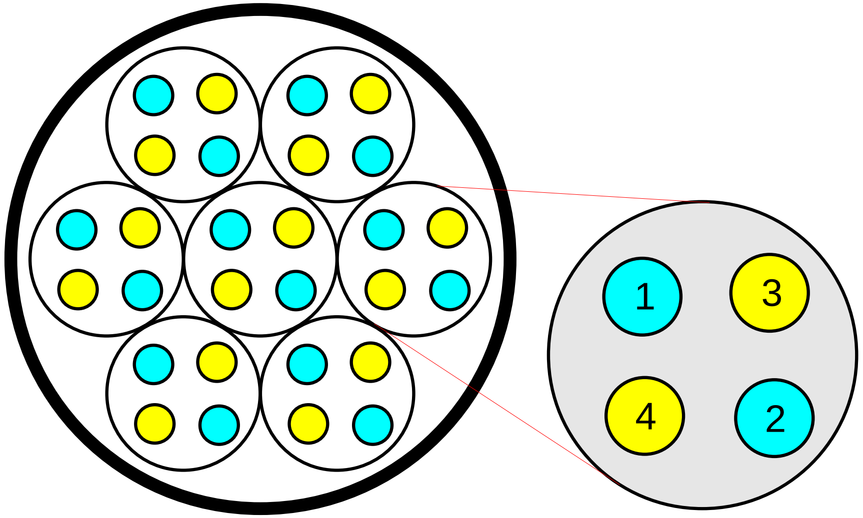
- Random perturbation of balance by imperfect geometry
- Scales proportionally with frequency (20 dB/decade)
- Scales with the root of the cable length (√L)

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

2. Understanding the cause of crosstalk

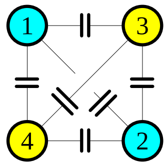
Cause of the second order effect





multi-quad cable

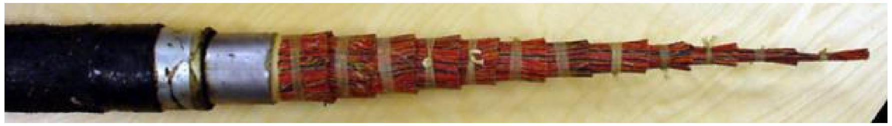
quad

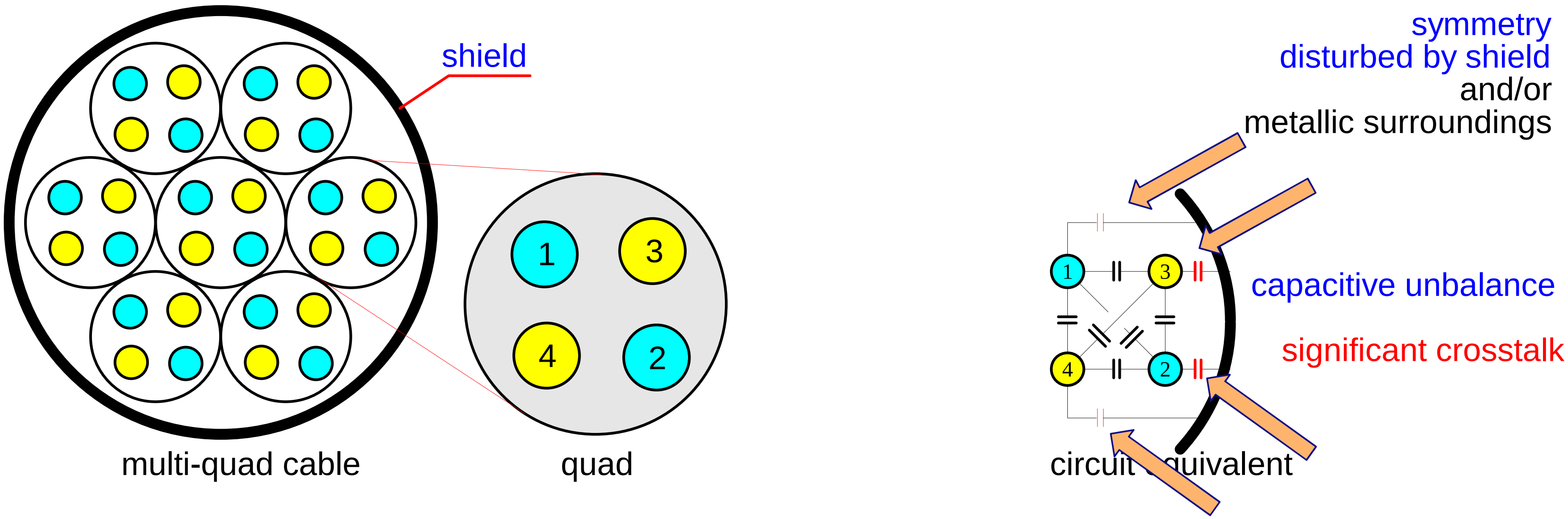


circuit equivalent

2. Understanding the cause of crosstalk

Cause of the second order effect





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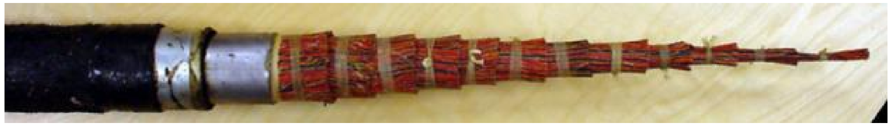
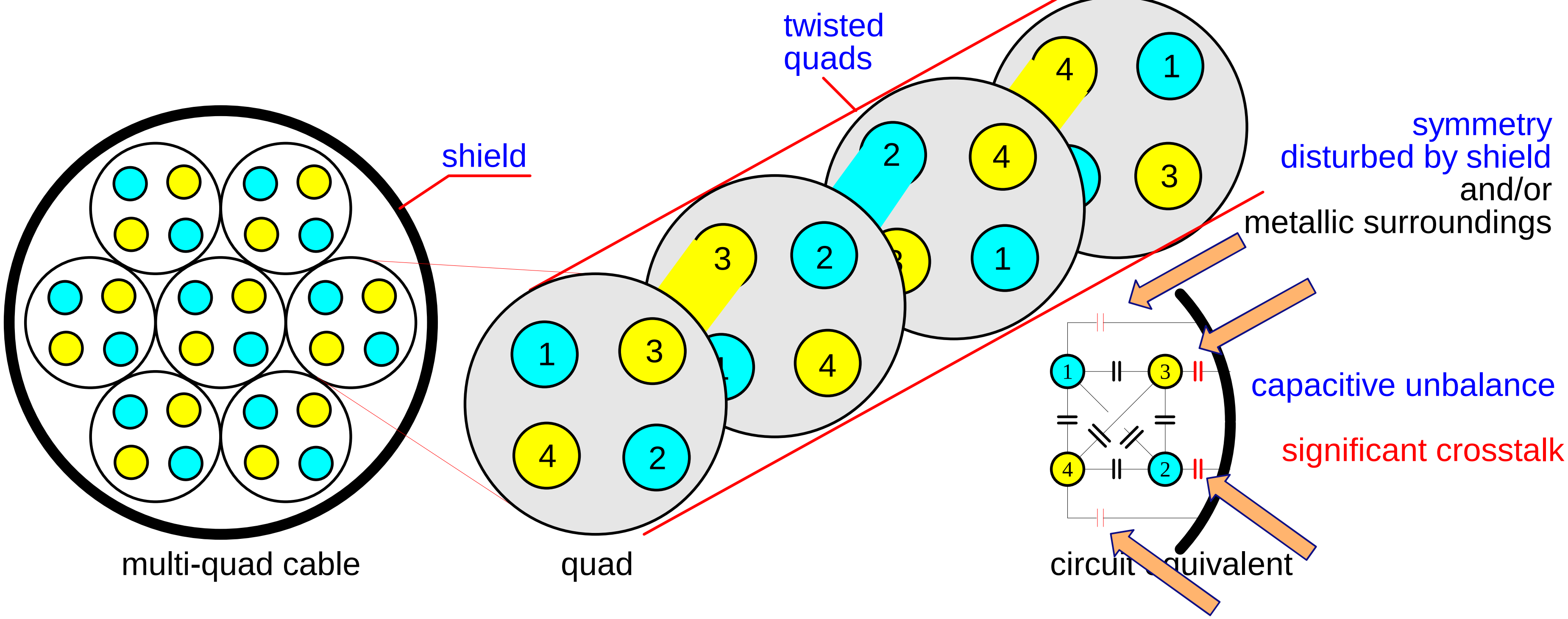
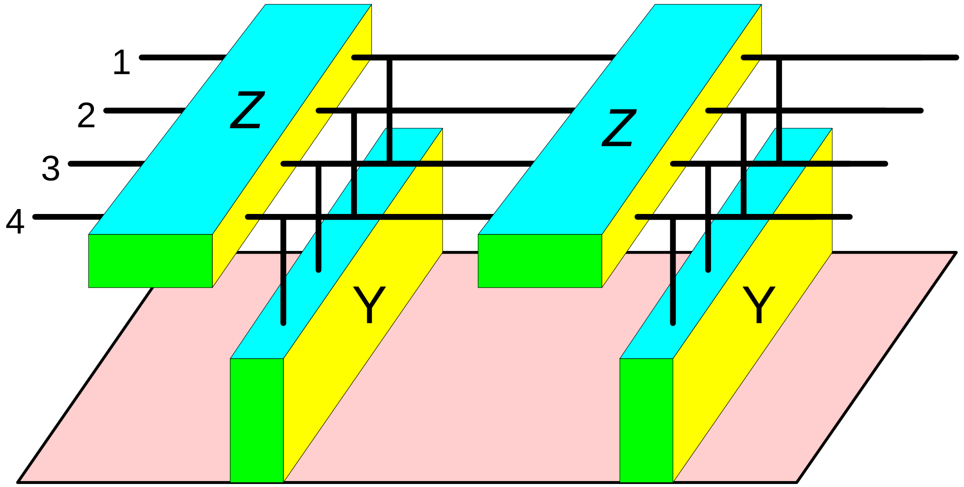




Twisting a quad restores capacitive balance only on *average*
Significant crosstalk reduction within the quad à residual crosstalk
Tighter twisting of a quad à lowers residual crosstalk (= 2nd order effect)

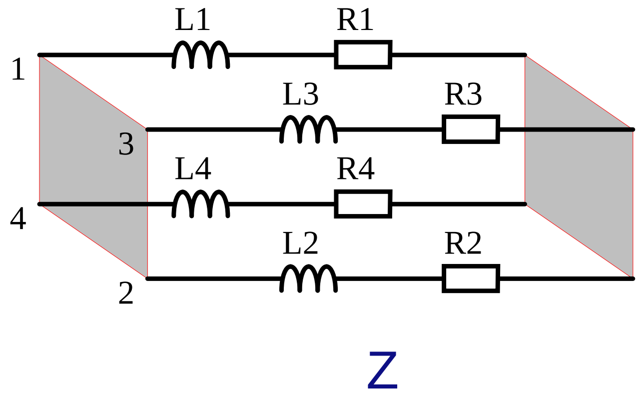
3. Brute force modelling crosstalk within a quad

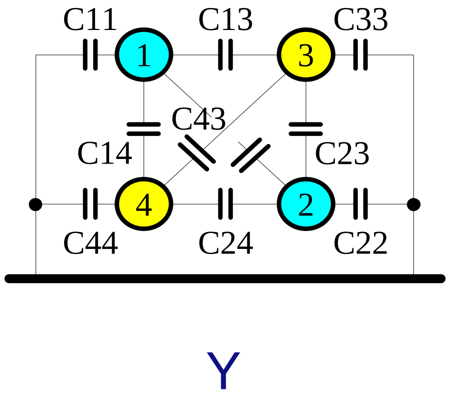
Four wires and a shield = eight port



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

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

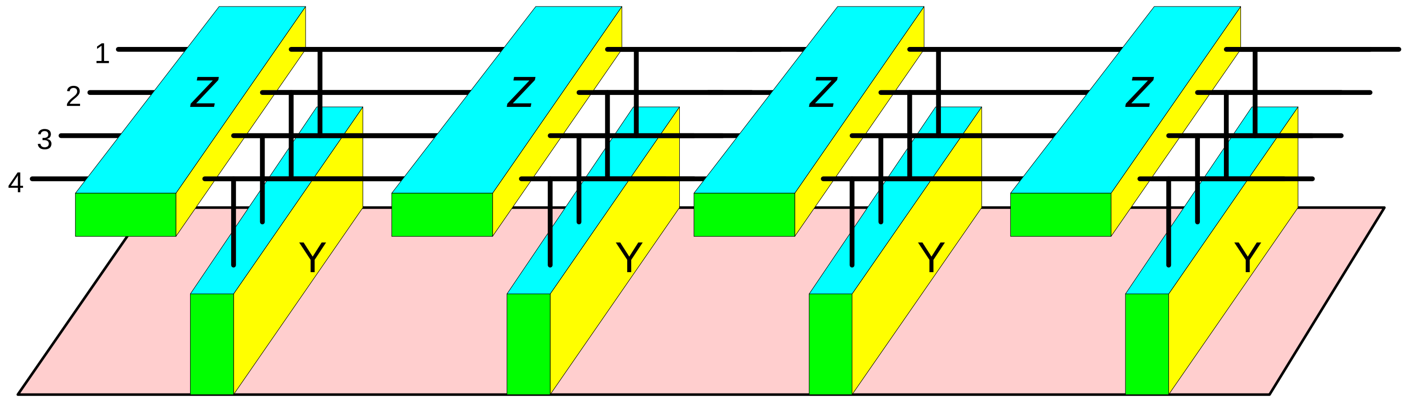




Clayton R. Paul, *Analysis of multiconductor transmission lines,* IEEE press, 2008

3. Brute force modelling crosstalk within a quad

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

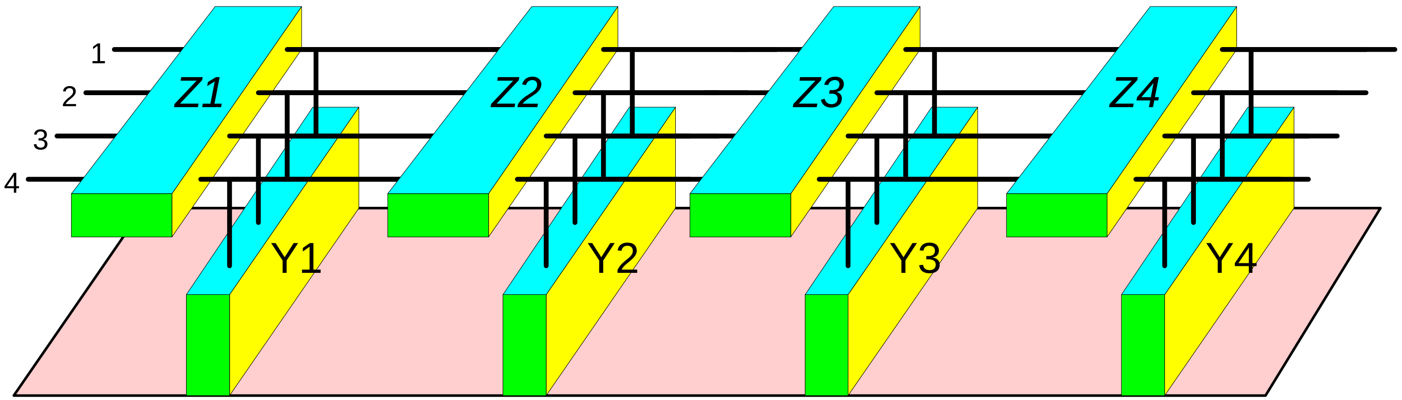


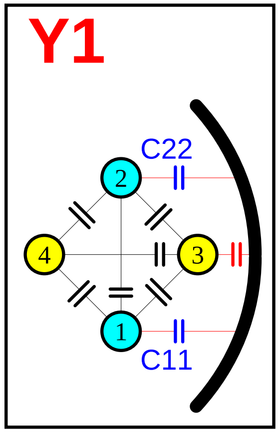
With only 9 values (for R,L,C) you can do a very good cable simulation ……

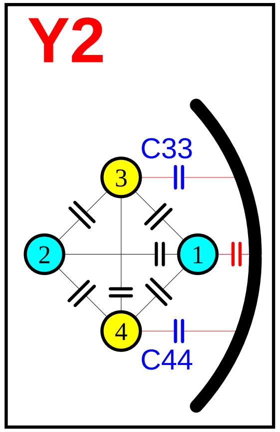
…. but the dual slope effect will not be visible

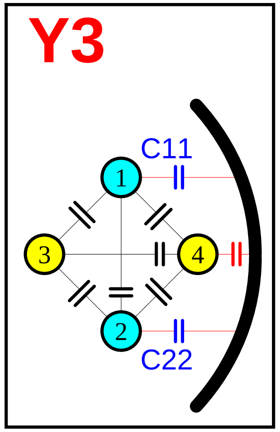
3. Brute force modelling crosstalk within a quad

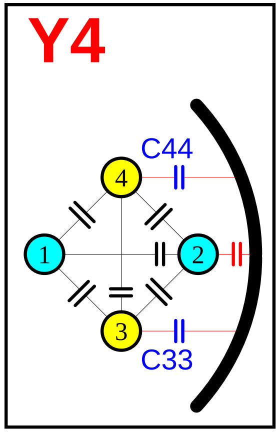
“Infinite” cascade **à** eight port cable model **à** adding a twist











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

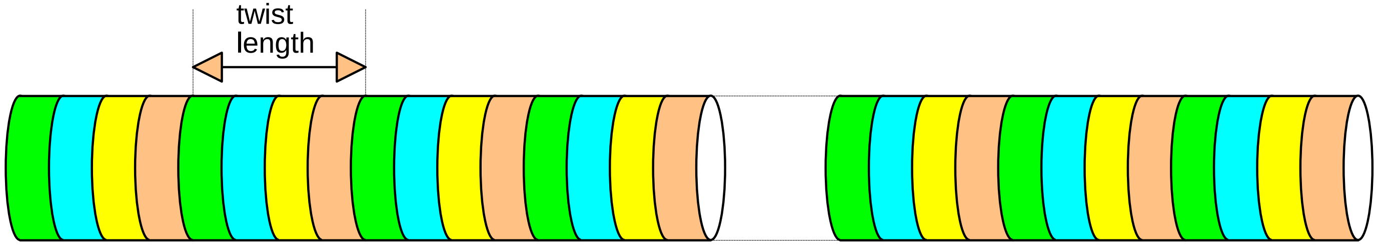
4 sections/twist ?
16 sections/twist ?
64 sections/twist ?

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

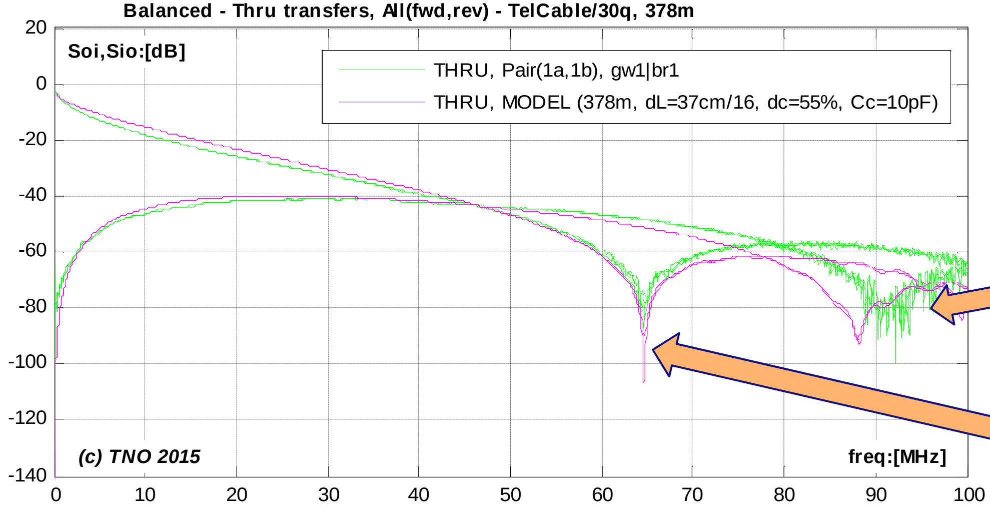
à 10000 twists in a cable
à 40000 segments in a cable
à And they all should go in the cascade

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



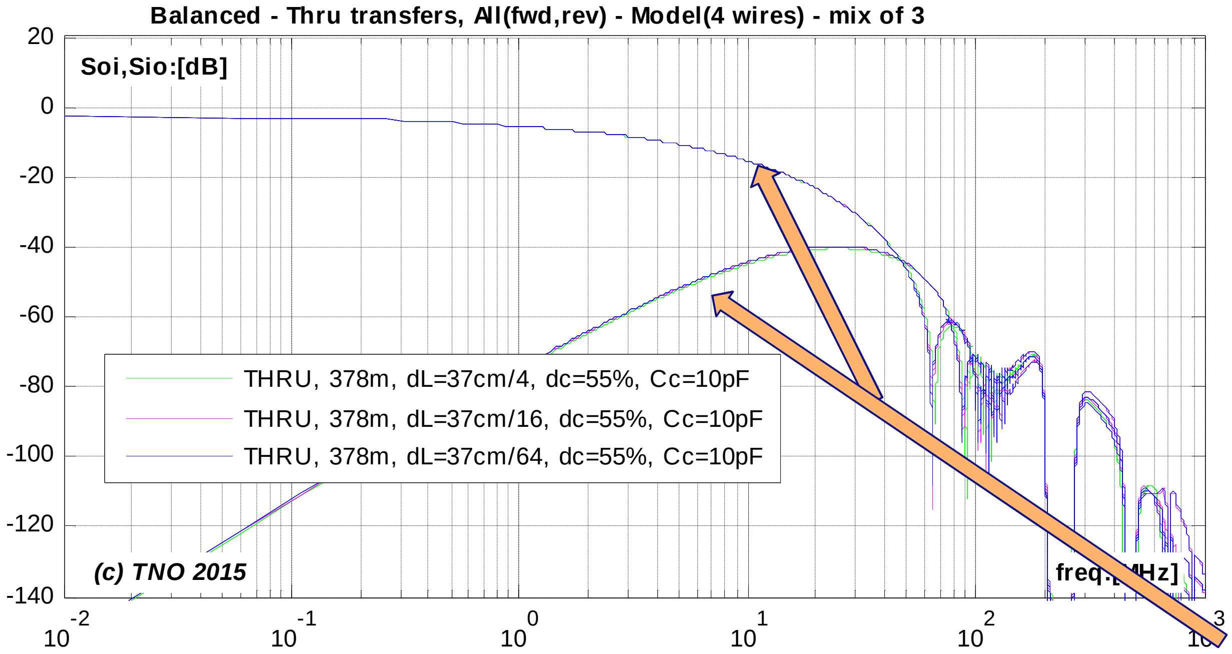
Very good match between model and measurement

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 …

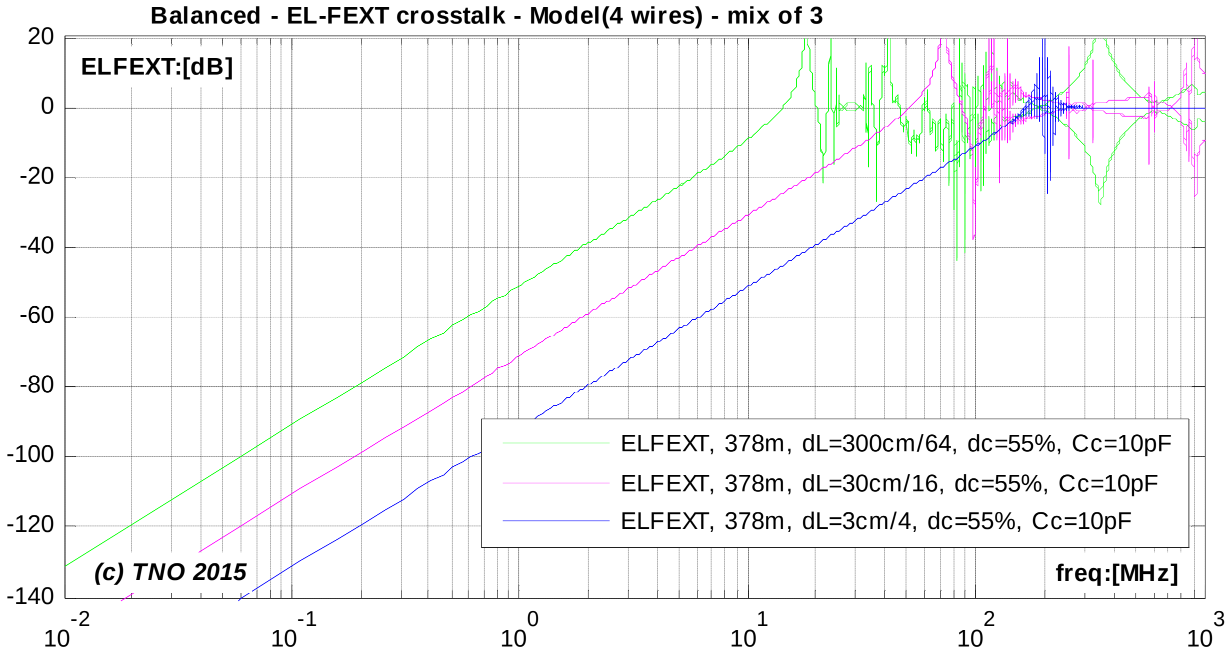
With different segments/twist
- **4 segments/twist**
- **16 segments/twist**
- **64 segments/twist**

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

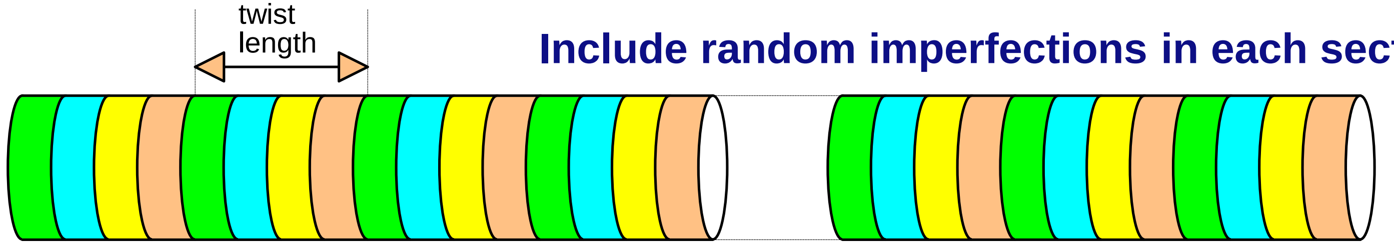
EL-FEXT has 40 dB slope (second order effect)
Even when all random perturbations (first order effect) is absent

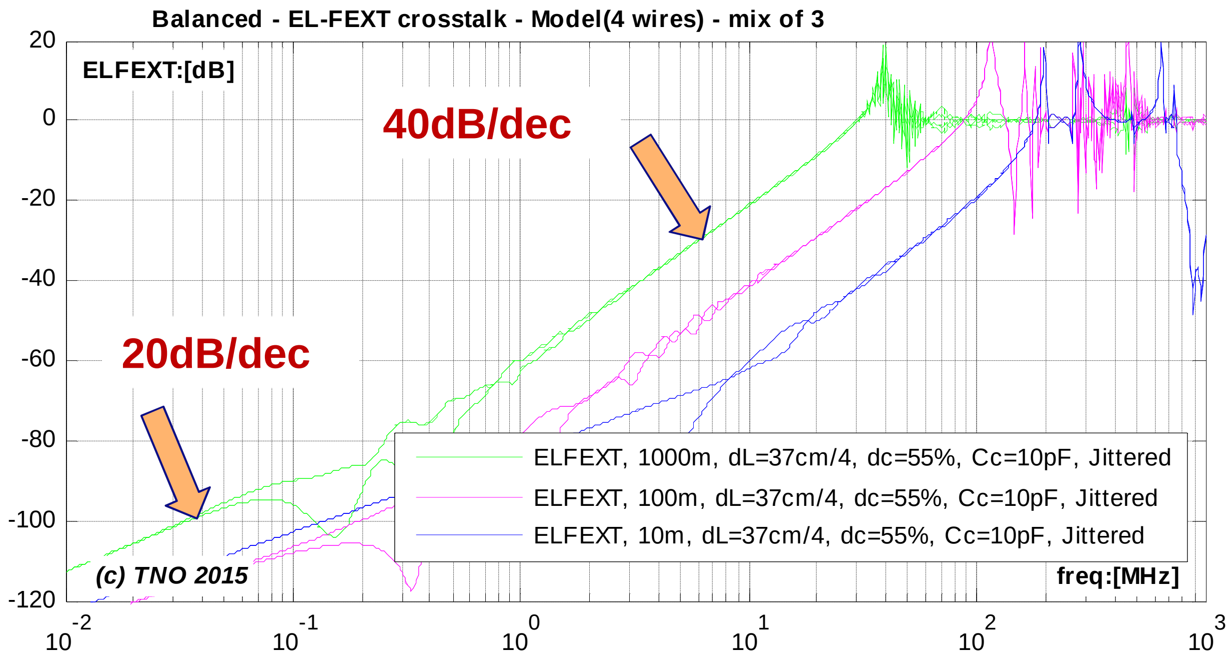
An decrease of the twist length by a factor 10 …
… decreases the EL-FEXT by 20 dB (second order effect)

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





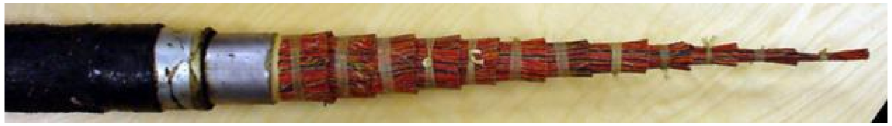
Three different simulation runs

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

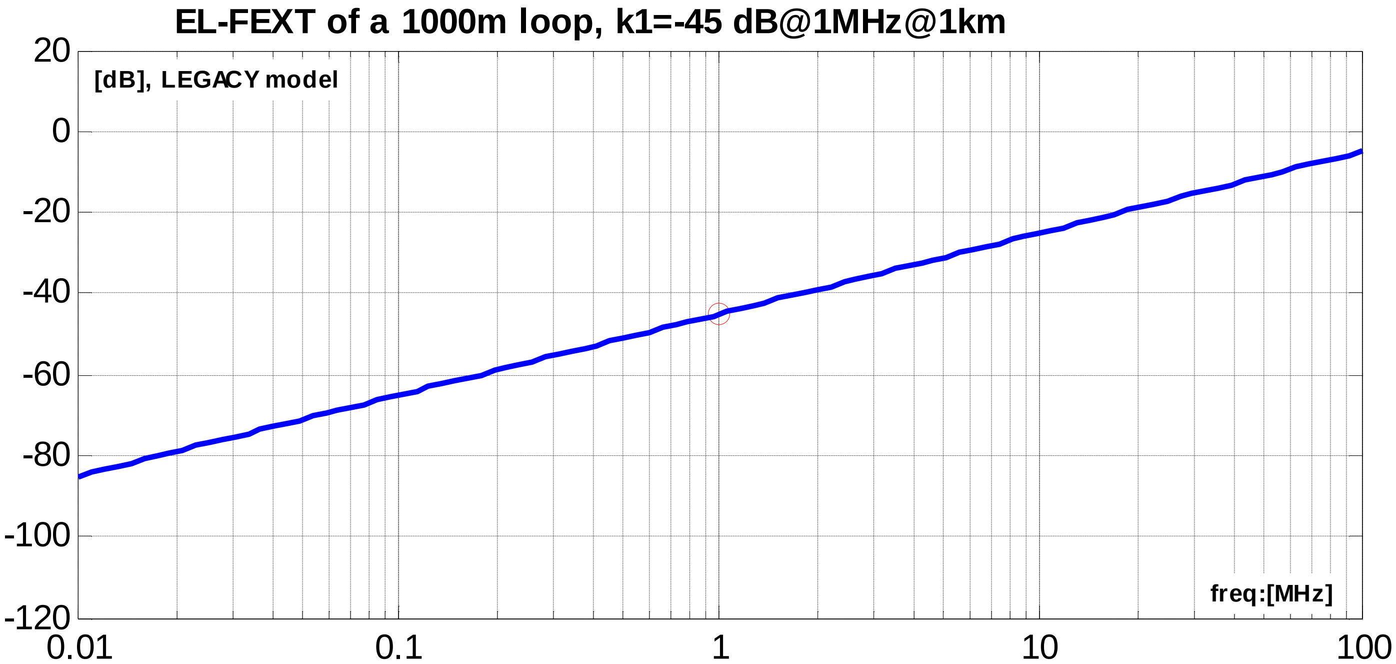
- Deterministic perturbation of balance by metallic surroundings
- Scales proportionally with square of frequency (40 dB/decade)
- Scales with the cable length (L)

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**

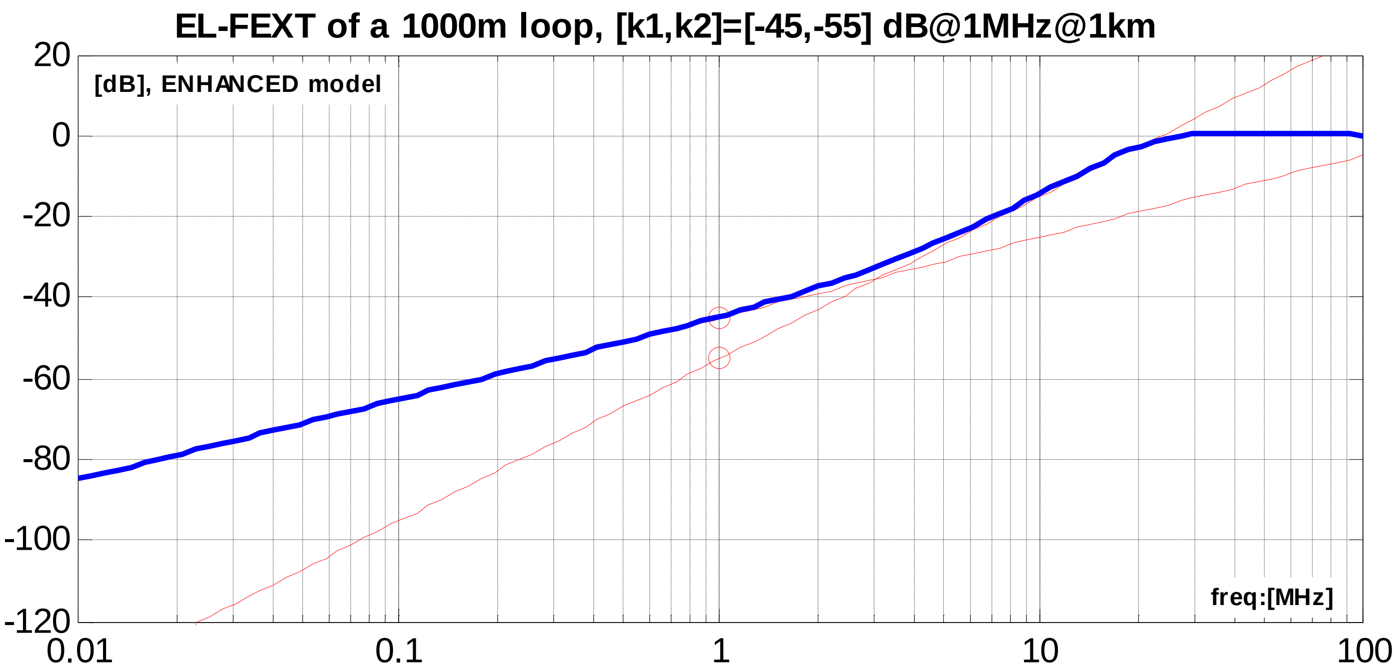


4. Simplifying the system model on EL-FEXT

Fair prediction as function of frequency and cable length

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**



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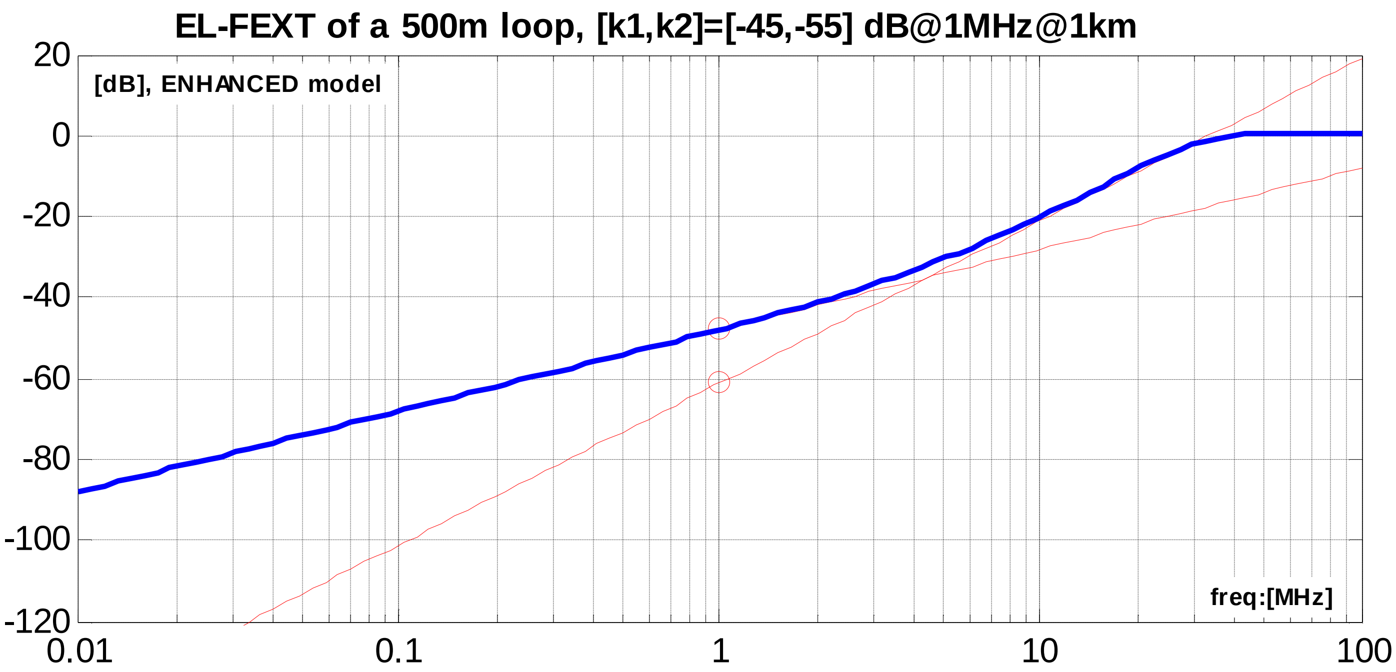

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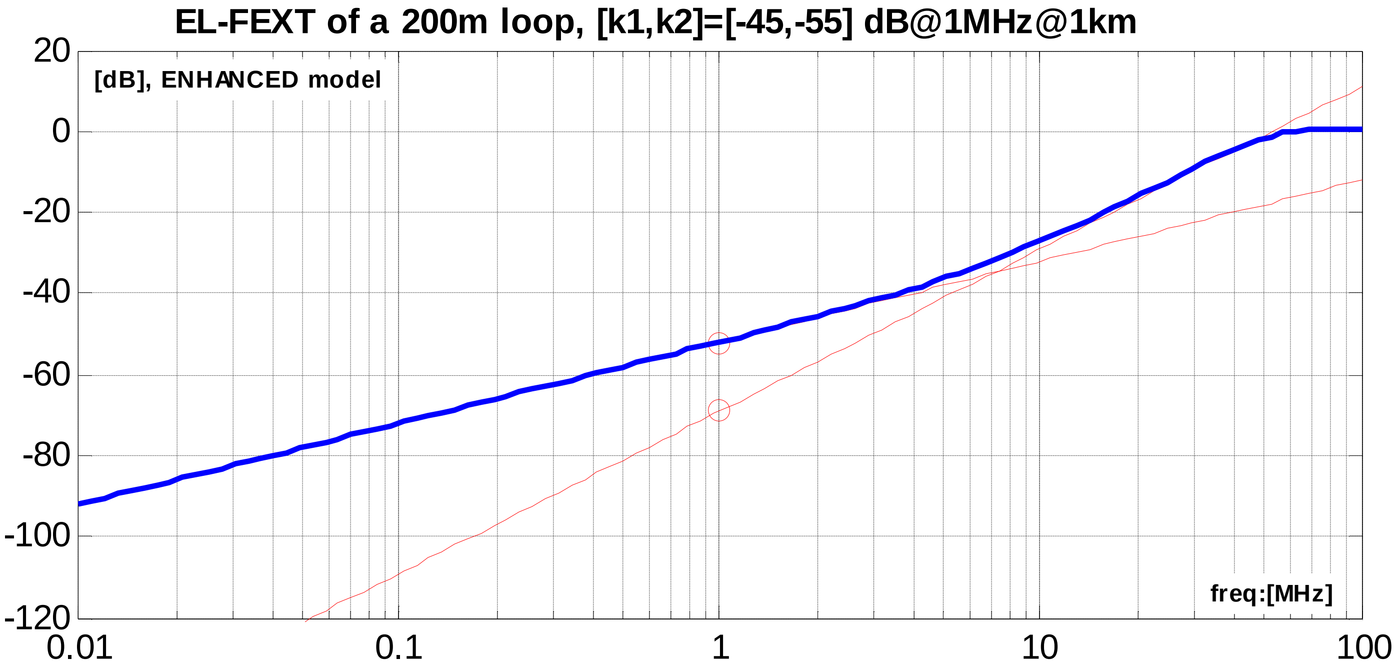

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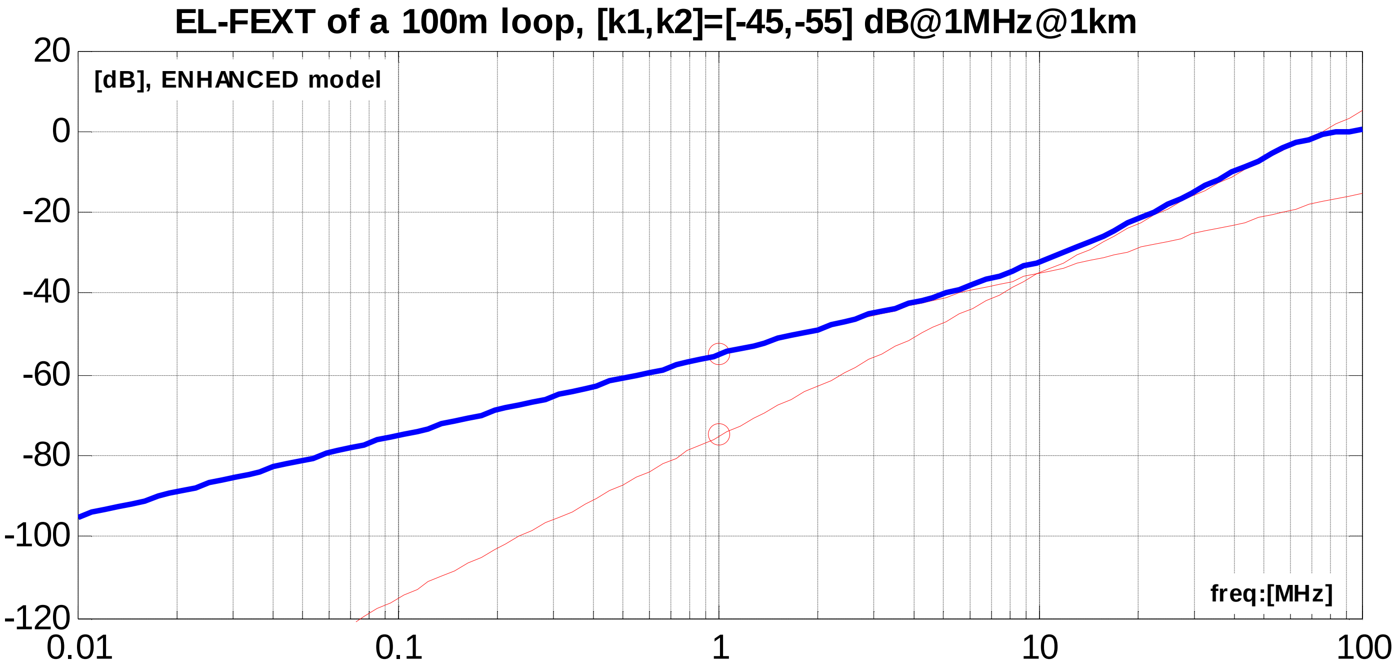
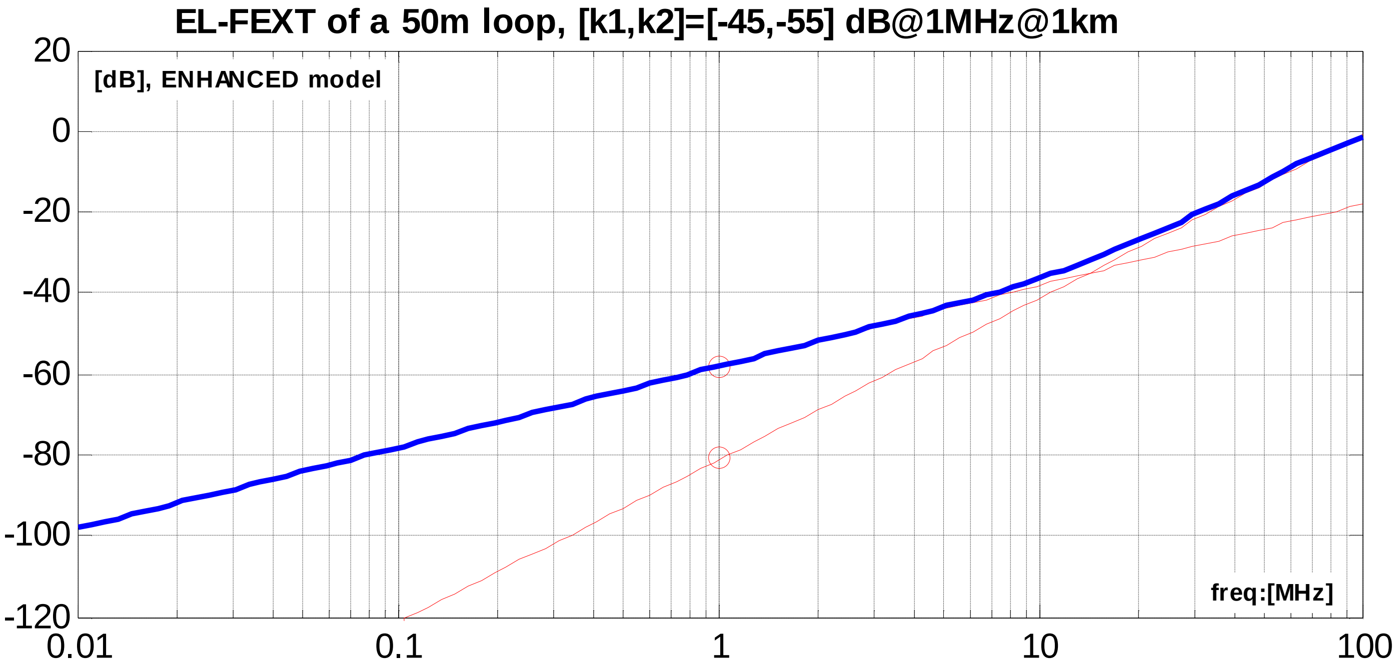


4. Simplifying the system model on EL-FEXT

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**



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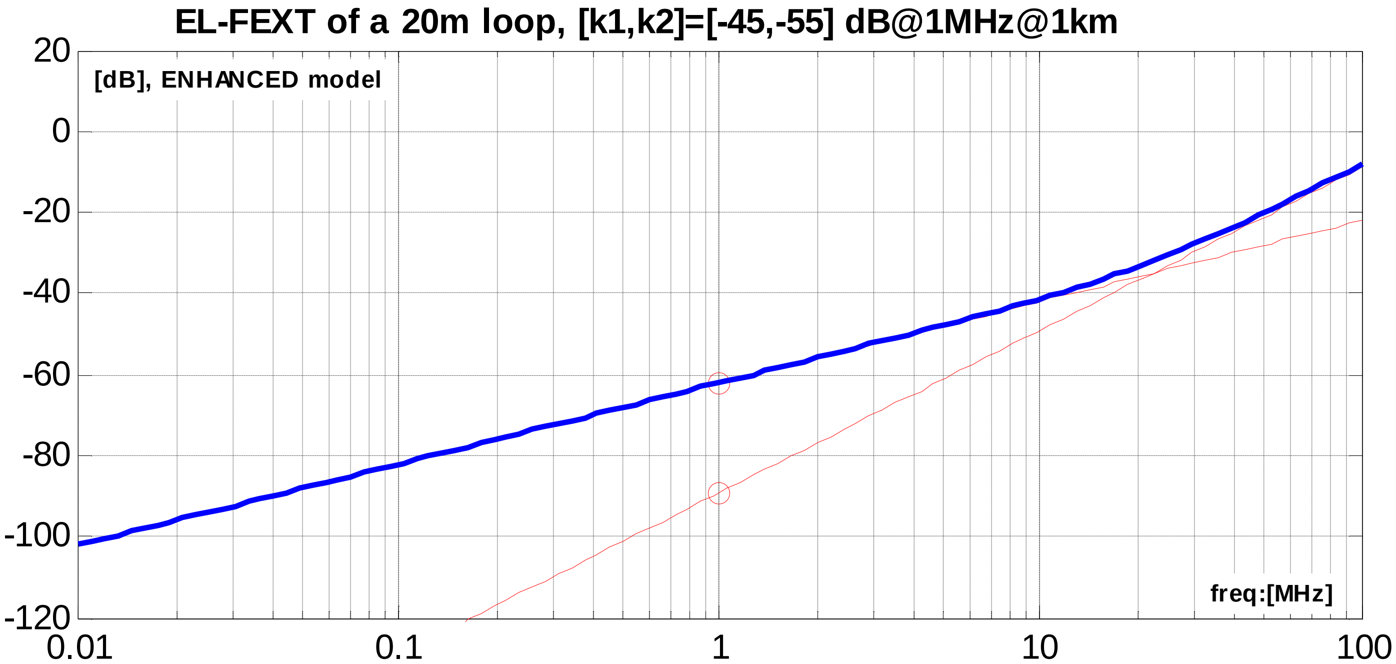

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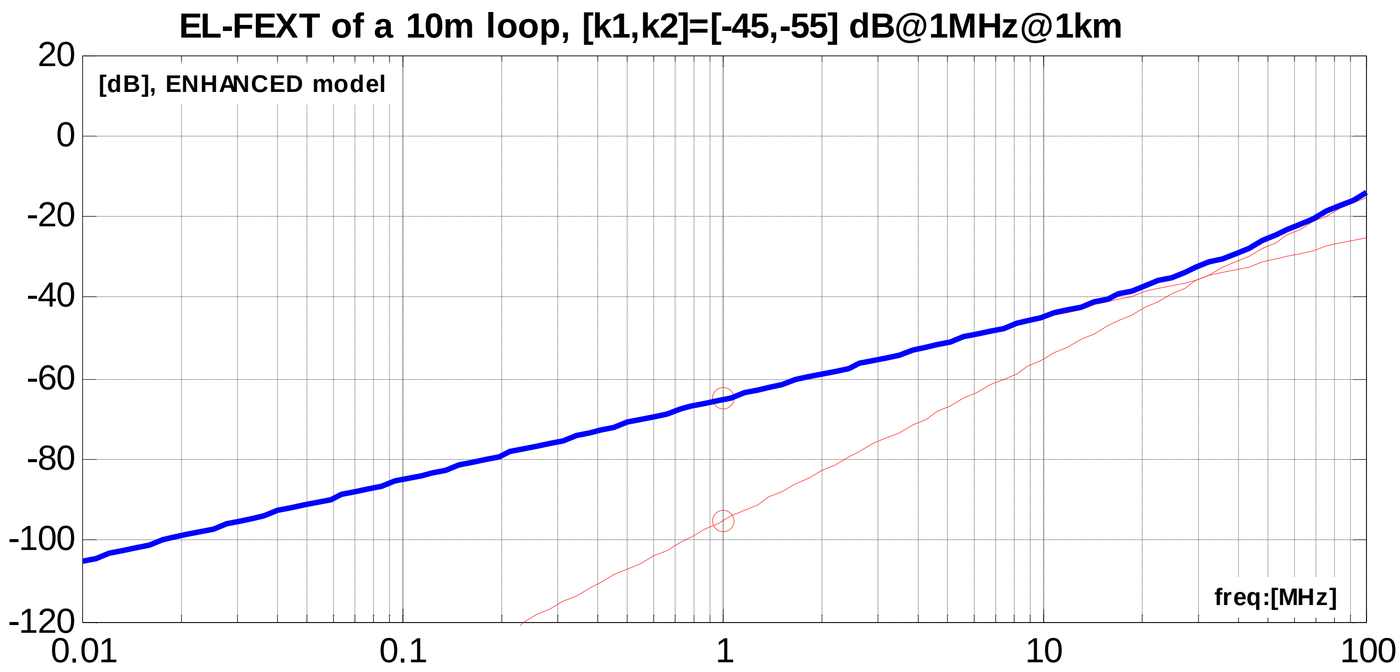

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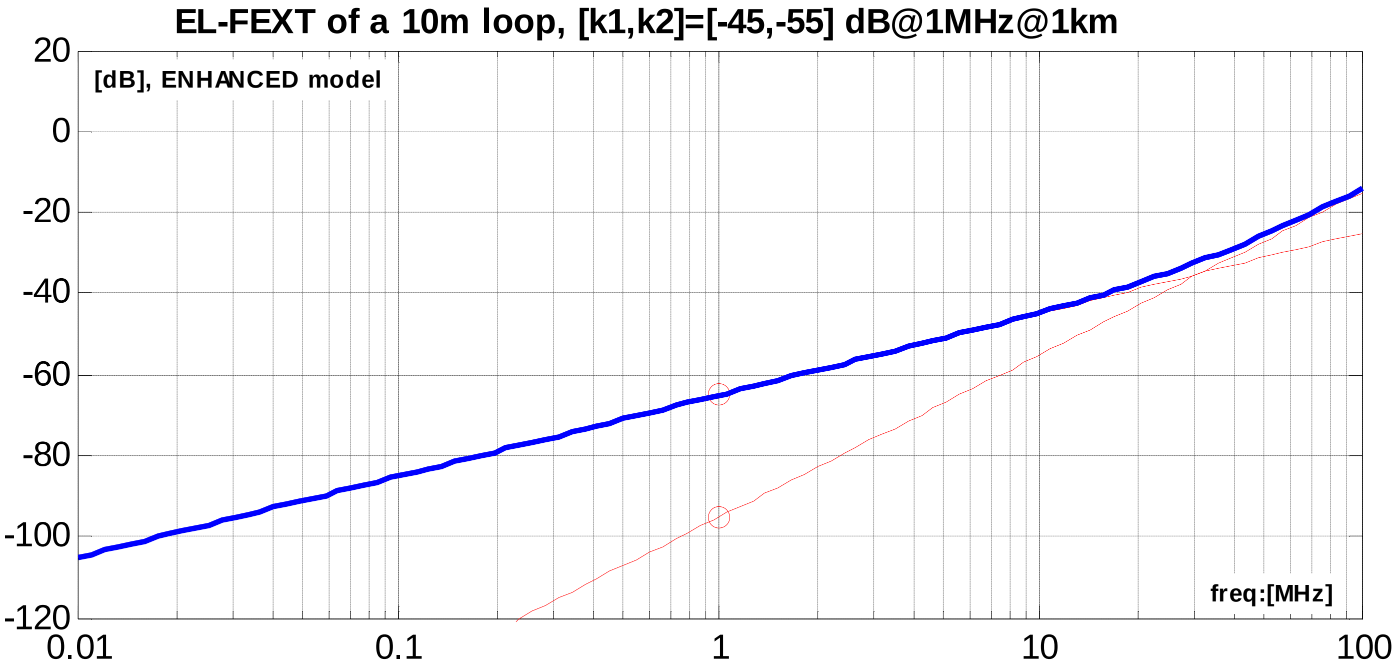
A second order high-pass filter curve meets all these requirements



4. Simplifying the system model on EL-FEXT

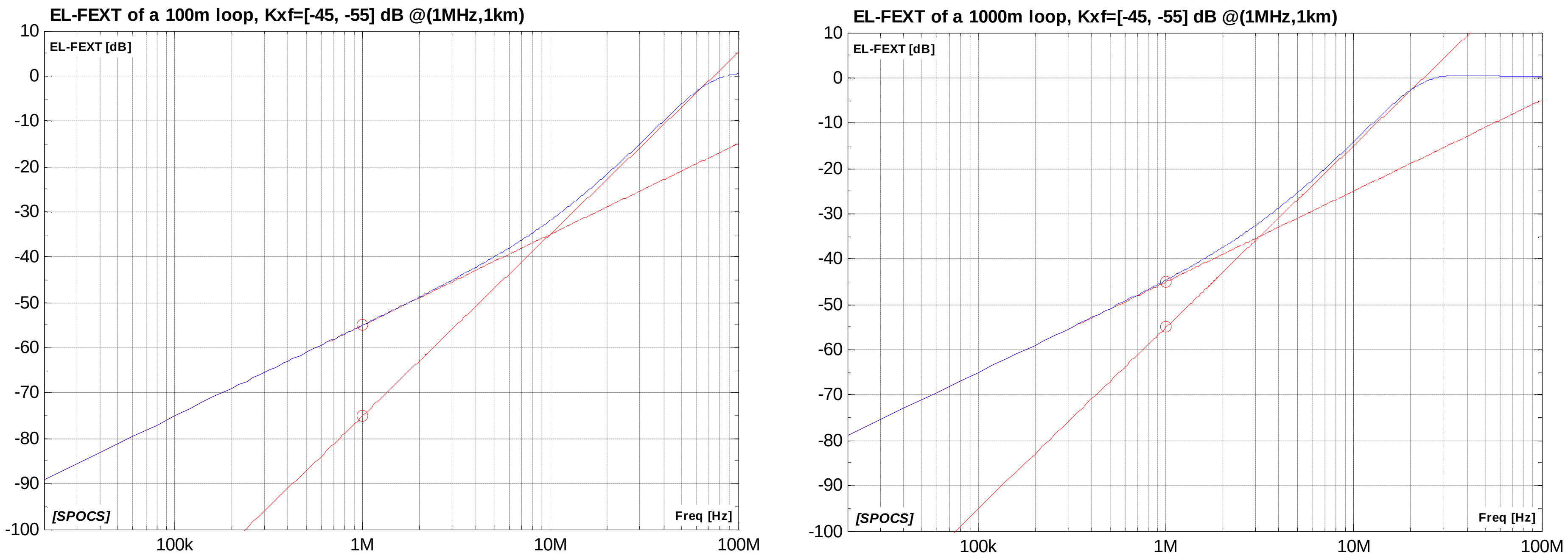
Fair prediction as function of frequency and cable length

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