Improving PLC to DSL Interference Mitigation Methods by Considering Mode Conversion Effects

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Abstract— **The DSL technologies are expected to face many interferences in conventional deployments, such as RFI. One way to mitigate the destructive effects of RFI is to use the correlation between the RFI observed in differential mode and the RFI observed in common mode. This strategy is considered in many works found in the literature. However, they do not show how to overcome the impairments caused by the signal that leaks from differential to common mode (mode conversion), which causes considerable performance decrease. The work presented here shows how to overcome the conversion mode impairment, through a simple adjust in the current common mode based PLC mitigation methods. Additionally, we show the impact of the mode conversion in the conventional methods, and the SINR improvement achieved by our method.**

Keywords— **Digital Subscriber Line, Mode Conversion, Common Mode, Power Line Communication, Interference Mitigation**

I. INTRODUCTION

The environment of transmission of the DSL systems has lot of interferences sources, which can be rougly classified as Radio Frequency Interference (RFI), impulsive noise, thermal noise and crosstalk. The RFI impacts severely the DSL (Digital Subscriber Line) transmissions because the twisted pair acts like an antenna and pick ups some radio signals. A strategy to mitigate the damaging effects of this interference is to use differential mode signalling, which is the transmission mode that employs two conductors to transmit symmetric parcels of a signal [1], [2]. However, due to line imperfect balance [3], the signals coming from external transmissions couple in the *common mode* (CM), and then leaks to *differential mode* (DM). Another way to overcome the effects of the RFI is to use the correlation between the interference signals at CM and DM, to cancel the interference at DM through a filter structure. These methods assume that the DSL channel varies slowly, which is a reasonable assumption for wireline channels [4].

The work in [5] has presented a experiment in which a HAM (Amateur Radio) transmitter positioned 10 m distant from a twisted pair causes a interference that is observed both in CM and DM. The results has indicated that the correlation, in time domain, between the RFI observed in CM and in DM are strongly correlated, and that the information in CM could be used to combat the RFI in DM. In [6] a method to mitigate the narrowband RFI is proposed. It has developed a strategy based on the use of an adaptive filter tap obtained from a *recursive least squares* (RLS) algorithm to the signal taken from CM in order to estimate the RFI in DM. The results has shown suppression of up to 50 dB of RFI caused by HAM transmission.

A common mode based method to cancel RFI in VDSL (Very-high-bit-rate Digital Subscriber Line) systems is presented in [7]. It uses a wideband adaptive filter derived from a least-mean-squares (LMS) algorithm to estimate the RFI in DM based on CM information. The simulations showed a reduction in the order of 15-20 dB in the RFI caused by AM radio transmission.

In [3] the CM signal is used as reference to a time domain adaptive (NLMS) wideband crosstalk canceller to reduce the effect of the crosstalk on the DM signal in ADSL (Asymmetric Digital Subscriber Line). The simulation results has shown significant improvement in the bit error rate (BER). To complement the previous method, the work in [8] has presented a simple model for DM to CM and CM to DM leakage. Simulations of a FDD-ADSL (frequency-division duplex ADSL) link with FEXT (far end crosstalk) from a short link have shown the potential of the proposed canceller, which have improved the SNR in up to 15 dB.

In [9] is presented an evaluation of the performance of three strategies to cancel the crosstalk in DM based on the information in CM. It concludes that the best way is to use an adaptive canceller (LMS or RLS based), which is trained when the transmitter is silent, because the mode conversion form DM to CM can interfere in the correct convergence values of the filter. The effectiveness of the previous method is reinforced in [10], in which the performance of the wideband adaptive cancellation filter was evaluated in scenarios with VDSL transmissions. In [11], the adaptive canceller is applied in a tone based way, in scenarios with equal-length FEXT and near-far FEXT. The performance of the mitigation is compared for situations with varying numbers of FEXT sources.

The predictors derived from Wiener filter are common in the literature. Nevertheless, there is another strategy to set this filter, as exposed in [12], [13], which defines the filter based on the ratio between the RFI observed at DM and CM. In these works is shown that the mitigation process achieves almost the single line performance in scenarios with only one active *power line communication* (PLC) transmitter at time [16].

The previous papers have investigated the use of the CM as reference to mitigate interference, but they do not show to treat the mode conversion (MC) [14] from DM to CM, which is the portion of the DM that leaks to CM. The MC signal is a spurious signal in the CM based mitigation process, because it

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sum itself with the target interference in CM, and consequently the filter derived from this situation will be trained incorrectly. The work in [3] has indicated the presence of the MC as an impairment, but it only neglects its impacts due to MC to be weaker than interferences in CM. However, the works in [8], [9], [11] assign the MC as limiting factor to CM based interference mitigation methods. The investigation of how to reduce the impacts of the MC in the CM based methods is important due to growing of the of the bandwidth used in xDSL systems, because in high frequencies the DSL signals become to be impaired by many radio services and the MC tends to become more intense [14].

In this text, we propose a method to reduce the effect of the leaked signals from the DM to CM, applied to the work presented in [13], due it to be the the more recent method to mitigate RFI based in the CM information presented in the literature. The evaluation will be performed over G.fast transmissions [15].

The Section II describes the modelling of the problem, and addresses the MC omitting in the [13]. Section III quantifies the effect of the MC in the work in [13]. In the Section IV we present a method to overcome the effect of the MC. The Section V presents the simulation results. Finally, Section VI shows the conclusions of this work.

II. STANDARD MODEL FOR COMMON-MODE BASED RFI MITIGATION

The model presented in [13] was developed in the frequency domain, in which a RFI source, specifically PLC, generates a interference that impairs the DSL transmission. Below we have the equation which represents the model

$$\begin{bmatrix} y_d \\ y_c \end{bmatrix} = \begin{bmatrix} H_{dd} \\ 0 \end{bmatrix} x_d + \begin{bmatrix} A_d \\ A_c \end{bmatrix} z + \begin{bmatrix} n_d \\ n_c \end{bmatrix} \tag{1}$$

where y_d and y_c are the received signal in the DSL system in differential mode (DM) and common mode (CM), respectively. H_{dd} denotes the transfer function of the DM channel, x_d is the transmitted signal in the DM, A_d and A_c are the coupling channel from the PLC source to the DM and the CM of the twisted pair, respectively, z is the transmitted signal in the PLC system, and, n_d and n_c are the background noise in the DM and CM, respectively. The formulation above shows that this modelling considers that the received signal in the CM of the DSL system is composed by the thermal noise and by the interference generated by PLC. From now, we will assume that $u_d = A_d z$, $r_d = u_d + n_d$, $u_c = A_c z$ and $r_c = u_c + n_c$.

The RFI mitigation method exhibited in [13] uses the PLC interference in CM, u_c, to estimate the interference in DM, u_d. This method is called *frequency domain interference canceller* (FDIC), and in its training phase it calculates a factor which relates the u_c and u_d. This factor, C_F, is calculated by

$$C_F = \frac{1}{K} \sum_{k=1}^{K} \frac{r_d}{r_c} \tag{2}$$

where K is the number of realizations used to estimate C_F. In the Eq. 2 is used r_d and r_c instead u_c and u_d to find a relation between RFI portions, beacuse is not possible to exclude the background noise in the signal aquisitions. Note that the factor is calculated by the simple ratio between the interferences in DM and CM. However, this strategy is developed to work in scenarios with only one interferer, as highlighted by [13]. In this scenario with a single interference source, a simple ratio can be used to find a predictor to u_d based in u_c, $\tilde{u}_d = C_F u_c$ (the tilde $\tilde{u}_d$ represented the estimated value of u_d). After we have C_F, we can use, in showtime, the following equation to mitigate the interference in DM

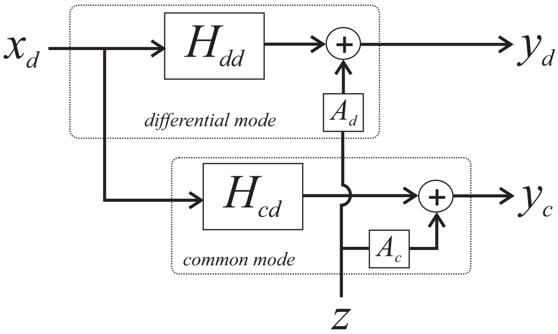

Fig. 1. Block diagram for the adjusted model.

$$\begin{aligned} \bar{y}_d &= y_d - C_F y_c \\ &= H_{dd} x_d + u_d + n_d - \tilde{u}_d \\ &= H_{dd} x_d + n_d + e \end{aligned} \tag{3}$$

where e is the error in the estimation of u_d, which is related with the number of realization to estimate the factor C_F and due to the background noise in the CM. In [13] is presented a performance evaluation in which it shows that this method achieve great interference reduction in DM.

The model above omits the mode conversion from DM to CM, i.e., the leakage of the signal from the DM to CM, $H_{cd} x_d$. Updating the model in the Eq. 1 to consider the mode conversion, we get the system in the Fig.1. The adjusted math model becomes

$$\begin{bmatrix} y_d \\ y_c \end{bmatrix} = \begin{bmatrix} H_{dd} \\ H_{cd} \end{bmatrix} x_d + \begin{bmatrix} A_d \\ A_c \end{bmatrix} z + \begin{bmatrix} n_d \\ n_c \end{bmatrix} \tag{4}$$

which now tell us that in the received signal y_c we have, beyond the background noise and the PLC interference, the parcel $H_{cd} x_d$.

The parcel $H_{cd} x_d$ represents an extra impairment in the u_c estimation at the DSL systems which use the interference in CM to estimate the interference in DM. In fact, the portion $H_{cd} x_d$ can be considered as noise in the estimation. The impact of the power noise level in the performance of the mitigation method was well evaluated in the [12], which has reported a performance degradation with the increase of the noise level. In the current situation, the total impairment caused by the MC at DM is equal to the MC parcel at CM multiplied by the FDIC factor, $C_F H_{cd} x_d$.

III. EVALUATION OF THE IMPACT OF THE CM IN THE MSE

The *mean equare error* (MSE) is a measure of how much the estimative $\tilde{u}_d$ is distant from the true value u_d. In this works we will define the MSE as the difference between u_d

and $\tilde{u}_d$, $e = u_d - \tilde{u}_d$. Then the MSE is calculated as $MSE = E[ee^*]$, where $E[.]$ denotes expectation. In order to evaluate the impact of the MC in the MSE, we will first to calculate the MSE without to consider the MC, and after we will address the MC in the MSE. Without the MC effect, we get for the MSE

$$\begin{aligned} MSE = {} & \epsilon_p |A_d|^2 - \epsilon_p C^* A_d A_c^* - \epsilon_p C A_d^* A_c \\ & + \epsilon_p |C|^2 |A_c|^2 + \sigma_c^2 |C|^2 \end{aligned} \quad (5)$$

where ϵ_p is the power of the RFI source and σ_c^2 is the power of the background noise in the CM. Now, if we consider the MC in the model, the MSE becomes

$$\begin{aligned} MSE_{MC} = {} & \epsilon_p |A_d|^2 - \epsilon_p C^* A_d A_c^* - \epsilon_p C A_d^* A_c \\ & + \epsilon_p |C|^2 |A_c|^2 + \sigma^2 |C|^2 + \epsilon_x |C|^2 |H_{cd}|^2 \end{aligned}$$

where ϵ_x is the PSD of the transmitted signal at DM.

IV. PROPOSED MC-BASED RFI MITIGATING ALGORITHM - ICMCR

In this section we present a method that reduces the effect of the MC in the interference cancellation, which we called *interference cancelation with mode convertion reduction* (ICMCR). We can apply processing only at receiver to reduce the impact of the MC. In this perspective we apply the FDIC tap-coefficient as indicate in [13]:

$$\begin{aligned} \hat{y}_c &= C_F y_c \\ &= C_F h_{cd} x_d + C_F u_c + C_F n_c \\ &= C_F h_{cd} x_d + u_d + e + \tilde{n}_c \end{aligned} \quad (6)$$

Nevertheless, in DM, we will change the decoding, because now the total portions composing the received signal in this mode are

$$\begin{aligned} \bar{y}_d &= y_d - \hat{y}_c \\ &= H_{dd} x_d + u_d + n_d - C_F H_{cd} x_d - u_d - e - \tilde{n}_c \\ &= (H_{dd} - C_F H_{cd}) x_d + n_d - e - \tilde{n}_c \end{aligned} \quad (7)$$

Then, instead to decode the signal using the standard frequency equalizer (FEQ) $1/H_{dd}$, we use a updated FEQ which takes account the conversion mode, $1/(H_{dd} - C_F H_{cd})$.

V. RESULTS

In this section we present the results that were achieved with simulation in Matlab, using transfers functions obtained in the Computer Simulation Technology (CST). These simulations were configured to represent scenarios in which a G.fast transmission was impaired by one PLC interferer. We have simulated 2 scenarios in the CST, with a 50 m long twisted pair, distant 1.5 m from a power line, also 50 m long, in order to represent interference from PLC to DSL. However, in one scenario the twisted pair was equivalent to a pair from a CAT5 cable, and in the second one the twisted pair was equivalent to a CAT6 one. The transfer functions calculate were: the DM direct channels, the mode conversion from DM to CM, and the coupling channel from the power line to the DM and to the CM of the twisted pairs. The transfer function obtained for these 2 twisted pairs differs mainly by the magnitude of the coupling and MC channels, but the direct channels are similar. The Fig. 2 shows a comparison between the MC in both pairs. We can note that the MC in the CAT5 is, in general, more intense than in the CAT6, reaching differences up to 15 dB. The Table I contains some parameters used in the CST and in the simulations to evaluate the performance of the RFI mitigation methods, which were based on [15], [16].

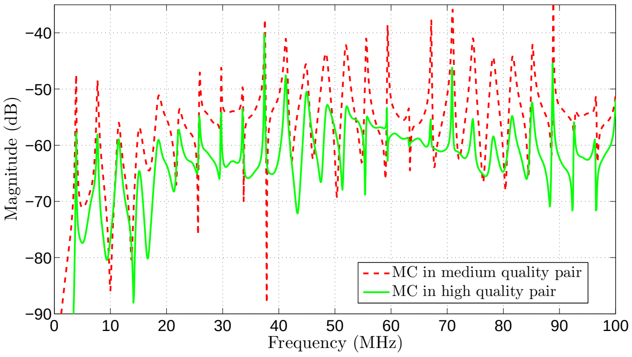

Fig. 2. Comparison between the MC in the CAT5 and CAT6 pair.

TABLE I

SIMULATION PARAMETERS.

Parameter	Value
DSL Bandwidth	106 MHz
DSL Number of Tones	2048
DSL Tx PSD	-76 dBm/Hz
Background Noise PSD	-140 dBm/Hz
DSL SINR Gap	9.75 dB
DSL Noise Margin	6 dB
PLC Tx PSD	-50 dBm/Hz

The Fig. 3 and the Fig. 4 show a comparison between the SINRs (Signal-to-interference-plus-noise ratio) achieved in the scenarios with CAT5 and CAT6 cables, respectively. In these figures *SNR single line* denotes the situation in which the *additive white gaussian noise* (AWGN) is the only impairment, *SNR AWGN + PLC* is the case in which the DSL transmission is impaired by AWGN and PLC, *SNR ICMCR* represents the performance of the our method, and *SNR MC FDIC* represents the performance of the FDIC method, *Error Due MC* is the power of the parcel $C_F H_{cd} x_d$, *PLC coupling at DM* denotes the power of the PLC signal at DM, and the blue doted curve denotes the level of the background noise. The 3 last curves (*Error Due MC*, *PLC coupling at DM* and *Background Noise Level*) were elevated by 60 dBs in order to reduce the vertical spread of the plots, meaning that the background noise level, which is plotted at -80 dBs, in the reality is at -140 dBs. Comparing these two figures we can clearly note the great magnitude of the interference of the PLC in the CAT5 when compared to CAT6, which is an expected result due to high quality of the CAT6 cable. Consequently, the SINRs achieved in the CAT6 scenarios are bigger than ones observed in the scenario with CAT5. We also can note the superiority performance of the ICMCR when compared

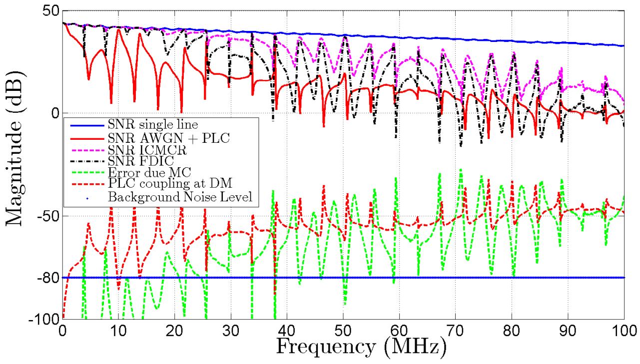

Fig. 3. Comparison among the SINR achieved in the scenario with the CAT5 cable. Beyond the SINRs: no RFI (AWGN), with RFI but with no mitigation (AWGN+RFI), FDIC mitigation and the ICMCR, also are depicted levels of interference and the error due to MC.

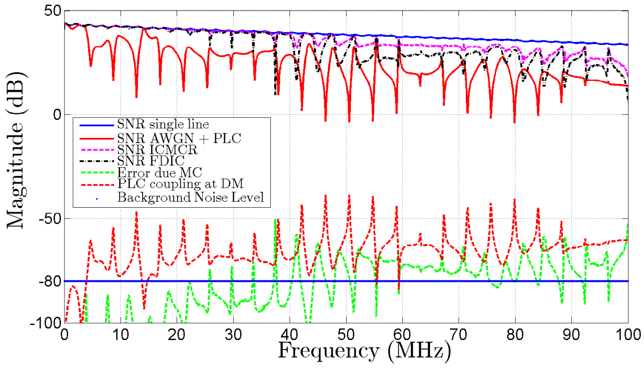

Fig. 4. Comparison among the SINR achieved in the scenario with the CAT6 cable. Beyond the SINRs: no RFI (AWGN), with RFI but with no mitigation (AWGN+RFI), FDIC mitigation and the ICMCR, also are depicted levels of interference and the error due to MC.

to FDIC, which in many tones presents SINRs more than 10 dBs higher than SINRs achieved by FDIC. These tones in which the FDIC is inferior are those ones in which the magnitude of $C_F H_{cd} x_d$ is higher than background noise level. This means that the MC impacts in the FDIC performance when its level becomes big when compared to noise floor. Additionally, we note that in some tones the performance of the FDIC is worst than in the situation with no mitigation (*SNR AWGN + PLC*). This happens when the power of $C_F H_{cd} x_d$ is higher than PLC interference at DM. This can be explained by the fact that MC is not combated by FDIC, and in the situations in which $C_F H_{cd} x_d$ is very strong, the FDIC creates an interference stronger than the first target of the method, PLC at DM. The Table II summarizes the rates achieved in the both scenarios. Clearly the rates achieved in the CAT6 scenarios were higher than in the CAT5 one, mainly due to the high SINR presented in the former case. We can also note, the rate gain of the ICMCR over FDIC, which has increased the rate in approximately 25 % in the CAT5 scenario, and 8 % in the CAT6 scenario. This indicates that the ICMCR can improve the transmission rate mainly in the transmissions with low quality cables, which tend to present high MC.

TABLE II

TRANSMISSION RATES (MBPS).

Transmission	CAT5	CAT6
Single Line	1042	1047
AWGN + PLC	409	696
ICMCR	790	977
FDIC	594	899

VI. CONCLUSIONS

The present work has presented a method to overcome the impairments caused by mode conversion from differential mode to common mode, in common mode based PLC mitigation methods in G.fast systems. The our method (ICMCR) considers the mode conversion portion at received signal in the common mode, and to overcome its effect, adjusts the FEQ at differential mode. The results have shown that when we consider the mode conversion, the traditional methods have their SINR decreased, because they do not have been developed to face this additional signal in mitigation process. The simulations showed that the ICMCR considerably increases the SINR when compared with the RFI mitigation method FDIC, in scenarios in which the RFI is caused by a single line PLC. These results were obtained using simulated transfer function, which were calculated in the CST. The future works include the use of measured transfer functions.

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