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TITLE: G.fast: Far-end crosstalk in twisted pair cabling; measurements and modelling

ABSTRACT

This contribution presents measurements on the far end crosstalk in telephony cables and how they compare with legacy models for FEXT. We show that the measured curves have some similarity with the curves predicted from legacy models. However, improvement of crosstalk models is recommended. As a first step, we introduce a first-order enhancement of that legacy model, which can prevent unrealistic high crosstalk levels at higher frequencies, but additional improvements are left for further study.
This contribution is provided for information only.

1. Introduction:

The estimation of channel capacity for G.fast [4,5] requires adequate models for transmission as well as for crosstalk. Legacy models for FEXT are based on the crosstalk from identical disturbers in ***all*** wire pairs. The validity of these models were never proven for frequencies above 30 MHz, and were never meant for use in combination with small numbers of disturbers [6].

This contribution presents measurements on the far end crosstalk in cables and how they compare with these legacy models for FEXT when applied to a ***single*** disturber. It is shown that the measured curves have some similarity with the curves predicted from legacy models, but one can argue whether these models are good enough for G.fast performance simulations or not. As a start we will also introduce a first-order enhancement of that legacy model for preventing unrealistic predictions at higher frequencies, and this might be the best solution for the time-being.

2. Modeling EL-FEXT

2.1 Legacy model for FEXT

The parametric model for far-end crosstalk, which is commonly used for al kinds of DSL performance studies in the past, is shown in the expression below. It evaluates the equivalent FEXT (which is different from an individual wire pair coupling), and a more detailed description of what it represent can be found in the ETSI Spectral Management standard [6], part 2, chapter 8.

$$H_{fext}(f,L,K_{xf}) = K_{xf} \times \left({}^{f}\!/_{f_0} \right) \times \sqrt{L/L_0} \times \left| s_T(f,L) \right|$$

- Variable ***f*** identifies the frequency. Constant ***f*₀** identifies a chosen reference frequency for dimensioning purposes, commonly set to f_0 = 1 MHz.

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[1]

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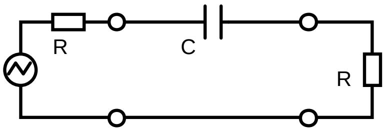
- Variable $\boldsymbol{L}$ identifies the physical length of the loop. Constant $\boldsymbol{L_0}$ identifies a chosen reference length for dimensioning purposes, commonly set to $L_0 = 1$ km.
- Function $\boldsymbol{s_T(f, L)}$ represents the frequency and length dependent amplitude of the transmission through the actual loop, normalized to a reference impedance R_n. This value equals $s_T=|s_{21}|$, where s_{21} is the forward scattering parameter of the loop normalized to R_n.
- Constant $\boldsymbol{K_{xf}}$ identifies an empirically obtained number that scales the FEXT transfer function $H_{fext}(f, L, K_{xf})$. The value for K_{xf} is cable specific, and is to be specified for each scenario being studied. A commonly used value (in dB) for generic European studies, not dedicated to any particular cable or region, is $K_{xf\_dB} = -45$ dB for $f_0 = 1$ MHz and $L_0 = 1$ km.

2.2 First order enhancement of legacy model for FEXT

One problem of the above legacy model for far-end crosstalk is that the predicted coupling keeps increasing with the frequency and that above a certain frequency the predicted FEXT becomes unrealistically higher than the assumed transmission. This was not an issue for VDSL2 studies, but higher frequencies are assumed to be used for G.fast. Therefore this models needs to be improved.

The legacy model is build-up from two parts: a coupling part ($K_{xf}\times f/f_0\times\sqrt{(L/L_0)}$), and a transmission part $s_T(f, L)$. The coupling part is linear proportional to the frequency, like the out-of-band transfer of a first-order high-pass filter. It scales with $\sqrt{(L/L_0)}$, and not with (L/L_0), since it is a cascade of many short section and the individual coupling values are random in nature.
If this coupling is assumed to be purely capacitive and is described by the transfer function of a series capacitance, then we will obtain a coupling that never exceeds the value of 1.

$$K_{xf}\times\left(f/f_0\right)\times\sqrt{L/L_0} \rightarrow$$



$$\rightarrow \left(\frac{jwRC}{1+jwRC}\right)=\left(\frac{j\cdot K_{xf}\left(f/f_0\right)\times\sqrt{L/L_0}}{1+j\cdot K_{xf}\left(f/f_0\right)\times\sqrt{L/L_0}}\right)$$

By using this replacement we get a first order enhancement of the legacy model that can be defined as follows:

$$\boxed{H_{fext}(f,L,K_{xf})=\left(\frac{j\cdot K_{xf}\left(f/f_0\right)\times\sqrt{L/L_0}}{1+j\cdot K_{xf}\left(f/f_0\right)\times\sqrt{L/L_0}}\right)\times s_T(f,L)}$$

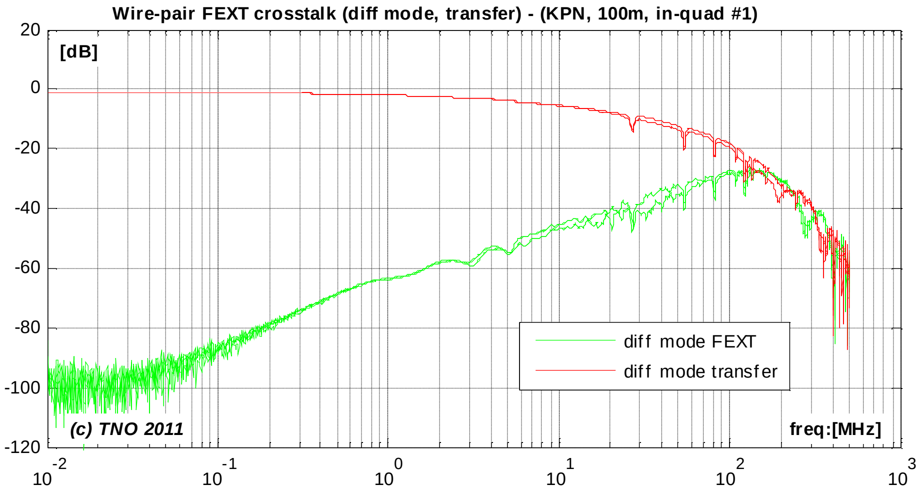
The magnitude of this transfer function approximates the transfer of the legacy model when $f < f_0/K_{xf}\cdot\sqrt{(L_0/L)}$, which holds for instance for frequencies below 177MHz when $K_{xf} = -45$dB and $f_0 = 1$ MHz and $L = L_0 = 1$ km. The phase of this transfer function may be a bit artificial, although the measurements in the next chapters demonstrate that this phase not a bad estimate of actual values.

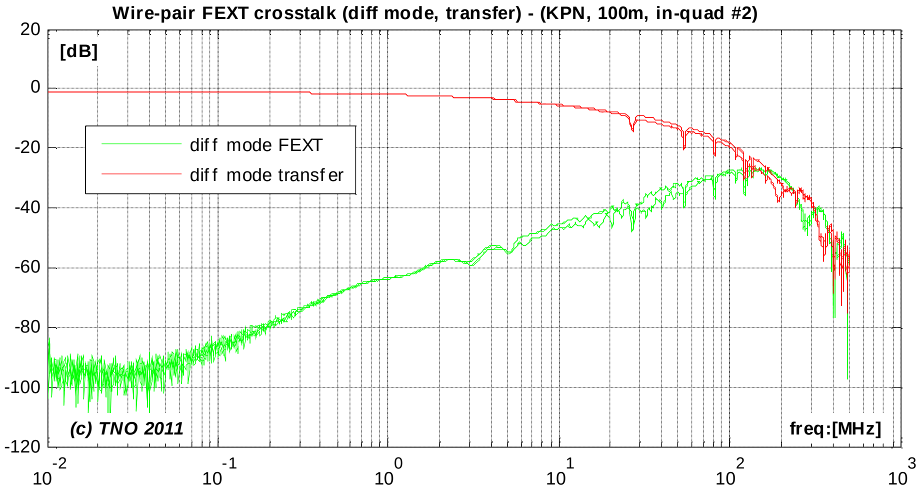
3. Measured crosstalk on access wiring (KPN Access cable)

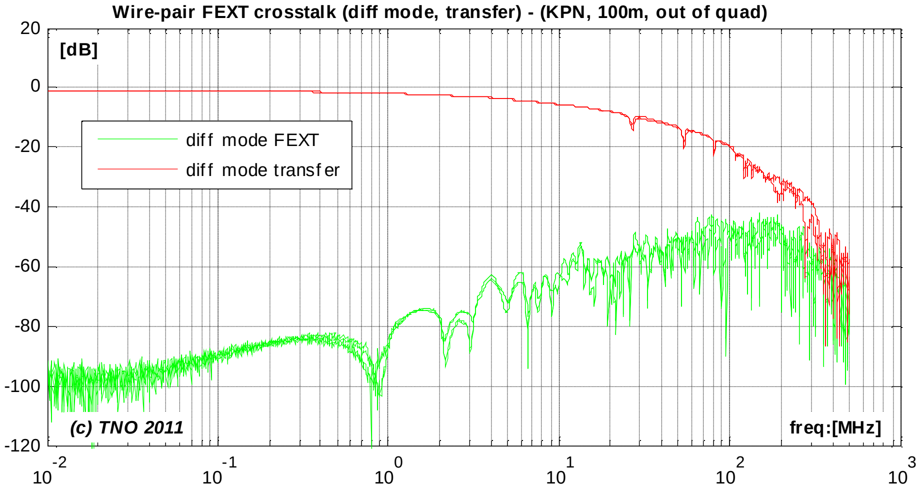
We measured far-end crosstalk between different wire pairs in a typical underground access cable being used in the Netherlands (KPN access cable. The cable section was about 100m long (104.1 m), and further details about its transmission characteristics can be found in [2]. This chapter concentrates on the results of several FEXT measurements on this cable.

3.1 FEXT Measurements (in-quad, out-of-quad)

The FEXT is the transfer function from one end and wire pair to another end and wire pair. The figures below compares the observed FEXT (between different wire pairs) with the transmission (via a single wire pair).
The first two figures show the observed crosstalk between wire pairs situated in the same quads, while the third one does the same for wire pairs situated in different quads with different twist lengths. As expected, the in-quad crosstalk is higher than the out-of-quad crosstalk. As expected, the curve of the in-quad crosstalk function is also smoother than for the out-of-quad crosstalk since all in-quad wire pairs follow the same geometry and have exactly the same twist.





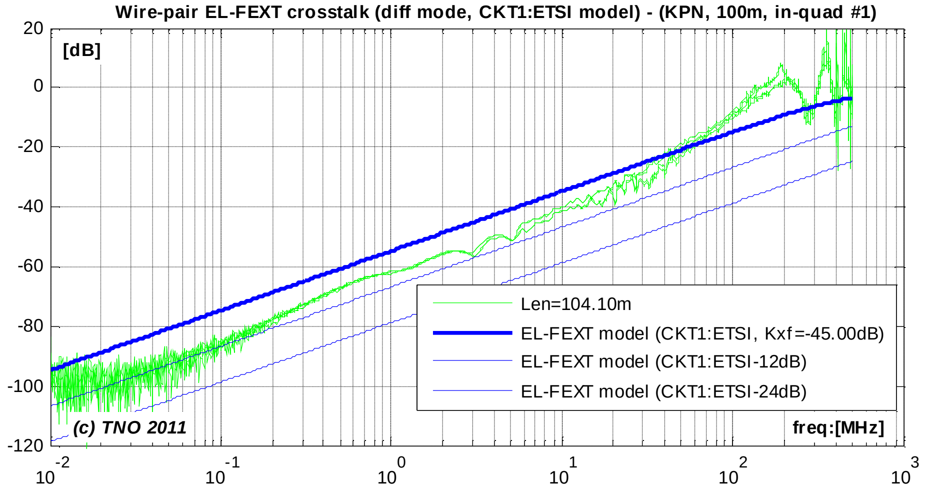


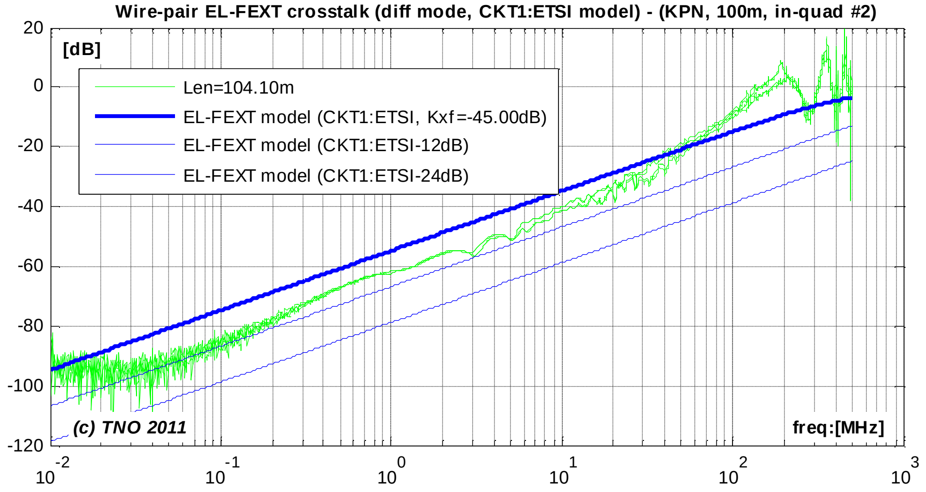
The figures demonstrate that the observed FEXT is so high above about 150MHz that FEXT and transfer are in the same order of magnitude. Due to all kinds of resonation effects, the crosstalk above 150 MHz is sometimes a bit higher than the transfer and sometimes a bit lower but on average they remain in the same order of magnitude.
The observed FEXT is so low below about 200 kHz that it becomes hardly measurable with the used measurement setup. As a result we can only draw conclusions about FEXT measurements on this particular cable when the frequency is above 2 MHz.

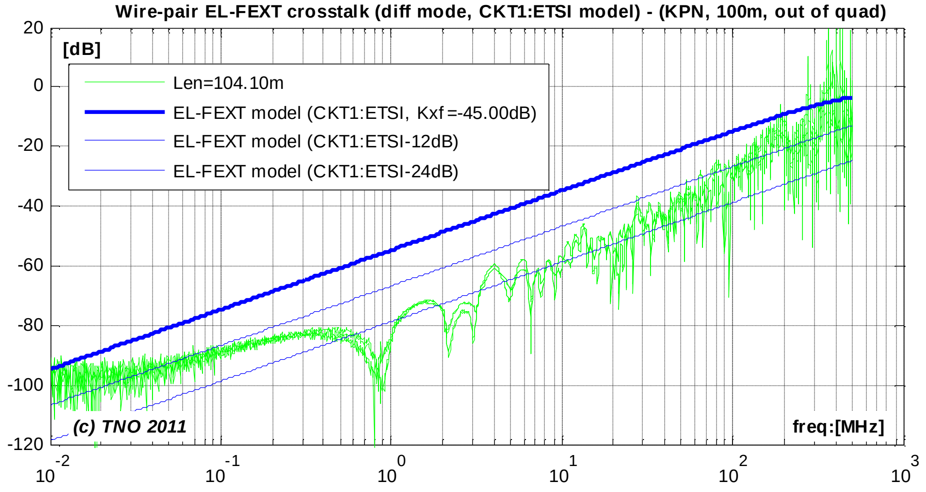
3.2 EL-FEXT Measurements (in-quad, out-of-quad)

The ratio between FEXT and transmission is indicative for the signal to noise ratio that will be observed at a DSL receiver. Therefore the FEXT itself is of limited interest, and the EL-FEXT (equal level) is far more meaningful. EL-FEXT is defined as the ratio between FEXT and transmission, and the figures below show it for several wire pairs. The first two figures show the observed crosstalk between wire pairs situated in the same quads, while the third one does the same for wire pairs situated in different quads. As expected, the in-quad crosstalk is higher than the out-of-quad crosstalk. And the curves of the in-quad crosstalk functions are also smoother than the one for the out-of-quad crosstalk since all in-quad wire pairs follow the same geometry and have exactly the same twist.

The rippling in crosstalk magnitude between the out-of-quad wire pairs may be caused by the fact that the lengths of the involved out-of-quad wire pairs are slightly different, while the lengths of the in-quad wire pairs are assumed to be more equal.







The above figures are all decorated with three different curves (all in blue) of the enhanced version of the classical EL-FEXT model. The highest line (called CKT1:ETSI) represents a crosstalk level that was commonly used in the past (within ETSI, FSAN, ANSI/ATIS, etc) as a near worst-case crosstalk example for studying ADSL and VDSL performance (-45 dB @ 1 MHz @ 1km, and scaled to a loop length of 104.1m).
The curves of our enhanced model bend only away from what the legacy model would have predicted when it approximates (or exceeds) 0dB. This prevent unrealistic EL-FEXT levels far above 0 dB. This deviation is only visible for curve “CKT1:ETSI” in the plot for the highest frequencies. The other lines are based on the same parametric model but with coupling values that are 12 and 24dB lower.

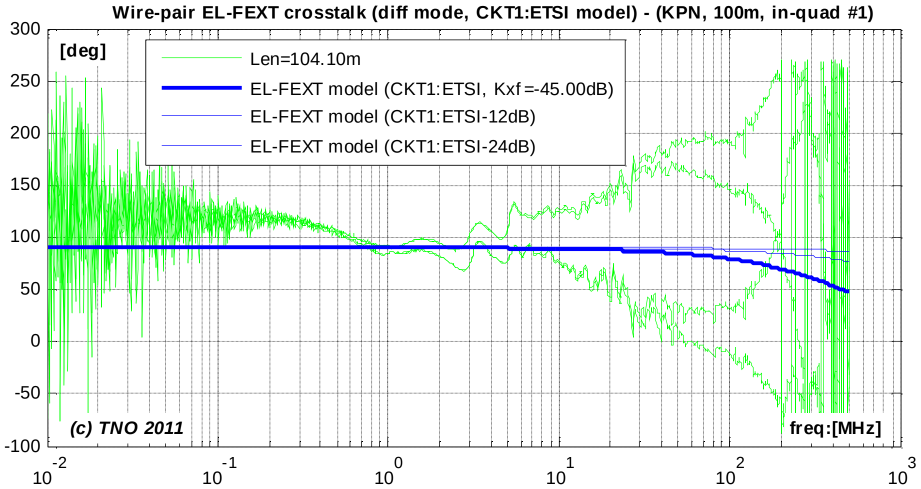
The observed EL-FEXT curves have some similarity with these models above 2 MHz, but one can argue whether these models are good enough for studying the performance of G.fast.

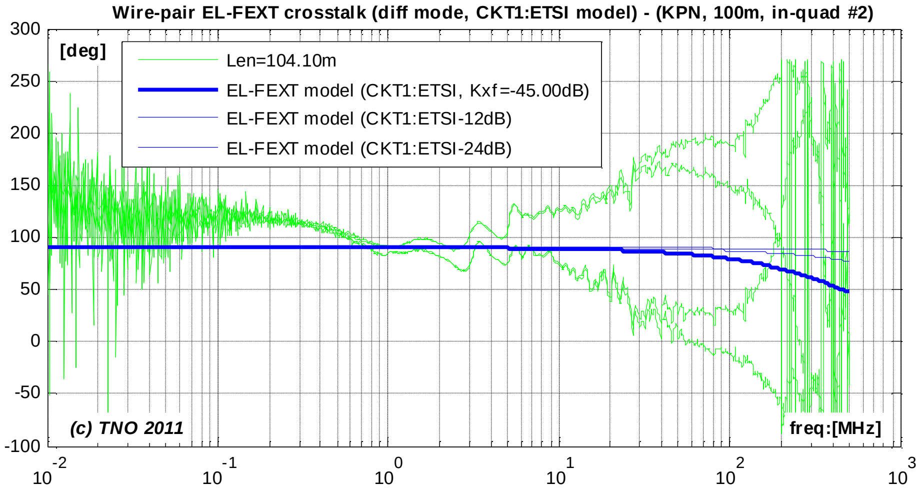
The slope of the measurement is about twice as steep as the legacy model above a certain frequency (30 MHz in this example), and the crosstalk coupling gets significantly higher than predicted by the (near worst case) assumptions of the past. This can be a significant problem since G.fast signals are assumed to operate in this band as well.

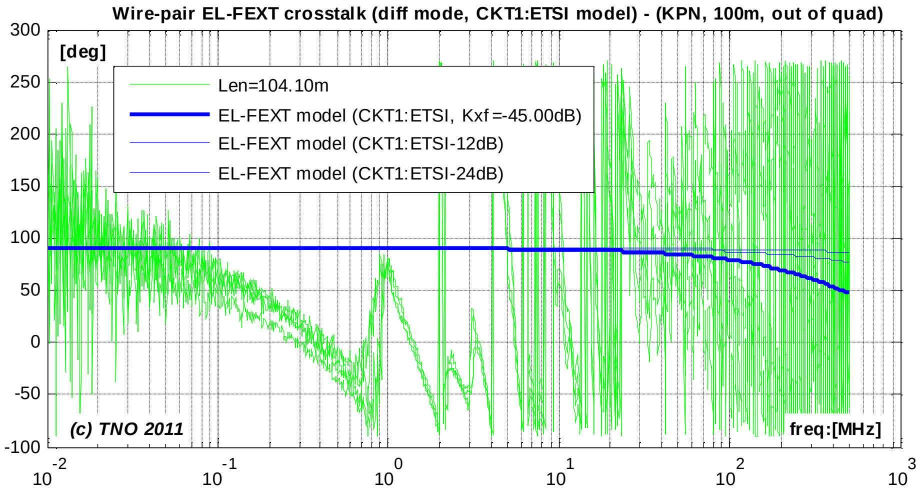
It may be obvious that the FEXT model needs further improvement, on top of the enhancement we introduced so far.

3.3 EL-FEXT Measurements (phase relations)

The enhanced model for EL-FEXT does not only predict a magnitude but also a phase. To learn how applicable is phase prediction is, we compared the measured phase of EL-FEXT with the predicted one. The first two figures below show the observed crosstalk phase between wire pairs situated in the same quads, while the third one does the same for wire pairs situated in different quads. Mark that the measurements are only reliable above 200 kHz, as explained at the beginning of this chapter.







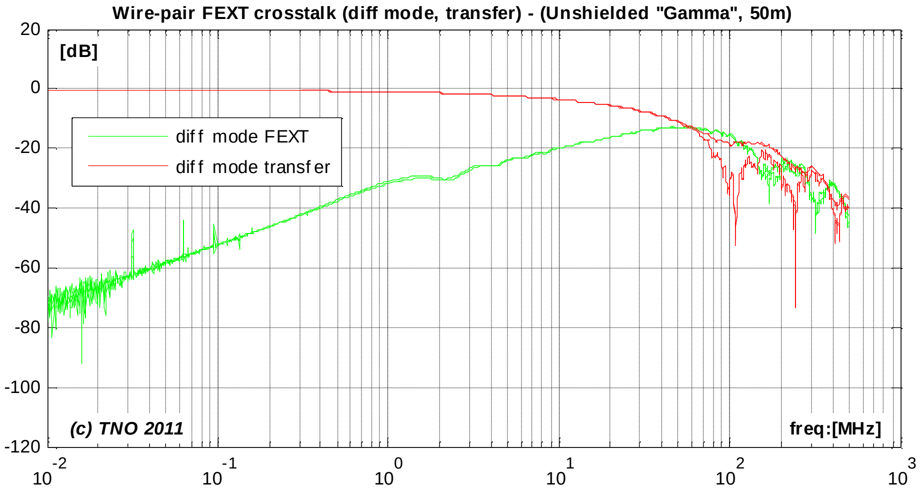
The observed FEXT phase of in-quad crosstalk is roughly at constant distance from the observed transmission phase over a wide frequency interval. Therefore the EL-FEXT is observed to be rather constant over a wide frequency band (in the order of +90 degrees, above 200 kHz). This may be an advantage when designing crosstalk canceling mechanisms for bonded G.fast systems using all the 4 wires of a quad simultaneously. As such, the phase prediction of the enhanced EL-FEXT model isn't that bad at all, although it suffers from the same limitations as observed before for magnitude predictions of that model.
The observed EL-FEXT phase of out-of-quad crosstalk is not so constant over a wide frequency interval, and this may be caused (again) by the fact that the lengths of the involved out-of-quad wire pairs are a slightly different.

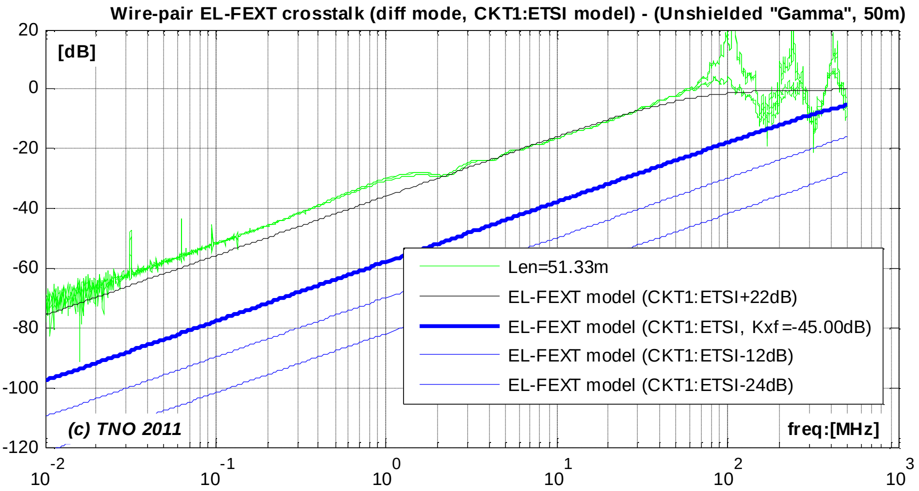
4. Measurements on in-house wiring ("Gamma")

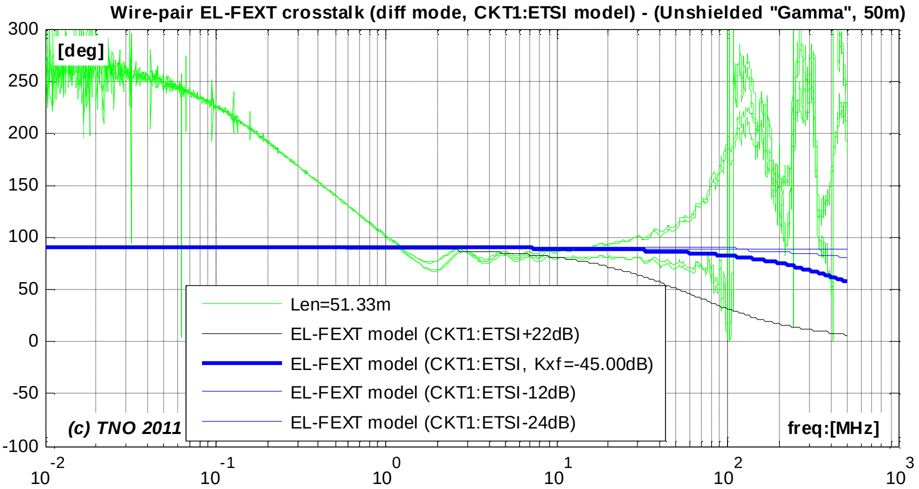
We also measured far-end crosstalk between the two wire pairs of 50m in-house "telephony" cabling, which was found in a consumer shop. The four wires of this cable are more or less organized in a quad, but the geometry of that quad is a bit flexible and can easily change by bending this low quality cable. This causes higher in-quad crosstalk values. The quad is also untwisted, but that has no effect on the in-quad crosstalk. More detail about the characteristics of this cable can be found in [1] and [2].

The three figures below show the measured FEXT (together with its transmission), the EL-FEXT (together with a model) and the phase of this EL-FEXT (also together with a model).

- The first figure below illustrates that above about 60 MHz the FEXT exceeds the transmission.
- The second figure below illustrates that the measured EL-FEXT is roughly 22 dB above the model for EL-FEXT used in many European studies. The shapes of measured and modeled curves have good similarities above 2 MHz, and that our first order enhancement of the FEXT model becomes essential above about 70 MHz.
- The third figure below illustrates that the phase predictions of the model isn't that bad above about 2 MHz.







6. Measurements on other type of wiring

We have also measured the far end crosstalk of the other two cable types that are described in [1] and [2], a Cat5e cable and an in-building multi quad telephony cable.

The observed FEXT of the CAT5e cable was so low that it went beyond the measurement capabilities of our setup. Therefore this aspect of these measurements were ignored.

The observed FEXT of the multi-quad telephony cable had very different characteristics than those presented above. This phenomena is still under study.

7. Summary

This paper should be presented under the G.fast agenda item, and addresses issue 5.1 and 4.7.2.1.x

The paper shows the results of far-end crosstalk measurements on real telephony cables and compares the measured curves with predicted curves from a model. The measured curves have some similarity with the curves predicted from legacy models, but one can argue whether these models are good enough for G.fast performance simulations or not.

As a first step, we introduced a first-order enhancement of that legacy model, which can prevent unrealistic high crosstalk levels at higher frequencies, but further improvements are left for further study. The inclusion of that model in G.fast is proposed in a separate contribution [3].

Further improvements of the FEXT model are needed as well, to account for slopes that increase above a certain frequency. This causes that the actual crosstalk coupling gets significantly higher than predicted, even when the near worst case assumptions of the past are used. Ignoring this can be a significant problem since G.fast signals are assumed to operate in this band as well.

This contribution is provided for information only.

8. References

[1] TNO (Rob van den Brink, Bas van den Heuvel), *"G.fast: Wideband transfer and crosstalk measurements on twisted pair cables"*, ITU contribution 11BM-021, April 18, 2011.

[2] TNO (Rob van den Brink, Bas van den Heuvel), "*G.fast: Wideband modeling of twisted pair cables as two-ports*" , ITU contribution 11GS3-028, Geneva Sept 2011.

[3] TNO (Rob van den Brink, Bas van den Heuvel), "*G.fast: Enhhanced model for FEXT*" , ITU contribution 11RV-023, Richmond, Nov 2011.

[4] Huawei (Dong Wei, Anni Wu), "*G.fast: Performance of G.fast when Coexisting with VDSL2*", ITU contribution 11GS3-067, Geneva Sept 2011.

[5] Ikanos (Massimo Sorbara, Stephanie Pereira), "*G.fast: Simulations for G.fast at 200m*", ITU contribution 11GS3-075, Geneva Sept 2011.

[6] ETSI TR 101 830-2, Transmission and Multiplexing (TM); Access networks; "*Spectral management on metallic access networks; Part 2: Technical methods for performance evaluations*." 2008.