

# An Empirical Rate Balanced Alien Xtalk Mitigation Method for G.fast Systems

Diego de Azevedo Gomes, Cláudio de Castro Coutinho Filho, João Victor Costa Carmona e Evaldo Pelaes

**Abstract**—The G.fast is the most recently DSL standard released by the ITU. The G.fast deployment environment is very noisy, in which several external interferences may impair the transmission. One of the most problematic interference source is the alien xtalk. Despite the difficult to mitigate this type of interference, there are some mitigation methods that reduce the impact of the alien xtalk over DSL systems. However, these methods present a setback that is to unbalance the transmission rates achieved by the coordinated lines. In this paper we propose an empirical method to achieve rate balancing simultaneously with alien xtalk mitigation. Additionally, we present a set of simulation results performed with cable measurements, that show the effectiveness of our method.

**Index Terms**—G.fast, Alien Crosstalk, Rate Balancing

## I. INTRODUCTION

The demand for higher data rates has taken the transmission rates of the access technologies to the order of the Gbps, such as the G.fast [1]. This technology was standardized by the *International Telecommunication Union*, which aims to achieve 1 Gbps over short copper loops, with a bandwidth of 106 or 212 MHz. Due to this large bandwidth, the G.fast is susceptible to a variety of interferences, both from the coordinated pairs (in-domain crosstalk) as from external sources, in which alien crosstalk (AXT) is one of the most dangerous. The issue of combating the in-domain crosstalk is addressed by the utilization of *Vectoring* techniques, i.e., a set of techniques capable of effectively canceling crosstalk, in order to provide better service quality and data transmission [2].

The term "Vectoring" is used to describe the definitions of the ITU G.Vector standard [3]. The Vectoring techniques have started to be implemented in the commercial networks in some parts of the globe and it will possibly be in focus in the next years.

In the Vectoring field, the Precoder Matrix is one of the most important structures, due to the possibility of surpassing the Far-End-Crosstalk (FEXT), i.e., the crosstalk caused by each line on every other at the far end of the cable. However, as the frequency increases (G.fast works with frequencies up to 200 MHz), the Linear Precoder, or Diagonalizing Precoder (DP), becomes unstable, with the crosstalk channel being even higher than the direct channel [4]. Given the fact that the crosstalk increases with frequency, a simple normalization

method is presented in [5]. The method, however, causes decrease in the system's performance, therefore impacting the final user rates. Similarly, a heuristic approach was proposed in [6]. The presented method was able of reducing the normalization penalty among lines. The so-called rate balancing techniques can also be found in other scenarios [7] [8] [9] given the impact of this situation.

A similar behavior is observed in the AXT mitigation methods, in which the rates of some lines achieve greater rates than other [10], [11], [12]. In [10] and [11], the lines are benefited distinctly due to the *decision feedback* structure, which provides more prediction taps for the last user, thus increasing the AXT mitigation, and, consequently, providing more rates for these lines. Conversely, in [12] the first lines appreciate the higher rates, because in this method the gains of each line are the diagonal elements of the upper-triangular matrix of a QR decomposition [13].

For that matter, this work introduces the rate-balancing methods, or techniques, to reduce the rate unbalancing in the AXT mitigation methods. As their name already attest, these techniques try to balance the bitrates among users (or lines) in the same binder at their Customer Premises Equipments (CPEs), by altering the order in which they are processed at the Central Office (CO). This sorting is able to achieve a good approximation among lines. In this context, a empirical low computational cost method is proposed to define a line order, that minimizes the total bitrate variance of all lines and maximizing the total bitrate sum. This can be a convenient tool for a proper comparison between each method and the optimal achieved results for testing their performance.

The paper is organized as follows. Section II describes the system model adopted in this document. The rate balancing method is presented in Section III. Section IV shows some simulation results of the application of the proposed method. Finally, Section V concludes the paper.

## II. AXT SYSTEM MODEL

In the current DSL infrastructure it is possible to find groups of pairs which are coordinated in at least one of the ends of the cables. This arrangement allows to employ MIMO techniques to combat in-domain crosstalk (crosstalk among the pairs of the same coordinated group), such as the standardized *vectoring* techniques described in [3]. However, this vectored group can share the same environment with pairs of another company. In this scenario, the vectored lines (VLs) are susceptible to suffer the impairment called alien crosstalk (or out-of-domain crosstalk), which is the crosstalk caused by

Diego de Azevedo Gomes, Cláudio de Castro Coutinho Filho, João Victor Carmona, Faculdade de Computação e Engenharia Elétrica, Universidade Federal do Sul e Sudeste do Pará, Marabá-PA, Brasil, E-mails: diagomes@unifesspa.edu.br, claudio.coutinho@unifesspa.edu.br, jvictor@unifesspa.edu.br; Evaldo Pelaes, Programa de Pós-Graduação em Engenharia Elétrica, Universidade Federal do Pará, Belém-PA, Brasil, pelaes@ufpa.br .

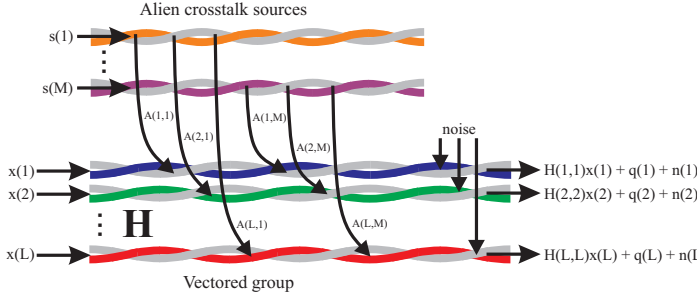


Fig. 1. Complete system with vectored lines and AXT.

lines that are not in the vectored group. Consequently, the total interference observed in the VLs is composed by the AXT and by the background noise (here we do not consider the interference caused by other types of sources, such as RFI, impulsive noise etc.). Figure 1 depicts this scenario, in which a group of  $L$  vectored lines is impaired by the crosstalk caused by  $M$  alien lines (ALs). Assuming that both VLs and ALs use DMT modulation, and that all lines are synchronized (there is no Inter-Carrier Interference - ICI), the received symbols,  $\mathbf{y}_k = [y_{1,k}, \dots, y_{L,k}]^T$ , in each independent  $k$  tone can be modelled by:

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{x}_k + \mathbf{z}_k, \quad k = 1, \dots, N \quad (1)$$

where  $N$  is the DFT length, i.e., the number of tones,  $\mathbf{H}_k$  is a complex  $L \times L$  matrix composed by the direct and in-domain crosstalk channel frequency values at tone  $k$ ,  $\mathbf{x}_k = [x_{1,k}, \dots, x_{L,k}]^T$  is the  $L \times 1$  vector containing the QAM encoded transmit symbols at the  $k$ -th tone and  $\mathbf{z}_k$  is an  $L \times 1$  vector corresponding to both additive white Gaussian (AWG) noise and AXT at the  $k$ -th tone, that is:

$$\mathbf{z}_k = \mathbf{q}_k + \mathbf{n}_k, \quad (2)$$

where  $\mathbf{q}_k = [q_{1,k}, \dots, q_{L,k}]^T$  and  $\mathbf{n}_k = [n_{1,k}, \dots, n_{L,k}]^T$  are the vectors corresponding to AXT and background noise, respectively. In Eq. 2,  $\mathbf{q}_k$  is obtained by the multiplication  $\mathbf{A}_k \mathbf{s}_k$ , where  $\mathbf{A}_k$  is a  $L \times M$  matrix with the coupling channels from the alien lines to the vectored lines, and  $\mathbf{s}_k$  is a  $L \times 1$  vector with the signals transmitted by the alien lines. In order to simplify the notation, the subscript  $k$  will be omitted in the following equations.

### III. RATE BALANCING FOR AXT MITIGATION

The majority of the multiline AXT mitigation methods are based on steps in which the decoding is carried out iteratively, in which the next lines (here we assume that the lines are organized in some order) need the information of previous lines to be decoded [10], [11], [12]. This structure allows the lines to share information and then the process is boosted. Nevertheless, this processing form causes the last lines to be more benefited from the mitigation. A consequence of this strategy is that the last lines achieve the greater rates, and the system, in a overall view, becomes unbalanced. Thus, we present here a strategy to make the AXT mitigation method to yield similar rates across the coordinated lines. We will take as basis the work presented in [12] (which we will call DFC),

because it needs processing only at the receiver, and then it can be applied in standard DSL applications. The DFC works as follows. In the training phase [1] the spatial correlation matrix of the total interference is computed as:

$$\mathbf{R}_{zz} = E[\mathbf{z}\mathbf{z}^H] \quad (3)$$

where the operator  $E[\cdot]$  denotes statistical expectation, and the overscript  $^H$  indicates transposing and conjugation. The spatial correlation matrix provides information to calculate the decorrelation matrix (or whitening matrix), which will remove the colored part of the interference

$$\mathbf{W} = \mathbf{R}_{zz}^{-1/2} \quad (4)$$

In the *showtime* transmission phase, the whitening matrix is used for multiplying the received symbols, as follows:

$$\begin{aligned} \tilde{\mathbf{y}} &= \mathbf{W}\mathbf{y} \\ &= \mathbf{W}\mathbf{H}\mathbf{x} + \tilde{\mathbf{z}} \end{aligned} \quad (5)$$

where  $\tilde{\mathbf{z}} = \mathbf{W}\mathbf{z}$ . This operation turns the correlation matrix of the interference into an identity matrix  $\mathbf{I}$ . However, the channel matrix has lost the column-wise diagonal dominance (CWDD). To overcome this problem, we compute the QR decomposition of the resulting matrix  $\mathbf{W}\mathbf{H}$  as

$$\mathbf{W}\mathbf{H} = \mathbf{Q}\mathbf{R} \quad (6)$$

where  $\mathbf{Q}$  is a  $L \times L$  unitary matrix, and  $\mathbf{R}$  is a  $L \times L$  upper-triangular matrix. Then, multiplying the Eq. 5 by  $\mathbf{Q}^H$ , we get

$$\begin{aligned} \hat{\mathbf{y}} &= \mathbf{Q}^H \tilde{\mathbf{y}} \\ &= \mathbf{R}\mathbf{x} + \mathbf{Q}^H \tilde{\mathbf{z}} \end{aligned} \quad (7)$$

. This operation allows the received signal to be decoded in a *successive interference cancellation* fashion [12]. Additionally, it does not change the power of the remaining interference since  $\mathbf{Q}^H$  is unitary.

This method unbalances the rates across the lines, because the gain of each line becomes the diagonal of the  $\mathbf{R}$  matrix, which contains decreasing values. Then, we propose the following strategy to balance the rates, which we call *ordered line permutation* (OLP). In the OLP, the decoding order of the lines is changed across the tones, in order to allow each line to get the advantage of being the first line (and having the greatest value of the diagonal of the  $\mathbf{R}$  matrix as its channel gain). For example, let us assume a G.fast system with 3 lines  $a$ ,  $b$  and  $c$ . At tone  $k$  we assume the order  $a$ ,  $b$  and  $c$ , in which the line  $a$  will get the greatest AXT cancellation; at tone  $k+1$  we change the line order to  $b$ ,  $c$  and  $a$ , in which line  $b$  will appreciate the best AXT cancelling; at tone  $k+2$  the order will be  $c$ ,  $a$  and  $b$ , and so on. This strategy is possible due to the transmission (and processing) independence among tones, and because the physical way in which the twisted pairs are plugged in the DSLAMs of the *Central Office* do not define the way in which the data streams will be processed.

### IV. RESULTS

In this section we present the results of the proposed method in comparison to the traditional use of the AXT mitigation method. In the simulations we used a program

TABLE I  
SIMULATION PARAMETERS.

| Parameter            | Value       |
|----------------------|-------------|
| Bandwidth            | 106 MHz     |
| Number of Tones      | 4096        |
| Tx PSD               | -76 dBm/Hz  |
| Background Noise PSD | -150 dBm/Hz |
| SINR Gap             | 9.75 dB     |
| Noise Margin         | 6 dB        |

developed in MatLab, which takes the impulse response of the channels to perform time domain simulations. Table I shows the parameters used in the simulations.

The data relative to the channels were obtained from measurements of 2 standard cables found in DSL deployments, and with a CAT5 cable impaired by other CAT5. One cable has 16 twisted pairs (C16) and was 200 m long. The other standard cable has 8 twisted pairs (C8), 100 m long. The CAT5 cables were 50 m long, representing a specific deployment, developed to achieve high bitrates.

In simulations we assumed very noisy scenarios, in which the number of alien lines was equal to the number of the vectored lines, to represent a situation in which the rates tend to be very unbalanced [14]. Thus, in simulations with the cable with 16 twisted pairs, 8 twisted pairs were used as the vectored lines and the other 8 were assumed to be the AXT sources. Similarly, when the simulations were fed by the cable with 8 twisted pairs, 4 lines were the vectored group, and the remaining ones were used as AXT lines. In simulations with CAT5, all the 4 pairs of a cable were assumed to be the vectored group, and the pairs of the other cable were the alien lines.

The evaluation was defined in a way in which we can observe the gain of the use of AXT mitigation, against a system that employs only in-domain crosstalk mitigation (vectoring). Additionally, the evaluation allows to compare the OLP with the traditional AXT mitigation method [12]. Table II summarizes the simulations results. Note that clearly the use of AXT mitigation method improves the overall performance of the system, observed by the increase in the aggregate rate (sum of the rates across the vectored lines) when AXT mitigation is active. For example, in simulations with the cable with 16 twisted pairs, the AXT mitigation has increased the aggregate rate in approximately 40 %. In this table one can also observe the high range of values in the column referent to traditional AXT mitigation, in which in simulations with C16 we have observed rate variations from 97.91 Mbps up to 145.81 Mbps, from 209.3 up to 354.11 in the simulations with C8, and from 317.08 up to 673.36 in the results for CAT5. In the former the standard deviation is approximately 21 Mbps, in the second the standard deviation is around 65 Mbps, and in the CAT5, 152.43 Mbps. Nevertheless, when the proposed method was employed, this standard deviation have passed to 1.96 Mbps, 2.17 Mbps, and 54.98, respectively, confirming the efficiency of the proposed method on balancing the rates. In spite of the method having achieved a considerable reduction in the bitrate's variance, the standard deviation in the CAT5 kept a great value, due to the great transmission rate achieved by the

TABLE II  
RATE ACHIEVED (IN MBPS) IN THE UPLINK DIRECTION BY EACH VECTORED LINE IN 2 DISTINCT CABLES IN SCENARIOS WITH AXT. *Vectoring* DENOTES THE SITUATION IN WHICH ONLY VECTORING IS EMPLOYED; *AXT mitigation* INDICATES THAT TRADITIONAL AXT MITIGATION WAS USED; AND, *AXT rate balancing* REFERS TO AXT MITIGATION WITH RATE BALANCING.

| Cable with 16 twisted pairs - 200 m |           |                |         |
|-------------------------------------|-----------|----------------|---------|
| Line                                | Vectoring | AXT mitigation | OLP     |
| a                                   | 91.36     | 91.38          | 121.44  |
| b                                   | 93.32     | 106.36         | 122.22  |
| c                                   | 111.81    | 145.81         | 124.10  |
| d                                   | 92.91     | 118.81         | 118.96  |
| e                                   | 97.58     | 142.74         | 121.49  |
| f                                   | 83.23     | 142.54         | 125.33  |
| g                                   | 57.51     | 97.91          | 123.63  |
| h                                   | 74.97     | 131.28         | 121.90  |
| aggregate rate                      | 702.67    | 976.81         | 979.06  |
| standard dev.                       | 16.23     | 21.64          | 1.96    |
| Cable with 8 twisted pairs - 100 m  |           |                |         |
| a                                   | 248.6     | 248.275        | 260.42  |
| b                                   | 297.68    | 354.11         | 260.795 |
| c                                   | 177.265   | 223.51         | 257.055 |
| d                                   | 166.075   | 209.03         | 256.68  |
| aggregate rate                      | 889.62    | 1034.925       | 1034.95 |
| standard dev.                       | 62.08     | 65.61          | 2.17    |
| CAT5 cable - 100 m                  |           |                |         |
| a                                   | 537.03    | 673.36         | 475.81  |
| b                                   | 241.19    | 317.08         | 484.57  |
| c                                   | 420.23    | 436.79         | 591.39  |
| d                                   | 548.23    | 548.48         | 484.82  |
| aggregate rate                      | 1746.68   | 1975.71        | 2036.59 |
| standard dev.                       | 142.59    | 152.43         | 54.98   |

line *c* when compared to the other ones. This fact is supported because, in general, the AXT channel to the line *a* is weaker than in the other one. Additionally, we can observe a increase in the rates across the scenarios, which is attributed, mainly, to the cable length reduction, that allows higher transmission rates.

We can also note in Table II that the rate of some lines was increased considerably with the OLP method when compared to the standard AXT mitigation method. For example, in simulations with the C16 the rate of the line *g* was increased approximately 22 %, and line *b* of the CAT5 simulations has experienced a rate improvement of around 35 %. In order to have a better view of the balance improvement provided by the proposed method, we have plotted the rates of lines from C16 and C8 in Figure 2 and Figure 3, respectively.

The transmission rates showed in Table II seem to be higher for the current consumption demand, and one could argue that the rate gained by the rate balancing is not significant due to the high value of the original transmission rate. However, this technique can, for example, supply a Wifi Network of a cafe, a hotel or a restaurant [15]. In these environments the transmission rate of the Internet access must be suitable to accommodate the many clients using online multimedia services, such as video conference. In the other hand, there are studies [16] that expect a fast growing in the number of equipments connected to the Internet (*Internet of Things* [17], for example), in which a balanced access network can provide a similar experience for all the subscribers. Additionally, this rate equilibrium allows the telecommunications companies to deliver similar service packages for the consumers, and to

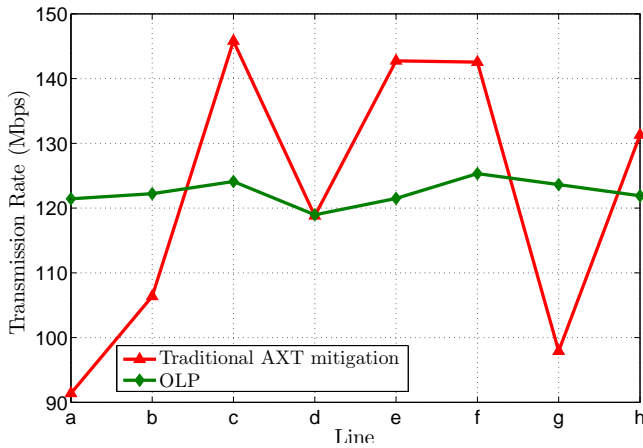


Fig. 2. Comparison of transmission rate achieved by each line with traditional AXT mitigation method and with OLP in the scenario with C16 cable.

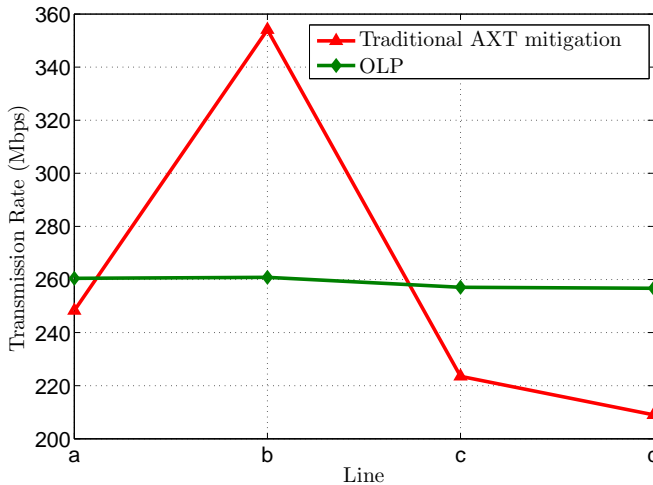


Fig. 3. Comparison of transmission rate achieved by each line with traditional AXT mitigation method and with OLP in the scenario with C8 cable.

provide the rates necessary for the current and future online services.

## V. CONCLUSIONS

This document has presented an empirical method to achieve rate balancing when alien xtalk mitigation is applied in G.fast systems (OLP). The OLP is quite simple and does not have an exhaustive phase for the search of the optimal users order. The OLP is applied in a tone perspective, in which the position of the lines in the decoding is regularly altered. The simulations results have shown good standard deviation reduction in the transmission rates through the coordinated lines, in which measurements of the standard DSL cables were used. For example, in a scenario with 4 lines, the standard deviation was reduced from 65 Mbps to 2.1 Mbps. Future works include the comparison of the OLP with the state of the art rate-balancing algorithms and an evaluation of the effect of the rate balancing in the QoE of the users.

## REFERENCES

- [1] ITU-T, "Fast access to subscriber terminals (G.fast) - physical layer specification," Rec. G. 9700-2014, International Telecommunication Union, May 2014.
- [2] Redouane Zidane, Sean Huberman, Christopher Leung, and Tho Le-Ngoc, "Vectored DSL: Benefits and Challenges for Service Providers," *IEEE Communications Magazine*, Feb. 2013.
- [3] ITU-T Rec. G.993.5-2010, "Self-FEXT cancellation (vectoring) for use with VDSL2 transceivers," 2010.
- [4] British Telecom, "G.fast: Release of BT cable measurements for use in simulations," Geneva, Switzerland: Contribution ITU-T 2013-01-Q4-066, 2013.
- [5] Raphael Cendrillon, George Ginis, Etienne Van den Bogaert, and Marc Moonen, "A near-optimal linear crosstalk precoder for downstream VDSL," *Communications, IEEE Transactions on*, vol. 55, no. 5, pp. 860–863, 2007.
- [6] Alcatel-Lucent, "G.fast: Comparison of linear and non-linear precoding," Geneva, Switzerland: Contribution ITU-T 2013-01-Q4-046, 2013.
- [7] C. Hellings and W. Utschick, "Energy-efficient rate balancing in vector broadcast channels with linear transceivers," in *2012 International Symposium on Wireless Communication Systems (ISWCS)*, Aug 2012, pp. 1044–1048.
- [8] A. Tarighati and J. Jalden, "Optimality of rate balancing in wireless sensor networks," *IEEE Transactions on Signal Processing*, vol. PP, no. 99, pp. 1–1, 2016.
- [9] N. Li, X. Tao, Q. Cui, J. Bai, and Y. Hu, "Secrecy rate balancing for the downlink multiuser miso system with independent confidential messages," in *2014 IEEE Wireless Communications and Networking Conference (WCNC)*, April 2014, pp. 2173–2177.
- [10] George Ginis and Chia-Ning Peng, "Alien crosstalk cancellation for multipair digital subscriber line systems," *Applied Signal Processing, EURASIP Journal on*, vol. 2006, pp. 1–12, 2006.
- [11] Aditya Awasthi, Naofal Al-Dhahir, Oren E. Eliezer, and Poras T. Balsara, "Alien crosstalk mitigation in vectored DSL systems for backhaul applications," *IEEE International Conference on Communications*, pp. 3852 – 3856, 2012.
- [12] Ahmad Al Amayreh, Jrme Le Masson, Maryline Hlard, and Meryem Ouzzif, "Alien crosstalk elimination in digital subscriber line systems," *IET Communications*, pp. 1714 – 1723, 2014.
- [13] Gilbert Strang, *Introduction to Applied Mathematics*, Wellesley-Cambridge Press, 1 edition, 1986.
- [14] Diego de Azevedo Gomes, Igor Freire, Aldebaro Klautau, and Evaldo Pelaes, "Feasibility of alien crosstalk mitigation with receiver-side MIMO processing on G.fast systems," *2015 International Workshop on Telecommunications*, Jun. 2015.
- [15] Zaware Shah, Siddarth Rau, and Adeel Baig, "Throughput comparison of ieee 802.11ac and ieee 802.11n in an indoor environment with interference," *International Telecommunication Networks and Applications Conference*, pp. 196–201, Nov. 2015.
- [16] Ericsson, "ERICSSON MOBILITY REPORT," Tech. Rep., 2015.
- [17] Lu Tan and Neng Wang, "Future internet: The internet of things," *3rd International Conference on Advanced Computer Theory and Engineering (ICACTE)*, pp. 376–380, Aug. 2010.