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Statistical Modeling of PLC-to-DSL Interference

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***Abstract*—This contribution presents a new results on the statistical characterization of PLC-to-DSL interference. The frequency-dependent couplings between power line cables and twisted-pair were estimated from measurements on a large number of residential inside wires. A parametric statistical model based on a mixture of two truncated Gaussian distributions is then set forth. The proposed statistical model allows the statistical evaluation of the impact of broadband PLC (BB-PLC) interference on various DSL technologies. To the best of the Authors' knowledge, this is the first statistical model for PLC-to-DSL interference to be proposed.**

I. INTRODUCTION

In Power Line Communications (PLC), signals are transmitted over existing power cables which are neither shielded nor balanced, especially in the home. As a consequence, unwanted radiated emissions occur when PLC is used and this phenomenon can cause Electro-Magnetic Compatibility (EMC) issues with other services that operate in the same frequency band of PLC. An important example of such EMC issues is the interference that BB-PLC may create to Digital Subscriber (DSL) technologies such as Very-high rate DSL (VDSL2) [1], Vectored VDSL2 (V-VDSL2) [2], and G.fast (Fast Access to Subscriber Terminals) [3]. In fact, over the past decade, the amount of frequency overlap between BB-PLC and DSL has grown considerably, and today spans either the band $1.8-30$ MHz (VDSL2, vectored and not) or the whole $1.8-100$ MHz (G.fast) [4].

VDSL2 uses high frequencies (up to 17 MHz or 30 MHz) to transmit at speeds of few hundred Mbps and over distances up to 1.5 km [1]. VDSL2 can still be limited by far-end crosstalk (FEXT) which can severely degrade VDSL data rates in dense deployments. Vectoring is a technique that allows canceling self-FEXT under certain deployment conditions, and has been standardized for use with VDSL2 [2]. When vectoring is supported, VDSL2 can maintain its data rates regardless of the number of self-crosstalkers. G.fast aims at providing broadband access over very short copper twisted pairs (up to 250m) at data rates up to 1 Gbps. G.fast also supports cancelation of self-FEXT (vectoring), and is being specified to operate over frequencies of up to 106 MHz [5].

Also BB-PLC has seen tremendous growth in terms of supported data rates and utilized frequencies [6]. Up to a few years ago, PLC data rates of around 200 Mbps were available using technologies based on the IEEE 1901 Broadband Powerline Standard [7], which uses frequencies up to 30 MHz (and optionally up to 50 MHz). More recently, advanced PLC technologies using frequencies up to 100 MHz and MIMO capabilities have appeared on the market, e.g. HomePlug AV2 [8] and ITU-T G.hn [9]. These advanced PLC technologies can achieve data rates up to 1 Gbps [10].

The issue of PLC-to-DSL interference has been addressed in the past decade by several researchers – see [11] and references therein, and also the excellent bibliographic review in [12]. The goal of these studies was mostly to understand the general effect of BB-PLC interference on DSL, especially its dependency on topological characteristics (e.g., cable separation, coupling length, power line load, telephone cabling twisting), and the effectiveness of interference mitigation techniques. However, to the best of the Authors' knowledge, statistical models on PLC-to-DSL interference are not publicly available and the impact of BB-PLC interference on DSL has not yet been assessed in detail.

This paper reports results from a vast measurement campaign of PLC-to-DSL interference and proposes a statistical model for PLC-to-DSL interference couplings. An analysis of the effects of BB-PLC interference on VDSL2, V-VDSL2, and G.fast can be found in a companion paper [11]. These results were first presented in March 2014 at the ITU-T DSL Standardization Working Group. Achieving a good understanding of the impact that BB-PLC interference may have on DSL is important today as proposals for relaxing the PLC PSD above 30 MHz are currently being discussed in CENELEC. The statistical model presented here and the simulation methodology given in [11] provide the necessary tools for carrying out an objective assessment of the impact that BB-PLC may have on various DSL technologies.

II. THE MEASUREMENT CAMPAIGN

Orange performed a measurement campaign in order to assess the effects of PLC interference on DSL. Some preliminary results were reported in [13]. A PLC-like signal was injected into an in-home power line outlet and the interference that coupled into telephone cables in the same home was measured in several houses/apartments. Measurements available to this work were carried out in 22 residential customer premises in France, including houses and apartments both old and new.

A. The Set-Up

The measurement set-up is shown in Figure 1. An Arbitrary Wave Generator (AWG, Tektronix AWG5002) was used as

PLC transmitter. By means of a passive coupler, a PLC signal was continuously injected in the electrical outlet.

The coupled PLC noise on the telephone copper pair in the same home is measured at the phone sockets in the time domain using a digital oscilloscope (Lecroy Waverunner 64Xi). A balun is used to adapt the impedance of the oscilloscope (50 Ohms) to the characteristic impedance of the telephone copper pairs (100 Ohms). The waveform generator and the oscilloscope were powered using the home electrical network but, in order to minimize the influence of the measurement equipment on the noise measurements, they were powered using a filtered power supply and they were also powered from a distant outlet. The sampling frequency both at the transmitter and the receiver was set to 250 MHz.

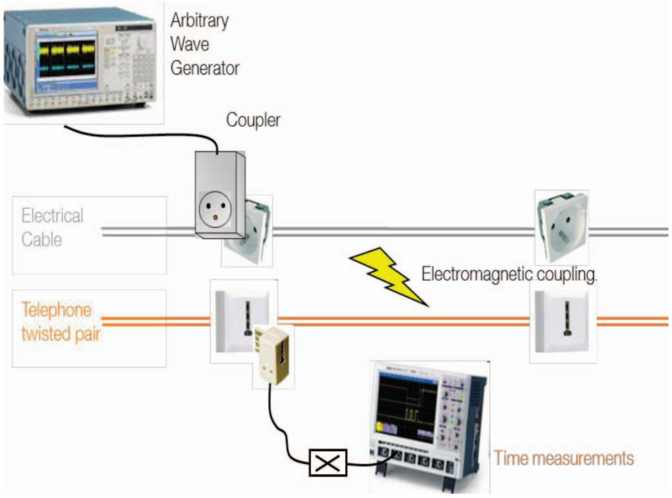


Figure 1: The measurement set-up.

Two sets of measured were collected and used in this work:

- A set of 240 measured PLC-to-DSL interference time-domain traces, each one representing a specific realization of interference coupling between a PLC outlet into which a PLC-like signal was injected and a phone socket.
- A set of 44 measured baseline ambient noise time-domain traces, collected at phone sockets in the absence of PLC interference.

B. The injected PLC signal

The injected PLC signal had a flat Power Spectral Density (PSD) of -60 dBm/Hz over a band up to 125 MHz. The coupler used for the injection of the PLC noise on the electrical line was custom built, exhibited good wideband characteristics between $1-100$ MHz, and introduced only a few dB attenuation.

Modern PLC technologies avoid the FM broadcast band ($87-100$ MHz) since it is very noisy, and limit transmission to 80 MHz (ITU-T G.hn) or to 87 MHz (HomePlug AV2) . The statistical considerations made here for the PLC-to-DSL interference band in the $1.8-100$ MHz apply also to the $1.8-87$ MHz band as the estimated couplings PDF for the two bands is basically identical (see Figure 3).

C. Processing of Measured interference

The baseline noise and PLC-to-DSL interference signals present on the customer's telephone copper pairs was measured with a digital oscilloscope sampling at 250 Msamples/sec and connected via an impedance matching balun to a phone socket. Each time-domain trace contained 25 million samples, corresponding to a duration of 100 ms. Further processing of the time-domain traces was performed to improve PSD estimation, specifically a modified Welch algorithm was used to estimate the noise PSD at a phone socket at 7.63 kHz spacing. PLC-to-twisted pair couplings where then computed by subtracting from the estimated noise PSD the PLC-like excitation signal of -60 dBm/Hz.

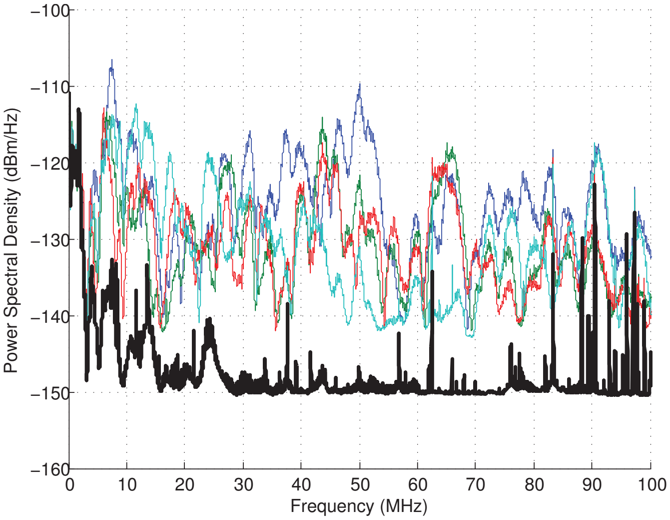


Figure 2: The ambient baseline noise PSD is shown in bold black. The four PSDs shown in other colors represent the noise PSDs observed on a phone pair when a PLC-like signal is injected into four different power outlets.

The measured PLC interference was found to be periodically time-varying (see the spectrogram in Figure 1 of [11]). This property is not surprising as it is well known that the PLC channel itself is a Linear and Periodically Time Varying (LPTV) channel [14], [15]. The PSD estimation method we chose led to an estimate of the PSD of the PLC noise signal which is an "average" PSD, i.e. each frequency component of the PSD assumes a value that is the time average of the spectrogram along the time-axis.

In this work, each time-domain measured noise trace was processed where each measurement represents a coupling realization (16,384 frequency domain coupling samples, from DC to 125 MHz) between a power line outlet and a phone socket or simply the ambient baseline noise. There are often multiple traces per home, each from different outlet-phone jack pairs. Only the couplings in the usual PLC frequency band of $1.8-100$ MHz were considered in this work, amounting to a total coupling population of 3.1 million samples.

In Figure 2, we show the estimated PSDs of the measured baseline noise (PLC is off) and the measured PLC-to-DSL interference observed on a telephone jack. The minimum measurable coupling is -90 dB as the noise is at floor at -150 dBm/Hz.

Narrowband interferers (NBIs) are clearly visible, especially in the first 30 MHz of band (shortwave radio) and in the $80-100$ MHz band (FM radio broadcast). In this work, we made no attempt to isolate NBIs so some estimated couplings may be higher than they would have been in the absence of NBIs. Similarly, other noise is also present on the telephone lines even when PLC is off and this noise can be substantial as shown in Figure 2. As a consequence, the estimated PLC-to-DSL couplings can never fall below the measured ambient noise, which changes from location to location. As a consequence, some PLC-to-DSL coupling estimates may be higher than their true value when the true coupling level is below the ambient noise level.

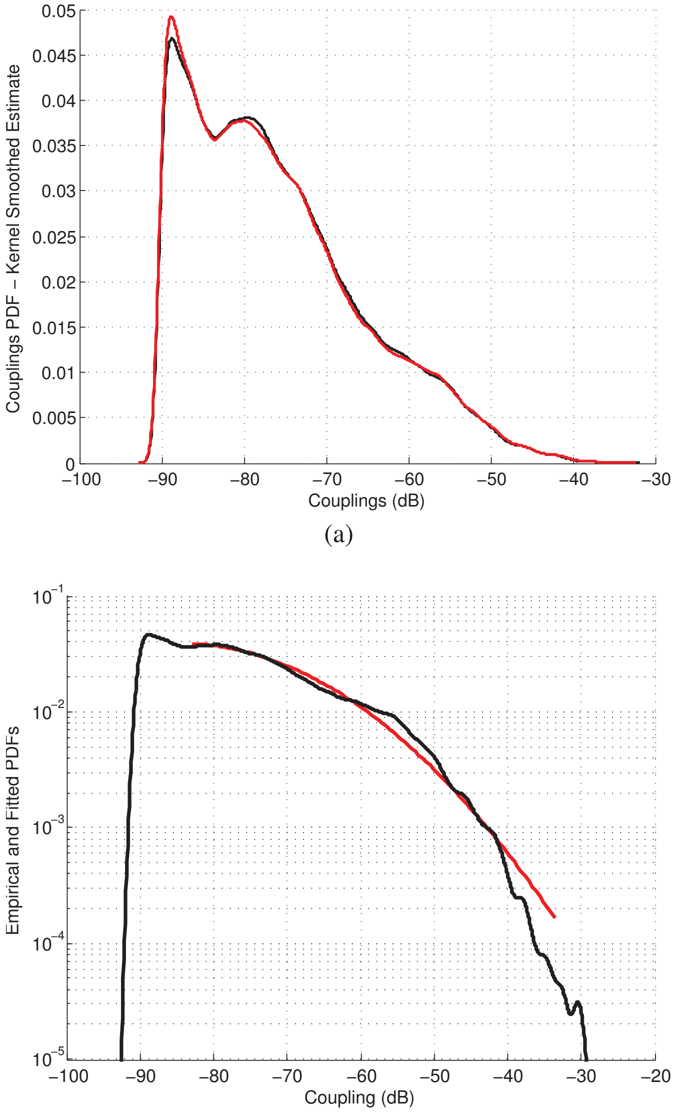
III. STATISTICAL CONSIDERATIONS ON THE COUPLINGS

The estimated Probability Density Function (PDF) for all the couplings in the two regions $1.8-87$ MHz and $1.8-100$ MHz is shown in Figure 3.(a). The same PDF is plotted in Figure 3.(b) in semilog scale together with the best Gaussian fit to the data truncated at -83 dB. The estimation of the mean and variance of a corresponding left-truncated Gaussian PDF was performed using the Levenberg-Marquardt algorithm. The mean and standard deviation values of the best fitting truncated Gaussian are -84.6 dB and 15.4 dB, respectively. The fitting PDF's area was also normalized to the probability that a coupling was -83 dB or higher, which was estimated to be 0.6936 from the Kaplan-Meier estimate of the empirical Cumulative Distribution Function (CDF).

As the red curve in Figure 3.(b) confirms, the fitting is quite good up to until coupling values of -41 dB after which the empirical PDF exhibits a marked slope change. This change in slope may be due to the presence of a second truncated Gaussian distribution, i.e. the empirical PDF could be a mixture of truncated Gaussians.

The effect of the noise floor is noticeable because of the truncation at -90 dB. However, the left side of the estimated PDF in Figure 3.(a) seems to suggest that there is a large number of low couplings in the range between -83 dB and -90 dB. This behavior may suggest the presence of another distribution governing the occurrence of couplings below -83 dB, or it could be due to the fact that in some cases the true value of a coupling is increased to the same level of the ambient baseline noise. New measurements performed using a higher transmit power for the PLC signal could be helpful in confirming the nature of this behavior.

To understand this phenomenon better, we plotted in Figure 4 the estimated PDF of the estimated couplings in various frequency bands. Across the three regions of the PDFs (left side, body, and right tail), we can identify similar but somewhat distinct behaviors. The vast majority of low couplings are concentrated in the first 5 MHz of bandwidth ($1-8-6.8$ MHz), and successive slices of 5 MHz show a decrease of probability in the occurrence of low couplings and a consequential rise of couplings of intermediate strength (the body of the PDFs).



(a)

(b)

Figure 3: (a) Estimated PDF (Gaussian kernel smoothing) of all couplings in the $1.8-100$ MHz band (black) and in the $1.8-87$ MHz band (red). (b) Estimated PDF in the $1.8-100$ MHz band (black) with a Gaussian distribution fitted to the data truncated at -83 dB (red).

Interestingly, the right tails of the estimated PDFs also show that the probability of very high couplings is around 2x-3x higher in the first 5 MHz of bandwidth than in any other 5 MHz bands or even across the whole 100 MHz band. More investigation is needed on understanding this phenomenon. A possible explanation is that the ambient baseline noise increases the minimum value of the estimated couplings, thus making low couplings higher than what they should have been if no ambient baseline noise were present.

The quantile-quantile (QQ) plots of the couplings for the $1.8-100$ MHz band is shown in Figure 5. Apart from obvious evidence of truncation, the QQ-plot has a rather linear trend for low moderate couplings, but then start deviating from it above -65 dB. This QQ-plot may be interpreted as suggesting the

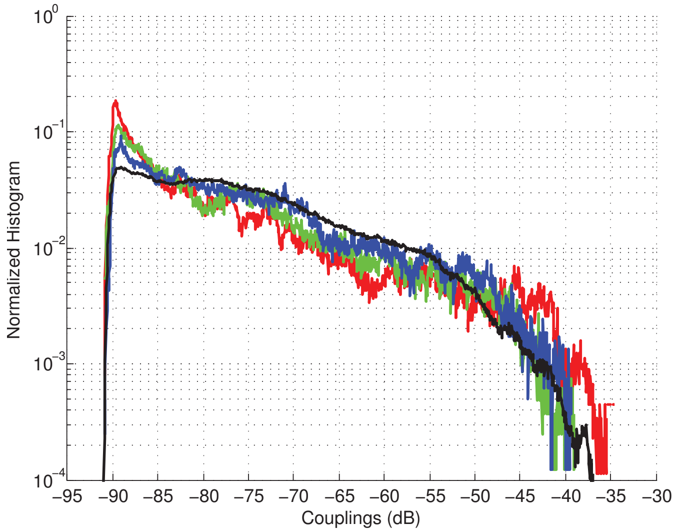


Figure 4: Estimated PDFs (histograms) of couplings in semilog scale and for various frequency bands: $1.8 - 6.8$ MHz (red), $6.8 - 11.8$ MHz (green), $11.8 - 16.8$ MHz (blue), and $1.8 - 100$ (black).

presence of a light-tailed distribution or the possible presence of a mixture of truncated Gaussian distributions.

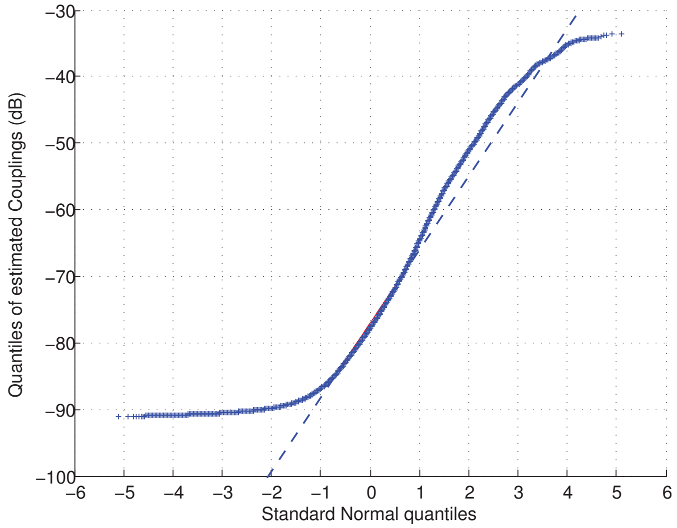


Figure 5: QQ-plot of estimated couplings in the 1.8-100 MHz band.

IV. THE STATISTICAL MODEL

In our investigation, we have verified that the empirical distribution of PLC-to-DSL interference couplings can be well fitted by two truncated Gaussian distributions plus a mass PDF that accounts for the weak couplings below a certain threshold LT_1. Thus, we can write the following model for the PDF of the couplings x when expressed in dB:

$$\begin{aligned} p(x) = {} & Pr\{X \le LT_1\} u_o(x - LT_1) + \\ & + Pr\{X \in L = [LT_1, RT_1]\} \boldsymbol{\mathcal{TN}}^{(1)}_{[LT_1, RT_1]}(\mu_1, \sigma_1) + \\ & + Pr\{X \in M = [LT_2, RT_2]\} \boldsymbol{\mathcal{TN}}^{(2)}_{[LT_2, RT_2]}(\mu_2, \sigma_2) \end{aligned} \quad (1)$$

where $\boldsymbol{\mathcal{TN}}^{(i)}_{[a,b]}(\mu_i, \sigma_i)$ denotes a Gaussian distribution with mean μ_i and standard deviation σ_i truncated to the interval $[a, b]$. If we denote as $\phi(x)$ the standard normal PDF with zero mean and unitary standard deviation and with $\Phi(x)$ its CDF, then we can express the truncated Gaussian PDFs in eq. (1) as follows ($i = 1, 2$):

$$\boldsymbol{\mathcal{TN}}^{(i)}_{[a,b]}(\mu_i, \sigma_i) = \frac{\frac{1}{\sigma_i}\phi(\frac{x-\mu_i}{\sigma_i})}{\Phi(\frac{b-\mu_i}{\sigma_i}) - \Phi(\frac{a-\mu_i}{\sigma_i})}, \quad (2)$$

When all the couplings in the band 1.8-100 MHz are considered, then the optimal intervals and the corresponding probabilities that couplings occur in those intervals are:

- $Pr\{X \le -83\} = 0.3064$
- $Pr\{X \in L = (-83, -41)\} = 0.6924$
- $Pr\{X \in M = [-41, -35]\} = 0.0012$,

while the mean and standard deviation of the truncated Gaussian PDFs appearing in eq. (1) are:

- $\mu_1 = -84.6$ dB, $\sigma_1 = 15.5$ dB
- $\mu_2 = -138$ dB, $\sigma_2 = 15$ dB.

The fitting of the empirical PDF in intervals L and M with two truncated Gaussians was carried out using again the Levenberg-Marquardt algorithm.

Besides being statistically valid, this approach is also physically meaningful as PLC and DSL signal propagation gives rise to normally distributed fading (in dB) [16]–[18], and this distribution should be preserved by electromagnetic coupling as coupling can be viewed as a form of filtering (linear transformation).

A. Model Validation

We have simulated the proposed model by generating 100 million couplings of which: 69,239,365 couplings were generated as a $\boldsymbol{\mathcal{TN}}_{[-83,-41]}(-84.6, 15.5)$, and 122,576 couplings were generated as a $\boldsymbol{\mathcal{TN}}_{[-41,-35]}(-138, 15)$. The remaining 30,638,059 couplings were generated as uniformly distributed random variables in the interval $[-91, -83]$, which we have ascertained gives good results as a mass PDF centered on -83 dB.

The PDF of the simulated couplings is plotted (red) in Figure 6 against the empirical PDF (black). The PDF fit is quite good across the whole range of coupling values, and remarkably in the tail region which is the critical part of the distribution as it governs the occurrence of high couplings which bear the most impact on DSL performance.

Remark 1: By considering the estimated PDFs in Figure 3, the QQ-plot in Figure 5, and the fitting results in Figure 6, we conclude that there is no strong evidence against modeling the PLC-to-DSL couplings as a mixture of two truncated Gaussian distributions. We point out that we have not resorted here to statistical tests for confirming the distribution nature of the couplings via p-value analysis, as for example done in previous work [16]–[18]. The reason for this is that it is well known that the p-value "artificially" decreases towards zero as sample size increases [19]. For the 3.1 million sample size we had at our disposal, the p-values associated to most statistical tests against

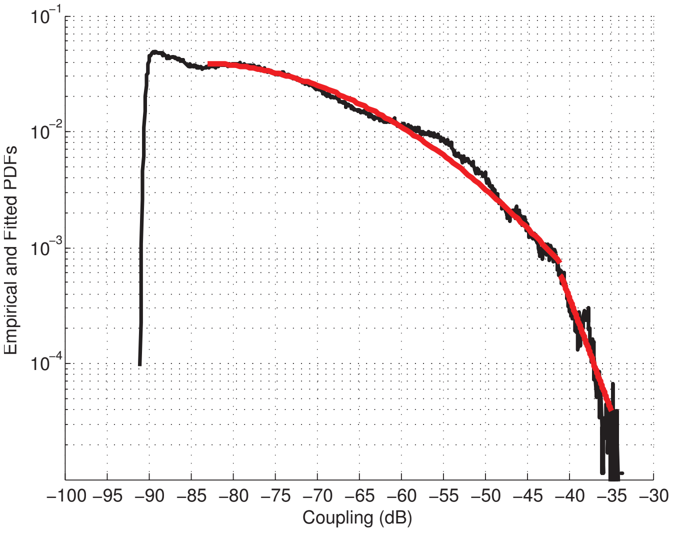


Figure 6: Estimated PDF of measured couplings (black) and simulated couplings (red) in the $1.8 - 100$ MHz band.

the null hypothesis would have been almost always very close to zero, thus making such investigation basically moot. On the other hand, the abundance of measured couplings allows us to rely well on probability plots, histogram analysis, and fitting results.

V. SIMULATION RESULTS

We have assessed the impact of PLC interference on G.fast lines, using both measured and simulated couplings. G.fast was simulated using the following typical assumptions:

- DMT with 2048 carriers. equally spaced in $0-106$ MHz.
- The transmit frequency band was from 23 MHz up to 106 MHz (mode compatible with VDSL2).
- The loop response and FEXT were based on a set of measurements reported by British Telecom on a 100 m distribution cable [20].
- A full cable of 10 active and vectored lines was simulated.
- Vectoring uses linear zero-forcing precoders.
- The G.fast PSD is always normalized, so that the transmit PSD is unaltered by precoding at all frequencies.
- The G.fast PSD is limited as in ITU-T G.9700, with PSD mask equal to -65 dBm/Hz below 30 MHz, and linearly sloping from -73 dBm/Hz at 30 MHz down to -76 dBm/Hz at 106 MHz. This is further limited to meet the 4.0 dBm total transmit power limit.

For the data rate calculation, downstream bit rates are calculated by summing the capacity calculation of each 51.75 kHz G.fast sub-carrier with a 9.75 dB SNR gap, with bits per Hz lower limited to at least one bit per Hz and upper limited to 12 bits per Hz. Margin was set to 6 dB, total coding gain to 3 dB, and AWGN at -140 dBm/Hz was added to the receiver in all cases. Since measured cable responses and FEXT were used, then the direct and crosstalk channels are different from line to line and this leads to variation in bit rates between lines. Furthermore, the linear precoder amplifies the signal power at high frequency where the crosstalk is much stronger than at lower frequency making the channel matrix not row-wise dominant as it would be when limiting upper frequencies to 30 MHz.

To simulate PLC interference, random couplings are generated according to the model proposed in Sect. IV. Each coupling is assigned to a G.fast sub-carrier and assignments are random and independent from each other. We have generated multiple realizations of couplings for each of the ten G.fast lines and calculated the average G.fast data rate, where averaging is done across coupling realizations and for every G.fast lines. The PLC transmit PSD follows the one specified in IEEE 1901 [7], HomePlug AV2 [10], and ITU-T G.hn [9], i.e. a PSD of -55 dBm/Hz is used up to 30 MHz and then the PSD drops to -85 dBm/Hz in the range $30-100$ MHz. It is also assumed that a PLC node is continuously transmitting at maximum power, which is a worst case scenario.

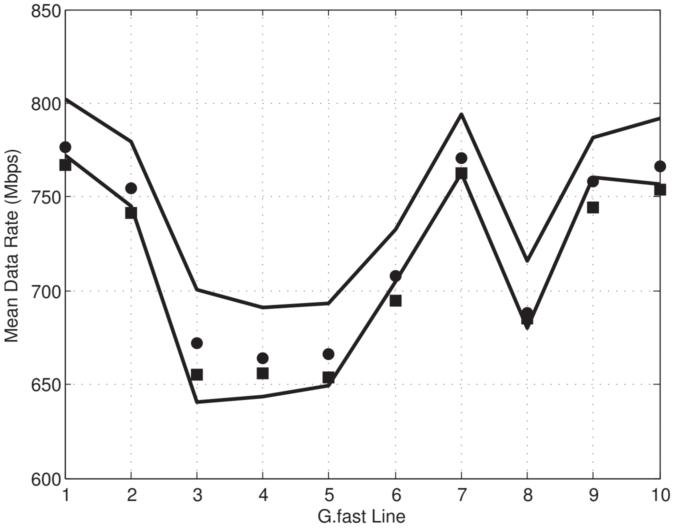


Figure 7: G.fast maximum data rates. Upper solid curve: data rates when there is no PLC-to-DSL interference. Lower curve: average data rate in the presence of measured PLC-to-DSL interference. Circles: average data rate when PLC-to-DSL interference is obtained using simulated couplings. Squares: average data rate when PLC-to-DSL interference is obtained using mean-adjusted simulated couplings.

The effect of PLC interference on G.fast under the above assumptions is shown in Figure 7, where G.fast data rates were assessed per line averaging over 24 measured coupling realizations (lower solid curve) and over 5 simulated coupling realizations (circles). The average (across lines) error relative to the case when measured couplings were used is only 1.7% and the maximum relative error is 4.8% (for line #3). Only 5 coupling realizations were sufficient to estimate the impact on G.fast with good accuracy. This is due to the fact that the proposed statistical model was derived using the same aggregated statistics of all the measured coupling population across all locations and considered frequencies. As a consequence, every simulated realization of 2048 couplings has approximately the same mean of the whole measured coupling population, which is -75.9 dB. If all interference realizations have the same coupling average across frequency, then the use of such realizations leads to a set of DSL data rates that exhibit little variability across realizations and this is why only a few realizations need to be simulated.

It is possible to achieve a lower average relative error by performing normalizing appropriately the simulated couplings, an operation that takes into account the fact that the means of the 240 measured coupling realizations varies quite a bit and ranges from -90 dB to -50 dB. We have noticed that normalizing the simulated couplings so that the mean of each realization matches the statistical distribution of the mean of the measured realizations yields better accuracy in estimating the impact of PLC interference on DSL data rates, even though more realizations must be generated compared to the case when mean-adjustment is not performed. Adopting this methodology and using 100 simulated realizations for every G.fast line, the average and maximum relative errors can be reduced to 1.1% and 2%, respectively – see the "square" data points in Figure 7.

Finally, we have also evaluated the suitability of the proposed model for outage analysis by comparing some notable percentiles of simulated and measured data. As shown in Figure 8, the worst case percentiles of simulated and measured couplings are quite close.

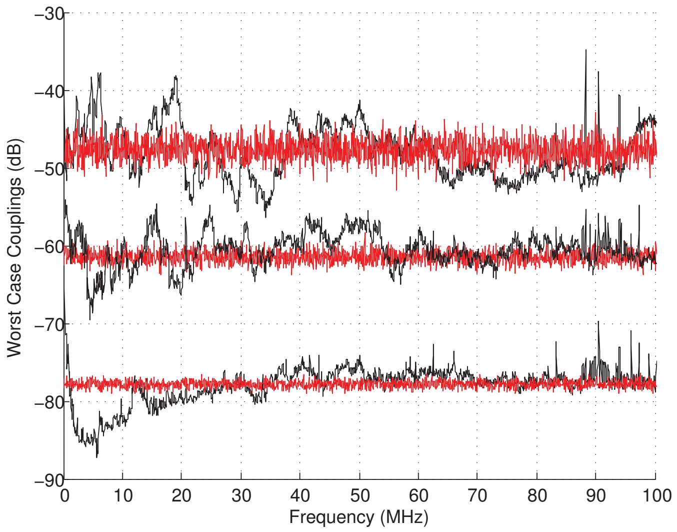


Figure 8: Median, 90% and 99% worst case couplings of measured (black) and simulated (red) couplings.

VI. CONCLUSIONS

For the first time, a statistical model for PLC-to-DSL interference has been proposed on the basis of a large-scale measurement campaign. The proposed model is based on a mixture of two truncated Gaussian distributions, it exhibits a good fit to the measured data both in the PDF body and the tail, and is also physically reasonable. The results presented here have been derived using measurements in France and their generality to other countries that may have different wiring practices and regulations requires further validation.

The availability of a statistical model allows the statistical evaluation of the impact of PLC interference on various DSL technologies. In this paper, we utilized this model to analyze the effects of interference from modern PLC transceivers into the new G.fast DSL standard. The same approach can be followed to extend the results to the case of VDSL2 and V-VDSL2. An analysis of the impact of PLC interference on VDSL2, V-VDSL, and G.fast based on the available empirical data can be found in [11].

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