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Title: Refinements in Text Proposal on Crosstalk Models

Source: Swisscom AG and TNO

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Status: For decision

Abstract

In this contribution some refinements of the current draft text on crosstalk models are proposed.

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1 Introduction

This contribution is dedicated to SP4 and SP5.

During the last meeting Swisscom was asked to work off-line with TNO and to bring a proposal that solves all open points concerning the crosstalk models. The proposed text of the Annex in the current contribution is based on the provisionally agreed text in the LL [1]. The major modifications are highlighted in yellow, i.e. purely typographical corrections are not highlighted.

2 Proposal

Swisscom and TNO ask that the text on crosstalk models proposed in this contribution is moved from the provisionally agreed status to the agreed status.

3 Conclusion

This contribution proposes some refinements of the current draft text on crosstalk models and asks to agree the text for the SpM-2 document.

4 References

1 m06p05a04_SpM-2_LL: “Living List for Spectrum Management, SpM – part 2, revision of TR 101 830-2”, Revision 4, January 31, 2007

5 Annex: Text Proposal

Text proposals, for inclusion in the revised SpM-2.

Text portions, proposed for inclusion in clause 8

8 Crosstalk models

Crosstalk is commonly a dominant contributor to the overall disturbance that impairs a transmission. Crosstalk models are to evaluate how much crosstalk originates from various disturbers that are distributed over the local loop wiring. In practice this is not restricted to a one-dimensional cable topology, since wires may fan out into different directions to connect for instance different customers to a central office.
This clause summarizes basic models for evaluating crosstalk in various scenarios. The models are presented here as individual building blocks, but a full analysis requires the use of a combination of these blocks.

8.1 Basic models for crosstalk cumulation

Cumulation models relate the crosstalk powers generated by multiple disturbers with the *number* and *type* of these disturbers.
The meaning of *the* crosstalk power is not obvious. When a cable with *N* wire-pairs is filled-up completely with similar disturbers, the resulting crosstalk power in each wire-pair (from *N*-1 disturbers connected to the other wire-pairs) is maximal and therefore unambiguous. This upper limit is the saturated crosstalk power for that type of disturber, for that particular wire-pair.
However if the number *M* of disturbers is lower (*M*<*N*-1), this crosstalk power will commonly change when another combination of *M* wire-pairs will be chosen. So an exact expression for the resulting crosstalk, as function of the *number* and *type* of disturbers, does not exist if it remains unknown to which wire-pairs they are connected.
What does exist are crosstalk powers that occur with a certain probability. To illustrate that, consider an experiment that connects 30 disturbers to a cable with 100 wire-pairs in 100.000 different ways. If the resulting noise is observed in one particular wire-pair, it is most likely that 100.000 different crosstalk noise powers will be observed. The result of such a “probability experiment” is therefore not a single power, but a (wide) range of powers with a certain probability distribution. Within this range, a certain crosstalk noise power can be found that is not exceeded in 99% of the cases (or 80% or 65% or whatsoever). That power level is named a *probability limit* for a particular wire-pair.
A cumulation model predicts how such a *limit* (at given probability) behaves as a function of number and type of disturbers. The use of 99% worst case limits is commonly used. When a study evaluates the performance under a noise power that equals such a probability limit, then the actual performance will in “most cases” be better then predicted in this way. The use of 100% worst case limits is commonly avoided, to prevent for over-pessimistic analyses.

8.1.1. Uniform cumulation model

The uniform cumulation model is restricted to the special case that all disturbers are from the same type. It assumes that the probability limit from *M* disturbers is proportional with $M^{1/Kn}$, where K_n is an empirical parameter (values like K_n=1/0,6 are commonly used for 99% worst case analyses). Expression 1 shows this uniform cumulation model. It uses a frequency dependent quantity P_{Xd} (the *normalized crosstalk power*) as intermediate result, that has been derived from the saturated crosstalk power (maximum crosstalk power at 100% cable fill), for that particular type of disturber. This saturated crosstalk power will most likely be different for each individual wire-pair, but a worst case value of all wire-pairs could be selected if a cable is to be modelled as a whole. Hence Expression 1 can be applied to predict probability limits in either a single wire-pair or in a cable as a whole. The difference is that in the latter case $P_X(N\text{-}1, f)$ is the saturated crosstalk power in the worst-case wire-pair (having the highest saturated value) and that $P_X(M,f)$ represents a statistical value (e.g. a 99% worst case value) taken from much more values then in the single wire-pair case.

The reliability of the model improves when *M*>>1. By definition, the model provides an exact value for the crosstalk power experienced within a specific victim wire-pair when *M*=(*N*-1).

$$P_X(M,f) = M^{1/K_n} \times P_{Xd}(f) \qquad \text{with } P_{Xd}(f) \overset{def}{=} \frac{P_X(N-1,f)}{(N-1)^{1/Kn}}$$

N = number of wire-pairs in the cable
M = number of similar disturbers (1 ≤ *M* ≤ *N*-1)
$P_X(M, f)$ = probability limit of crosstalk from *M* similar disturbers
$P_X(N\text{-}1, f)$ = saturated crosstalk power (at a complete cable fill)
$P_{Xd}(f)$ = normalized crosstalk power, for that particular disturber type
K_n = empirical constant (K_n=1/0,6 is commonly used)
f = frequency

Expression 1: Definition of uniform cumulation model

NOTE: For some cables used in the Netherlands, it has been observed that a slightly different value for K_n provides a better fit with measurements on these cables. For instance, values between 1/0,6 and 1/0,8 have been observed. For those cables, these values for K_n may be more appropriate for use in expression 1 and associated expressions.

8.1.2. FSAN sum for crosstalk cumulation

The FSAN sum is a cumulation model that is also applicable when different disturbers are involved. It is a generalization of the uniform cumulation model, and is specified in expression 2. The (frequency dependent) probability limit of the crosstalk, caused by *M* individual disturbers, is expressed below.

$$P_X(M,f) = \left(P_{Xd,1}(f)^{K_n} + P_{Xd,2}(f)^{K_n} + P_{Xd,3}(f)^{K_n} + \cdots + P_{Xd,M}(f)^{K_n}\right)^{1/K_n}, \quad with\ K_n = \frac{1}{0{,}6}$$

M = number of involved disturbers
$P_X(M,f)$ = probability limit of crosstalk from those M disturbers
$P_{Xd,k}(f)$ = normalized crosstalk power, for disturber k, as defined in expression 1.
K_n = empirical constant (K_n=1/0,6 is used for the FSAN sum)
f = frequency

Expression 2: FSAN sum for cumulating the power levels of *M* individual disturbers into the power level of an equivalent disturber

Factor K_n is assumed to be frequency independent. In the special case that all M disturbers generates equal power levels (P_{Xd}) at all frequencies of interest, the FSAN sum simplifies into $P_X(M, f) = P_{Xd}(f) \times M^{1/Kn}$. This demonstrates consistency with the uniform cumulation model. The FSAN sum operates directly on powers, and ignores the existence of source and termination impedances. If different impedances are involved (due to different disturber and victim types), their *available* power levels are to be combined according to the FSAN sum. Available power of a source is the power dissipated in a load resistance, equal to its source impedance.

8.2 Basic models for NEXT and FEXT coupling

These sub-models for crosstalk coupling are to evaluate the normalized crosstalk power, as defined before in expression 1, that a *single* disturbing modem pair couples into a specific (other) wire-pair in the cable. However, it should be noted that the models in this clause are restricted to *normalized* crosstalk coupling only, and are not intended for evaluating the *actual* crosstalk coupling between two individual wire-pairs. The actual coupling fluctuates rapidly with the frequency and changes significantly per wire-pair combination. Therefore the ratio between *normalized* crosstalk amplitude (measured at 100% cable fill, and subsequently normalized to a single disturber) and the disturber amplitude is being modeled.

The models for topologies with multiple disturber pairs are derived from these basic models.

- NEXT-coupling refers to the transfer function between ends of different pairs at the same cable section side (“near-end”).
- FEXT-coupling refers to the transfer function between ends of different pairs at the opposite cable section sides (“far-end”).

When P_d represents the (frequency dependent) transmit power of the involved disturber, and P_{Xd} represents the (frequency dependent) normalized crosstalk power (scaled down from the saturated crosstalk power at 100% cable fill), then this ratio becomes as follows:

$$H(f) = normalized\ crosstalk\ coupling = \sqrt{\frac{normalized\ crosstalk\ power}{disturber\ power}} = \sqrt{\frac{P_{Xd}(f)}{P_d(f)}}$$

Expression 3: Definition of normalized crosstalk coupling function.

The normalized crosstalk coupling is dependent from the wire-pair being connected to the victim modem pair. A possible approach for modeling coupling in cables as a *whole*, is to find the normalized crosstalk power (for a chosen disturber type) in each of the *N* wire-pairs of the cable, and then to find (for each frequency) the 99% worst case value of those *N* powers.

8.2.1 Normalized NEXT and FEXT coupling at an elementary cable section

The normalized coupling models for co-located NEXT and FEXT are restricted to the special case of an elementary cable section topology, as illustrated in figure 1. The LT side of a disturbing modem pair is in such a topology co-located with the LT-side of a victim modem, and the same applies to the NT side. It means that the two involved wire-pairs are coupled over the full length of that (elementary) cable or cable section.

Figure 1: Example of a two-node cable section topology

Expression 4 specifies the transfer functions of this normalized NEXT and FEXT coupling model. The termination impedances of the wire-pairs are fully ignored in this model, and all wire-pairs are assumed to be terminated by the *characteristic* impedance Z_0 of the cable. By doing so, a cascade of two loops can easily be evaluated by multiplying their respective characteristic transmissions, without bothering impedances.

$$
\begin{aligned}
H_{next}(f,L) &= K_{xn} \times \left(f \big/ f_0 \right)^{0,75} \times \sqrt{1-\left|s_T(f,L)\right|^4} \\
H_{fext}(f,L) &= K_{xf} \times \left(f \big/ f_0 \right) \times \sqrt{L/L_0} \times \left|s_T(f,L)\right|
\end{aligned}
$$

NOTE 1: Parameter ***f*** refers to the frequency. Constant $\boldsymbol{f_0}$ identifies a chosen reference frequency, commonly set to $\boldsymbol{f_0}$ = 1 MHz.

NOTE 2: Parameter ***L*** refers to the coupling length of the wire-pairs. Constant $\boldsymbol{L_0}$ identifies a chosen reference length, commonly set to $\boldsymbol{L_0}$ = 1 km.

NOTE 3: Values for $\boldsymbol{K_{xn}}$ and $\boldsymbol{K_{xf}}$ are cable specific, and are to be specified for each scenario being studied. Commonly used values (in dB) for generic European studies, not dedicated to any particular cable or region, are: K_{xn}_dB = –50 dB and K_{xf}_dB = –45 dB for f_0 = 1 MHz and L_0 = 1 km.

NOTE 4: Function $\boldsymbol{s_T(f, L)}$ represents the frequency and length dependent characteristic transmission of the wire-pairs. This equals the insertion loss when the cable is terminated at both ends with its characteristic impedance.

Expression 4: Transfer functions of co-located normalized NEXT and FEXT coupling

8.2.2 Normalized NEXT and FEXT coupling at distributed or branched cables

When crosstalk from a disturbing modem pair originates from locations that are not co-located with the victim modem pair, the two involved wire-pairs are not coupled over the full length. An example topology occurs when a victim modem-pair operates between cabinet and customer premises while a disturbing modem pair operates between central office and customer premises. Another example topology occurs when a cable is branched to different (customer) locations, from a certain point in the loop. Both examples are illustrated in figure 2.

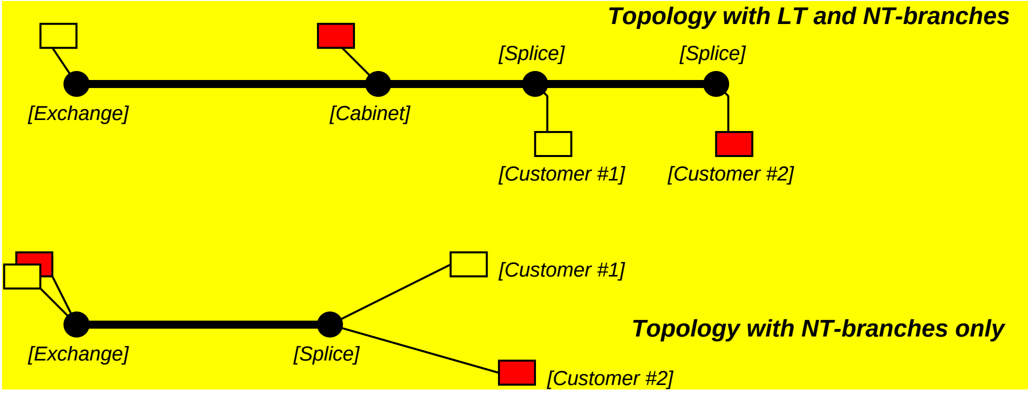
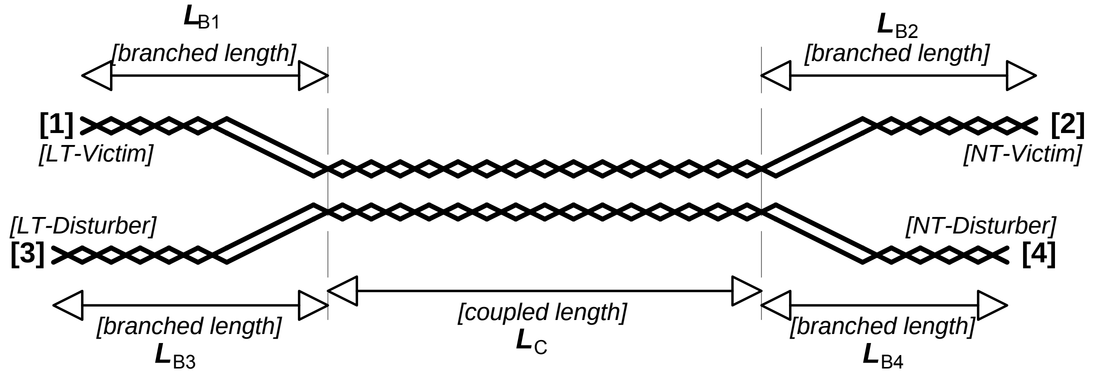


Figure 2: Two example topologies with branching

In all these distributed or branched examples, the interaction between disturbers and victims can be characterized by a common section that couples signals, and four independent sections (branches) that are attenuating signals only. This is illustrated in figure 3. Branches may have zero length in special topologies.



Victim modem pair, between port [1] and [2]
Disturbing modem pair, between port [3] and [4]

Transfer function		Involved ports	Coupling length L_C	Branch length L_B
LT-NEXT coupling:	$H_{next,LT}(f, L_C, L_B)$	[3] → [1]	L_C	$L_{B3} + L_{B1}$
NT-NEXT coupling:	$H_{next,NT}(f, L_C, L_B)$	[4] → [2]	L_C	$L_{B4} + L_{B2}$
LT-FEXT coupling:	$H_{fext,LT}(f, L_C, L_B)$	[4] → [1]	L_C	$L_{B4} + L_{B1}$
NT-FEXT coupling:	$H_{fext,NT}(f, L_C, L_B)$	[3] → [2]	L_C	$L_{B3} + L_{B2}$

Figure 3: Example of the lengths that are to be used for evaluating branched normalized NEXT and FEXT

The expressions for branched normalized crosstalk coupling are not so different from the co-located case. They mainly differ by the fact that *two* length values are involved instead of one: the coupling length L_C and the total branch length L_B. The branched model is simply derived from the co-located model, by incorporating the additional attenuation of these branches.

The table in figure 3 summarizes what the total branch length is for each combination of ports. The associated transfer functions from a disturbing transmitter to a victim modem are shown in expression 5. If L_B=0, the expressions simplify in those for the co-located case, and this demonstrates consistency between the two models.

This model assumes a single cable type, so that branch length could be added to the coupling length to account for its insertion loss. If this is not the case, the insertion losses of the branches have to be evaluated individually.

$$H_{next}(f,L_C,L_B) = K_{xn} \times \left(\frac{f}{f_0}\right)^{0,75} \times \sqrt{1-\left|s_T(f,L_C)\right|^4} \times \left|s_T(f,L_B)\right|$$

$$H_{fext}(f,L_C,L_B) = K_{xf} \times \left(\frac{f}{f_0}\right) \times \sqrt{L_C/L_0} \times \left|s_T(f,L_C+L_B)\right|$$

NOTE 1: Parameter ***f*** refers to the frequency.
Constant $\boldsymbol{f_0}$ identifies a chosen reference frequency, commonly set to f_0 = 1 MHz.

NOTE 2: Parameter $\boldsymbol{L_C}$ refers to the coupling length between the wire-pair connected to the disturbing transmitter and the wire-pair connected to the victim receiver. It represents the length they share in the same cable.
Constant $\boldsymbol{L_0}$ identifies a chosen reference length, commonly set to L_0 = 1 km.

NOTE 3: Parameter $\boldsymbol{L_B}$ refers to the respective branching length (for adding signal attenuation only) from a disturbing transmitter to a victim receiver.

NOTE 4: Values for $\boldsymbol{K_{xn}}$ and $\boldsymbol{K_{xf}}$ are cable specific, and are to be specified for each scenario being studied. Commonly used values (in dB) for generic European studies, not dedicated to any particular cable or region, are: K_{xn}_dB = –50 dB and
K_{xf}_dB = –45 dB for f_0 = 1 MHz and L_0 = 1 km.

NOTE 5: Function $\boldsymbol{s_T(f, L)}$ represents the frequency and length dependent characteristic transmission of the wire-pairs. This would be the insertion loss when the cable is terminated at both ends with its characteristic impedance.

Expression 5: Transfer functions of branched normalized NEXT and FEXT coupling

8.3 Basic models for crosstalk injection

same text as current clause 8.3

8.4 Overview of different network topologies

same text as current clause 8.4

8.5 Crosstalk evaluation for multi-node topologies

If a victim modem pair is impaired by disturbers from all kinds of locations, the evaluation of the crosstalk probability limits may be rather complex. Figure 4 shows an example of the wiring in a multi-node topology.

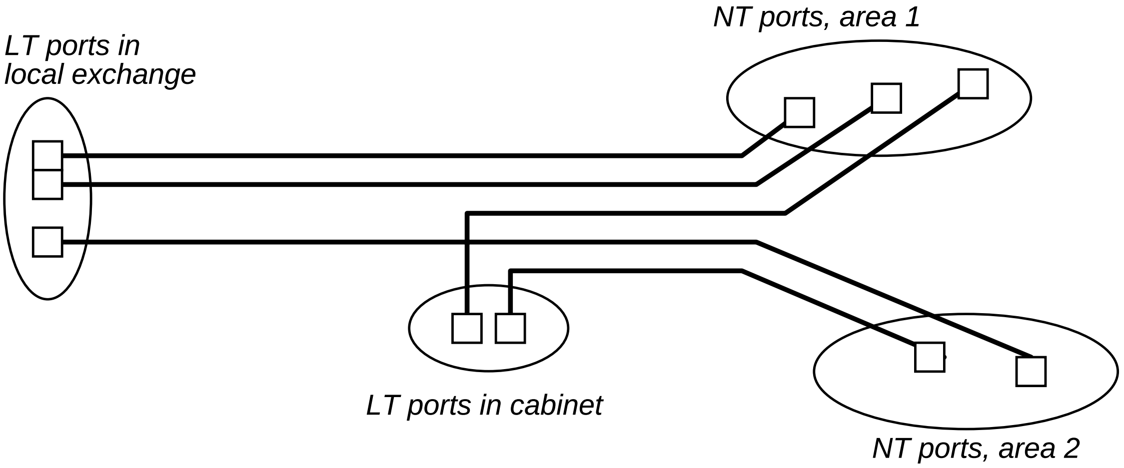


Figure 4: Example of the wiring in a multi-node topology.

Essentially, this example with five wire-pairs is a combination of four individual couplings between a disturbing modem pair and the victim modem pair. Each coupling function can be different (in coupling length, in branching length, etc). By evaluating these individual coupling functions one by one, the probability limits of the crosstalk from all involved disturbers can be derived.

The probability limit $P_{XN,NT}$ of the crosstalk power at the NT side of a victim modem pair, and the associated probability limit $P_{XN,LT}$ at the other side, can be evaluated as follows:

- First, evaluate for each individual disturber pair {k}, the four normalized crosstalk coupling functions between the two disturbers and the two victims. Appropriated models are provided in expression 5. When disturbers are not co-located with other disturbers, the coupling and branching lengths may be different for each disturber pair.
- Then, evaluate for each individual disturber pair {k} the normalized crosstalk power $P_{Xd\{k\}}$ from the transmit power $P_{d\{k\}}$ of the involved disturber. This is formulated below at both victim modems:
  Normalized NEXT at NT-side: $P_{XNd\{k\},NT} = P_{d\{k\},NT} \times |H_{next\{k\},NT}|^2$
  Normalized NEXT at LT-side: $P_{XNd\{k\},LT} = P_{d\{k\},LT} \times |H_{next\{k\},LT}|^2$
  Normalized FEXT at NT-side: $P_{XFd\{k\},NT} = P_{d\{k\},LT} \times |H_{fext\{k\},NT}|^2$
  Normalized FEXT at LT-side: $P_{XFd\{k\},LT} = P_{d\{k\},NT} \times |H_{fext\{k\},LT}|^2$
- Next, cumulate all these normalized individual NEXT powers with an appropriated cumulation model (for instance the FSAN sum in expression 2) into a probability limit of the NEXT.
- Do the same for normalized FEXT powers.

- Finally add both powers. If direct disturbers ($P_{\mathrm{bn,NT}}$ and $P_{\mathrm{bn,LT}}$) are also involved (like systems sharing the same wire-pair in another frequency band), then they can be added here as well.

Expression 6 evaluates the probability limit of the crosstalk at each receiver as explained above, in the case that FSAN summing is applied for the cumulation, and direct disturbers are involved at both sides.

$$P_{XN,NT} = \left(\sum_{k=1}^{M}\left(P_{d\{k\},NT} \times \left|H_{next\{k\},NT}\right|^{2}\right)^{Kn}\right)^{1/Kn} + \left(\sum_{k=1}^{M}\left(P_{d\{k\},LT} \times \left|H_{fext\{k\},LT}\right|^{2}\right)^{Kn}\right)^{1/Kn} + P_{bn,NT}$$

$$P_{XN,LT} = \left(\sum_{k=1}^{M}\left(P_{d\{k\},LT} \times \left|H_{next\{k\},LT}\right|^{2}\right)^{Kn}\right)^{1/Kn} + \left(\sum_{k=1}^{M}\left(P_{d\{k\},NT} \times \left|H_{fext\{k\},NT}\right|^{2}\right)^{Kn}\right)^{1/Kn} + P_{bn,LT}$$

NOTE1: Power $P_{\mathrm{d\{k\}}}$ represents the transmit power of an involved disturber *k*, and *M* represents the total number of involved disturbers in the cable

NOTE2: All involved powers *P* and coupling functions *H* are assumed to be frequency dependent, but this has been omitted to simplify the above expressions.

Expression 6: Evaluation of the probability limit of the crosstalk at each receiver

8.6 Crosstalk evaluation for two-node topologies

In the special (simplified) case that all disturbers are co-located with one of the two victim modems, the generalized approach in expression 6 can be simplified significantly. Such an approach can be applicable to scenarios with long distribution cables in which all customers can be regarded are virtually co-located (compared to the length of the distribution cable). Since they are all served from the same central office, the topology requires only two nodes (one on the LT side, and another one on the "common" NT side).

Figure 5 shows an example of the wiring in such a two-node topology.

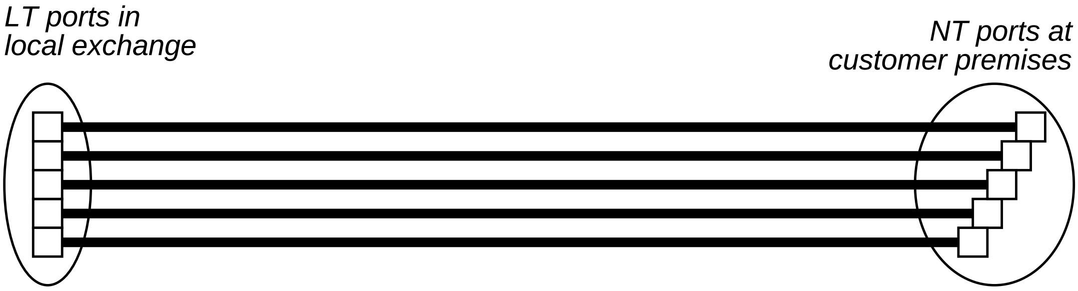


Figure 5: Example of the wiring in a two-node topology, where all wire-pairs are assumed to be of equal length.

An additional characteristic of two-node topologies is that all the NEXT coupling functions in expression 6 are assumed equal, and that the same applies for the FEXT coupling functions. The result is that the previous expression 6 for crosstalk simplifies into expression 7. By combining the powers $P_{d\{k\}}$ from all co-located disturbers into a single equivalent disturber $P_{d.eq}$ at that location, the crosstalk expression simplifies even further as shown in expression 8.

$$
\begin{aligned}
P_{XN,NT} &= \left(\sum_k \left(P_{d\{k\},NT}\right)^{Kn}\right)^{1/Kn} \times \left|H_{next}\right|^2 + \left(\sum_k \left(P_{d\{k\},LT}\right)^{Kn}\right)^{1/Kn} \times \left|H_{fext}\right|^2 + P_{bn,NT} \\
P_{XN,LT} &= \left(\sum_k \left(P_{d\{k\},LT}\right)^{Kn}\right)^{1/Kn} \times \left|H_{next}\right|^2 + \left(\sum_k \left(P_{d\{k\},NT}\right)^{Kn}\right)^{1/Kn} \times \left|H_{fext}\right|^2 + P_{bn,LT}
\end{aligned}
$$

Expression 7 Simplified version of expression 6, for the special case that all NEXT and all FEXT couplings are the same

$$
P_{d.eq} \overset{def}{=} \left(\sum_k \left(P_{d\{k\}}\right)^{Kn}\right)^{1/Kn} \quad \text{(for each end of the cable)}
$$

$$
\begin{aligned}
P_{XN,NT} &= P_{d.eq,NT} \times \left|H_{next}\right|^2 + P_{d.eq,LT} \times \left|H_{fext}\right|^2 + P_{bn,NT} \\
P_{XN,LT} &= P_{d.eq,LT} \times \left|H_{next}\right|^2 + P_{d.eq,NT} \times \left|H_{fext}\right|^2 + P_{bn,LT}
\end{aligned}
$$

NOTE All involved powers *P* and coupling functions *H* are assumed to be frequency dependent, but this has been omitted for simplifying the above expressions.

Expression 8: Evaluation of the crosstalk from two locations.

A convenient way of presenting the evaluation of the various crosstalk powers is the use of a flow diagram. This is shown in figure 6 (for downstream) and 7 (for upstream) for the two-node topology. It illustrates how the various building blocks of expression 8 work together when deriving the probability limits of the crosstalk.
The flow diagram illustrates that the crosstalk can be evaluated in steps.

- The diagram combines for each end of the cable the disturber output powers (P_{d1}, P_{d2}, …) into a single equivalent disturber ($P_{d.eq}$), as if the cumulation operates directly on these disturber powers. This has been illustrated in figures 6 and 7 by a box drawn around the involved building blocks.
  Using the equivalent disturber concept as intermediate result yields an elegant concept to break down the complexity of a full noise scenario into smaller pieces, but works only for two-node topologies.
- Next, the diagram evaluates the probability limit of the crosstalk noise (P_{XN}), that is coupled into the wire-pair of the victim modem being studied. Figures 6 and 7 illustrate what portion of the equivalent disturbance is coupled into that wire-pair by using models for (co-located) normalized *NEXT* and *FEXT*.
- If direct disturbers are involved, their power (P_{bn}) can be added to the probability limit of the crosstalk noise. Such a direct disturber can be used to represent for instance (a) line shared noise (from POTS/ISDN to ADSL), (b) all kinds of unidentified (“background”) noise sources or (c) anything else not being incorporated in the NEXT and FEXT coupling mod-

els.
Since it is a generic diagram, the power of this direct noise is left undefined here. Commonly used values are zero, or powers as low as P_{bn} = -140 dBm/Hz.

Mark that the impedance of each disturber is fully ignored in this evaluation of the crosstalk. In practice however, the impedance of a victim modem may be different for different types of victim modems. This is not as unrealistic as it may look at a first glance. When the received noise power is assumed to remain at constant level, and when the impedance of the victim modem drops, then the received noise voltage drops too. The same applies for the received signal, and this causes that the resulting changes in received signal-to-noise ratio are significantly lower. The noise injection model can be used to improve this even further, by introducing an additional impedance-dependency.

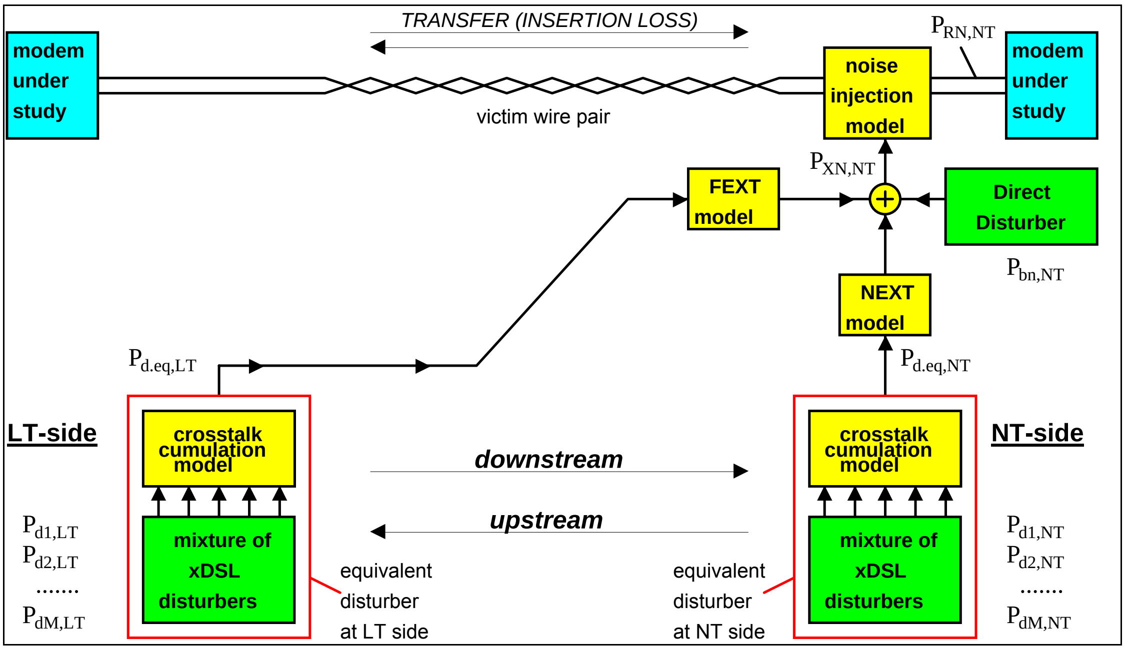


Figure 6: Flow diagram to evaluate crosstalk probability limits for two-node topologies, at the NT side (for evaluating downstream performance)

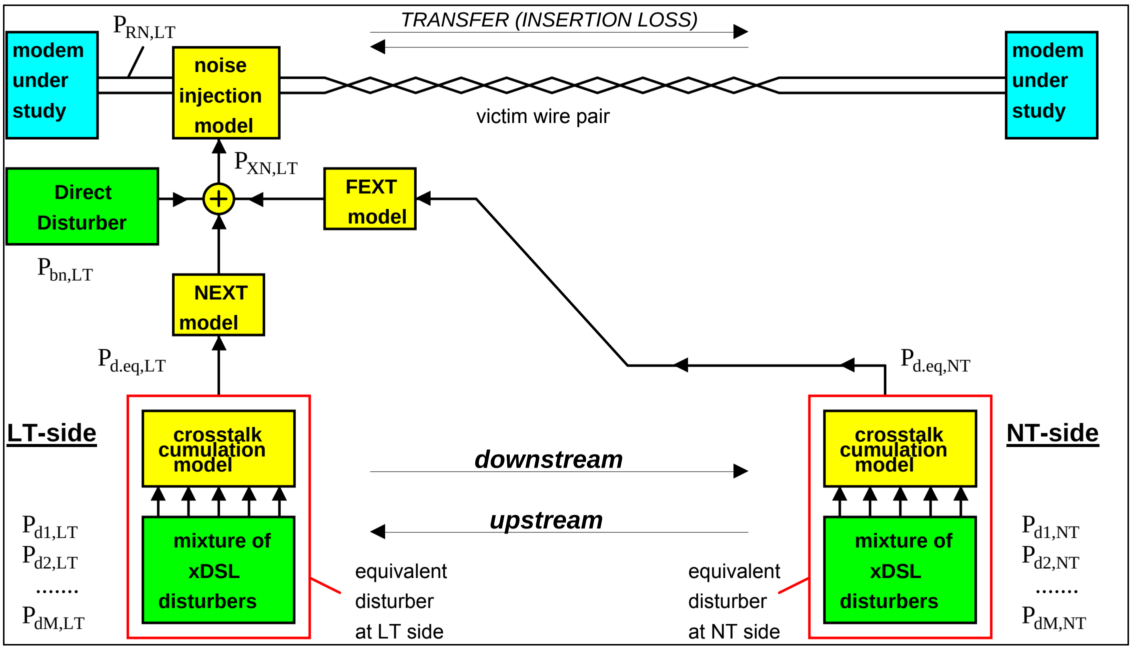


Figure 7: Flow diagram to evaluate the crosstalk probability limits for two-node topologies, at the LT side (for evaluating upstream performance)

End of literal text proposals