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MMSE-based Partial Crosstalk Cancellation for Upstream VDSL[1]

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Abstract

In current DSL systems, crosstalk is a major problem. In the case of in-domain crosstalk and AWGN, it has been shown that the crosstalk can be effectively mitigated using a linear zero-forcing canceler. Furthermore, the complexity can be reduced by only canceling the crosstalk from major crosstalkers on each tone, which is reffered to as partial cancellation. However, such approach does not work e.g. in the case of alien crosstalk. As alien crosstalk is spatially correlated, the zero-forcing canceler performs very poorly, hence an alternative linear canceler has to be examined. In this paper, we demonstrate that an MMSE crosstalk canceler provides much improved performance than the zero-forcing canceler in this scenario and additionally, we also present an efficient algorithm to perform partial MMSE partial cancellation.

MMSE-based Partial Crosstalk Cancellation for Upstream VDSL

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***Index Terms*—DSL, interference cancellation, partial crosstalk cancellation, LMMSE, Alien crosstalk**

I. Introduction

To meet the demand for higher data rates, recent DSL systems use higher frequencies, e.g. up to 30 MHz [1]. At these frequencies, it has been shown that in-domain as well as out-of-domain (alien) crosstalk between different DSL lines in the same bundle becomes the dominant source of interference, limiting the performance of the DSL systems.

Crosstalk cancellation is one way to mitigate the effect of crosstalk. Several crosstalk cancellation techniques have been proposed in [2] [3] [4] [5] [6]. Different techniques may require different levels of transmitter and receiver coordination. In the case of upstream VDSL, only receiver coordination is possible, therefore a successive interference cancellation scheme performs optimally [4] [5]. The upstream VDSL channel matrix has a columnwise diagonally dominant (CWDD) structure, which is due to the fact that the power on the direct channel of a particular user is always much higher than the power sent over any crosstalk channel by the same user. In [6] under the assumption that the background noise is AWGN, it is shown that the CWDD structure allows a simple linear zero-forcing canceler to perform near optimally. Furthermore, due to the spatial as well as the frequency selective nature of the crosstalk it was shown in [7] that the complexity of the cancellation can be reduced significantly using a technique called partial cancellation, where only the interference originating from strong interferers is canceled.

However, in the case of spatially correlated background noise e.g., alien crosstalk, a prewhitening operation is needed to whiten the noise [8]. This operation destroys the CWDD structure of the channel matrix. The linear zero-forcing canceler is then found to perform very poorly. In this scenario, a decision feedback canceler can be used. However the complexity of the decision feedback canceler is significantly higher, therefore the use of linear canceler is still desirable. When the noise covariance matrix is assumed to be known, an Minimum Mean Squared Error (MMSE) canceler can be used, which takes the noise covariance matrix into account and tries to minimize its effect. The MMSE canceler is therefore considered here as a good intermediate choice in the case of alien crosstalk.

One of the advantages of using a zero-forcing canceler is its relatively easy extension to partial cancellation. However in MMSE cancelers there is no obvious strategy that can be followed to realize partial cancellation. Earlier approaches [9] [10] adopt some per-user/per canceler exhaustive search method, which is computationally complex.

In this paper, firstly, we show that the MMSE canceler performs significantly better than the zero-forcing canceler in the presence of alien crosstalk. Secondly, we present a simple algorithm for partial MMSE crosstalk cancellation.

In section II, the upstream VDSL system model is presented and crosstalk cancellation problem in the presence of spatially correlated background noise is defined. In section III various cancellation techniques for in-domain crosstalk are presented and then compared with the out-of-domain crosstalk cancellation techniques. Furthermore in section IV, the possibility of an efficient algorithm for partial MMSE crosstalk cancellation is explored and an algorithm is proposed. Simulation results for the proposed algorithm are presented in section V. Finally, in section VI conclusions are drawn.

II. System model

In this paper, our focus is solely on DMT-based upstream VDSL transmission, where the receivers are co-located. The

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system is described by

$$\underbrace{\begin{bmatrix} y_1^k \\ \vdots \\ y_N^k \end{bmatrix}}_{\mathbf{y}^k} = \underbrace{\begin{bmatrix} h_{(1,1)}^k & \cdots & h_{(1,N)}^k \\ \vdots & \ddots & \cdots \\ h_{(N,1)}^k & \cdots & h_{(N,N)}^k \end{bmatrix}}_{\mathbf{H}^k} \underbrace{\begin{bmatrix} x_1^k \\ \vdots \\ x_N^k \end{bmatrix}}_{\mathbf{x}^k} + \underbrace{\begin{bmatrix} n_1^k \\ \vdots \\ n_N^k \end{bmatrix}}_{\mathbf{n}^k}, \tag{1}$$

where k is the tone index ($k = 1 \cdots K$). x_n^k and y_n^k are the transmitted and received symbols in line n on tone k and n_n^k is spatially white additive Gaussian background noise experienced by line n on tone k such that $E\{\mathbf{n}^k \mathbf{n}^{kH}\} = \sigma_k^2 \mathbf{I}_N$. $h_{(n,n)}^k$ is the direct channel for line n on tone k and $h_{(n,m)}^k$ is the crosstalk channel from line m into line n. Let $E\{\mathbf{x}^k \mathbf{x}^{kH}\} = \mathbf{S}^k$, where $\{.\}^H$ denotes the Hermitian transpose operation. Since the transmitters are not coordinated, $\mathbf{S}^k$ is a diagonal matrix. Furthermore it is assumed that the transmitters have a fixed transmit spectrum, which can not be changed during the data transmission. Here, the channel matrix $\mathbf{H}^k$ is CWDD [6].

In the presence of alien crosstalk, the above model becomes

$$\begin{bmatrix} y_1^k \\ \vdots \\ y_N^k \end{bmatrix} = \begin{bmatrix} h_{(1,1)}^k & \cdots & h_{(1,N)}^k \\ \vdots & \ddots & \cdots \\ h_{(N,1)}^k & \cdots & h_{(N,N)}^k \end{bmatrix} \begin{bmatrix} x_1^k \\ \vdots \\ x_N^k \end{bmatrix} + \underbrace{\begin{bmatrix} h_{(1,axt1)}^k & \cdots & h_{(1,axtm)}^k \\ \vdots & \ddots & \cdots \\ h_{(N,axt1)}^k & \cdots & h_{(N,axtm)}^k \end{bmatrix} \begin{bmatrix} x_{axt1}^k \\ \vdots \\ x_{axtm}^k \end{bmatrix}}_{\text{Alien Crosstalk } (\mathbf{a}^k)} + \begin{bmatrix} n_1^k \\ \vdots \\ n_N^k \end{bmatrix}. \tag{2}$$

Here $\mathbf{a}^k$ is the vector containing the sum of all the alien crosstalk contributions to each line. Hence (2) can be succinctly written as

$$\begin{aligned} \mathbf{y}^k &= \mathbf{H}^k \mathbf{x}^k + \underbrace{\mathbf{a}^k + \mathbf{n}^k}_{\mathbf{z}^k} \\ \mathbf{y}^k &= \mathbf{H}^k \mathbf{x}^k + \mathbf{z}^k \end{aligned} \tag{3}$$

Even though the individual alien crosstalk channels are not known at the receiver side, it is assumed that the total noise covariance matrix $\mathbf{R}_n = E\{\mathbf{z}^k \mathbf{z}^{kH}\}$ is known or can be estimated. The alien crosstalk is spatially correlated therefore the resulting covariance matrix $\mathbf{R}_n$ is not a diagonal matrix.

III. Crosstalk cancellation

The upstream VDSL scenario with receiver coordination and no transmitter coordination corresponds to the multiple access channel (MAC) in information theory. The capacity of this MAC in the AWGN case can then be written as [6]

$$\mathbf{b} = \sum_k \log_2 |\mathbf{I}_N + \frac{1}{\Gamma} \sigma_k^{-2} \mathbf{H}^k \mathbf{S}^k \mathbf{H}^{kH}|, \tag{4}$$

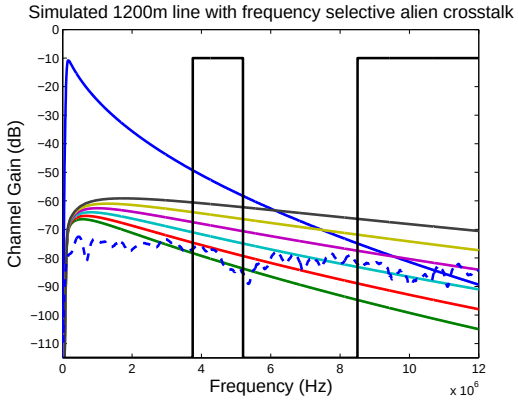


Fig. 1. A simulated channel for a 1200m line with 6 in-domain crosstalkers ranging from 600m to 1100m and an alien-crosstalker (in dashed line). Solid black rectangular line represent the transmit band for upstream VDSL.

where Γ is the SNR gap. In [6] it was shown that due to the CWDD structure of the channel matrix $\mathbf{H}^k$, a simple linear zero-forcing canceler can be used to obtain near-optimal capacity approaching performance.

In the case of alien crosstalk, the noise becomes spatially correlated. The capacity formula then includes a prewhitening operation and can be written as [8]

$$\tilde{\mathbf{b}} = \sum_k \log_2 |\mathbf{I}_N + \frac{1}{\Gamma} \underbrace{(\mathbf{R}_n^{-1/2} \mathbf{H}^k)}_{\tilde{\mathbf{H}}^k} \mathbf{S}^k (\mathbf{R}_n^{-1/2} \mathbf{H}^k)^H|, \tag{5}$$

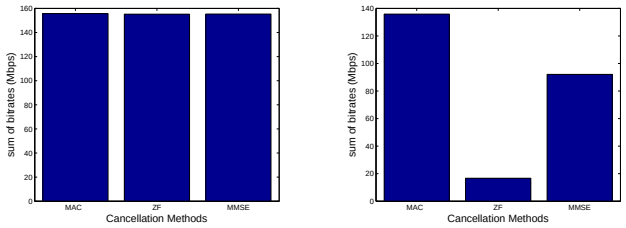
where $\mathbf{R}_n$ is the noise covariance matrix and $\tilde{\mathbf{H}}^k$ is the equivalent channel matrix after prewhitening. This equivalent channel matrix is no longer CWDD and hence a zero-forcing canceler no longer provides near-optimal performance. In this scenario, it was shown in [4] [5] that a decision feedback canceler performs optimally. A decision feedback canceler however, is significantly more complex than a simple linear canceler like the zero-forcing canceler. A MMSE canceler, which takes the noise covariance matrix into account, can therefore be considered a good intermediate choice in the case of alien crosstalk.

A multiuser MMSE detector/canceler can be written as follows [11]

$$\mathbf{W}^k = \mathbf{S}^k \tilde{\mathbf{H}}^{kH} (\tilde{\mathbf{H}}^k \mathbf{S}^k \tilde{\mathbf{H}}^{kH} + \mathbf{I}_n)^{-1}, \tag{6}$$

where $\mathbf{W}^k$ is the $N \times N$ multiuser MMSE detector/canceler matrix. Unlike the zero-forcing canceler, the MMSE canceler takes the structure of the noise covariance into account and hence is able to cancel the alien crosstalk much more efficiently. For a Gaussian interference in a high signal-to-noise ratio the MMSE canceler approaches the zero-forcing canceler.

Fig. 1 plots a direct channel characteristics for a 1200 m line and also shows the in-domain crosstalk from 6 other lines ranging from 600m to 1100 m with increments of 100m as simulated using the analytical channel model as given in [14]. The dashed line in **Fig.** 1 gives an example of a highly frequency selective alien crosstalk.



(a) (b)

Fig. 2. Comparison of the total bitrate achieved through MAC capacity formula, zero-forcing canceler and MMSE canceler when alien crosstalk is (a) not present (b) present

In the absence of alien crosstalk, it can be seen from **Fig.**2(a) that the performance of the zero-forcing canceler and the MMSE canceler are similar when the full crosstalk is canceled. Both the cancelers approach the MAC capacity achieved with a decision feedback cancellation. As can be seen from **Fig.**2(b), as soon as alien crosstalk is introduced the performance decreases for the linear cancelers. The performance of the zero-forcing canceler is extremely poor whereas the MMSE canceler still provides relatively good performance. This is our motivation for using the MMSE canceler as a single in-between solution. The complexity of full MMSE crosstalk cancellation however is still $\mathcal{O}(N^2)$ [6], hence for a large number of lines the crosstalk cancellation becomes computationally heavy. This provides the motivation for partial crosstalk cancellation.

IV. Partial Crosstalk Cancellation

In [6], a simple partial cancellation scheme exploiting the spatial and frequency selectivity of the crosstalk was presented for the zero-forcing canceler. Only strong crosstalkers are canceled which reduces complexity significantly without any dramatic performance degradation. For the MMSE canceler however there is no obvious strategy, that can be followed to realize partial cancellation. Before delving into different schemes to select the interferers to be canceled, we first establish how the partial crosstalk canceler coefficients can be computed once the interferers to be canceled have been selected.

A. Computation of partial MMSE crosstalk canceler coefficients

In this section, the implementation of a general partial MMSE crosstalk canceler will be discussed. Let us assume that there are N lines, therefore there are $N-1$ crosstalkers to be canceled for each individual line. Let $p_{k,n}$ be the number of lines observed i.e., used by the crosstalk canceler, to detect the signal in line n on tone k, where $p_{k,n} = N-1$ denotes full crosstalk cancellation and $p_{k,n} = 0$ corresponds no crosstalk cancellation i.e. single user detection (SUD). Let $\mathcal{M}_n^k$ be the set of indices of all the lines which are observed in order to detect the signal in line n on tone k, including the index of line n. This can be written as

$$\mathcal{M}_n^k \triangleq \{m_{k,n}(1) \cdots m_{k,n}(p_{k,n}+1)\}. \tag{7}$$

Similarly, we define $\underline{\mathcal{M}}_n^k$ as the set of all the lines that are not taken into consideration when detecting user n on tone k and can be written as

$$\underline{\mathcal{M}}_n^k \triangleq \mathcal{N} \backslash \mathcal{M}_n^k, \tag{8}$$

where $\mathcal{N}$ is a set containing indices of all the lines. Let $\overline{\mathbf{H}}_n^k$ be the channel matrix containing the channels from all the lines that are taken into account while detecting signal in line n on tone k, which is given as

$$\overline{\mathbf{H}}_n^k \triangleq \left[[\mathbf{H}^k]_{rows\mathcal{M}_n^k, cols\mathcal{M}_n^k} \right], \tag{9}$$

and $\underline{\mathbf{H}}_n^k$ be the matrix containing all the crosstalk channels into the observed lines, from all other lines

$$\underline{\mathbf{H}}_n^k \triangleq \left[[\mathbf{H}^k]_{rows\mathcal{M}_n^k, cols\underline{\mathcal{M}}_n^k} \right]. \tag{10}$$

Similarly $\overline{\mathbf{R}}_n$ and $\tilde{\mathbf{H}}_n^k$ are defined as the noise covariance matrix of the observed lines and the effective observed channel after prewhitening, i.e.,

$$\overline{\mathbf{R}}_n \triangleq \left[[\mathbf{R}_n]_{rows\mathcal{M}_n^k, cols\mathcal{M}_n^k} \right] + \underline{\mathbf{H}}_n^k \underline{\mathbf{S}}_n^k \underline{\mathbf{H}}_n^{kH} \tag{11}$$

$$\tilde{\mathbf{H}}_n^k \triangleq \overline{\mathbf{R}}_n{}^{-1/2} \overline{\mathbf{H}}_n^k, \tag{12}$$

where $\underline{\mathbf{S}}_n^k$ is the matrix containing the power transmitted on all the unobserved lines with indices given by the set $\underline{\mathcal{M}}_n^k$. Now the partial MMSE cancellation coefficient $\overline{\mathbf{w}}_n^k$ can be calculated using (6), (11) and (12) and can be written as

$$\overline{\mathbf{w}}_n^k \triangleq \bar{\mathbf{e}}_q^H \left(\mathbf{S}_n^k \tilde{\mathbf{H}}_n^{kH} \left(\tilde{\mathbf{H}}_n^k \mathbf{S}_n^k \tilde{\mathbf{H}}_n^{kH} + \mathbf{I}_{p_{k,n}+1} \right)^{-1} \right), \tag{13}$$

where $\bar{\mathbf{e}}_q^H \triangleq \left[\mathbf{I}_{p_{k,n}+1} \right]_{col\, q}$. $\left[\mathbf{I}_{p_{k,n}+1} \right]_{col\, q}$ represents the column q of the identity matrix $\mathbf{I}$ of size $p_{k,n}+1$. q is the position of the user n in the set $\mathcal{M}$ and $\mathbf{S}_n^k$ is the matrix containing the power transmitted onto the observed lines.

B. Partial MMSE crosstalk cancellation problem

In order to cancel the crosstalk on tone k in line n by another line m, a cancellation tap is used. For a given number of cancellation taps C^{tot}, the partial crosstalk cancellation problem amounts to maximizing the total capacity of the network using upto C^{tot} cancellation taps. This can be written as following maximization problem,

$$\max_{\mathbf{c}} \sum_{k=1}^{K} \sum_{n=1}^{N} \tilde{b}_k^n$$
$$\text{s.t } \mathbf{C} = \sum_{k=1}^{K} \sum_{m=1}^{N} \sum_{n=1}^{N} c_k^{n,m} \leq C^{tot}, \tag{14}$$

where $n, m = 1 \cdots N$, $k = 1 \cdots K$, $\mathbf{c} = [\mathbf{c}_1, \mathbf{c}_2, ..., \mathbf{c}_K]$. $[\mathbf{c}_k]_{n,m} = c_k^{n,m}$. $\tilde{b}_k^n$ is the data rate of the line n on the tone k. $c_k^{n,m} = 1$ indicates that a cancellation tap has been assigned to cancel the crosstalk from line m into line n on the tone k. $\mathbf{c}_k$ is an $N \times N$ matrix containing the cancellation tap configurations

$c_k^{n,m}$ between all users on tone k. The global optimum for this optimization can be found by exhaustively searching through all possible cancellation tap configurations. However, the cancellation tap constraint is coupled over tones, which results in an exponential complexity in number of tones. This complexity can be made linear by using a dual decomposition. To achieve this the constraint in the optimization problem is moved into unconstrained part with the help of the Lagrange multiplier. This can then be written as

$$\mathbf{c}^{opt} = \underset{\mathbf{c}}{\text{argmax}} \sum_{k=1}^{K}\sum_{n=1}^{N} \tilde{b}_k^n + \lambda \left(C^{tot} - \sum_{k=1}^{K}\sum_{m=1}^{N}\sum_{n=1}^{N} c_k^{n,m} \right)$$
$$\text{subject to } \lambda \geq 0 \qquad n = 1 \cdots N \tag{15}$$

For a given λ, the optimization problem decouples over tones hence it can be solved in a per-tone fasion. The per-tone optimization can then be written as

$$\text{For } k = 1 \cdots K$$
$$\mathbf{c}_k^{opt} = \underset{\mathbf{c}_k}{\text{argmax}} \sum_{n=1}^{N} \tilde{b}_k^n - \sum_{m=1}^{N}\sum_{n=1}^{N} \lambda c_k^{n,m}. \tag{16}$$

Maximization of (16) can be performed by an exhaustive search over all the interfering lines for the line n on the tone k. This provides the globally optimal solution. Additionally, the constraint can be enforced by tuning λ. Algorithm to efficiently tune the Lagrange multiplier is given in [12] [13]. However even in the dual domain, the exhaustive search has to be performed on all the $N-1$ interfering lines for a given line n.

C. Selection of partial MMSE cancellation tap

In the zero-forcing canceler, the exhaustive search can be avoided by choosing the largest interferer first for the given line n [7]. However, for MMSE partial canceler no such strategy exists. Selecting the cancellation tap based on only the information from the crosstalk channels or the covariance matrix of the background noise do not perform good in all the scenarios. In order to counter this problem, a simple strategy can be devised using the available information about both the crosstalk channel and the background noise covariance matrix together. For line n, the total information provided by the background noise covariance can be written as the following empirical formula

$$n_{emp}^m \triangleq \underbrace{r_{nn}\left(\frac{r_{nm}}{\sum_i r_{ni}}\right)}_{I}\underbrace{\left(\frac{r_{mm}}{|h_{mm}|^2 s_m}\right)}_{II}, \tag{17}$$

where r_{ij} is the entry in i-th row and j-th column in the noise covariance matrix $\overline{\mathbf{R}}_{\mathbf{n}}$ and h_{ij} is the entry in i-th row and j-th column of the channel matrix $\overline{\mathbf{H}}_n^k$. s_m is the power transmitted by the user m. The part I of (17) represents the ratio of the total alien crosstalk given by the covariance matrix of the background noise if the line m is selected to be canceled. The part II in (17) accounts for the fact that the effective alien crosstalk that can be canceled also depends on the signal-to-interference-noise ratio (SINR) of the line m. Moreover, the crosstalk from the line m is also canceled when it gets selected. Therefore for line n, the total effective interference that can be canceled if line m is selected to be canceled is given by

$$I_{eff}^m = n_{emp}^m + |h_{nm}|^2 s_m \tag{18}$$

Hence the interferer to be canceled is chosen such that the maximum I_{eff}^m is achieved. The performance thus achieved can be close to the optimum performance. **Algorithm** 1 gives a simple approach to effectively assign the cancellation tap to cancel the maximum amount of interference.

TABLE I
SIMULATION PARAMETERS

Number of DMT tones	4096
Tone width	4.3125 kHz
symbol rate	4 kHz
Coding gain	3 dB
Noise margin	6 dB
Symbol error probability	$< 10^{-7}$
Transmit PSD	Flat (-60 dBm/Hz)
FDD band plan	998
Cable type	0.5 mm

Algorithm 1 partial MMSE crosstalk cancellation tap selection using the combined information

1: **for** a given user n **do**
2: Compute I_{eff}^m for all the interferers given by $\underline{\mathcal{M}}_n^k$ by using (18)
3: Choose the line which provides maximum I_{eff}^m
4: **end for**

V. SIMULATION RESULTS

Simulations were run for a distributed scenario consisting of 7 users ranging from 600m to 1200m in 100m increments. The channels are generated using the analytical model in [14]. An alien crosstalk line of 500m is generated using a semi-analytical model. The general simulation parameters are summarized in **Table** I.

We now compare the partial crosstalk cancellation strategy given in **Algorithm** 1 against various other strategies. The optimum partial cancellation tap assignment is given by the exhaustive search algorithm. Therefore, this provides the performance upper limit that can be achieved. This can be seen in **Fig.** 4. In order to avoid the exhaustive search step, the information from the crosstalk channel matrix and the noise covariance matrix can be used. Using information from the crosstalk channel alone (descending XT power and ascending XT power in **Fig.** 4) or the information from the noise covariance matrix alone (descending noise corr. and ascending noise corr. in **Fig.** 4) do not result in the performance close to the performace by the optimum tap assignment scheme. This is due to the fact that canceling maximum of either the crosstalk

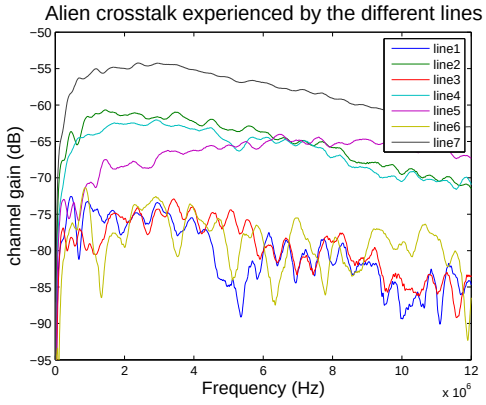


Fig. 3. A highly frequency and line selective alien crosstalk experienced by different lines (users)

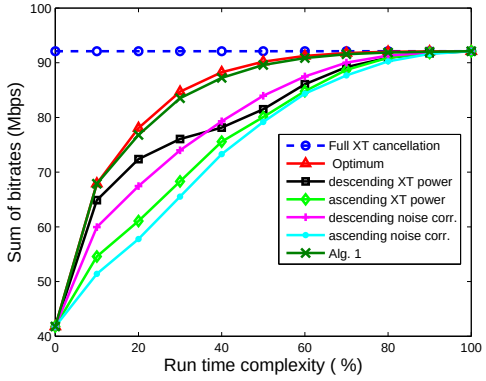


Fig. 4. The performance comparison of the different algorithms for partial cancellation using MMSE canceler for upstream VDSL with alien crosstalk

power or alien crosstalk alone do not necessarily translate into the maximum effective interference cancellation. The partial MMSE crosstalk cancellation tap selection using combined information as presented in **Algorithm** 1 uses the information about both the noise covariance and the crosstalk, hence it performs very near to the optimum performance.

VI. Conclusion

In this paper, we have considered crosstalk cancellation in the presence of spatially correlated background noise such as alien crosstalk in upstream VDSL, where receivers are collocated. We have shown that an MMSE canceler performs significantly better than a zero-forcing canceler. It was demonstrated that the MMSE partial cancelers using only in-domain interferer power or the noise covariance matrix do not perform well in all scenario. Therefore, a simple alternative approach incorporating the information from both in-domain interferers and the noise covariance was proposed. It was also shown that this simple algorithm performs close to optimally.

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