Estimation of dual ended measurements from one side of a copper wire loop with linear regression

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***Abstract*—The Centralized Radio Access Network (C-RAN) architectures in the future mobile networks will have to employ, besides the optical links, the already available ethernet copper infrastructure in the connection between Base Band Units (BBU's) and Remote Radio Heads (RRH's) in order to cut implementation costs. This approach should include techniques to mitigate the crosstalk between twisted wires, which employ measurements that uses equipment at both loop ends. However, the service is stopped whenever such measurements are performed. This paper proposes a method based on linear regression to perform the most part of those measurements just from the BBU.**

***Index Terms*—C-RAN, linear regression, twisted wires, crosstalk**

I. Introduction

The new mobile network architectures development points to the centralization of the data processing in an equipment called Base Band Unit (BBU), that coordinates remote antennas, the Remote Radio Heads (RRHs) [1]. It is an approach mainly devised to use optical fiber channels to connect its elements, but an implementation must consider the use of other connectivity technologies to cut deployment costs [2]. Due to great availability of copper infrastructures, ethernet cables will play an important role in the future 5G networks.

In order to have a performance similar to fiber in 5G, the copper infrastructure will face problems such as attenuation and crosstalk. The first can be treated with shorter implementation lengths, while the former will demand crosstalk mitigations techniques like vectoring [3]. However a system with this approach needs to perform periodically Far End Crosstalk (FEXT) measurements, which will hamper its the performance during the procedure.

One solution is to estimate FEXT instead of directly measure it. There are patented methods developed for use with DSL technologies that try to solve this problem [4] [5] [6] . They are based on FEXT calculations in one of the loop equipment using information such as Near End Crosstalk (NEXT) measurements, line length and Quiet Line Noise.

Although all the cited patents present methods for crosstalk estimation from only one side of a loop, those solutions still need data acquired with dual ended measurements for the whole frequency range. Our proposal, however, not only can provide FEXT estimations from NEXT crosstalk, but also Insertion Loss (IL) values calculated using Return Losses (RL), both essential for implementation of vectoring [3] and to enable high data rates over copper wires. The method needs to perform dual loop measurements on some range of the spectrum, in order to obtain data to adjust its linear regression.

II. Proposed Solution

The electromagnetic characteristics of a copper pair derive from physical attributes as cable length, twist rate, distance between wires and frequency of operation. Therefore it is reasonable to assume that the FEXT and NEXT of a twisted pair (or respectively, IL and RL) depend on the same variables and a mathematical relation between both can be obtained.

In order to achieve such relation, we note that a point d_i in the FEXT curve, localized at the i-th frequency position, might have a higher correlation with the points in the NEXT curve around this i-th position. It is also reasonable to suppose that the frequency has an important influence on the correlation between these curves. The simplest way to represent these correlations is to express d_i as a linear function of a frequency point f_i and n consecutive points in the NEXT curve, centered at f_i (n is odd). The equation (1) presents an example of this approach for $n = 3$:

$$d_i = \theta_{s1} s_{i-1} + \theta_{s2} s_i + \theta_{s3} s_{i+1} + \theta_f f_i + \theta_0, \qquad (1)$$

where s_i is the point in the NEXT curve localized at the i-th frequency position, the relation between FEXT, NEXT and frequency points are represented by the weights θ_{s1}, θ_{s2}, θ_{s3} and θ_f, respectively, and θ_0 is an independent term for increasing the degree of freedom of (1). The Figure 1 shows a graphical representation of this idea.

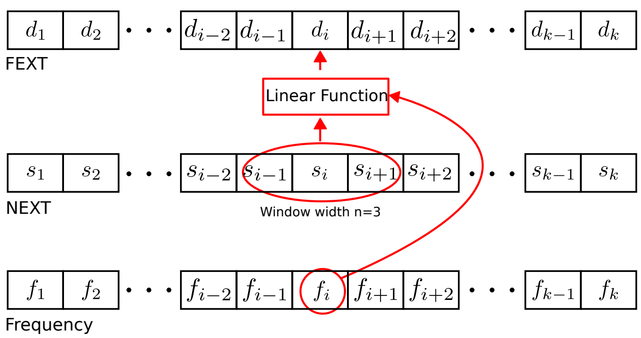

Fig. 1. A point i of FEXT vector is represented as a weighted sum between and $n = 3$ elements of NEXT grouped on a window centralized at si position. The same idea can be applied for a pair of IL and RL curves.

In order to determine the values of the θ weights, linear regression is used. For this matter, the data must be arranged into a linear system of equations. A general matrix representation of (1) can be expressed as (2), where k is the total length of the vector used in the linear regression.

$$\begin{bmatrix} d_{\frac{n+1}{2}} \\ d_{\frac{n+1}{2}+1} \\ d_{\frac{n+1}{2}+2} \\ \vdots \\ d_{k-\frac{n-1}{2}} \end{bmatrix} = \begin{bmatrix} s_1 & s_2 & s_3 & \cdots & s_n & f_{\frac{n+1}{2}} & 1 \\ s_2 & s_3 & s_4 & \cdots & s_{n+1} & f_{\frac{n+1}{2}+1} & 1 \\ s_1 & s_2 & s_3 & \cdots & s_{n+2} & f_{\frac{n+1}{2}+2} & 1 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ s_{k-n+1} & s_{k-n+2} & s_{k-n+3} & \cdots & s_k & f_{k-\frac{n-1}{2}} & 1 \end{bmatrix} \times \begin{bmatrix} \theta_{s1} \\ \theta_{s2} \\ \theta_{s3} \\ \vdots \\ \theta_n \\ \theta_f \\ \theta_0 \end{bmatrix} \tag{2}$$

Denoting the terms in (2) as for the FEXT vector, for the vector and for the matrix containing NEXT and frequency points, we can express the values which minimize the mean squared error of the linear regression as:

$$\Theta = (S^T S)^{-1} S^T D \tag{3}$$

Note that (3) provides the values that correlate NEXT and FEXT measurements for the same frequency range, for a given n value. Therefore, θ can be applied to (1) in order to estimate the FEXT values at an arbitrary frequency range where just NEXT measurements are available.

The optimal value of n (window width) must be determined experimentally and will depend on the sample rate, the bandwidth used in linear adjustment and on the whole frequency range that the equipment operates. Using a set of NEXT and FEXT measurements, once determined a range for linear adjustment, many values of n can be tested. Comparing the determination coefficient (r^2) between calculated and measured FEXT's of the set, a n value that leads to a r^2 closer to 1 can be chosen.

TABLE I
CONSTITUTING CHARACTERISTICS OF THE SIMULATED CABLE.

Characteristic	**Value**
Conductor Diameter (AWG)	24
Insulation Thickness (mm)	0,2447
Jacket Thickness (mm)	0,6
Jacket Permittivity	3,0
Insulation Permittivity	2,26
Load Impedance (Ω)	100
Twist Lengths (mm)	12,7, 18,19, 13,37 and 19,61 [1]

[1] Respectively for each pair 1, 2, 3, and 4 (Figure 2)

III. Validation

A. Tests with simulated data

An example of application of the proposed method is presented on the following. Specifically, the aim is to estimate the high frequency FEXT on a copper line from its NEXT. A CAT5 cable was simulated using the OPTem Cable Designer software [7] to generate the FEXT and NEXT. The design of the twisted pairs employed the constituting parameters of Table I.

The pairs were organized as shown in Figure 2.

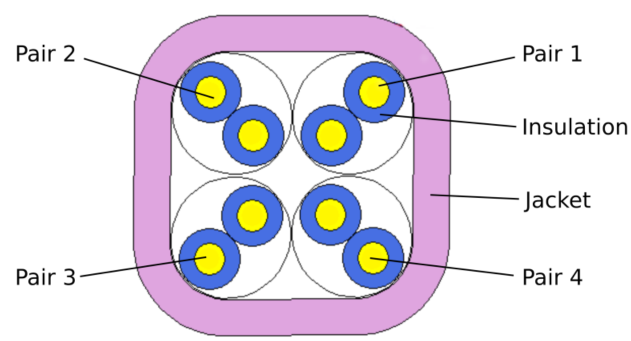

Fig. 2. Structure of the Cat 5 cable used to simulate NEXT and FEXT.

The simulation was performed for a range from 0 to 100 MHz, containing 200 sample points. In general, the crosstalk curves show some distortions at low frequencies; therefore they do not represent the overall behavior of the NEXT/FEXT. In our analysis, we excluded the first points up to 20 MHz.

For magnitude and phase estimations, we divided the bandwidth into two ranges, one for the linear regression, from 20.5 MHz to 40 MHz (40 points), and other for the high-frequency FEXT estimation using the resulting linear function, from 40.5 MHz to 100 MHz (120 points). In the assumed scenario, the ideal n value found was 17 for magnitude, which corresponds to a bandwidth of 8.5 MHz, and 1 for phase.

The determination coefficient (r^2) that shows how good the data is estimated by the linear regression, assuming values from 0 (worst estimation) to 1 (best estimation), was 0.9934 for magnitude, Figure 3, and 0.9999 for phase, Figure 4.

Using the same configuration of window sizes, adjustment and test frequency ranges employed for FEXT estimation,

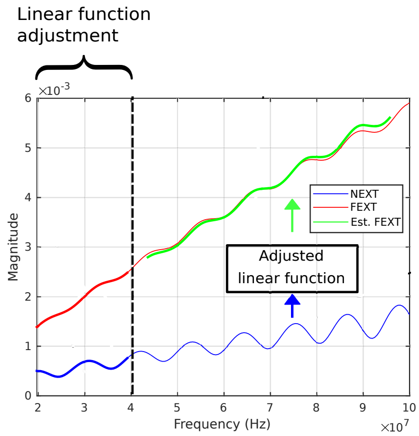

Fig. 3. Magnitude of the FEXT and NEXT crosstalk for the pairs 2 and 4 of the simulated cable and the estimated FEXT magnitude. For simplicity, the frequency points employed in the analysis were omitted.

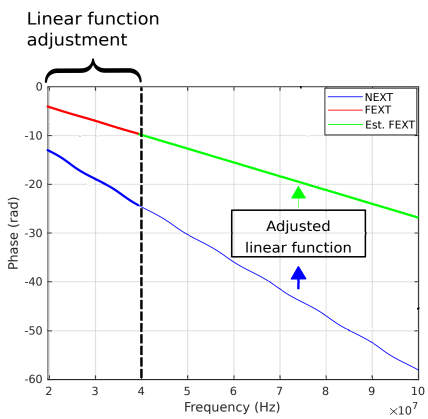

Fig. 4. Phase of the FEXT and NEXT crosstalk for the pairs 2 and 4 of the simulated cable and the estimated FEXT phase. For simplicity, the frequency points employed in the analysis were omitted.

curves of magnitude and phase of IL were generated from RL data. The Figures 5 and 6 show the results, that presented a very good approximation.

B. Tests with measured data

On the following, we present the results obtained for measured crosstalk of a 50m CAT6 cable with cross-section as illustrated in Figure 7. The measured frequency band is from 100 KHz to 212 MHz, with 1601 samples. Like we did with the simulated data the first points with distortions were discarded. We used the band from 13.3 MHz to 49.63 MHz (375 samples) for the linear regression (see Figure 8). The n value used for the magnitude was equivalent to a bandwidth of 8.5 MHz, the same used on the tests of simulated curves.

Figure 9 shows FEXT estimations for the same measurements used in Figure 8. But this time, we use a given upper frequency band as the input of the proposed method, aiming at estimating an arbitrary lower frequency band. The objective here is to demonstrate the potential application of the proposed

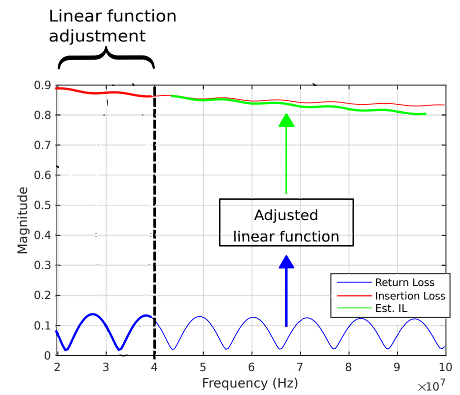

Fig. 5. Magnitude of IL and RL for the pair 1 of the simulated cable and the correspondent magnitude of the estimated IL with $r^2 = 0.9022$. For simplicity, the frequency points employed in the analysis were omitted.

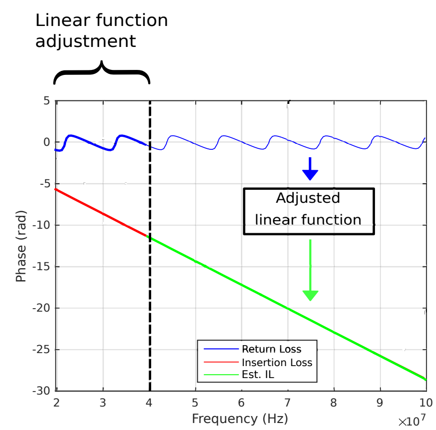

Fig. 6. Phase of IL and RL for the pair 1 of the simulated cable and the correspondent phase of the estimated IL with $r^2 = 0.9998$. For simplicity, the frequency points employed in the analysis were omitted.

Fig. 7. Illustration of the cross-section of the CAT cables used for tests with measurements

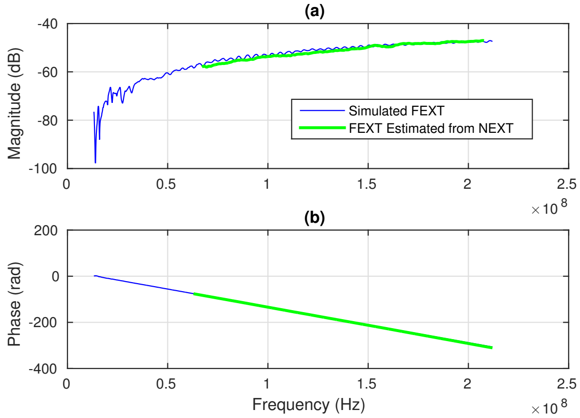

Fig. 8. Measured and estimated FEXT's from pair blue to pair green of the CAT6 cable used in the tests. (a) Magnitude with $r^2 = 0.9147$ for a $n = 65$ (b) Phase with $r^2 = 0.9989$ for a $n = 1$.

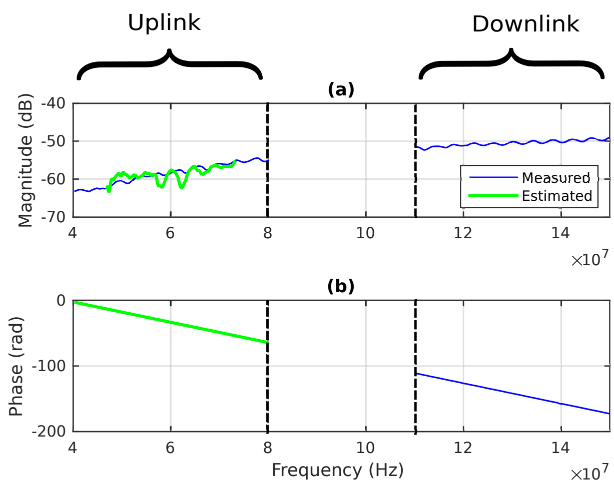

Fig. 9. Measured and estimated FEXT's from pair blue to pair green of the CAT6 cable used in the tests. (a) Magnitude with $r^2 = 0.8736$ for $n = 103$ (approx. 13.5 MHz) (b) Phase with $r^2 = 1.0$ for $n = 1$.

method for radio dot system (RDS) [8]. In this way, the measurements presented above were divided into two bands, one corresponding to the RDS downlink (110-150 MHz) and another corresponding to the uplink (40-80MHz). The downlink was used in the linear regression and the adjusted linear function was used to estimate FEXT at the uplink band. For this test case, the n corresponding to 8.5 MHz could not be used, as done previously. Thus, we had to choose other bandwidth (13.5 MHz) to obtain better results.

C. Comparison between the patents and the proposed method

In [4], one assumes that NEXT and FEXT between an aggressor line and a victim line are related by (4), where H_B is the transfer function of the line (*a priori* knowledge).

$$FEXT_{AB} = NEXT_{AB} H_B \tag{4}$$

Using (4) it is possible to obtain FEXT magnitude and phase with no need of parameters adjustment. However, a measurement procedure using the terminal equipment at both sides of the loop are required to determine H_B beforehand. Another problem is that (4) is inaccurate due to the fact that it assumes that the electromagnetic coupling occurs only at near to the signal source instead of along the loop.

In [5], the magnitude and phase of FEXT can be determined from (5) which assumes the coupling capacitance between pairs A and B along the cable length.

$$FEXT_{AB} = \frac{j\omega}{2} Z_0 |H_b| \sum_{k=0}^{L/\Delta d} C_{AB}(k\Delta d) \tag{5}$$

This patent does not specify a formal procedure to obtain the value and depends on prior knowledge of the characteristic impedance, Z_0, and the line length, L.

[6] presents a method of FEXT estimation using Quiet Line Noise (QLN) measurements. A QLN measurement of a line A, at the upstream frequencies (f_u), is basically composed of two components: The Power Spectral Density (PSD) of the sum of FEXT power from the other adjacent lines near to A and the PSD of the background noise, denoted by N:

$$10^{\frac{QLN_A(f_u)}{10} - 3} = [k|H_A(f_u)|^2 f_u^2] S(f_u) + N \tag{6}$$

The first member of (6) is the measured QLM in line A converted from dBm to Watts. $S(f_u)$ is the mean PSD of the transmitted signals in the adjacent lines of A. The term between brackets represents the power transfer function of the aggregated FEXT in line A, $|FEXT_A(f_d)|^2$, of which the frequency relation is defined by the worst case model presented on [9] and k is a coupling coefficient.

Initially, k and N are estimated using least squares method in (6), performed at the upstream frequencies. The k coefficient is then used in the expression between brackets of (6) to estimate the aggregated FEXT power at the downstream frequencies – $|FEXT_A(f_d)|^2$.

This method is not suitable for techniques of crosstalk mitigation like vectoring [3] because it does not provide the phase of FEXT and cannot calculate the pair-to-pair FEXT, just its worst-case described in the idealized model of [9]. Additionally, it is also necessary to perform dual loop measurements along the whole frequency band to determine the transfer function H_A.

Using the FEXT magnitude data presented at subsection III-B, we compared the crosstalk estimation made for the patented methods [4] and [6] and our proposal. Again, the uplink frequency range for radio dot was used for noise estimation while downlink frequencies were employed in the linear regression adjust, Figure 10. As explained, the patent [5] does not specify a formal procedure to calculate the coupling capacitance between the cables, which makes impossible to estimate the FEXT with this method.

Figure 11 shows another comparison between the proposed method and the patents [4] and [6], where measurements made

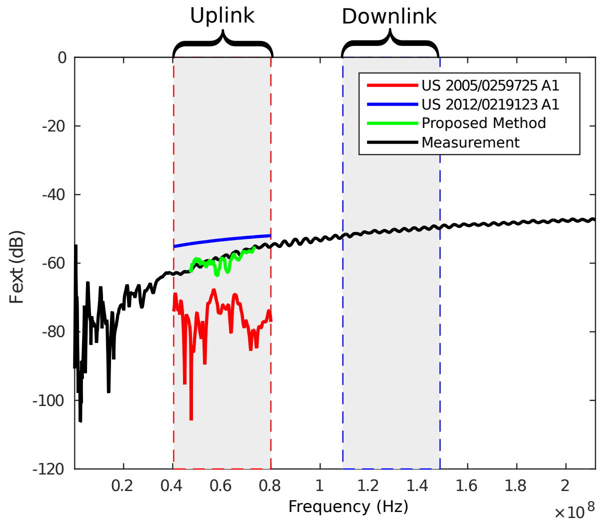

Fig. 10. Comparison between the FEXT estimation using the patents [4] and [6] and the proposed method, using measurements of a 50 meters CAT6.

on a 10 meters CAT5e were used. Different from the results presented in Figure 10, the patents estimation achieved closer results to the measurements. In both cases, we noticed that the proposed method obtained a good approximation of the FEXT magnitude.

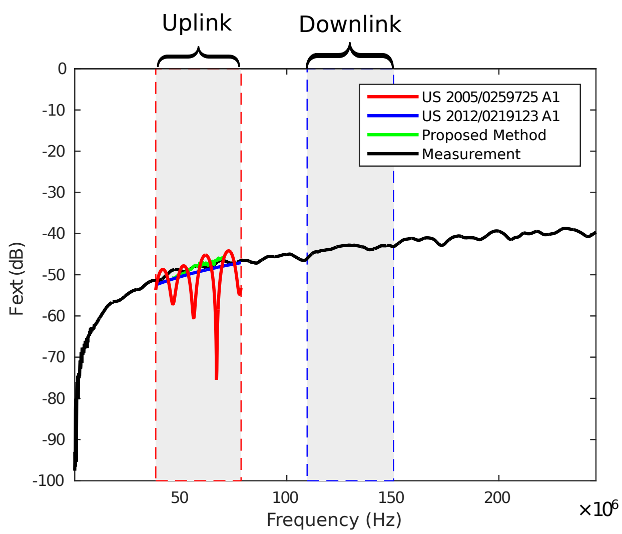

Fig. 11. Comparison between the FEXT estimation using the patents [4] and [6] and the proposed method, using measurements of a 10 meters CAT5e.

IV. Conclusion

The proposed method obtains good estimations of FEXT in both simulated data and measurements of twisted pair cables. It is also possible to estimate IL from RL, reaching high values of r^2, which can not be done with the presented patents.

We note, however, that these patents also provide good estimations of FEXT, as shown in Figure 11. Thus, the advantages of the proposed method are mainly in the fact that it does not require dual ended loop measurements throughout all the frequency range of operation, besides not being specific for FEXT estimations.

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