Project: **WT-285**

Title: **A simplified EL-FEXT model, addressing the dual slope effect and its length-dependency.**

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

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Abstract: This contribution is a proposal to model the dual slope effect EL-FEXT in a simple and convenient manner for performance simulations, and is intended for inclusion into TR-285. This model has recently been contributed to ITU (2016-04-Q4-021) and is essentially an extension to the legacy (single slope) model for EL-FEXT, as described in ETSI TR 101 830-2. The model addresses not only the first and the second order slopes independently but also scales each of them differently with the cable length. Moreover, it prevents the prediction of unrealistic (ever increasing) EL-FEXT values for very high frequencies.
This contribution is based on a detailed understanding of the physical cause of that phenomenon, which is described in our contributions bbf2016.685 and bbf2016.686.

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 each of them 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.

2 Full modelling of the dual slope behavior of EL-FEXT

A detailed analysis of the dual slope effect is described in [1], a paper which is recently submitted to IEEE for possible publication, and attached to bbf2016.686. That paper demonstrates that the dual slope effect of EL-FEXT is a combination of a first order effect (20 dB/decade) caused by (well known) random imperfections in the symmetry of the wiring and a second order residual effect (40 dB/decade) that is deterministic in nature. And that second order effect dominates above a certain break frequency until the EL-FEXT approximates zero dB.

That second order effect is caused by the interaction between the twist in the wires and its metallic surroundings (e.g. shield). The twist reduces the crosstalk due to capacitive unbalance significantly by balancing the capacitive coupling to its metallic surroundings on ***average***. But a residual EL-FEXT term remains due to the repetitive/alternating variations around an average capacitance to surroundings. And that residual term happens to increase with 40 dB/decade, and becomes visible as a the dual slope effect when it dominates the first order effect.

The paper in [1] uses a full multi-port approach to model the twist, and demonstrates that such an approach can offer a very good match between model and measurements, as shown in figure 1. But that multi-port model is kept in [1] as simple as possible to concentrate on the cause of the dual slope effect. Both transmission and FEXT are well predicted by that model, and even the dip in transmission near 64 MHz is predicted quite well. This is shown in figure 1.

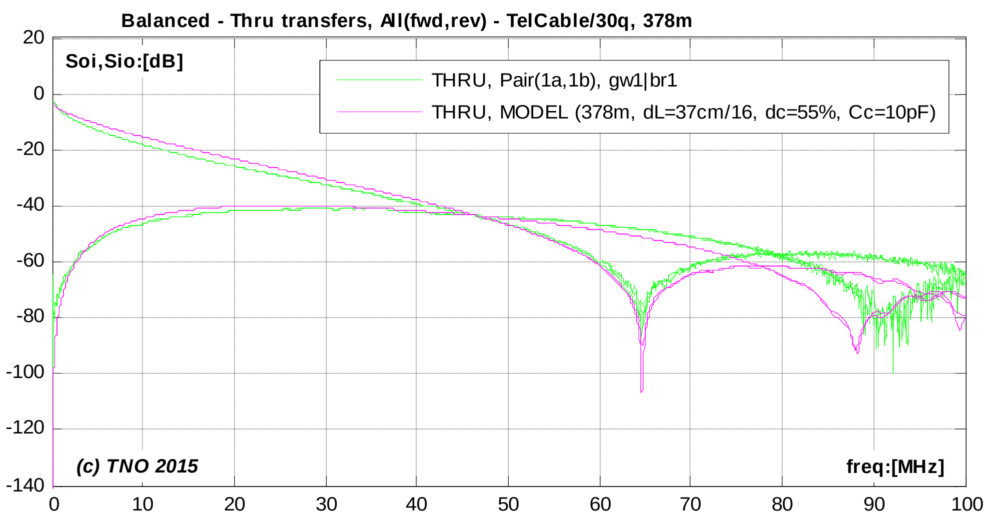

Figure 1 Match between a sample cable measurement and the full multi-port model proposed in [1]. Both transmission and FEXT are well predicted by the model, and this even applies to the dip in transmission near 64 MHz.

The full multi-port model is subsequently used in [1] to show how much the magnitude of the second order EL-FEXT changes with cable design parameters like twist length and capacitance to shield. But in all cases the slope of that second order effect is exactly 40 dB/decade up to a frequency where the EL-FEXT approaches zero dB.

3 Simplified modelling of the dual slope behavior of EL-FEXT

Our full multi-port model in [1] may be too complicated for studying modem performance in cables and therefore we propose an additional but simplified EL-FEXT model for such studies and propose to have it included in TR-285. It appears like an extension to the legacy ETSI model for EL-FEXT [17] and requires only one additional parameter value to specify the EL-FEXT for arbitrary cable lengths:

- A first value K_{xf1}, specifying the first order EL-FEXT at 1 MHz for a 1 km loop
- A second value K_{xf2}, specifying the second order EL-FEXT at 1 MHz for a 1 km loop

The legacy ETSI model [17] for EL-FEXT has the following characteristics:

- The crosstalk effect has a slope of exactly 20 dB/decade.
- The presence of a second order effect is lacking.
- The crosstalk becomes unrealistic high for high frequencies since it keeps growing above 0dB.
- The magnitude of the crosstalk scales with the root of the cable length.

Our (simplified) model proposed in [1] fulfills at least the following requirements:

- The first order crosstalk effect has a slope of exactly 20 dB/decade.
- The second order crosstalk effect has a slope of exactly 40 dB/decade.
- The EL-FEXT does not exceeds levels above 0 dB.
- The magnitude of the first order crosstalk effect scales with the root of the cable length.
- The magnitude of the second order crosstalk effect scales proportional with the cable length.

The model is specified with a single analytical function and is essentially a refinement of what TNO proposed before in 2012 [2].

Figure 2 and 3 show the desired behavior of our (simplified) model for two different cable lengths.

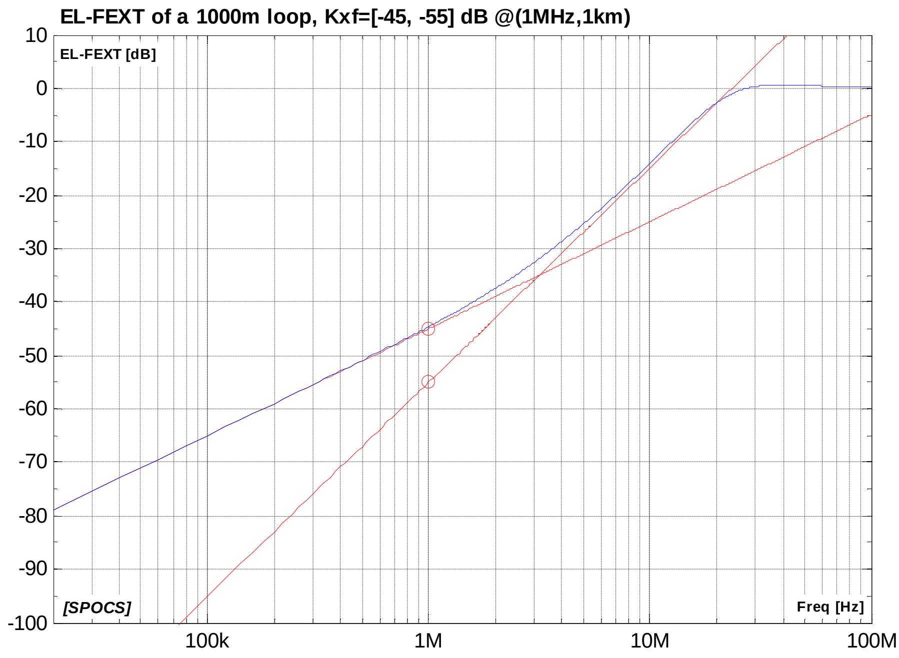

Figure 2. Crosstalk prediction of the proposed EL-FEXT model, for a 1km loop, when the model is characterized as K_{xf1}= -45 dB and K_{xf2}= -55 dB, both specified at 1 MHz and 1km. The asymptotes are crossing at 1 MHz the values of K_{xf1} and K_{xf2} since it is a 1 km loop.
The model prevents that the maximum coupling increases 0 dB at high frequencies.

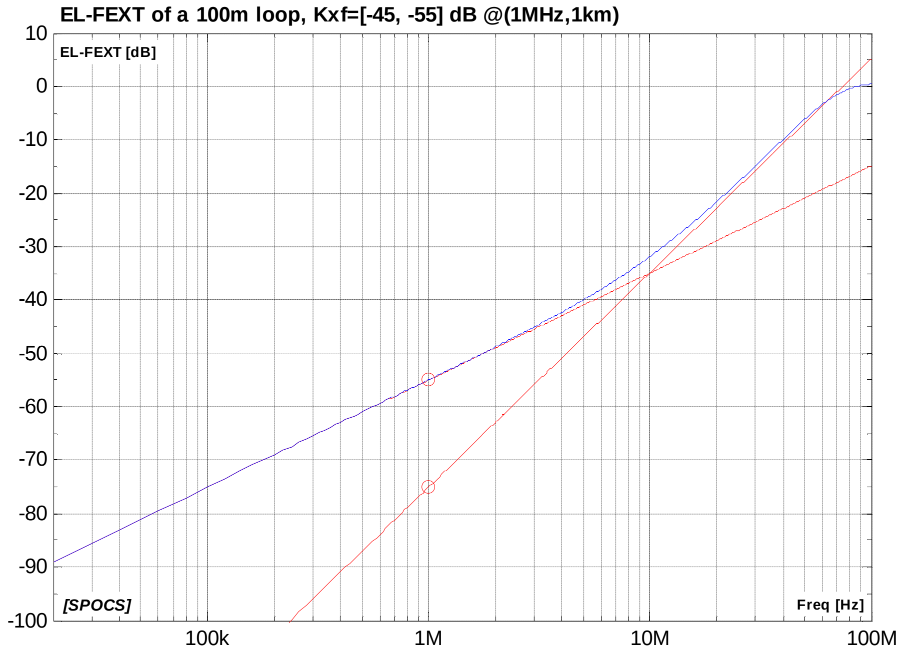

Figure 3. Crosstalk prediction of the proposed EL-FEXT model for a 100m loop, using the same parameter values as in figure 2. Since the vertical offset of both asymptotes scale differently with the cable length, the break frequency in this figure (10 MHz) is different from its value in the previous figure (3 MHz).

Our model used in figure 2 and 3 is expressed as the transfer function of a second order high-pass filter via:

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

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

If we normalize this formula with L_0 = 1km and $\omega_0 = 2\pi\cdot 1$ MHz and obtain values for K_{XF1} and K_{XF2} via measurements on a single cable length, then the model is fully specified for all cable lengths, and limited around 0 dB.

4 Text Proposal

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A.2.3 FEXT
In dealing with FEXT, account must be taken of two salient characteristics noted in the experimental observations of the G.fast environment, the Dual Slope Effect and the Time Variation Effect. The Dual Slope Effect may not always be visible in cables and the Time Variation Effect may not always be present.

A.2.3.1 Dual Slope Effect
The FEXT coupling function from the near end of path "k" to the far end of path "r" over a coupling length L is essentially the product of the transfer function $S_T(j\omega, L)$ representing the direct transmission through path "k" and the transfer function $H_{ELFEXT}(j\omega, L)$ representing the equal level FEXT from the near end of path "r" to the far end of path "k".
This EL-FEXT is a combination of two independent coupling mechanisms: a first order and a second order crosstalk effect. Both effects can exist without the other, are completely independent from each other, and each of them scale differently with the cable length L.

- The origin of the first order coupling effect is well known and is random in nature [16, 17]. Its contribution to the EL-FEXT increases with 20 dB/decade over a wide frequency interval, and scales proportionally with the *root* of the cable length (in a statistical sense)
- The origin of the second order coupling effect is deterministic in nature [1] (assuming that the cable geometry is deterministic as well). Its contribution to the EL-FEXT increases with 40 dB/decade over a wide frequency interval, and scales *proportionally* with the cable length.
- The EL-FEXT between two wire pairs is the sum of both coupling effects, and when their magnitude makes them both visible, the EL-FEXT has a dual slope behavior. When the first one dominates, this dual–slope effect may not be visible and the opposite has occasionally been observed as well.

Figure [*]a and [*]b provides an illustration of the EL-FEXT predicted by the model for two different cable lengths:

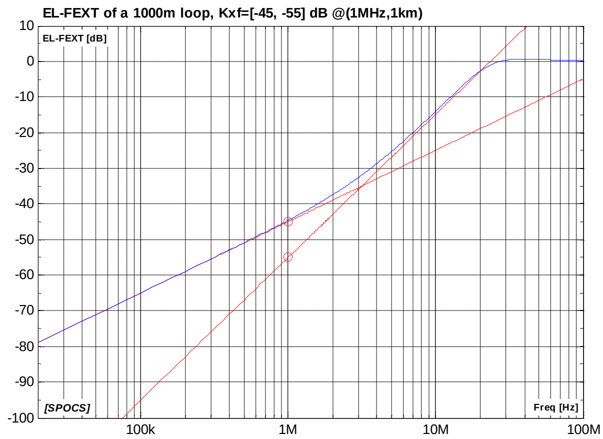

Figure [*]a. Crosstalk prediction of the EL-FEXT model, for a 1km loop, when the model is characterized as K_{xf1}= -45 dB and K_{xf2}= -55 dB, both values specified at 1 MHz and 1km. The asymptotes are crossing at 1 MHz the values of K_{xf1} and K_{xf2} since it is a 1 km loop.
The model prevents that the maximum coupling increases 0 dB at high frequencies.

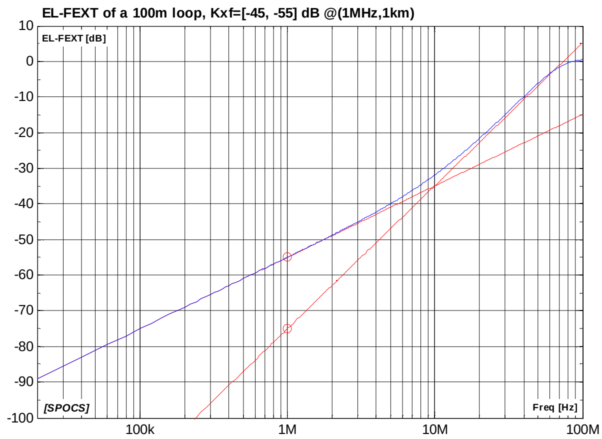

Figure [*]b. Crosstalk prediction of the EL-FEXT model for a 100m loop, using the same parameter values as in figure [*]a. Since the vertical offset of both asymptotes scale differently with the cable length, the break frequency in this figure (10 MHz) is different from its value in the previous figure (3 MHz).

The dual slope model of the FEXT coupling between two wire pairs is essentially an extension to a well-known (first order) legacy model [16, 17] and augmented with a second order effect. The EL-FEXT transfer function follows the generic curve of a second order high-pass filter curve, and is specified as shown in expression [*].

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

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

NOTE 1: Parameter $\boldsymbol{\omega}$ refers to the angular frequency $(\omega=2\pi\cdot f)$. Constant j refers to the imaginary unit and constant $\omega_0=2\pi\cdot f_0$ identifies a chosen reference frequency, commonly set to f_0 = 1 MHz.

NOTE 2: Parameter L refers to the coupling length of the wire pairs. Constant L_0 refers to a chosen reference length, commonly set to L_0 = 1 km.

NOTE 3: Values for K_{XF1} and K_{XF2} are cable specific, and are to be specified for each scenario being studied. Example values are K_{xf1}= -45 dB and K_{xf2}= -55 dB, both values specified at f_0 = 1 MHz and L_0 = 1 km.

NOTE 4: Function $S_T(j\omega, L)$ represents the frequency and length dependent transfer function of the direct path, when inserted between a source and load impedance (transmission)

Expression [*]: Magnitude of the FEXT coupling between two wire pairs over a coupling length *L*.

If a particular study involves multiple wire pairs, then the spread in coupling values can be taken into account. A matrix with offset values for <specify BBF cable> are specified in table <see present TR285 document>

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5 Summary

This contribution is a proposal for modelling the most relevant aspects of the dual slope effect in FEXT with the goal of improving the collection of cable modelling techniques brought together in TR-285. See also BBF2016.685 [18] and BBF.2016.686 [19] for further details.

6 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.

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

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