
TITLE **Evaluating the crosstalk for multi-node topologies**

PROJECT SpM-2 (study point SP2-4 and SP-2-5)

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STATUS for decision, and inclusion into SpM-2

ABSTRACT[1] This contribution is to solve and close the question on how to evaluate crosstalk in multi-node topologies. It provides literal text for replacing chapter 8 of the current SpM-2 standard, to incorporate a description on multi-node crosstalk modeling.
(The changes are only related to the list of supporters)

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1. Why modeling crosstalk in multi-node topologies?

The current text in chapter 8 of SpM-2 on crosstalk modeling is restricted to an (over)simplified case that all victims and disturbers are co-located at only two locations: the beginning and the end of the cable. This gives reasonable results when studying scenarios where all LT modems are co-located at a local exchange, but is inadequate when modems like VDSL2 are being deployed from the cabinet, and most of the customers are distributed along the line within a distance of about 1 km.
This is the reason why SpM-2 should be enhanced with models that are also suitable for multi-node topologies, and why a study point has been allocated to this.

So far, many proposals have been contributed to TM6 to have this solved [1,2,3,4,5,6,7,8,9, 10,11,12,13]. Unfortunately, none of these proposals were considered as mature enough for inclusion into SpM-2 [7,10]. It demonstrates that the solution is not obvious and that the issue is complicated.
In addition, the complexity of the problem is such that a mature solution cannot simply add some extra definitions to the current text in SpM-2. We consider it as much better to introduce the concept of crosstalk coupling from multiple disturbers at multiple locations right from the beginning of chapter 8, and to show that the simplified version (only two nodes) is no more then a special case of the more generic one (multiple nodes).

Since the original text was too much dedicated to the two-node topology (cumulation operated directly on the disturber outputs, and not on the normalized crosstalk of each disturber), that an overall revision of the text was required. This contribution proposes a solution for that.

2. Literal text proposal for crosstalk modelling

The text below is a literal text proposal for replacing chapter 8 of SpM-2. Many fragments were reused and/or rephrased to prepare the reader for multi-node crosstalk modeling from the beginning. By doing

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[1] **The scientific work behind this contribution has also been funded by MUSE, a European consortium of vendors, operators and knowledge institutes, cooperating within the 6th framework programme of the European Commission.**

so, duplication of similar formulas could be avoided, and consistency between two-node and multi-node could be achieved.
When existing text can be reused, it is explicitly said so, otherwise the proposed text is to replace the text in the present version of SpM-2.

START OF LITERAL TEXT PROPOSAL
(References to clauses without further specification refer to the SpM-2 standard itself)

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 originate 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 are to relate the crosstalk noise levels from multiple disturbers with the *number* and *type* of these disturbers.
The meaning of *the* crosstalk noise level is not obvious. When a cable with N wire pairs is filled-up completely with similar disturbers, the resulting crosstalk level 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 level for that type of disturber, for that particular wire-pair.
However if the number M of disturbers is lower ($M<N-1$), this crosstalk level 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 levels 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 levels will be observed. The result of such a “probability experiment” is therefore not a single level, but a (wide) range of levels with a certain probability distribution.
Within this range, a certain crosstalk noise level can be found that is not exceeded in 99% of the cases (or 80% or 65% or whatsoever). That 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 level 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/K_n}, 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 level*) as intermediate result, that has been derived from the saturated crosstalk level (maximum cross talk level at 100% cable fill), for that particular type of disturber. This quantity will most likely be different for each wire-pair connected to a victim.
The reliability of the model improves when M>>1, and becomes exact (by definition) 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 ($1 \leq M \leq N$-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 expresions.

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.

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

M = number of involved disturbers
$P_X(f)$ = 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 $P_X(f) = P_{Xd}(f) \times M^{1/Kn}$. 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 level, as defined before in expression 1, originating from a *single* (disturbing) modem pair, in a single type of cable. The models for topologies with multiple disturber pairs are derived from these basic models.
NEXT-coupling refers to the transfer function from a disturbing modem to a victim modem at the same side of the cable ("near-end"). FEXT-coupling refers to the transfer function from that disturber to a victim at the other side of the cable ("far-end").

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. When expressed in powers, this ratio becomes as follows:

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

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 1% worst case value of those *N* powers.

8.2.1 Co-located normalized NEXT and FEXT coupling

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

Expression 3 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.

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

NOTE 1: Parameter **f** refers to the frequency. Constant **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 wirepairs. Constant **L_0** identifies a chosen reference length, commonly set to L_0 = 1 km.

NOTE 3: Values for **K_{xn}** and **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 **$s_T(f, L)$** 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 3: Transfer functions of co-located normalized NEXT and FEXT coupling

8.2.2 Distributed or branched normalized NEXT and FEXT coupling

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 1.

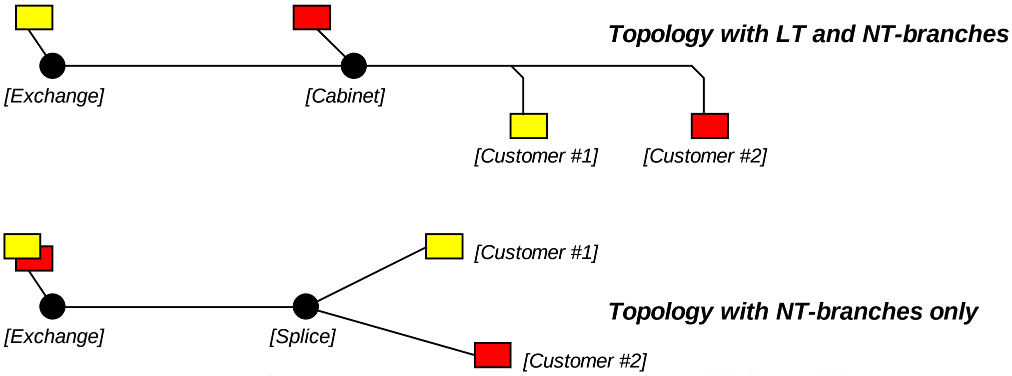
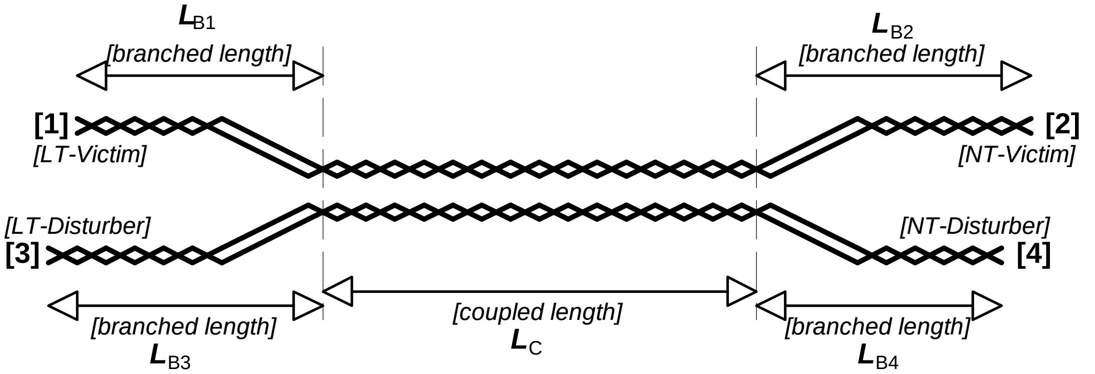


Figure 1: Two example topologies with branching

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 2. 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-NEXT coupling:	$H_{fext,NT}(f, L_C, L_B)$	[3] → [2]	L_C	$L_{B3} + L_{B2}$

Figure 2: 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 2 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 4. 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.

$$H_{next}(f,L_C,L_{Bn}) = K_{xn} \times \left(\frac{f}{f_0}\right)^{0,75} \times \sqrt{1-|s_T(f,L_C)|^4} \times |s_T(f,L_C+L_{Bn})|$$
$$H_{fext}(f,L_C,L_{Bf}) = K_{xf} \times \left(\frac{f}{f_0}\right) \times \sqrt{L_C/L_0} \times |s_T(f,L_C+L_{Bf})|$$

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

NOTE 2: Parameter 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 L_0 identifies a chosen reference length, commonly set to L_0 = 1 km.

NOTE 3: Parameters L_{Bn} and L_{Bf} refer to the respective branching lengths (for adding signal attenuation only) from a disturbing transmitter to a victim receiver.

NOTE 4: Values for K_{xn} and 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 $s_T(f, L)$ 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 4: 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 3 shows an example of the wiring in a multi-node topology.

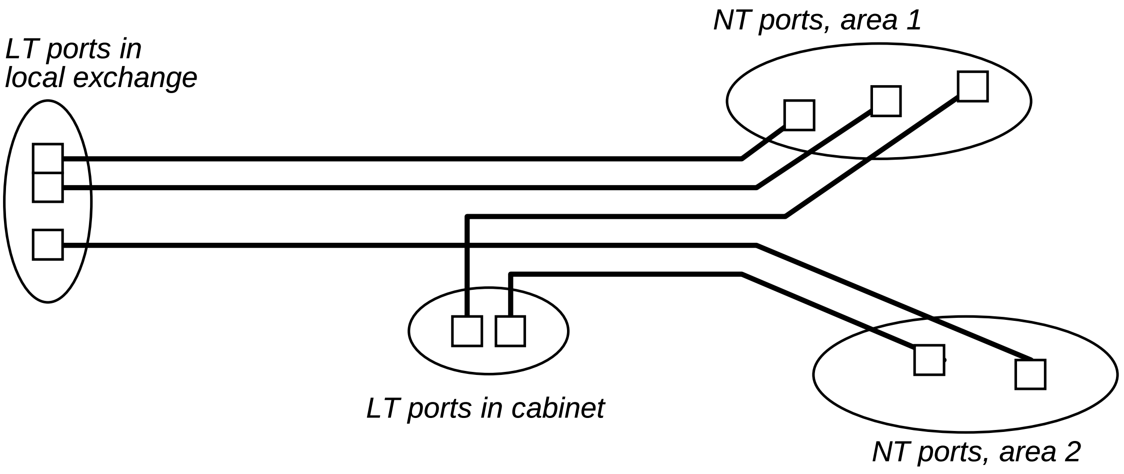


Figure 3: Example of the wiring in a multi-node topology.

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 $P_{\mathrm{XN,NT}}$ of the crosstalk power at the NT side of a victim modem pair, and the associated probability limit $P_{\mathrm{XN,LT}}$ 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 4. 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}, their normalized crosstalk power $P_{\mathrm{Xd\{k\}}}$ at both victim modems, as formulated below:
  Normalized NEXT at NT-side: $P_{\mathrm{XNd\{k\},NT}} = P_{\mathrm{d\{k\},NT}} \times |H_{\mathrm{next,NT}}|^2$
  Normalized NEXT at LT-side: $P_{\mathrm{XNd\{k\},LT}} = P_{\mathrm{d\{k\},LT}} \times |H_{\mathrm{next,LT}}|^2$
  Normalized FEXT at NT-side: $P_{\mathrm{XFd\{k\},NT}} = P_{\mathrm{d\{k\},LT}} \times |H_{\mathrm{fext,NT}}|^2$
  Normalized FEXT at LT-side: $P_{\mathrm{XFd\{k\},LT}} = P_{\mathrm{d\{k\},NT}} \times |H_{\mathrm{fext,LT}}|^2$
- 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 5 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.

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

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

NOTE 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 5: 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 5 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 4 shows an example of the wiring in such a two-node topology.

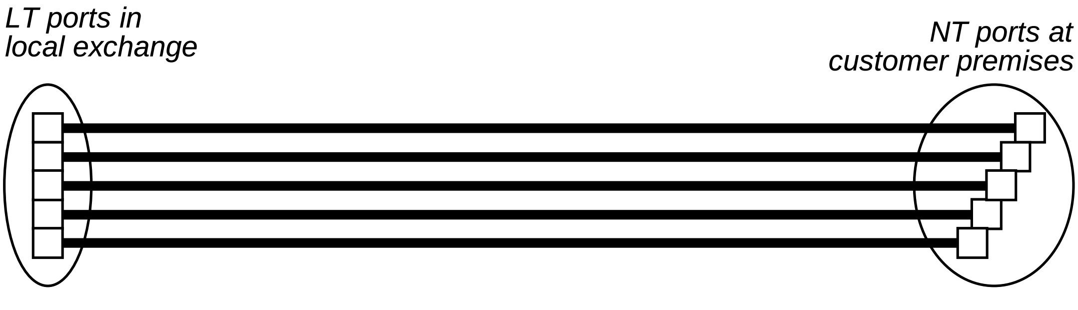


Figure 4: Example of the wiring in a two-node topology, where all wire-pairs are assumed to be of equal length.

An additional characteristic of two-node topologies is that all the NEXT coupling functions in expression 5 are assumed equal, and that the same applies for the FEXT coupling functions. The result is that the previous expression 5 for crosstalk simplifies into expression 6. 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 7.

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

Expression 6

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

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

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 7: Evaluation of the crosstalk from two locations.

A convenient way of presenting the evaluation of the various crosstalk levels is the use of a flow diagram. This is shown in figure 5 (for downstream) and 6 (for upstream) for the two-node topology. It illustrates how the various building blocks of expression 7 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 levels (P_{d1}, P_{d2}, …) into a single equivalent disturber ($P_{d.eq}$), as if the cumulation operates directly on these disturber levels. This has been illustrated in figures 5 and 6 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 5 and 6 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 level (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 models.
  Since it is a generic diagram, the power level of this direct noise level is left undefined here. Commonly used values are zero, or levels 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.

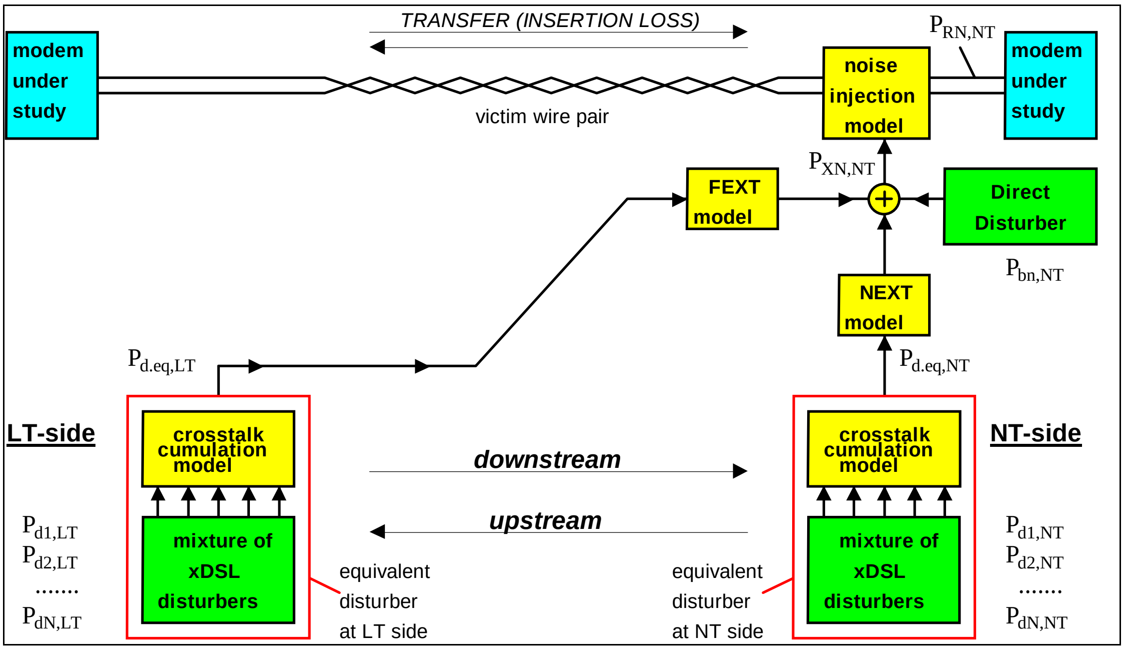


Figure 5: Flow diagram to evaluate crosstalk probability limits for two-node topologies, at the NT side (for evaluating downstream performance)

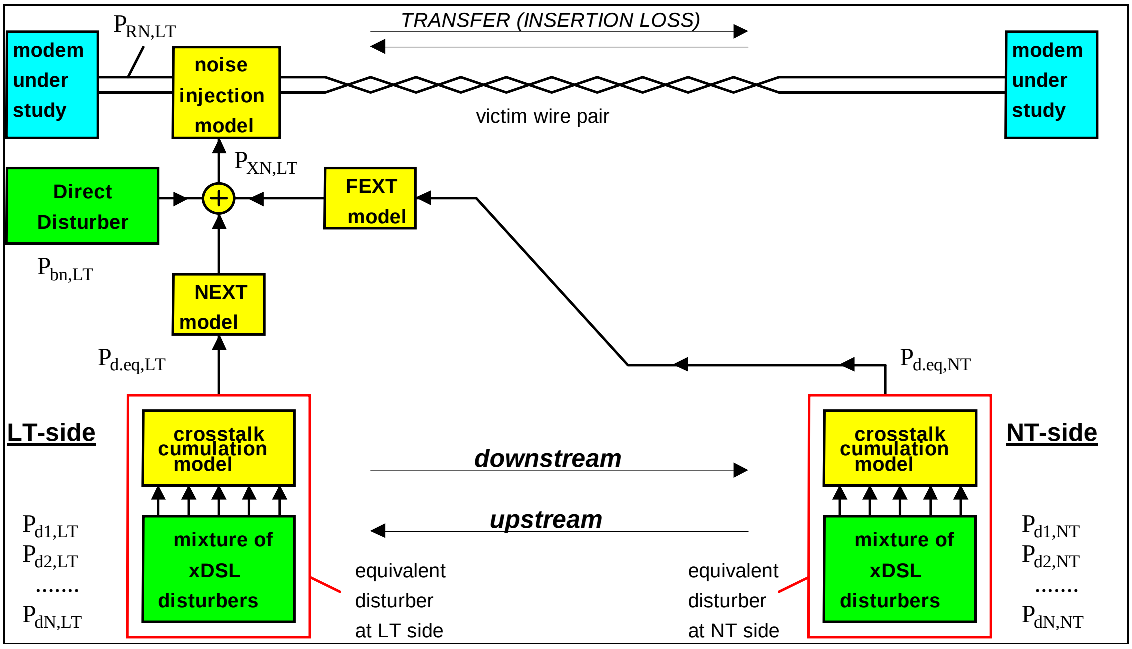


Figure 6: Flow diagram to evaluate the crosstalk probability limits for two-node topologies, at the LT side (for evaluating upstream performance)

END OF LITERAL TEXT PROPOSAL

3. Conclusion and proposal to ETSI-TM6

In this contribution, we presented a full text proposal, to incorporate multi-node crosstalk modeling in the SpM-2 standard. Many fragment of the existing chapter 8 were reused and/or rephrased to make the text consistent and as compact as possible. The proposed text is considered as mature, and solves the questions in both study point SP2-4 and SP2-5.

We propose to adopt this text as a solution for both study point SP2-4 and SP2-5, and to replace the current chapter 8 of SpM-2 with this text.

4. References

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