TECHNICAL REPORT

TR-285
Broadband Copper Cable Models

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Issue History

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TABLE OF CONTENTS

List of Figures

List of Tables

Executive Summary

See Executive Summary/TR-285.

New reference cable models added:

1. Polyethylene-foam insulated plant quad structured cable and Paper-air insulated 2 layered star quad cables as deployed by various European network operators, in Annex C

2. Coax cable and configurations based on North American use cases, in Annex D

1 Purpose and Scope

1.1 Purpose

The purpose of this Technical Report is to support the development of testing capabilities at frequencies above 30 MHz by providing detailed models of copper cables. This work complements emerging specifications for G.fast access technology and FTTdp transmission deployment.

1.2 Scope

This Technical Report focuses on the subject of modeling copper cables at frequencies above 30 MHz. This Technical Report provides models that can be used in Broadband Forum specifications for testing of G.fast implementations.

These models include the single line parameters, the transfer function of the direct path, the transfer function of the FEXT coupling, and the input impedance of the line.

This Technical Report addresses the cable that extends from the Distribution Point (DP) to the Network Interface Device (NID) at the Customer Premises.

1.3 Conventions

In this Technical Report, several words are used to signify the requirements of the specification. These words are always capitalized. More information can be found be in RFC 2119 [1].

MUST	This word, or the term “REQUIRED”, means that the definition is an absolute requirement of the specification.
MUST NOT	This phrase means that the definition is an absolute prohibition of the specification.
SHOULD	This word, or the term “RECOMMENDED”, means that there could exist valid reasons in particular circumstances to ignore this item, but the full implications need to be understood and carefully weighed before choosing a different course.
SHOULD NOT	This phrase, or the phrase "NOT RECOMMENDED" means that there could exist valid reasons in particular circumstances when the particular behavior is acceptable or even useful, but the full implications need to be understood and the case carefully weighed before implementing any behavior described with this label.
MAY	This word, or the term “OPTIONAL”, means that this item is one of an allowed set of alternatives. An implementation that does not include this option MUST be prepared to inter-operate with another implementation that does include the option.

1.4 References

The following references are of relevance to this Technical Report. At the time of publication, the editions indicated were valid. All references are subject to revision; users of this Technical Report are therefore encouraged to investigate the possibility of applying the most recent edition of the references listed below.
A list of currently valid Broadband Forum Technical Reports is published at www.broadband-forum.org.

Document	Title	Source	Year
[1] RFC 2119	Key words for use in RFCs to indicate Requirement Levels [2]	BBF	1997
[2] Jon Freeman	Fundamentals of Microwave Transmission Lines	Wiley-Interscience	1996
[3] David Large, James Farmer	Broadband Cable Access Networks – Chapter 2	Morgan Kaufmann	2009

1.5 The following definitions are used throughout this Technical Report.

See Definitions / TR-285i1

1.6 Abbreviations

See Abbreviations / TR-285i1

DMT	Discrete Multi-Tone
FTU-O	FTU at the Optical Network Unit (i.e., operator end of the loop)
ELFEXT	Equal Length Far End Crosstalk
FTU-R	FTU at the Remote site (i.e., subscriber end of the loop)
IL	Insertion Loss
MAE	Mean Absolute Error
RG-x	Radio Guide – Standard Coaxial Cable designations.
Diplexer	A two port to one port multiplexer

2 Technical Report Impact

2.1 Energy Efficiency

TR-285 has no impact on energy efficiency

2.2 IPv6

TR-285 has no impact on IPv6.

2.3 Security

TR-285 has no impact on security.

2.4 Privacy

Any issues regarding privacy are not affected by TR-285.

Annex C: Reference Cable Models for Quad Cable Deployed by European Operators.

C.1 Reference Cable Model for PE4D-ALT 4x10x0.6mm Quad Cable

The PE4D-ALT 4x10x0.6mm is a polyethylene-foam insulated 2-layered star quad cable with aluminum cable mantle deployed since the early 1990's. It consists of 2 core and 8 outer quads.

C.1.1 Insertion Loss

Insertion Loss (IL) is described by the ITU-T single line model. The parameter values for the multi-pair approximation are given in Table 1. The model describes accurately magnitude and phase of the Insertion Loss.

Table 1: ITU-T Single Line Model for PE4D-ALT 10x4x0.6mm

ITU-T Model	$Z_{0\infty}$	η_{VF}	R_{s0}	q_L	q_H	q_x	q_y	q_c	ϕ	f_d
PE4D-ALT 10x4x0.6mm	130	0.735	0.125	2.5	0.75	1	0	0	0.0071	1

C.1.2 ELFEXT

The ELFEXT magnitude is described by a dual slope model. The lower slope has 20dB/decade steepness; the upper slope has 40dB/decade steepness. The model assumes homogeneity and linearity over the full cable length. It is expressed by the following formula:

$$|ELFEXT| = \begin{cases} 20dB \cdot log_{10}(f) + B_{20dB} \cdot x + C_{20dB}, & 0 < f < f_T \\ 40dB \cdot log_{10}(f) + B_{40dB} \cdot x + C_{40dB}, & f \geq f_T \end{cases}$$

Where

$$f_T = 10^{\frac{x \cdot (B_{20dB} - B_{40dB}) + C_{20dB} - C_{40dB}}{20dB}} \cdot Hz$$

$f: Frequency\ in\ [Hz]$

$f_T: Transition\ frequency\ from\ 20\ to\ 40dB\ per\ decade\ slope\ in\ [Hz]$

$C_{20dB}: Offset\ magnitude\ at\ 1Hz\ for\ 20dB\ per\ decade\ slope\ for\ x = 0\ in\ [dB]$

$C_{40dB}: Offset\ magnitude\ at\ 1Hz\ for\ 40dB\ per\ decade\ slope\ for\ x = 0\ in\ [dB]$

$B_{20dB}: Increase\ of\ ELFEXT\ magnitude\ per\ m\ cable\ length\ for\ 20dB\ per\ decade\ slope\ in\ [dB]$

$B_{40dB}: Increase\ of\ ELFEXT\ magnitude\ per\ m\ cable\ length\ for\ 40dB\ per\ decade\ slope\ in\ [dB]$

$x: Cable\ length\ in\ [m]$

The ELFEXT phase is described by the following model.

For inductive coupling:

- ELFEXT phase from pair k to pair l: $\varphi_{c,k\to l}(f) = \frac{\pi}{2} \cdot e^{-f/F_{kl}}$
- ELFEXT phase from pair l to pair k: $\varphi_{c,l\to k}(f) = \pi - \varphi_{c,k\to l}(f)$

For capacitive coupling:

- ELFEXT phase from pair k to pair l: $\varphi_{c,k\to l}(f) = -\frac{\pi}{2} \cdot e^{-f/F_{kl}}$
- ELFEXT phase from pair l to pair k: $\varphi_{c,l\to k}(f) = -\pi - \varphi_{c,k\to l}(f)$

Where

- for in-quad pairings: $F_{kl} = 10MHz$
- for inter-quad pairings: $F_{kl} = 50MHz$
- one half of the pairings have capacitive coupling and the other half inductive coupling.

The figure below illustrates the ELFEXT phase model.

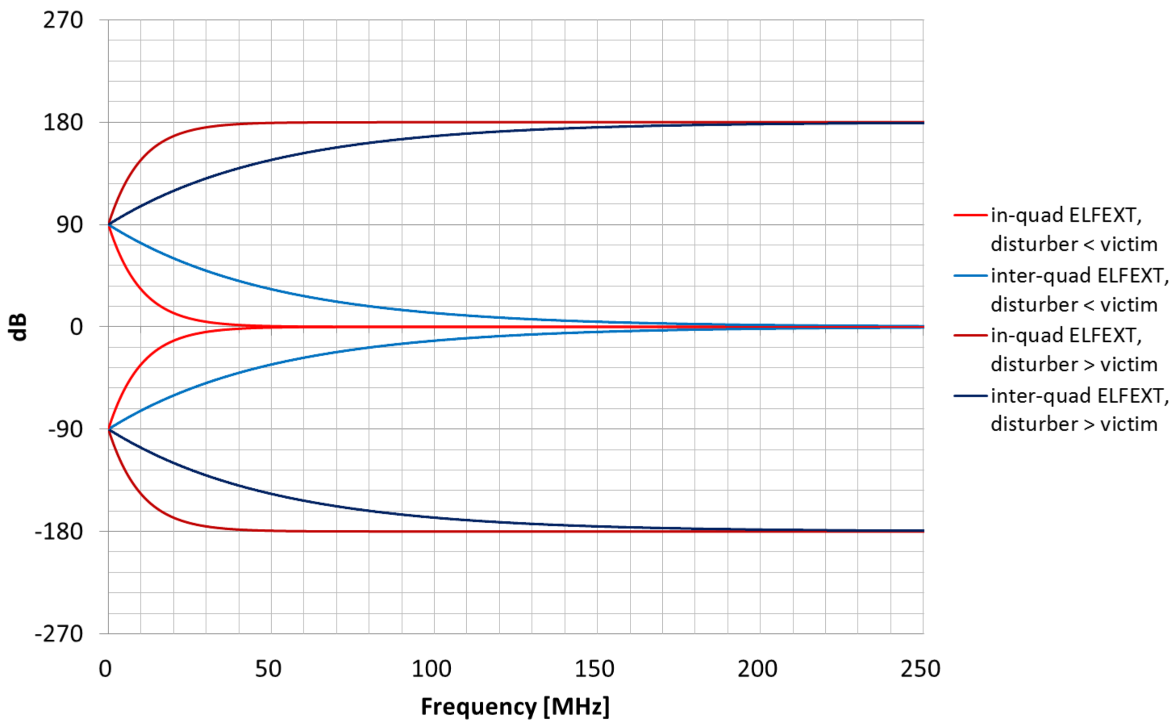


Figure 1: ELFEXT Phases for PE4D-ALT 10x40x0.6mm, 100m cable

Given by the large variability of crosstalk observed between different crosstalk pairings in the cable, a statistical approach is used by indicating mean and 95-percentile parameter values. Since in-quad and inter-quad crosstalk differ considerably, parameter values are indicated separately for both cases. For the PE4D-ALT 4x10x0.6mm cable model all parameters are given in Table 2:

Table 2: PE4D-ALT 4x10x0.6mm Cable Parameters

	ELFEXT inter-quad pairings		ELFEXT in-quad pairings	
parameter	**mean**	**95-percentile**	**mean**	**95-percentile**
C_{20dB}	*-204 dB*	*-189 dB*	*-195 dB*	*-187 dB*
C_{40dB}	*-362 dB*	*-340 dB*	*-340 dB*	*-334 dB*
B_{20dB}	*0.06dB/m*	*0.06dB/m*	*0.06dB/m*	*0.06dB/m*
B_{40dB}	*0.12dB/m*	*0.12dB/m*	*0.12dB/m*	*0.12dB/m*

For both, inter-quad and in-quad pairings, independent normal distributions for the values of C_{20dB} and C_{40dB} in dB can be assumed.

From the model parameters given above f_T is calculated as an example for the two cable lengths 50 and 100m:

Table 3: Calculated f_T from the parameters in Table 1

	ELFEXT inter-quad pairings		ELFEXT in-quad pairings	
parameter	**mean**	**95-percentile**	**mean**	**95-percentile**
f_T *at 50m*	*56 MHz*	*25 MHz*	*13 MHz*	*16 MHz*
f_T *at 100m*	*40 MHz*	*18 MHz*	*9 MHz*	*11 MHz*

Since the number of inter-quad pairings is dominant in the 4x10x0.6mm PE4D cable, the statistical parameter values over all pairings of the PE4D-ALT 4x10x0.6mm cable, compared to those over inter-quad pairings only, are approximately equal.

To build a complete quad cable ELFEXT model, both, an in-quad and an inter-quad crosstalk model is necessary. Even if the share of in-quad crosstalk pairings in a cable is small, in-quad crosstalk still plays a dominant role for self-FEXT cancellation systems (vectoring).

Figure 2 shows the model curves for 100m cable length:

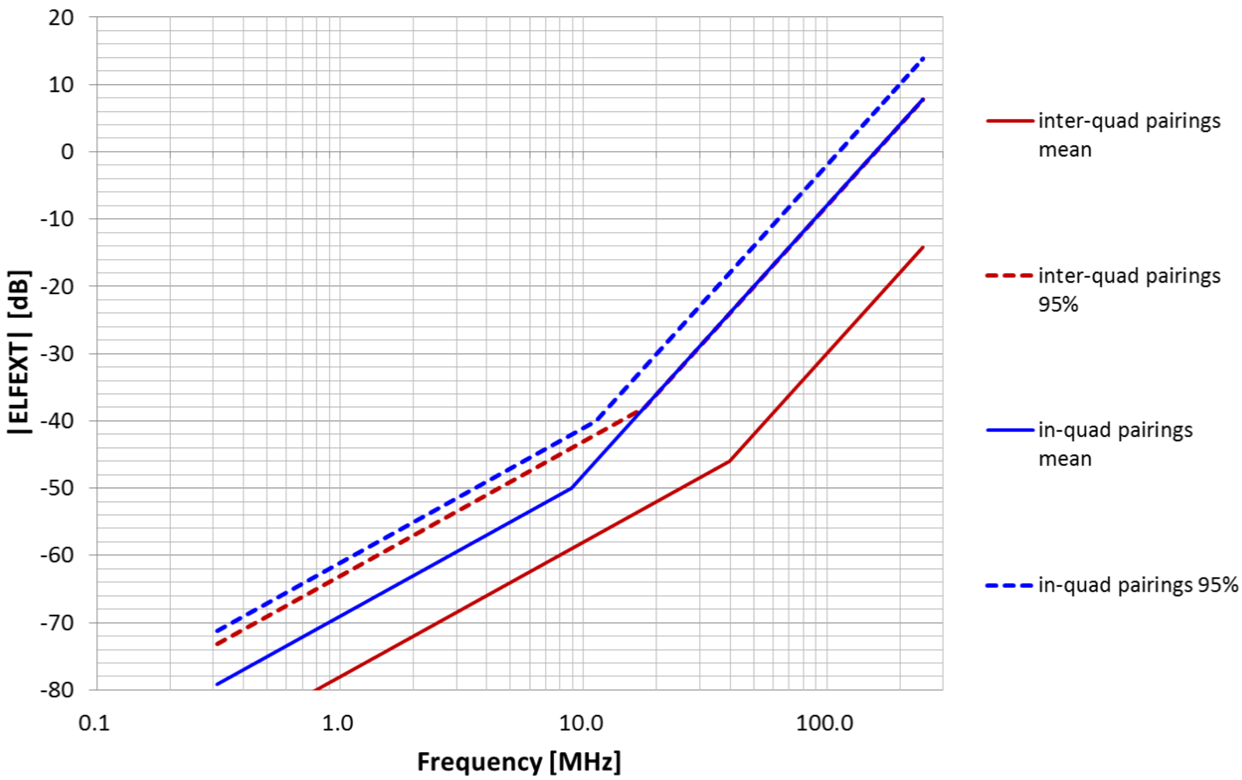


Figure 2: Statistical Dual Slope ELFEXT Model for 100m PE4D-ALT 4x10x0.6mm Cable

Figure 3 compares the mean value model curves for 50m and 100m cable length:

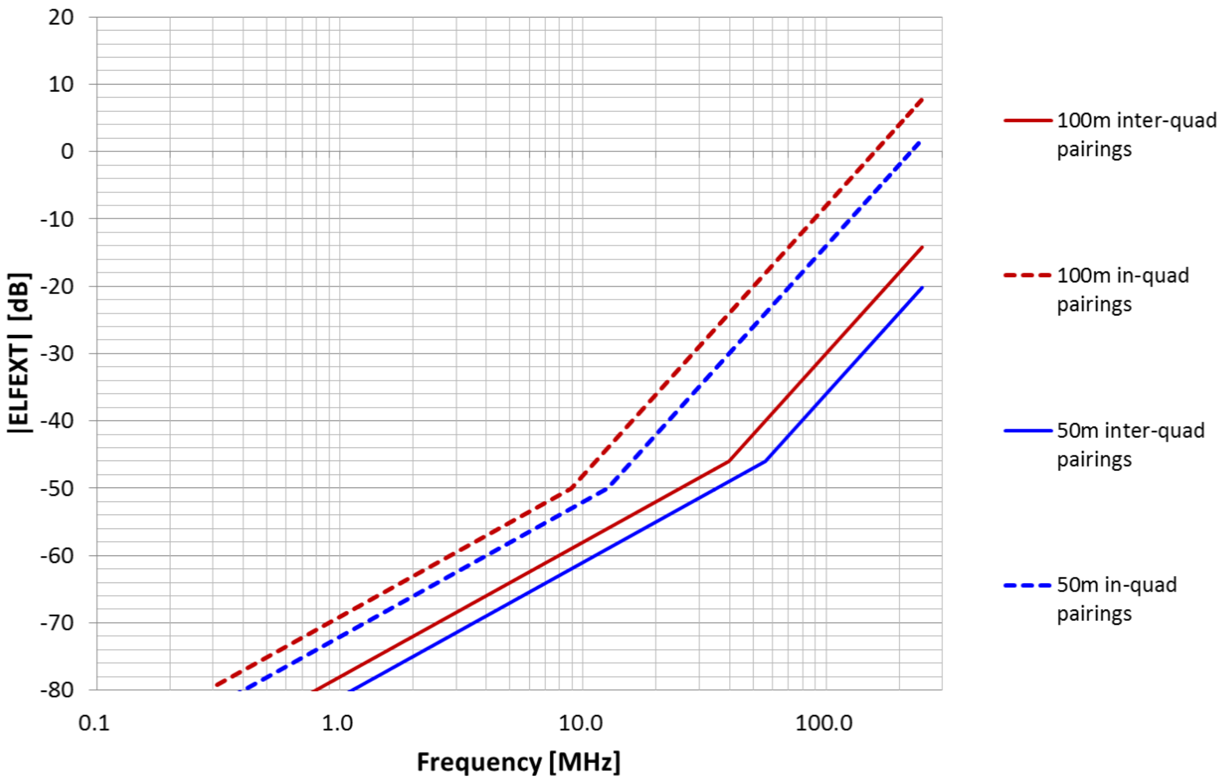


Figure 3: Statistical Dual Slope ELFEXT Model for PE4D-ALT 4x10x.06mm Cable. Mean Values for 50m and 100m

The ELFEXT model given reflects the following quad cable crosstalk characteristics, consistently found in experimental cable data:

- In-quad crosstalk is typically higher than inter-quad crosstalk
- The dual slope transition frequency f_T of in-quad crosstalk is typically lower than that for inter-quad crosstalk
- The dual slope transition frequency f_T decreases with cable length

Overall, higher electromagnetic coupling between two pairs means lower dual slope transition frequency f_T.

C.2 Reference Cable Model for P-Pb 4x10x0.6mm Quad Cable

The P-Pb 4x10x0.6mm is a paper-air insulated 2-layered star quad cable with lead cable mantle, which used to be deployed mostly in European networks until the 1990's. It consists of 2 core and 8 outer quads.

C.2.1 Insertion Loss

Insertion Loss (IL) is described by the ITU-T single line model. The parameter values for the multi-pair approximation are given in Table 4. The model describes accurately magnitude and phase of Insertion Loss.

Table 4: ITU-T Single Line Model for P-Pb 10x4x0.6mm cable

ITU-T Model	$Z_{0\infty}$	η_{VF}	R_{s0}	q_L	q_H	q_x	q_y	q_c	ϕ	f_d
P-Pb 10x4x0.6mm	130	0.735	0.125	1.5	0.75	2	0	0	0.013	1

Note: The parameters given above correspond to non-deployed cables under lab conditions. It is however known that Insertion Loss of paper-air insulated cables may increase considerably when deployed and not protected sufficiently from humidity.

C.2.2 ELFEXT

The ELFEXT magnitude is described by a dual slope model. The lower slope has 20dB/decade steepness; the upper slope has 40dB/decade steepness. The model assumes homogeneity and linearity over the full cable length. It is expressed by the following formula:

$$|ELFEXT| = \begin{cases} 20dB \cdot log_{10}(f) + B_{20dB} \cdot x + C_{20dB}, & 0 < f < f_T \\ 40dB \cdot log_{10}(f) + B_{40dB} \cdot x + C_{40dB}, & f \geq f_T \end{cases}$$

Where

$$f_T = 10^{\frac{x \cdot (B_{20dB} - B_{40dB}) + C_{20dB} - C_{40dB}}{20dB}} \cdot Hz$$

$f: Frequency\ in\ [Hz]$

$f_T: Transition\ frequency\ from\ 20\ to\ 40dB\ per\ decade\ slope\ in\ [Hz]$

$C_{20dB}: Offset\ magnitude\ at\ 1Hz\ for\ 20dB\ per\ decade\ slope\ for\ x = 0\ in\ [dB]$

$C_{40dB}: Offset\ magnitude\ at\ 1Hz\ for\ 40dB\ per\ decade\ slope\ for\ x = 0\ in\ [dB]$

$B_{20dB}: Increase\ of\ ELFEXT\ magnitude\ per\ m\ cable\ length\ for\ 20dB\ per\ decade\ slope\ in\ [dB]$

$B_{40dB}: Increase\ of\ ELFEXT\ magnitude\ per\ m\ cable\ length\ for\ 40dB\ per\ decade\ slope\ in\ [dB]$

$x: Cable\ length\ in\ [m]$

The ELFEXT phase is described by the following model:

For inductive coupling:

- ELFEXT phase from pair k to pair l: $\varphi_{c,k\to l}(f) = \frac{\pi}{2} \cdot e^{-f/F_{kl}}$
- ELFEXT phase from pair l to pair k: $\varphi_{c,l\to k}(f) = \pi - \varphi_{c,k\to l}(f)$

For capacitive coupling:

- ELFEXT phase from pair k to pair l: $\varphi_{c,k\to l}(f) = -\frac{\pi}{2} \cdot e^{-f/F_{kl}}$
- ELFEXT phase from pair l to pair k: $\varphi_{c,l\to k}(f) = -\pi - \varphi_{c,k\to l}(f)$

Where

- for in-quad pairings: $F_{kl} = 10MHz$
- for inter-quad pairings: $F_{kl} = 50MHz$
- one half of the pairings have capacitive coupling and the other half inductive coupling.

The figure below illustrates the ELFEXT phase model.

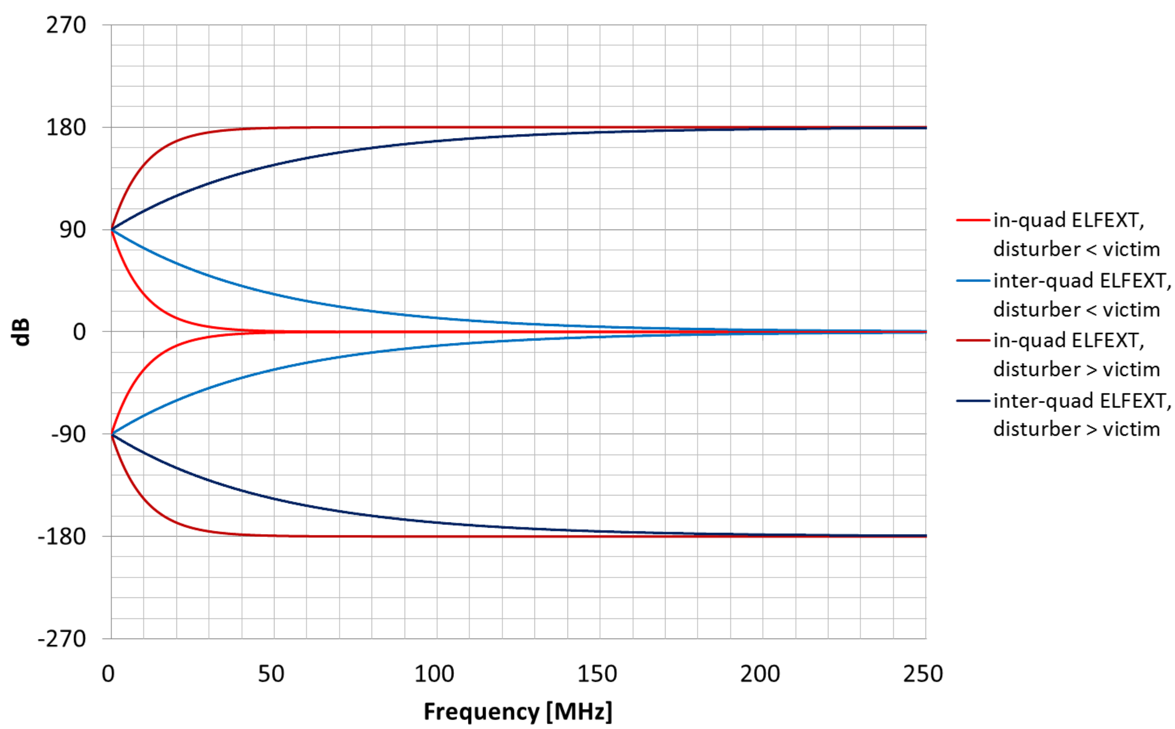


Figure 4: ELFEXT Phases for the P-Pb 1-x4x0.6mm, 100m cable

Since the number of inter-quad pairings is dominant in the P-Pb 4x10x0.6mm cable, the statistical parameter values over all pairings of the P-Pb 4x10x0.6mm cable, compared to those over inter-quad pairings only, are approximately equal. However, to build a complete quad cable ELFEXT model, both, an in-quad and an inter-quad crosstalk model is necessary. Even if the share of in-quad crosstalk pairings in a cable is small, in-quad crosstalk still plays a dominant role for self-FEXT cancellation systems (vectoring).

Given by the large variability of crosstalk observed between different crosstalk pairings in the cable, a statistical approach is used by indicating mean and 95-percentile parameter values.

For the P-Pb 4x10x0.6mm cable model all parameters are given in Table 5:

Table 5: P-Pb 4x10x0.6mm Cable Parameters

	ELFEXT inter-quad pairings		ELFEXT in-quad pairings	
parameter	**mean**	**95-percentile**	**mean**	**95-percentile**
C_{20dB}	*-195 dB*	*-177 dB*	*-188 dB*	*-179 dB*
C_{40dB}	*-349 dB*	*-333 dB*	*-329 dB*	*-302 dB*
B_{20dB}	*0.06dB/m*	*0.06dB/m*	*0.06dB/m*	*0.06dB/m*
B_{40dB}	*0.12dB/m*	*0.12dB/m*	*0.12dB/m*	*0.12dB/m*

<u>*Note:*</u> *The parameters given above correspond to a non-deployed cable under lab conditions. It is however known that Crosstalk of paper-air insulated cables may increase considerably when deployed and not protected sufficiently from humidity.*

For both, inter-quad and in-quad pairings, independent normal distributions for the values of C_{20dB} and C_{40dB} in dB can be assumed.

From the model parameters given above f_T is calculated as an example for the two cable lengths 50 and 100m:

Table 6: Calculated f_T from the parameters in Table 5

	ELFEXT inter-quad pairings		ELFEXT in-quad pairings	
parameter	**mean**	**95-percentile**	**mean**	**95-percentile**
f_T *at 50m*	*35 MHz*	*45 MHz*	*8 MHz*	*1 MHz*
f_T *at 100m*	*25 MHz*	*32 MHz*	*6 MHz*	*1 MHz*

Figure 5 shows the model curves for 100m cable length:

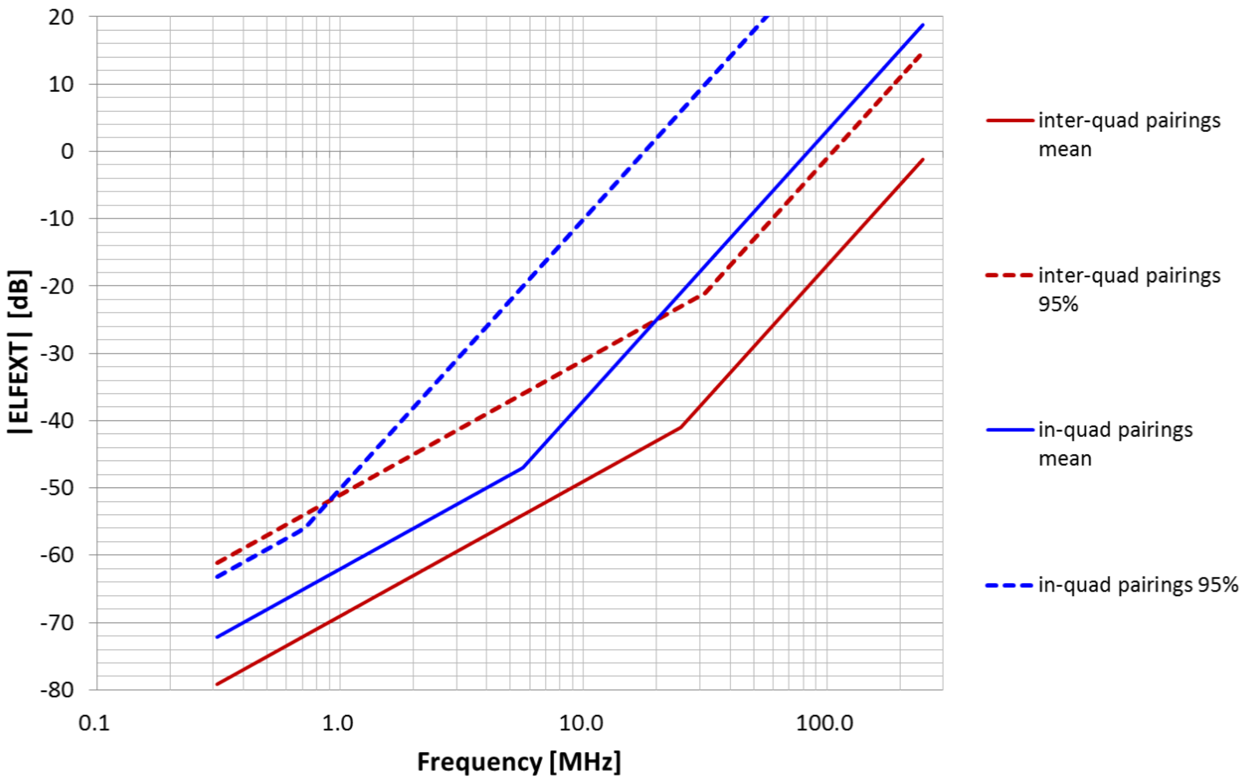


Figure 5: Statistical Dual Slope ELFEXT Model for 100m P-Pb 4x10x0.6mm Cable

Figure 6 compares the mean value model curves for 50m and 100m cable length:

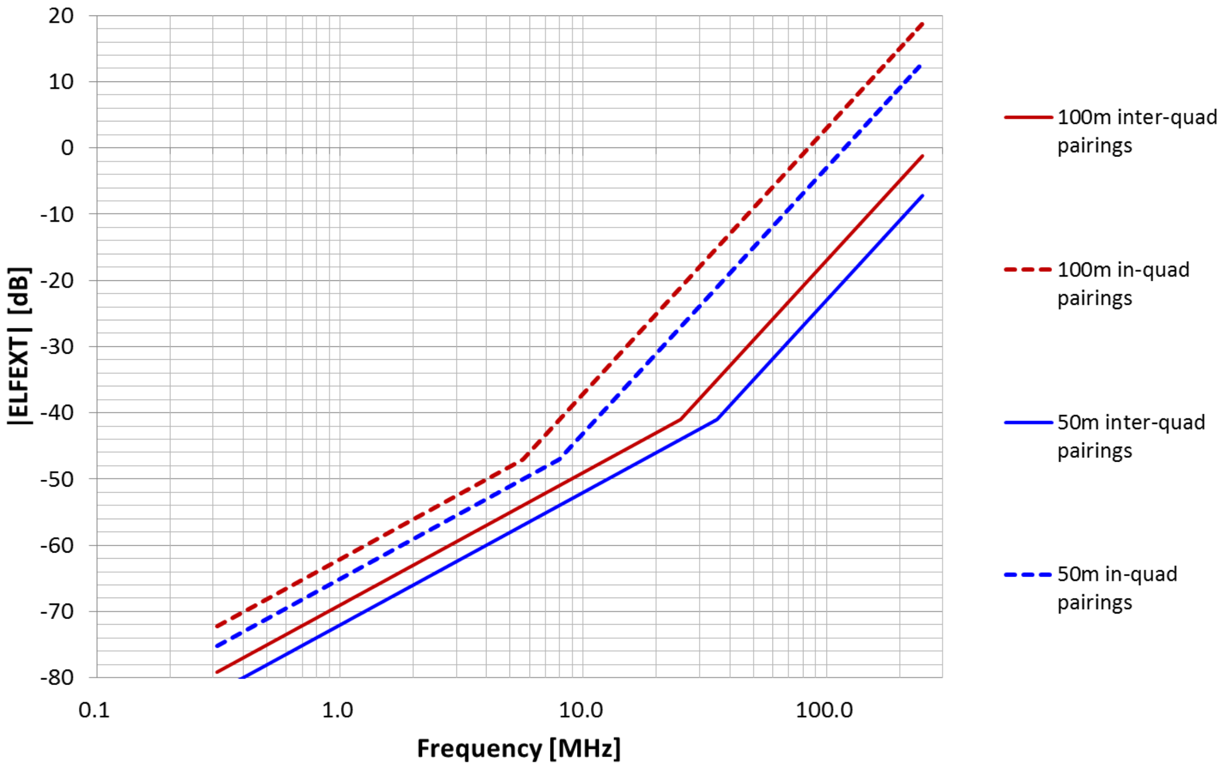


Figure 6: Statistical Dual Slope ELFEXT Model for P-Pb 4x10x0.6mm Cable

The ELFEXT model given reflects the following quad cable crosstalk characteristics, consistently found in experimental cable data:

- In-quad crosstalk is typically higher than inter-quad crosstalk
- The dual slope transition frequency f_T of in-quad crosstalk is typically lower than that for inter-quad crosstalk
- The dual slope transition frequency f_T decreases with cable length

Overall, higher electromagnetic coupling between two pairs means lower dual slope transition frequency f_T.

Annex D: Coax Cable Configuration Based on North American Use Cases / Applications.

D.1 Coax Cable Configuration and Modeling

In Figure 7 and Figure 8 all cable sections are RG6 type coax and all connectors are F type. Polyethylene foam is used for coax insulation; the center conductor may be copper-clad steel.

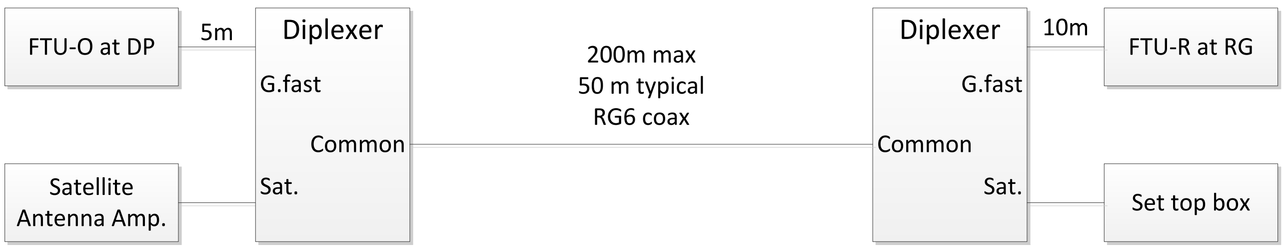


Figure 7: Coax configuration for G.fast with Satellite TV

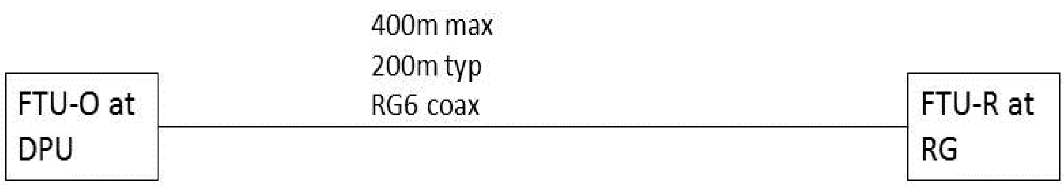


Figure 8: Coax configuration with G.fast only

Both diplexers have identical characteristics. There are typically no splitters or bridged taps in the G.fast path. There are no in-line amplification devices in the G.fast or satellite signal path. The signals at the Satellite port reside at 2.3 MHz and 950 to 2150 MHz.

Typical diplexer characteristics from G.fast port to Common port:

Passband:	0-0.5 and 5-806 MHz
Insertion loss:	5 dB from 30 kHz to 500 kHz
	4 dB from 4 to 5 MHz
	2 dB from 6 to 7 MHz
	1.5 dB from 6 to 212 MHz
	2.5 dB 212 to 806 MHz
	>40 dB out of band

Return loss with all ports terminated with 75 ohms: 10 dB

The coax cable signal loss characteristics in dB per 100m are shown in Table 7

Table 7: Insertion Loss Characteristic of Coax cable Types [2]

	RG-59	RG-6	RG-11
1 MHz	1.31	0.66	0.66
10 MHz	4.59	1.97	1.31
50 MHz	5.90	4.59	3.28
100 MHz	8.86	6.56	5.25
200 MHz	11.81	9.18	7.54
400 MHz	16.07	14.10	11.48
700 MHz	22.63	18.37	15.42
900 MHz	25.58	19.68	17.71
1000 MHz	27.22	20.00	18.37
2150 MHz	39.69	32.47	21.65
IL (dB)/ 100m			

The maximum distance of the coax deployment is modeled by RG-6 cable is shown in Figure 7 and Figure 8. A longer coax deployment distance is possible by utilizing the lower loss RG-11 cable. Conversely, the maximum coax distance could be reduced with RG-59 cable to the equivalent loss distance of the RG-6.

The exponential approximation of the coax insertion loss characteristic is given by:

$$IL = a f^{b} + c\ f + d \quad (dB/100m)$$

$$f\ =\ \text{Frequency in MHz}$$

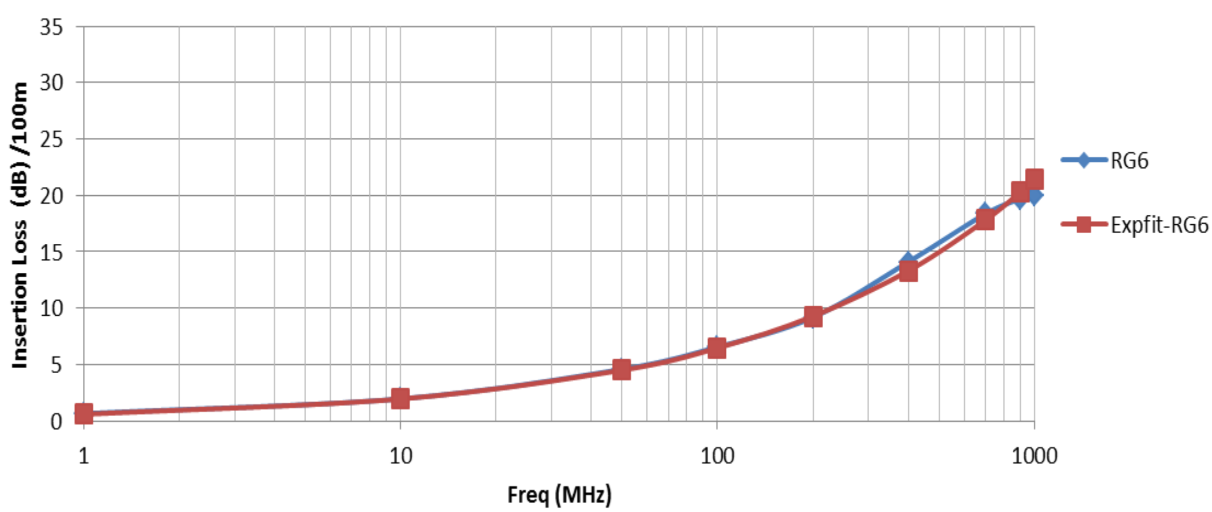


Figure 9: Exponential Approximation of Coax Insertion Loss vs. Frequency for RG-6.

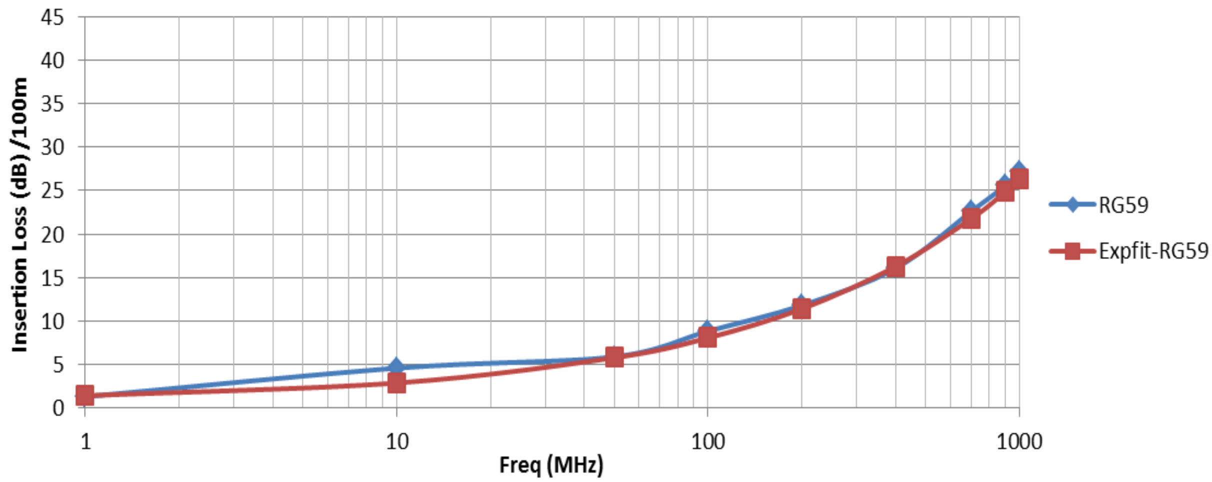


Figure 10: Exponential Approximation of Coax Insertion Loss vs. Frequency for RG-59.

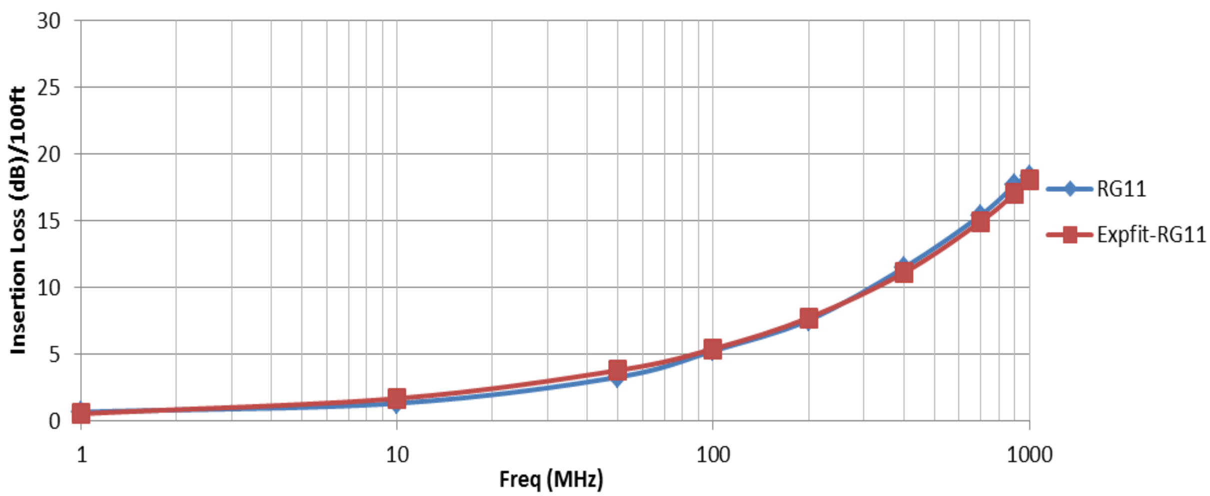


Figure 11: Exponential Approximation of Coax Insertion Loss vs. Frequency for RG-59.

The approximation coefficients for each of the coax cable are given in Table 8 below with MAE (Mean Absolute Error) < 0.5 dB within 1GHz band.

Table 8: Exponential Approximation of Coax Cable Insertion Loss Coefficients.

Cable Type/Coefficients	a	b	c	d
RG-6	0.5904	0.525	0	0
RG-59	0.5904	0.545	0	0.82
RG-11	0.5248	0.5	0.0015	0

In addition to the attenuation approximation, there are interests in simulating the time domain models of the coaxial cable based on circuit analysis.

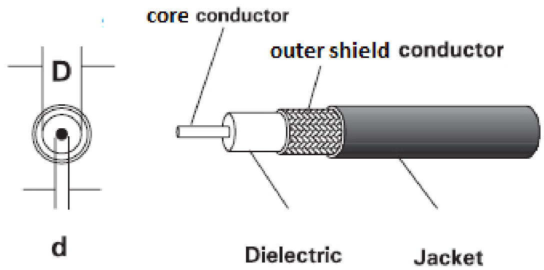


Figure 12: Typical Cable Construction [3]

D = the inner diameter of the shield
d = the outer diameter of the core conductor
The characteristic impedance of the coaxial cable can be calculated as

$$Z_0 = \frac{138}{\sqrt{\varepsilon_r}} \log\left(\frac{D}{d}\right)$$

Where

ε_r = the **relative** dielectric constant of the dielectric between the outer shield and the core

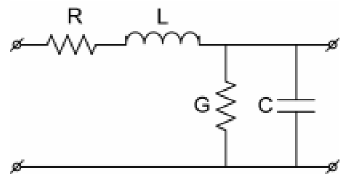
Table 9: Typical Coax Characteristic [3]

Cable Type	d (mm)	D (mm)	Z_0 (ohm)	R_{DC}(ohm/km)	C(pF/m)	Vp
RG-6	1.024	4.7	75	18.04	53	0.83
RG-59	0.58	3.7	75	33.292	67	0.68
RG-11	1.63	7.25	75	5.6	66	0.84

The relative propagation velocity is the ratio between velocity in cable and the free-space velocity which is near the speed of light at 3 x 10^8 m/sec or 984 ft / µs.

$$V_P = \frac{1}{\sqrt{\varepsilon_r}}$$

The R,L,G,C parameters could be derived from these basic circuit elements for construction of the impulse response of the coaxial cable similar to what is done for the twisted-pair cable.



$$L = \frac{\mu_o \mu_r}{2\pi} \ln\left(\frac{D}{d}\right); C = \frac{2\pi\varepsilon_o\varepsilon_r}{\ln\left(\frac{D}{d}\right)}; G \sim = 0$$

Figure 13: RLGC Circuit model for Coax Cable

Note: The relative permeability (μ_r) of the copper and aluminum used in typical coax cable (such as RG-6, RG-11 and RG-59) approximately equals to 1

End of Broadband Forum Technical Report TR-285 Issue 1 Amendment 1

