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Crosstalk cancellation for xDSL with restricted access to lines

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Abstract— **Crosstalk cancellation for Digital Subscriber Lines (DSL), also termed *vectoring*, can significantly increase achievable data rates but requires signal-level access of vectoring chip units (VCU) to interfering users in a cable. Due to practical limitations, however, an individual VCU attached to a line card in a DSL access multiplexer (DSLAM) typically can only access the signals of a fraction of users causing crosstalk to each other. In this paper, the performance gain of vectoring with enhanced access to lines obtained by allowing a limited exchange of user signals between VCUs over one or multiple interfaces in the DSLAM is studied. An algorithm to select the user signals to be shared between VCUs is proposed. Simulations in various deployment scenarios show that large sum rate gains can be achieved even by sharing only a fraction of line signals in the system.**

I. Introduction

Crosstalk in xDSL systems occurs due to electromagnetic coupling between copper wires in a multipair telephone cable [1]. While near-end crosstalk (NEXT) can be avoided via duplexing, far-end crosstalk (FEXT) causes strong disturbances on the victim's line and is the dominant impairmant in ADSL and VDSL systems severely limiting achievable data rates.

Vectoring, also known as *Dynamic Spectrum Management (DSM) Level 3* ([2], [3]), has been proposed for VDSL2 which employs joint signal processing at transmitter or receiver side for users in the multiple-input multiple-output (MIMO) interference channel to mitigate the capacity loss due to crosstalk. Such cancellation and precompensation techniques are able to remove crosstalk between users nearly perfectly, but require signal-level access to all participating lines. Therefore, they typically have to be carried out by VCUs at the exchange side of the local loop where modems are co-located in the DSLAM.

In practice, lines coming from a common cable and, thus, interfering with each other are randomly connected to ports of different *line cards* in a DSLAM. Usually, a VCU can only access lines connected to ports of the line card it is attached to and, thus, crosstalk between users connected to different line cards cannot be removed via vectoring. Furthermore, due to the high complexity of canceller chip designs, it may become necessary to have multiple VCUs per line card where each one processes signals from only a fraction of the line card's ports. Then, each VCU could possibly only access signals of users for which it carries out vectoring.

To diminish the described access restrictions, it may be reasonable to install one or more communication interfaces, termed *vectoring interfaces* here, in a DSLAM which connect several VCUs from different or the same line card and enable the exchange of a limited number of user signals. Here we assume that the interfaces operate in *bus* mode where broadcasted line signals can be received by all connected VCUs. If only two VCUs are connected, the vectoring interface corresponds to a simple *point-to-point* connection.

Figure 1 shows a scenario where two line cards in a DSLAM at the *Central Office (CO)* or a remote cabinet have each attached a pair of VCUs and are processing a total of N lines coming from two cables. On each line card, there are two *uni-directional* point-to-point interfaces connecting a pair of VCUs. Alternatively, an architecture with a single *bi-directional* interface per line card is imaginable. Additionally, a bus vectoring interface allows the exchange of user signals between all four VCUs of both line cards.

As the capacity of those interfaces is limited and the impact of crosstalk on data rates varies between disturbers, a novel problem which user signals to share between VCUs arises. In this work, we consider the optimization problem which line signals to broadcast over one or several interfaces between VCUs so that the sum rate achieved by vectored transmission with the resulting extended access to lines is maximized. This can be seen as a *partial crosstalk cancellation* problem but differs from those studied in previous works in that the constraint is the limited access to crosstalking lines while those found in e.g. [4] deal with limited processing power of VCUs.

The remainder of this paper is organized as follows: Section II describes the system model of Discrete Multi-Tone (DMT) transmission in the MIMO crosstalk channel as used in our study. In Section III, the optimization problem is defined and an algorithm for its solution is derived. Section IV discusses the performance gain of line signal sharing obtained from simulations for various VDSL2 deployment scenarios. Finally, Section V gives some concluding remarks.

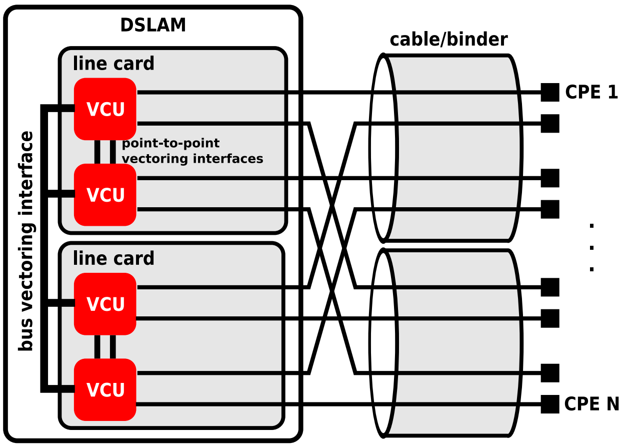

Fig. 1: xDSL scenario with restricted signal-level access of VCUs to lines.

II. System Model

For an N-user DSL system using DMT with tones $k = 1, \ldots, K$, we define the input and output vectors as

$$\boldsymbol{x}_k = [x_k^1, \ldots, x_k^N]^\top \tag{1}$$

and

$$\boldsymbol{y}_k = [y_k^1, \ldots, y_k^N]^\top . \tag{2}$$

where x_k^n and y_k^n (n here denotes an index) are the input and output of user $n = 1, \ldots, N$ on tone k, respectively. Furthermore, we define the vector $\boldsymbol{z}_k = [z_k^1, \ldots, z_k^N]^\top$ of white Gaussian noise terms z_k^n with covariance matrix $E\{\boldsymbol{z}_k \boldsymbol{z}_k^\top\} = \sigma_z^2 \boldsymbol{I}_N$ modeling receiver background noise where $\boldsymbol{I}_N$ denotes the $N \times N$ identity matrix. Assuming perfect carrier synchronization, each tone can be modeled as an independent MIMO channel with $N \times N$ channel matrix

$$\boldsymbol{H}_k = \begin{bmatrix} h_k^{1,1} & \cdots & h_k^{1,N} \\ \vdots & \ddots & \vdots \\ h_k^{N} & \cdots & h_k^{N,N} \end{bmatrix} \tag{3}$$

leading to

$$\boldsymbol{y}_k = \boldsymbol{H}_k \boldsymbol{x}_k + \boldsymbol{z}_k . \tag{4}$$

The diagonal elements $h_k^{n,n}$ of $\boldsymbol{H}_k$ contain the direct channel coefficients of user n while the off-diagonal elements $h_k^{n,m}$ ($m \neq n$) are the FEXT channel coefficients from disturber m to user n.

III. Line Selection for Vectoring Interfaces

Let us consider a scenario with vectoring interfaces $u = 1, \ldots, U$ each constrained by a capacity of D^u line signals (again, u here denotes an index). We define the vectoring interface configuration $\boldsymbol{d}$ as

$$\boldsymbol{d} = (\boldsymbol{d}_1, \ldots, \boldsymbol{d}_N) \tag{5}$$

with

$$\boldsymbol{d}_n = (d_n^1, \ldots, d_n^U)^T \qquad d_n^u \in \{0, 1\}. \tag{6}$$

Here, d_n^u equals 1 if the signal of user n is shared over interface u and 0 if not. Furthermore, we define the binary coefficients $a_{n,m}^u \in \{0, 1\}$ where $a_{n,m}^u = 1$ if the crosstalk of user m on user n's line can be cancelled if user m's signal is shared on interface u and $a_{n,m}^u = 0$ otherwise. This models the scenario topology, i.e. how vectoring chips, interfaces and lines are connected to each other. Let $s_k^n = E\{|x_k^n|^2\}$ denote the average transmit power of user n on tone k. We define the *channel gain*

$$g_k^{n,m} = \begin{cases} \Gamma^{-1} |h_k^{n,n}|^2 & \text{if } n = m, \\ |h_k^{n,m}|^2 & \text{if } n \neq m. \end{cases} \tag{7}$$

where Γ denotes the *signal-to-noise ratio (SNR) gap to capacity* [5] which is a function of the target bit error rate, line code, coding gain and noise margin.

An optimization problem can be formulated where we seek the configuration $\boldsymbol{d}$ which maximizes the sum rate subject to the capacity constraints of the individual interfaces, i.e.

$$\max_{\boldsymbol{d}} f_s \sum_n \sum_k \log_2 \Bigg(1 + \frac{g_k^{n,n} s_k^n}{\sum_m g_k^{n,m} \Big(1 - \sigma_1 \big(\sum_u d_m^u a_{n,m}^u \big) \Big) + \sigma_z^2} \Bigg) \tag{8}$$

$$\text{s.t.} \sum_n d_n^u \leq D^u \qquad u = 1, \ldots, U$$

$$\text{where } \sigma_1(x) = \begin{cases} 1 & \text{if } x \geq 1, \\ 0 & \text{if } x < 1 \end{cases}$$

and f_s is the symbol rate of the DMT system. Unfortunately, one observes that the constraints and the nonconvex objective couples the variables d_n^u so that a solution would require an exhaustive search of complexity $O(2^{NU})$, which is not feasible for realistic values of N. To circumvent the exponential complexity in N, we propose to approximate the original problem by another one where the objective is separable in the users $n = 1, \ldots, N$. Given the rate gain of cancelling crosstalker m on all tones in the detection of user n as

$$g_n(m) = f_s \sum_k \log_2 \left(1 + \frac{g_k^{n,n} s_k^n}{\sigma_z^2}\right) - f_s \sum_k \log_2 \left(1 + \frac{g_k^{n,n} s_k^n}{g_k^{n,m} s_k^m + \sigma_z^2}\right), \quad (9)$$

we define the problem

$$\max_{\boldsymbol{d}} \sum_n \sum_m g_n(m) \sigma_1 \big(\sum_u d_m^u a_{n,m}^u \big) \quad (10)$$

$$\text{s.t.} \sum_n d_n^u \leq D^u \qquad u = 1, \ldots, U$$

whose dual is given by

$$\min_{\boldsymbol{\mu}} \max_{\boldsymbol{d}} L(\boldsymbol{\mu}, \boldsymbol{d}) \quad (11)$$

$$\text{s.t. } \mu^u \geq 0 \qquad u = 1, \ldots, U$$

where

$$\begin{aligned} L(\boldsymbol{\mu}, \boldsymbol{d}) &= \sum_n \sum_m g_n(m) \sigma \big(\sum_u d_m^u a_{n,m}^u \big) \quad (12) \\ &\quad + \sum_u \mu^u \big(D^u - \sum_m d_m^u \big) \\ &= \sum_m L_m(\boldsymbol{\mu}, \boldsymbol{d}_m) + \sum_u \mu^u D^u \end{aligned}$$

is the Lagrangian with

$$\begin{aligned} L_m(\boldsymbol{\mu}, \boldsymbol{d}_m) &= \sum_n g_n(m) \sigma \big(\sum_u d_m^u a_{n,m}^u \big) \quad (13) \\ &\quad - \sum_u \mu^u d_m^u \end{aligned}$$

and Lagrange multipliers

$$\boldsymbol{\mu} = (\mu^1, \ldots, \mu^U)^\top. \quad (14)$$

The objective of problem (10) can be regarded as an approximation to the sum rate objective of the original problem (8), but ignores the nonlinear coupling of disturbers in their influence on user data rates. As can be seen, the exhaustive search required to find $\max_{\boldsymbol{d}} L(\boldsymbol{\mu}, \boldsymbol{d})$ for given $\boldsymbol{\mu}$ can be reduced to N exhaustive searches of complexity $O(2^U)$ required to find $\max_{\boldsymbol{d}_m} L_m(\boldsymbol{\mu}, \boldsymbol{d}_m)$. The remaining exponential complexity in U is a non-issue, since in practical problems the number of interfaces over which a particular user can be shared is expected to be low.

IV. Performance

To quantify the benefit of sharing line signals, simulations in upstream and downstream VDSL2 deployment scenarios with a structure as depicted in Figure 2 have been carried out. 100 VDSL2 services are deployed through four 25-pair binders whose lines are randomly connected to the ports of the four line cards in the DSLAM. The loop lengths $L(n)$ are randomly drawn from a uniform distribution in the interval $[100\,\mathrm{m}; 1300\,\mathrm{m}]$. Each line card has a single VCU carrying out vectoring for the connected users. It is assumed that no constraints w.r.t. the run-time complexity are imposed on the crosstalk cancellers.

For the sake of simplicity, we consider the case where a single vectoring interface allows to share a limited number D of user signals via broadcasting between all four VCUs. Further more, we study performance in scenarios where all 25 users in a cable are participating in vectoring as well as the case where in each cable ten of the 25 users are not connected to a line card supporting vectoring and thus cause *out-of-domain* FEXT to the other 15 lines in the cable subject to our study. For upstream, all of these ten alien disturbers per cable are assumed to carry a VDSL2 service while for downstream, five of them are ADSL2+ users and the other five are VDSL2 lines. All VDSL2 users transmit with flat PSD level of $-60\,\mathrm{dBm/Hz}$. The alien ADSL2+ users transmit with the nominal PSD (NOMPSD) defined in Table B.1.2-1/G.992.5 [6] linearly scaled down to achieve an aggregate transmit power of $19.9\,\mathrm{dBm}$. To model space selectivity of crosstalk [4] in a 25-pair binder, the MIMO FEXT model defined in [7] was used. Other simulation scenario parameters are summarized in Table I.

Here we study the sum rate gains that can be obtained from sharing only a fraction of the N user signals in the system, i.e. $D = 0, \ldots, N$ where $N = 60$ in scenarios with alien disturbers and $N = 100$ in scenarios where all users in a cable participate in vectoring. If $D = 0$, no exchange of user signals is possible between VCUs and thus each VCU can only remove FEXT originating from lines

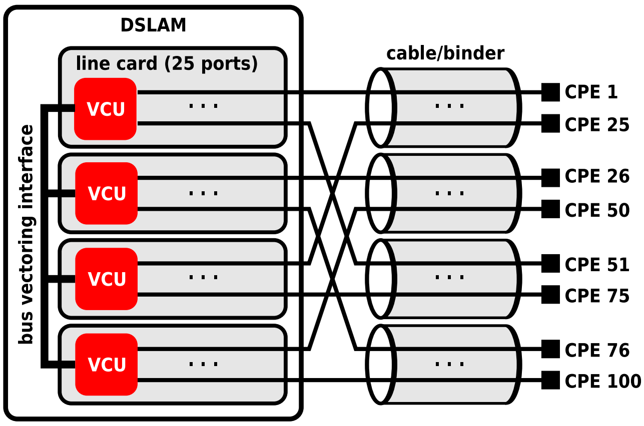

Fig. 2: Topology of simulated VDSL2 deployment scenarios

TABLE I: Simulation scenario parameters

Parameter	Value
Cable type	TP100 [8]
MIMO FEXT model	ATIS NIPP-NAI [7]
VDSL2 band plan	998-M2x-NUS0 [9]
Backround noise PSD N_0	$-140\,\mathrm{dBm/Hz}$
Number of tones K	4096
Tone spacing Δf	$4.3125\,\mathrm{kHz}$
SNR gap Γ	$12.8\,\mathrm{dB}$

connected to the corresponding line card. If $D = N$, no access restrictions exist so that full vectoring is possible.

The achieved sum rates in different scenarios as the proportion of shared users D/N is increased are given in Figure 3. The curves were obtained by averaging over the results from $M = 20$ scenario realizations. Looking at Figure 3a, we find that in downstream without alien noise, full vectoring without access restrictions (i.e. $D = N$) can double the achievable sum rate compared to uncoordinated transmission. Unfortunately, the concave curve shape suggests that significant gains can only be obtained by sharing the majority of user signals in the given scenario. The explanation is three-fold: first, in sum rate analysis, short lines contribute the most but in downstream, loop length variations in the scenario mostly do not affect crosstalk strength for them and are thus not reflected in the results. Secondly, selecting a line signal to be shared enables enhanced crosstalk cancellation for all users, leading to an averaging effect of space selectivity of FEXT in the cable. Thirdly, as has been remarked in [4], even when the most dominant crosstalkers have been cancelled and a few weak disturbers remain, cancelling one of the latter causes the SINR and therefore the data rate to grow rapidly.

Figure 3b depicts the result in the downstream scenario with ten alien FEXT disturbers per cable. As could be expected, the absolute and relative gain achieved by full vectoring has shrunk considerably compared to the previous scenario. At the same, the curve now shows a concave shape which can be explained by the fact that due to the alien crosstalk, the effect of rapid SINR growth as described above is not as prominent as before.

In Figure 3c the sum rate gains of limited signal sharing in upstream without alien disturbers are shown. Here the near-far effect leads to strong crosstalk originating from only the short lines in the binder. Consequently, we find that by only sharing half of the user signals (i.e. those with short loop lengths), more than 80% of the sum rate gain of full vectoring can be achieved. As can be observed in Figure 3d, the effect is even more pronounced when there are alien disturbers present in the cable.

V. Conclusion

In this paper, we have investigated the problem of restricted signal-level access to lines for vectored transmission. We have proposed a system architecture which allows the limited exchange of line signals between VCUs. An optimization problem to find the set of signals to share which maximizes the sum rate subject to capacity constraints of the vectoring interfaces has been formulated. Since this problem has been found too complex for practical application, a suboptimal algorithm based on dual decomposition was derived.

Simulations in VDSL2 deployment scenarios show that in downstream, the majority of user signals have to be exchanged between VCUs to achieve significant gains. In upstream, however, due to the near-far effect, sharing of only the short lines yields considerable sum rate gains.

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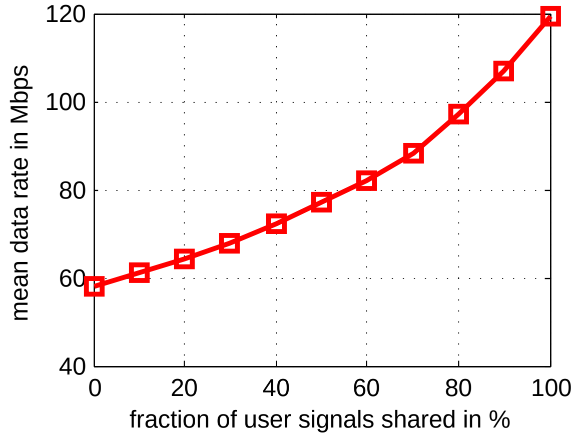
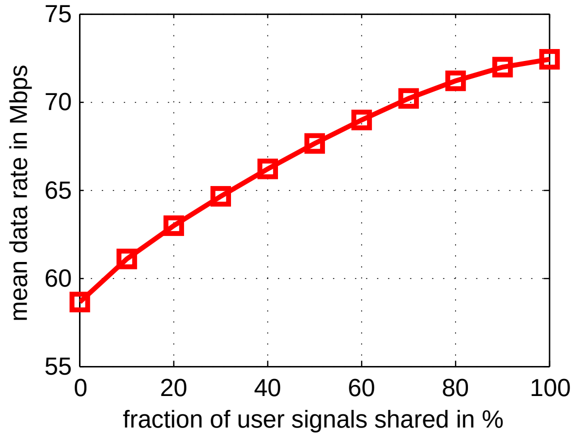
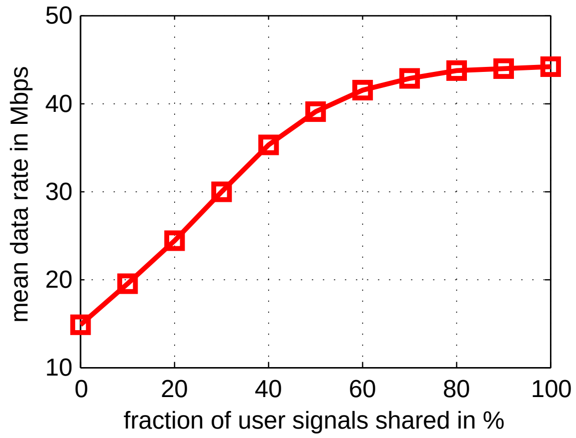


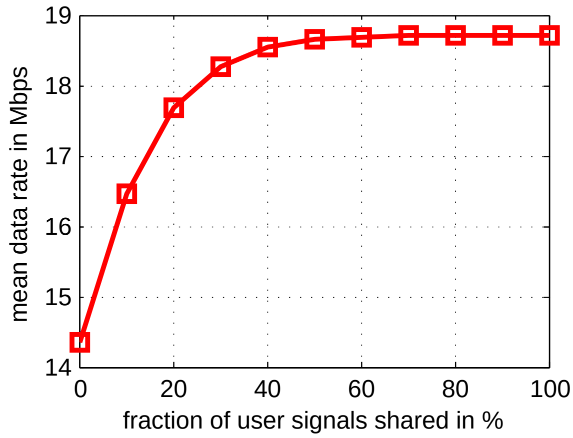
(a) Downstream scenario without alien noise



(b) Downstream scenario with 5 alien ADSL2+ and 5 alien VDSL2 disturbers per cable



(c) Upstream scenario without alien noise



(d) Upstream scenario with 10 alien VDSL2 disturbers per cable

Fig. 3: Mean user data rates in various VDSL2 deployment scenarios obtained by sharing a limited number of user signals between VCUs in a DSLAM for enhanced line access

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