Crosstalk Models for Short VDSL2 Lines from Measured 30 MHz Data

E. Karipidis, N. Sidiropoulos, A. Leshem, Li Youming, R. Tarafi, and M. Ouzzif

Abstract

In recent years, there is growing interest in hybrid fiber-copper access solutions, as in fiber to the basement (FTTB) and fiber to the curb/cabinet (FTTC). The twisted pair segment in these architectures is in the range of a few hundred meters, thus supporting transmission over tens of MHz. This paper provides crosstalk models derived from measured data for quad cable, lengths between 75 and 590 meters, and frequencies up to 30 MHz. The results indicate that the log-normal statistical model (with a simple parametric law for the frequency-dependent mean) fits well up to 30 MHz for both FEXT and NEXT. This extends earlier log-normal statistical modeling and validation results for NEXT over bandwidths in the order of a few MHz. The fitted crosstalk power spectra are useful for modem design and simulation. Insertion loss, phase, and impulse response duration characteristics of the direct channels are also provided.

Index Terms

VDSL, VDSL2, channel measurement, NEXT, FEXT, insertion loss, statistical modeling and validation, log-normal distribution, regression, crosstalk power spectra

I. Introduction

Hybrid fiber-copper access solutions, such as fiber to the basement (FTTB) and fiber to the curb/cabinet (FTTC), entail twisted pair segments in the order of a few hundred meters - thus supporting transmission

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over up to 30 MHz. Very-high bit rate digital subscriber line (VDSL) and the emerging VDSL2 draft are the pertinent high-speed transmission modalities for these lengths. This scenario is very different from the typical asymmetric digital subscriber line (ADSL) or high bit-rate digital subscriber line (HDSL) environment. For the shortest loops, for example, the shape of the far-end crosstalk (FEXT) power spectrum can be expected to be similar to the shape of the near-end crosstalk (NEXT) power spectrum; while it is *a priori* unclear that NEXT and FEXT models [3], [4] developed and fitted to ADSL/HDSL bandwidths, will hold up over a much wider bandwidth.

This paper describes the results of an extensive channel measurement campaign conducted by France Telecom R&D, and associated data analysis undertaken by the authors in order to better understand the properties of these very short copper channels. A large number of FEXT, NEXT, and insertion loss (IL) channels were measured and analyzed, for lengths ranging from 75 to 590 meters and bandwidth up to 30 MHz. The main contribution is three-fold. First, the simple parametric models in [3] are tested and validated over the target lengths and range of frequencies. Second, the log-normal model for the marginal distribution of both NEXT and FEXT is validated, extending earlier results [3], [4]. Finally certain key fitted model parameters are provided, which are important for system development and service provisioning.

The rest of this paper is structured as follows. Section II provides a concise description of the measurement process and associated apparatus, while Section III reviews the basic parametric models for IL, NEXT, and FEXT. Section IV presents the main results: fitted models for the crosstalk spectra plus model validation (IV-A,IV-B). Section IV also provides useful data regarding IL (IV-C), and the phase and essential duration of the direct channels (IV-D, IV-E). Conclusions are drawn in Section V.

II. Description Of The Channel Measurement Process And Apparatus

IL, NEXT, and FEXT were measured for different lengths of 0.4mm gauge S88.28.4 cable, comprising 14 quads ($14 \times 2 = 28$ loops) [7]. The measured lengths were 75, 150, 300, and 590 meters. A network analyzer (NA) was employed in the measurement process. A power splitter was used to inject half of the source power to the cable, while the other half was diverted to the reference input R of the NA. The output of the measured channel was connected to input A of the NA, and the ratio A/R was recorded. When measuring crosstalk between pairs i and j, pairs i and j were terminated using 120 Ohm resistances; all other pairs in the binder were left open-circuit.

An impedance transformer (balun) was used to connect the measured pair with the measurement device. The reference for the baluns is *North Hills 0302BB* (10kHz–60MHz), except for FEXT and IL for 300 and 590 meters, for which the reference is *North Hills 413BF* (100kHz–100MHz). Prior to taking actual measurements, a calibration procedure was employed to offset the combined effect of the baluns and the coaxial cables.

Three different network analyzers were used, depending on cable length:

- 75 meters: *HP8753ES*, resolution bandwidth = 20Hz.
- 150 meters: *HP8751A*, resolution bandwidth = 20Hz.
- 300 and 590 meters: *HP4395A*, resolution bandwidth = 100Hz.

For all the measurements, the setup was as follows:

- Source power = 15 dBm.
- Start frequency = 10 kHz.
- Stop frequency = 30 MHz.
- Number of points = 801.
- Frequency sweep scale = logarithmic.

15 dBm was the maximum source power available in the lab. For each measured length, all possible $\big($i.e., $\binom{28}{2} = 378\big)$ crosstalk channels in the binder were actually measured. In addition to NEXT and FEXT, IL and phase for the 28 direct channels were also measured.

Due to the fact that measurements were taken in logarithmic frequency scale, there was a need to interpolate the measured data over a linear frequency scale. For each measured channel, shape-preserving piecewise cubic (Hermite) interpolation of the log-scale amplitude of the frequency samples was used, to obtain 6955 equi-spaced frequency samples (spacing = 4.3125 kHz) from the 801 measured log-scale frequency samples. The choice of frequency sweep scale (linear versus logarithmic) hinges on a number of factors. A logarithmic scale packs higher sample density in the lower frequencies, wherein NEXT and FEXT typically exhibit faster variation with frequency, and can be relatively close to the measurement error floor. In this case, a logarithmic frequency sweep naturally yields more reliable interpolated channel estimates in the lower frequencies. On the other hand, this comes at the expense of lower sample density in the higher frequencies.

III. Modeling of Copper Channels

A good overview of twisted pair channel models can be found in [3] (see also [4], [5], [6]). A summary of the most pertinent facts follows.

A. Insertion Loss

The magnitude squared of insertion loss obeys a simple parametric model [3]

$$|H^{\mathrm{IL}}(f,l)|^2 = \mathrm{e}^{-2\alpha l\sqrt{f}}, \tag{1}$$

where f is the frequency in Hz, l is the length of the channel, and α is a constant. In dB,

$$20\log_{10}|H^{\mathrm{IL}}(f,l)| = \beta(l)\sqrt{f}, \tag{2}$$

where we have defined $\beta(l) = -20\alpha l \log_{10}(\mathrm{e})$.

B. NEXT

NEXT can be modeled as [3], [4]

$$|H^{\mathrm{N}}(f)|^2 = Kf^{3/2}, \tag{3}$$

where K is a log-normal random variable. In dB,

$$20\log_{10}|H^{\mathrm{N}}(f)| = 10\log_{10}(K) + 15\log_{10}(f), \tag{4}$$

where now $10\log_{10}(K)$ is a normal random variable. It follows that $20\log_{10}|H^{\mathrm{N}}(f)|$ is a normal variable, with frequency-dependent mean.

Lin [6] has shown that $10\log_{10}(K)$ can be better modeled by a gamma distribution, under certain conditions. In particular, a gamma distribution can better fit the tails of the empirical distribution. On the other hand, the normal distribution is simpler and widely used in this context, because it fits quite well.

C. FEXT

FEXT can be modeled as [3]

$$|H^{\mathrm{F}}(f,l)|^2 = K(l)f^2|H^{\mathrm{IL}}(f,l)|^2, \tag{5}$$

where $K(l)$ is a log-normal random variable, which now depends on length, l. In dB and using equation (2),

$$20\log_{10}|H^{\mathrm{F}}(f,l)| = 10\log_{10}(K(l)) + \beta(l)\sqrt{f} + 20\log_{10}(f), \tag{6}$$

where now $10\log_{10}(K(l))$ is a normal random variable, and thus $20\log_{10}|H^{\mathrm{F}}(f,l)|$ is a normal variable too, with frequency-dependent mean.

IV. Results

A. Fitted Cross-Spectra and log-Normal Model Validation

Results for NEXT are presented first; FEXT follows, in order of increasing loop length. The NEXT power spectrum is approximately independent of loop length for the lengths considered[1], as can be verified from the fitted parameter in Figure 12. For brevity, detailed plots are therefore only provided for 300 meter NEXT. There are two plots per channel type and length considered. The first shows the measured mean log-power of all available channels of the given type, and the associated fitted model, as a function of frequency. As per Section III, we use the following parametric model for the mean NEXT log-power:

$$\mathrm{E}[20\log_{10}|H^{\mathrm{N}}(f)|] \approx c_1 + 15\log_{10}(f), \tag{7}$$

where $c_1 = \mathrm{E}[10\log_{10}(K)]$. The parameter c_1 is fitted to the model as follows. First, $\mathrm{E}[20\log_{10}|H^{\mathrm{N}}(f)|]$ is replaced by its sample estimate, $\mu_s(f)$. Then, the sought parameter is fitted to $\mu_s(f)$ in a Least-Squares (LS) sense. That is, c_1 is chosen to minimize

$$\sum_f |\mu_s(f) - (c_1 + 15\log_{10}(f))|^2, \tag{8}$$

yielding $\hat{c}_1$ equal to the mean of $\mu_s(f) - 15\log_{10}(f)$. The situation is similar for FEXT, except that this time the parametric mean regression model is

$$\mathrm{E}[20\log_{10}|H^{\mathrm{F}}(f,l)|] \approx c_1(l) + c_2(l)\sqrt{f} + 20\log_{10}(f), \tag{9}$$

where $c_1(l) = \mathrm{E}[10\log_{10}(K(l))]$ is now length-dependent, and $c_2(l) \equiv \beta(l)$, as per the associated discussion in Section III. Fitting the two parameters is a standard linear LS problem.

The fitted curve is plotted along with $\mu_s(f)$ in the first of each pair of plots corresponding to each type of channel. The standard deviation (std) of the channel's log-power response is found to be approximately constant over the entire 30MHz frequency band; its average value is reported in the caption of the respective mean power plot.

After frequency-dependent mean removal ("centering" or "de-trending") using the fitted parametric model, the residual frequency samples should behave like zero-mean normal random variables, if the log-normal model of the marginal distribution is correct. In the second plot of each pair, the validity of this assumption is assessed, by a so-called *normal probability plot*, which is produced using Matlab's *normplot* routine. The purpose of a normal probability plot is to graphically assess whether the data could

[1]NEXT generally depends on loop length, see [1].

come from a normal distribution. If so, the normal probability plot should be linear. Other distributions will introduce curvature in the plot. The normal probability plot helps in assessing deviations from normality, especially in the tails of the distribution. For 300m NEXT, a third figure has been included showing a histogram of the mean-centered log-power responses, accumulated across all channels of the given type and across all frequencies. A Gaussian probability density function has been fitted to the said data (*not* the histogram *per se*), and overlaid on top of the same plot. Gaussian fitting is performed in the Maximum Likelihood (ML) sense, which boils down to using the sample estimate of the variance of the centered data. This figure helps to assess (deviation from) normality, however tail inconsistencies are relatively hard to detect this way. For this reason, and for the sake of brevity, we are only showing normal probability plots for the FEXT channels.

NEXT plots for 300 meters are presented in Figures 1–3. Figure 2 indicates that the normal distribution is a reasonable approximation, while a gamma distribution could be used to further improve the fit of the tails [6]. Plots for FEXT are shown in Figure pairs 4–5, 6–7, 8–9, and 10–11, for 75, 150, 300, and 590 meters, respectively.

The results indicate that the simple parametric models in [3] describe sufficiently well the mean log-power of the crosstalk channels, except for the 590m FEXT case, where there is a noticeable deviation of the fitted model from the measured mean power, as high as 3dB in the frequencies approximately up to 2MHz (see Figure 10). In order to obtain a better fit, we can generalize the model of equation (5) by relaxing the f^2 term to $f^{\gamma(l)}$, where $\gamma(l)$ is a length-dependent parameter. Then, equation (6) becomes

$$20\log_{10}|H^{\mathrm{F}}(f,l)| = 10\log_{10}(K(l)) + \beta(l)\sqrt{f} + 10\gamma(l)\log_{10}(f), \tag{10}$$

and the parametric mean regression model becomes

$$\mathrm{E}[20\log_{10}|H^{\mathrm{F}}(f,l)|] \approx c_1(l) + c_2(l)\sqrt{f} + c_3(l)\log_{10}(f), \tag{11}$$

where $c_3(l) \equiv 10\gamma(l)$. That is, we are effectively introducing a third degree of freedom. The resulting profile and parameters of this fit are reported along with the original ones in Figure 10 for comparison purposes.

B. Fitted Regression Parameters versus Length

The fitted frequency-dependent mean model parameters are also plotted in Figures 12 and 13, versus length. For NEXT, $c_1 \approx -158.7$ (-165.4 for Kerpez's model [4]) independent of length, as expected. For FEXT, both parameters show a nice affine dependence on length. In Figure 13 the fitted parameter

$c_2(l) \equiv \beta(l)$ of the frequency-dependent mean model for the direct channel is shown to be an affine function of length as well.

C. Insertion Loss

Figure 14 shows the sample mean IL (in dB) and the associated fitted model, for all four lengths. Notice that the usable bandwidth indeed extends to 30 MHz for the shortest (75m) loop, but is effectively limited to about 7.5 MHz for the longest (590m) loop considered. At that point, the loop's IL drops under -50dB. Figure 13 shows the dependence on loop length of the model parameter $c_2(l) \equiv \beta(l)$ in Equation (2).

D. Phase of Direct Channels

Figure 15 shows the unwrapped phase of all 28 direct channels, for 75, 150, 300, and 590 meters. Note that the (unwrapped) phase is approximately linear.

E. Impulse Response Duration

One parameter that is important from the viewpoint of modem design is the duration of the impulse response of the direct channel. For a multicarrier line code, this affects both the length of the cyclic prefix, and the number of taps (and thus cost and complexity) of the time-domain channel shortening equalizer (TEQ). We plot the dB magnitude of the direct channel's impulse response in Figures 16, and 17, for length 75, and 150 meters, respectively. The 99% energy breakpoint (the "essential duration" that contains 99% of the total energy) is also shown on each Figure. The impulse responses were calculated via Riemann sum approximation[2] of the inverse continuous-time Fourier transform of the interpolated frequency samples, using conjugate folding for the negative frequencies. Note that this approximation introduces aliasing error in the tails of the estimated impulse response. This is unavoidable, because we work with samples of the continuous-time Fourier transform, and the impulse responses are not sufficiently time-limited; thus time-domain aliasing is introduced as per the sampling theorem. This prohibits reliable estimation of, e.g., the 99.99% energy breakpoint. The 99% energy breakpoint, on the other hand, is at least 18 times lower than the period of the aliased impulse response, and thus can be reliably estimated.

[2]For computational savings, this can be implemented via the (inverse) FFT.

V. Conclusions

Simple parametric crosstalk models are useful tools in VDSL system engineering. The evolution towards FTTC / FTTB architectures implies shorter twisted pair segments, and correspondingly wider usable system bandwidth. This brings up the issue of whether or not existing models for NEXT and FEXT are valid in the FTTC / FTTB scenario.

An extensive measurement campaign was undertaken in order to address this question. An important conclusion of the ensuing analysis is that the simple log-normal statistical models in [3] capture the essential aspects of both NEXT and FEXT over the extended range of frequencies considered. Intuition regarding the behavior of FEXT for the shortest loops has been confirmed by analysis. A number of useful fitted model parameters were also provided.

Acknowledgements: The authors would like to thank the anonymous reviewers for their insightful comments.

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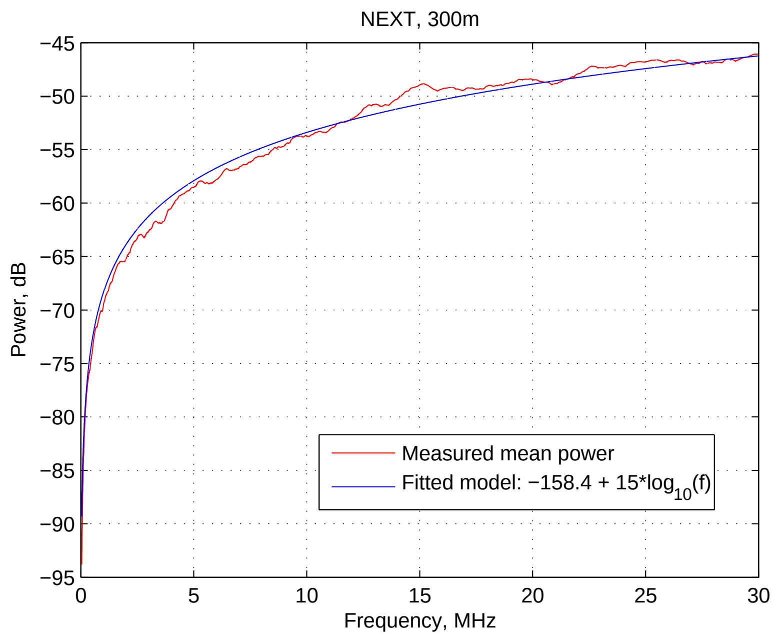

Fig. 1. Measured mean power and fitted model for NEXT, 300m (mean std = 9.5dB)

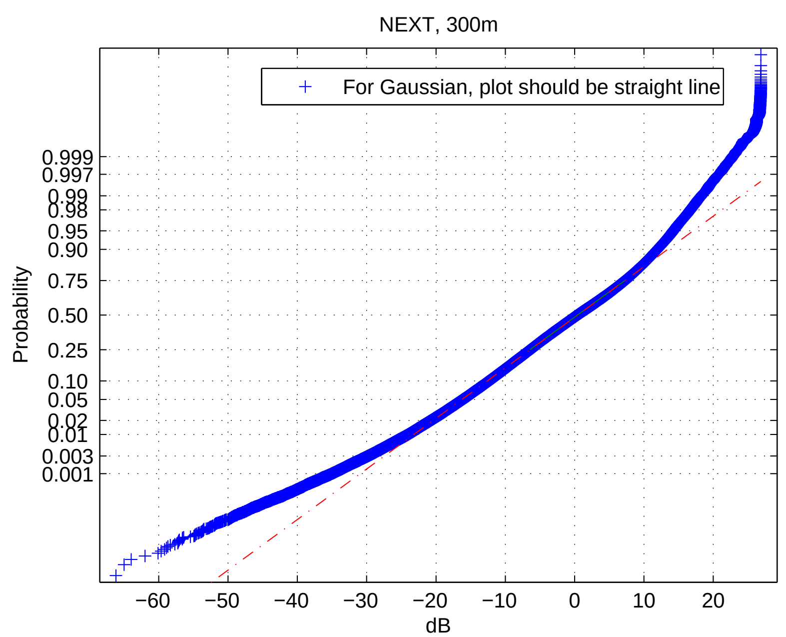

Fig. 2. Deviation from Gaussian p.d.f for NEXT, 300m

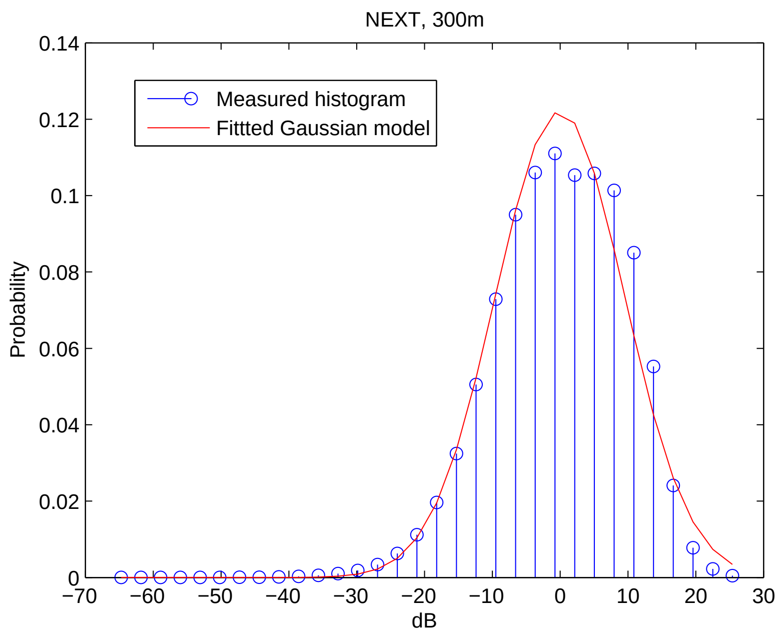

Fig. 3. Histogram of the mean-centered power for NEXT, 300m

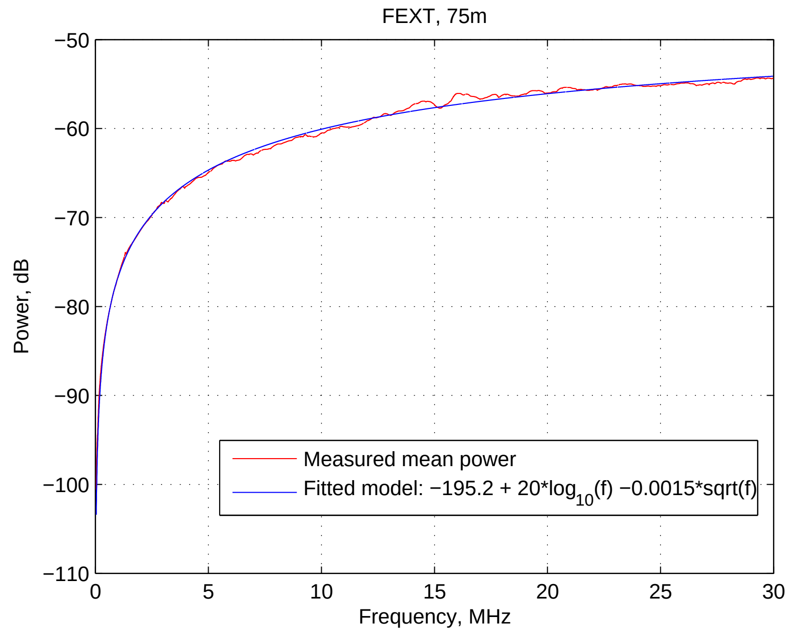

Fig. 4. Measured mean power and fitted model for FEXT, 75m (mean std = 9dB)

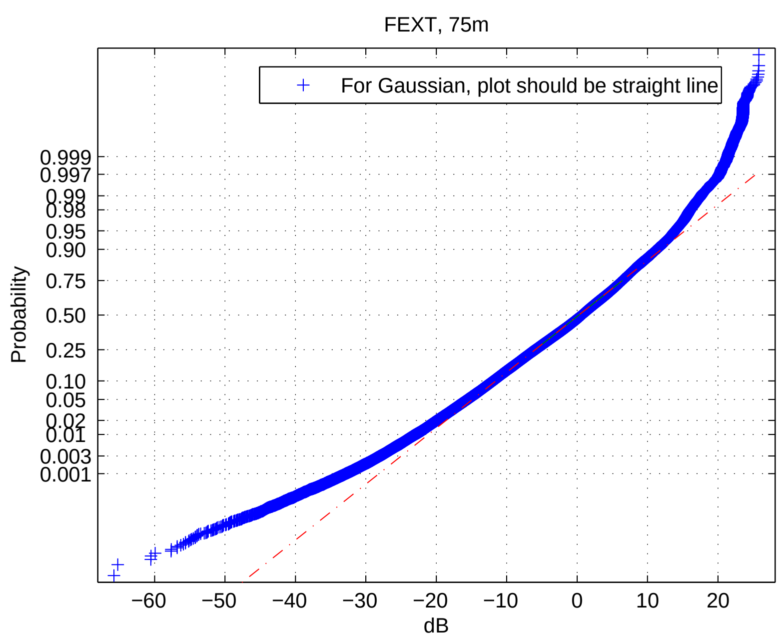

Fig. 5. Deviation from Gaussian p.d.f for FEXT, 75m

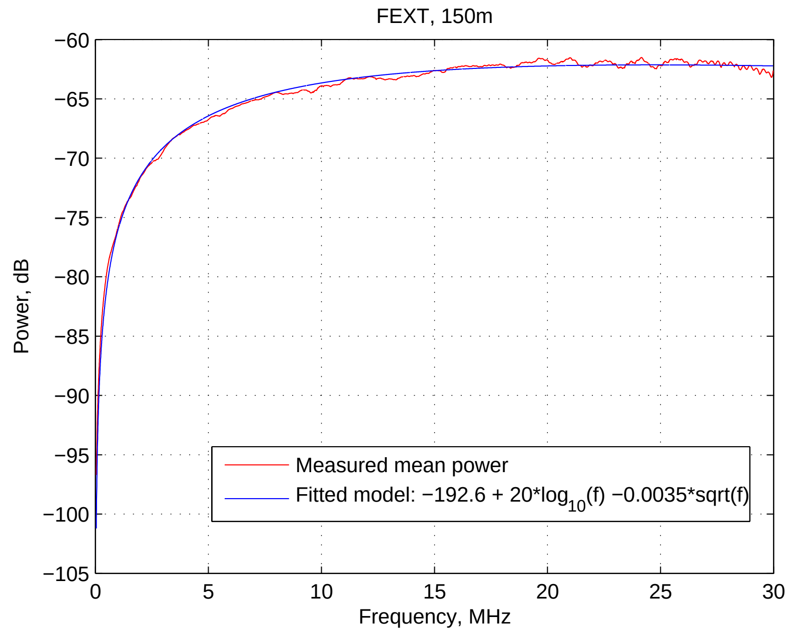

Fig. 6. Measured mean power and fitted model for FEXT, 150m (mean std = 9dB)

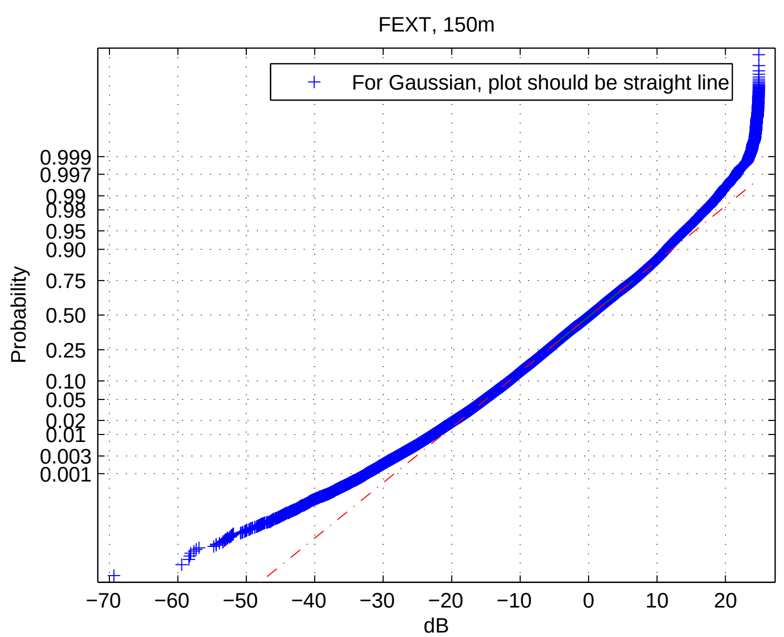

Fig. 7. Deviation from Gaussian p.d.f for FEXT, 150m

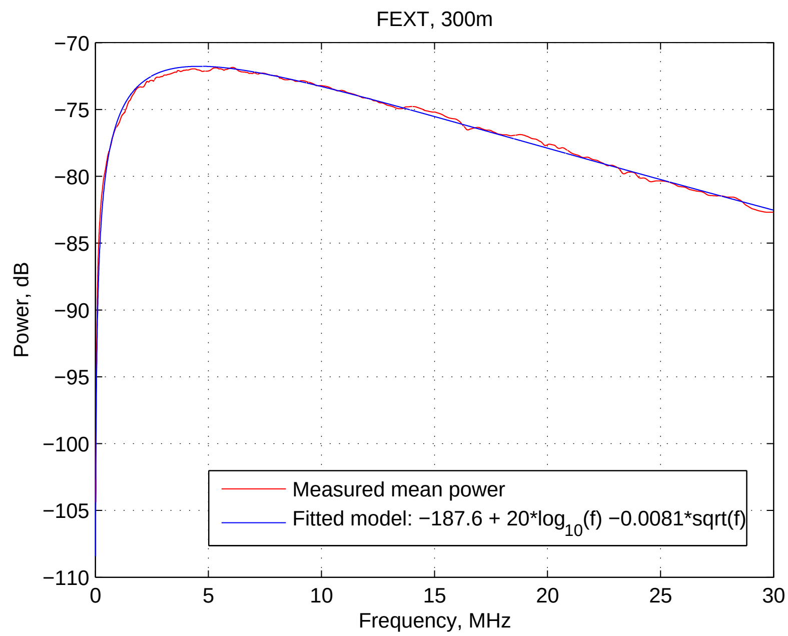

Fig. 8. Measured mean power and fitted model for FEXT, 300m (mean std = 8.8dB)

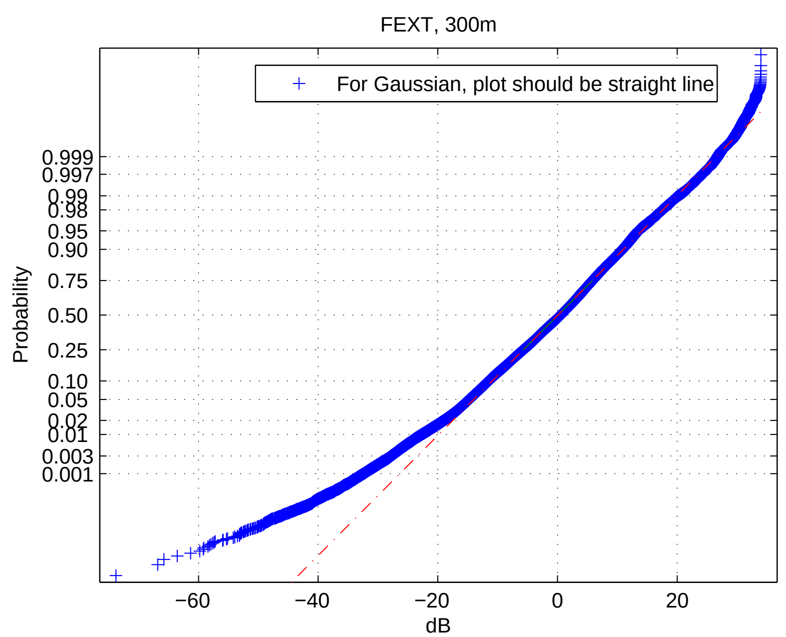

Fig. 9. Deviation from Gaussian p.d.f for FEXT, 300m

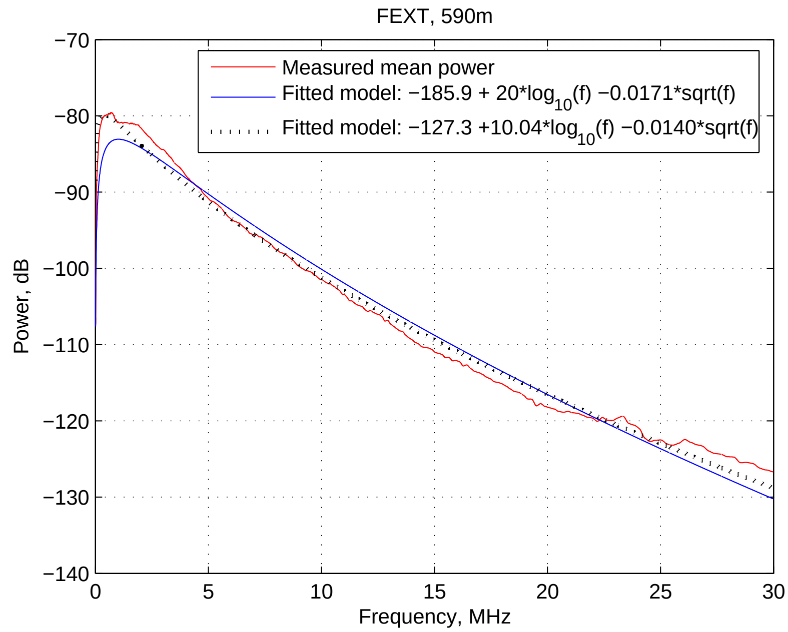

Fig. 10. Measured mean power and fitted model for FEXT, 590m (mean std = 11.2dB)

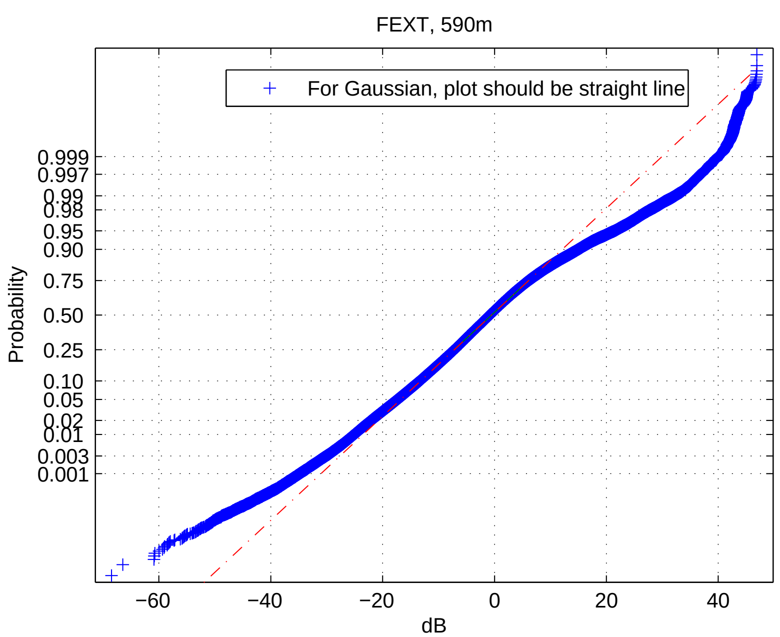

Fig. 11. Deviation from Gaussian p.d.f for FEXT, 590m

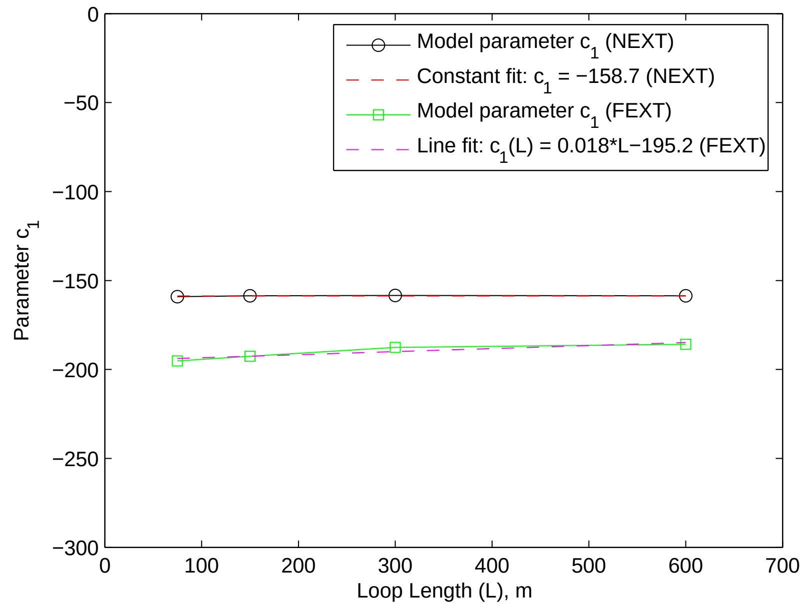

Fig. 12. Fitted regression parameter c_1

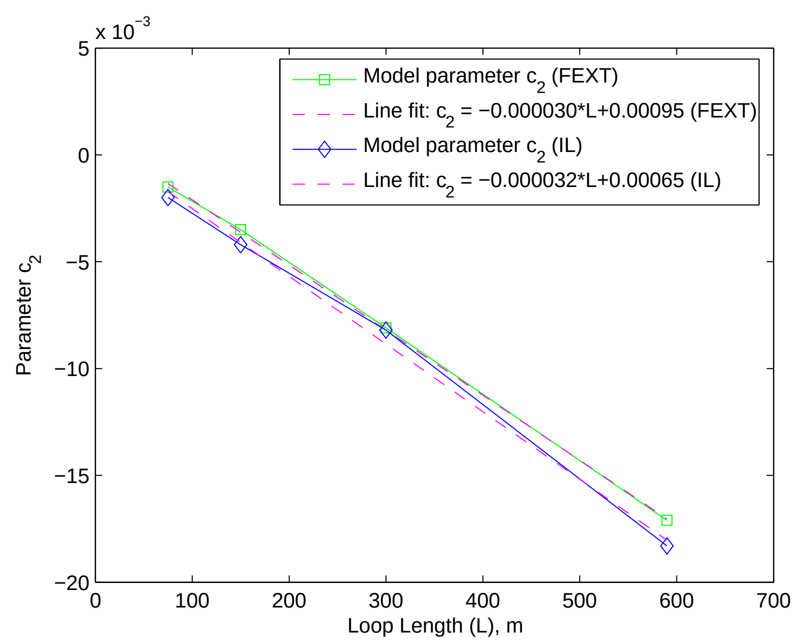

Fig. 13. Fitted regression parameter c_2

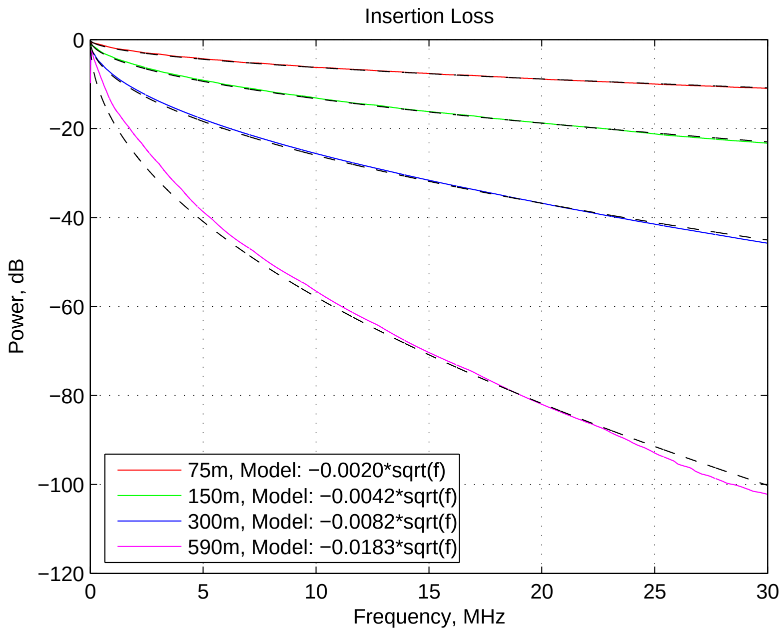

Fig. 14. Measured mean power of direct channel and fitted model

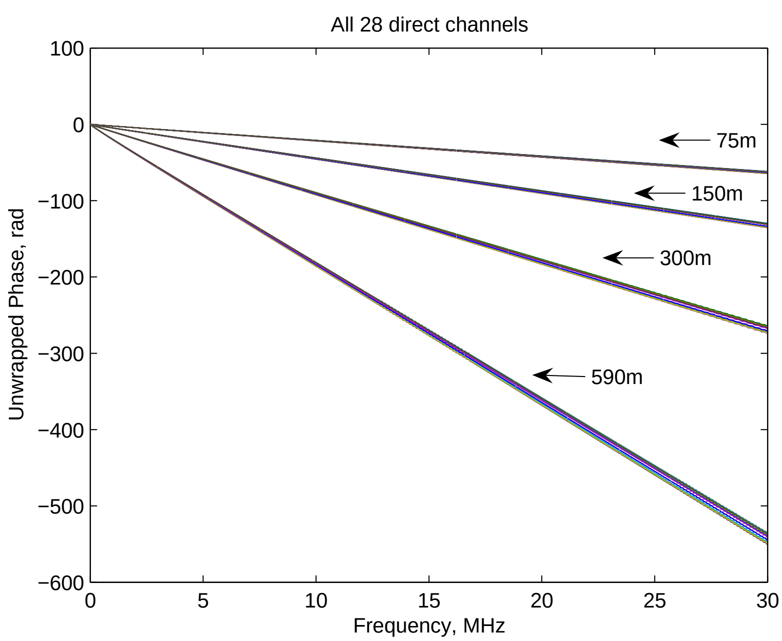

Fig. 15. Unwrapped phase of direct channels

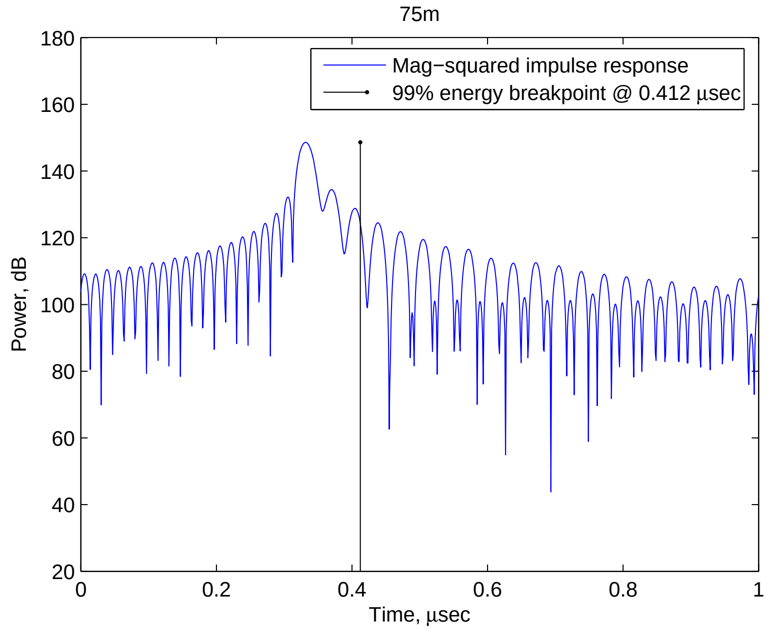

Fig. 16. Magnitude squared of direct channel's impulse response, 75m

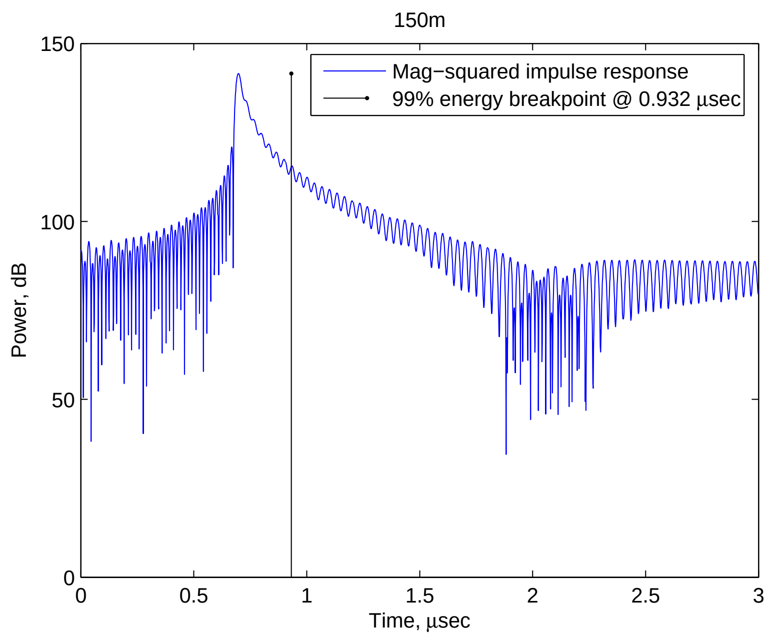

Fig. 17. Magnitude squared of direct channel's impulse response, 150m