Evaluation of Binder Management for Partially Controlled DSL Vectoring Systems

Daniel Hincapie and Gerhard Maierbacher
Fraunhofer Institute for Embedded
Systems and Communication Technologies ESK
Hansastrasse 32, D-80686 Munich, Germany
Email: {daniel.hincapie, gerhard.maierbacher}@esk.fraunhofer.de

Andreas Achtzehn and Marina Petrova
Institute for Networked Systems,
RWTH Aachen University
Kackertstrasse 9, D-52072 Aachen, Germany
Email: {aac, mpe}@inets.rwth-aachen.de

***Abstract*—Crosstalk between physically co-located lines is a pressing issue in VDSL2 access networks. In order to enhance the crosstalk mitigation capabilities of the latest extension to VDSL2, vectoring G.993.5, full control over all lines within the same cable binder is required. However, this is not always possible in practical deployments due to regulatory, structural, or late technology adoption constraints. In these cases a technique to minimize interference from non-controlled lines, known as binder management, aims at rearranging the line configuration within each binder. In this work, we quantify the advantages of binder management in a partially controlled setup. We initially establish a model of a commonly used 50-pair cable binder and provide its far-end crosstalk (FEXT) characterization. We then carry out an extensive simulation study for various degrees of control over the lines and realistic line length distributions to yield tangible metrics on vectoring performance for downstream transmission. Our results show that binder management is of limited use in partially controlled systems. Consequently, we provide an additional comparison study to help DSL providers to evaluate the remaining gains of upgrading to VDSL2-vectoring in such scenarios for different levels of dominance in the cable binder.**

I. Introduction

Digital Subscriber Line (DSL) systems are the predominant technology for providing high-speed wired internet connectivity. Today operators are in the position to offer improved services to home and office customers, e.g., by enabling video streaming and cloud-based applications. However, due to the success of the DSL technology, a pressing problem has arisen from the fact that a larger number of DSL lines is physically located in the same cable binder. The interference originating from nearby lines severely limits the achievable individual throughputs. This has motivated the introduction of means to compensate for this so called far-end crosstalk (FEXT) [1]. Through the latest vectoring extension G.993.5 [2], the current generation of very high speed digital subscriber line 2 (VDSL2) network devices is enhanced with vectoring pre- and postprocessing techniques that tailor all DSL transmissions within the same binder as to minimize FEXT interference.

One assumption with respect to the benefits of vectoring is that the vectoring-implementing entity, usually the DSL Access Multiplexer (DSLAM), has full control over all DSL transmission within the binder. However, this assumption does not necessarily hold in practice. Non-controlled systems may coexist with vectored systems in the same cable binder, generating alien crosstalk noise that cannot be compensated by vectoring. For example, as part of the local loop unbundling (LLU) regulatory framework [3], it is envisioned to continue to grant multiple providers simultaneous access to the cable infrastructure. Any technical collaboration between them with the purpose of exchanging vectoring control data will likely be difficult to implement. Furthermore, building constraints occasionally require parallel installation of multiple non-co-located DSLAMs of the same operator, which may not be able to coordinate their vectoring activities between each other (due to the increased communications overhead or system incompatibilities). Finally, even if all systems are served by the same DSLAM and same provider, some legacy customer premises equipment (CPE) may not support VDSL2-vectoring.

To reduce the impact of alien crosstalk, several Spectrum Management (SM) techniques have been developed, e.g., see [4], [5] and references therein. In order to maximize system capacity, they enforce coordination between vectoring units, often relying on a direct information exchange. Alternatively, binder management was proposed to minimize crosstalk optimizing the physical location of vectored lines within a cable binder [6]–[8]; cable pairs that are served through the same vectored systems are put in close proximity, while non-vectored lines are kept as far as possible from their interfered counterparts. However, its realization in existing services is tedious for providers and its real benefits are still unknown.

In this paper, we study the achievable performance of vectoring systems with special focus on *downstream transmission* when binder management is exercised in more realistic partially controlled setups[1]. In particular, we select three scenarios that are commonly seen as worst, best, and average cases of how cable pairs within binders are distributed among competing providers. Comparing the effects of intra-binder line distribution allows us to derive first conclusive results on the sensibleness of performing binder management. For this purpose, we analyze empirical measurements to develop a

This work has been partially financed by the research project *"FlexDP-Flexible Breitband Distribution Points"*, funded by the Bayerische Forschungsstiftung (Bavarian Research Foundation). We acknowledge partial funding from DFG (Deutsche Forschungsgemeinschaft) through the UMIC research centre at RWTH Aachen university.

[1]The same evaluation can be carried out for upstream transmission.

FEXT model of a commonly used 50-pair cable binder. In our subsequent simulation study, we characterize the performance of the vectoring setup when different fractions of the lines are under control of two different vectoring units. Our results show that carrying out binder management to mitigate the degrading effect of non-controlled cross-talkers on vectored lines does not provide significant benefits for partially controlled systems. Under these premises we present comparative results of the performance of non-vectored and vectored systems and estimate the remaining gains of deploying vectoring in partially controlled scenarios.

The rest of this paper is organized as follows: Section II presents the system model and the vectoring scheme implemented for simulating the vectoring systems. Section III describes the approach and results of the stochastic characterization of the 50-pair cable. Section IV defines the simulation environment. Section V presents the performance results for the aforementioned scenarios and a comparison study for (non-)vectored systems. Finally, concluding remarks are given in Section VI.

II. System model

We consider a digital subscriber line (DSL) system with a set of N users and K frequency sub-carriers. Using synchronous DMT modulation, there is no inter-carrier interference (ICI) [1] and the transmission over each sub-carrier k can be modeled independently as

$$\mathbf{y_k} = \mathbf{H_k} \cdot \mathbf{x_k} + \mathbf{z_k}, \tag{1}$$

where $\mathbf{x_k} = [x_k^1, \ldots, x_k^N]^T$, $\mathbf{y_k} = [y_k^1, \ldots, y_k^N]^T$ and $\mathbf{z_k} = [z_k^1, \ldots, z_k^N]^T$ represent the transmitted signal, the received signal and the total additive noise for users $1 \ldots N$ on sub-carrier k, $1 \leq k \leq K$, respectively. $\mathbf{H_k}$ is an $N \times N$ channel matrix where $[\mathbf{H_k}]_{(n,m)} = h_k^{(n,m)}$ is the gain of the channel from transmitter m to receiver n on sub-carrier k. The direct channel gains are given by the main diagonal elements $h_k^{(n,n)}$, whereas the interfering FEXT channel gains correspond to the out-of-diagonal elements $h_k^{(n,m)}$ for $n \neq m$. The transmit power spectrum density (PSD) of user n on sub-carrier k is $s_k^n = \mathcal{E}\{|x_k|^2\}/\Delta_f$, where Δ_f is the sub-carrier bandwidth [1].

The number of bits that can be transmitted at an arbitrary low bit error rate (BER) by user n on sub-carrier k is

$$b_k^n \triangleq \log_2 \left(1 + \frac{1}{\Gamma} \frac{|h_k^{n,n}|^2 s_k^n}{\sum_{n=1, m \neq n}^{N} |h_k^{n,m}|^2 s_k^m + \sigma_k^n} \right), \tag{2}$$

where $\sum_{m \neq n}^{N} |h_k^{n,m}|^2 s_k^m$ is the FEXT noise power, Γ is the Shannon gap and $\sigma_k^n \triangleq \mathbb{E}\left\{|z_k^n|^2\right\}/\Delta_f$ is the noise PSD of user n on sub-channel k. Therefore, the achievable data rate R for user n is $R^n = f_s \sum_{k=1}^{K} b_k^n$, where f_s is the symbol rate of the system.

The power of the transmitted signals is bounded by two constraints. First, the cumulative power along all transmitted sub-carriers of user n is limited to a standardized value denoted by P^n. The second constraint limits the individual sub-carriers power transmission s_k^n to a standardized PSD mask, denoted for every sub-carrier k as $s_k^{n,mask}$ [2]. These constraints are formally described as

$$\Delta_f \sum_{k=1}^{K} s_k^n \leq P^n, \tag{3}$$

and

$$0 \leq s_k^n \leq s_k^{n,mask} \ , \ \forall \, n \in 1 \leq n \leq N. \tag{4}$$

The adopted model of the DSL system considers each sub-carrier channel as an independent multiple-input multiple-output (MIMO) channel, which enables us to pre- and post-compensate the signals in downstream and upstream direction, respectively, to mitigate the impact of the interference originating from the same sub-carrier being used by other users in the same binder [9]. This concept is known as *vectoring*. We refer the reader to [1] for an extensive review of vectoring schemes.

For downstream pre-compensation, [10] proposes a near-optimal linear precoder called the diagonalizing precoder (DP). The DP has the form

$$\mathbf{y_k} = \mathbf{H_k} \cdot \left(\frac{1}{\beta_k^{DP}} \cdot \mathbf{H_k}^{-1} \cdot \mathrm{diag}(\mathbf{H_k}) \right) \cdot \mathbf{x_k} + \mathbf{z_k}, \tag{5}$$

$$\beta_k^{DP} = \max_n \sum_{m \in N} |[\mathbf{H_k}^{-1}]_{(n,m)} \cdot h_k^{m,m}|^2 \tag{6}$$

where $\beta_k^{DP}$is a scaling factor to ensure that the system meets the PSD mask constraint defined in (4) [1], [10]. The resulting system yields an effective bit capacity for sub-carrier k and user n of

$$b_k^n = \log_2 \left(1 + \frac{1}{\Gamma \cdot \left(\beta_k^{DP}\right)^2} \frac{|h_k^{n,n}|^2 \cdot s_k^n}{\sigma_k^n} \right). \tag{7}$$

III. Characterization of the FEXT channel

The MIMO channel for each user is composed of one direct channel and $N-1$ interfering channels. The direct channel is the insertion loss of the telephone pair connecting DSLAM ports and CPEs. Models of the direct channel have been established and standardized for different cable types in [11].

Interfering channels are described by their crosstalk gain, i.e., the FEXT transfer function between pairs. The standard described in [12] defines a FEXT model based on "1% worst case" coupling values which have been empirically obtained from measurements of several cable types. The model offers a reference estimation of the FEXT channel, but is rather pessimistic; it does not take the dispersion of the FEXT magnitude experienced by the interfered pair due to the relative position of the interfering pairs into account [13]. In reality, closer interfering pairs generate stronger crosstalk magnitude than those located farther away within the binder. To model such dispersion, known as *space selectivity*, the work in

[13] extends the standardized model in [12] and proposes a stochastic model that defines the FEXT transfer function as

$$H_{stoch}(f) = |H_{WC-FEXT}(f,d)| \cdot \mathrm{e}^{\mathrm{j}\varphi(f)} \cdot 10^{-0.05\chi(f)} \quad , \quad (8)$$

where $|H_{WC-FEXT}(f,d)|$ is the magnitude of the 1% worst case model, f is the frequency in Hz, d is the coupling distance in meters, φ is a random variable uniformly distributed in the interval $[0, 2\pi]$, and $\chi(f)$ is a Gaussian random variable expressed in dB with mean $\mu_{dB}(f)$ and standard deviation $\sigma_{dB}(f)$. The latter models the FEXT magnitude dispersion.

A. Binder Model

The stochastic approach described in [13] requires statistical characterization of the variable $\chi(f)$ for every binder, because the space selectivity depends on its internal pair distribution. Earlier works provide characterization for different binder models, e.g., [2], [13]–[15]. As a contribution of this paper, we present for the first time the characterization of a quad-based 50-pair binder largely used in the German access network, the cable A-2Y(L)50×2×0.4 (poly-ethylene isolated, 50 pairs, 0,4 mm). Its layout is shown in Figure 1. A more extensive report of the measurements used to characterize the binder can be found in [16].

The internal pair distribution of the binder in Figure 1 is formed by five 10-pair binders of the model proposed in [2, Appendix I], referred to here as *sub-binders*. Our characterization requires this original model to be extended. We propose to divide the FEXT magnitude into 5 groups according to their inter-pair relationships. The groups are determined by two parameters. First, the *hierarchical level* in which the relationship is evaluated, i.e., intra-quad (within a quad), inter-quad (between quads of the same sub-binder) and inter-sub-binder (between sub-binders of the same binder); and second, the *relative position* of the evaluated level. Relative positions are defined as near and far-neighbor in accordance with [2]. Thus, the combination of level and relative position determines the groups. Since a quad contains 2 twisted pairs, only the intra-quad/near-neighbor relationship is possible at intra-quad level and therefore, the 5 defined levels are: intra-quad, inter-quad near- and far-neighbor, and inter-sub-binder near- and far-neighbor. Figure 1 depicts, for example, the 5 groups for the pairs 1 and 2 of the 50-pair binder.

TABLE I
STATISTICAL PARAMETERS OF THE CHARACTERIZED 50-PAIR BINDER

Relationship	μ (dB)			σ (dB)		
	short	medium	long	short	medium	long
Intra-quad	21.7	18.3	16.8	9.3	7.9	7.2
Inter-quad near	21.7	18.1	20.5	9.3	7.8	8.8
Inter-quad far	19.6	15.3	15.9	8.4	6.6	6.8
Inter-binder near	20.8	17.9	17.6	8.9	7.7	7.6
Inter-binder far	19.3	16.9	16.2	8.3	7.2	7

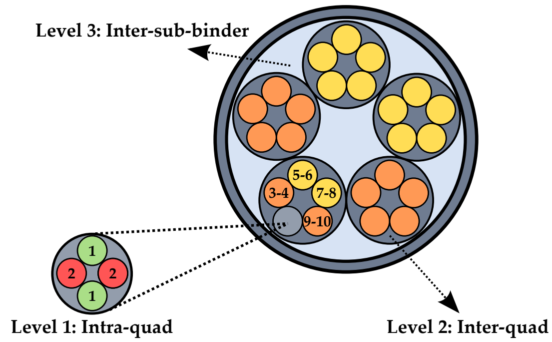


Fig. 1. 50-pair cable binder layout and inter-pair relationships. Hierarchical levels (intra-quad, inter-quad and inter-sub-binder) are indicated by arrows, whereas relative pair positions (near/far-neighbors) are denoted by different colors. If pair 1 is evaluated, red, orange and yellow pairs correspond to intra-quad, near- and far-neighbors, respectively.

B. Characterization Results

We repeated the empirical FEXT measurements in [16] for three cable binder lengths $l \in \{300, 550, 1050\}(m)$. Each of these lengths are within the short, medium and long length intervals specified in [17] for vectoring systems testing. Therefore, we have taken their measurements as representative of each interval and independently evaluated them in order to obtain individual models for short, medium and long coupling lengths. Statistical parameters of this inter-pair relationship are provided in Table I. We statistically characterize the random variable $\chi(f)$ by extracting the mean $\mu_{dB}(f)$ and standard deviation $\sigma_{dB}(f)$ of the FEXT magnitude relative to the 1% worst case magnitude at every VDSL2 sub-carrier frequency and for the five inter-pair relationships. To obtain a tractable model, we selected a representative distribution with frequency-independent values μ_{dB} and σ_{dB} for every relationship, calculating divergence statistics between a theoretical Gaussian distribution and the empirical distribution, and using the best fit. While we note that in practice the distribution of FEXT magnitude is more complex, we deem the Gaussian approximation appropriate for the assessment carried out in this paper.

IV. Simulation Setup

We have implemented a custom VDSL2 simulator with support for modeling VDSL2-vectoring. In the simulation, vectoring entities are collocated and the individual line lengths are drawn according to a Gamma distribution with shape parameter $\alpha = 2$ and scale parameter $\beta = 302$, i.e., CPEs are generally non-co-located. This distribution is considered realistic for global cable length distributions [18]. The insertion loss of the direct channel is modeled according to [11, Section 5.3]. For each of the N x (N-1)=2450 crosstalk paths we derive the coupling length and the inter-pair relationship. Then, we select the corresponding set of random variables $\chi(f)$ according to the parameters in Table I. We assume in our study asymmetric crosstalk paths, i.e., $[\mathbf{H_k}]_{(n,m)} \neq [\mathbf{H_k}]_{(m,n)}$ for $n \neq m$. Vectoring is applied by calculating the DP matrix [10] and performing the operation defined in (5). We assume

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Band plan and mask	998ADE17-M2x-B
Carrier spacing	4.3125 kHz
Noise floor σ^2	-130 dBm/Hz
Shannon gap Γ	10.75 dB
Efficiency	0.785
Bitloading cap b_{max}	15 bits

perfect channel knowledge at the vectoring DSLAM. The simulation parameters of the VDSL2 transceivers are listed in Table II.

We consider full binder occupation, i.e., $N = 50$ lines in the binder are used. The lines are controlled by two different and non-cooperative systems. SM techniques are not applied. The number of lines controlled by every system is denoted by N_1 and N_2, subject to meet the full binder occupancy condition, i.e., $N_1 + N_2 = N$.

To establish indicative results on the benefits of performing binder management, three comparative setups are evaluated. First, binder management is applied so that all controlled lines of each system are allocated in neighboring positions, i.e., the average distance to non-controlled lines is maximized. We assume that such arrangement corresponds to the best case and thus refer to it the *optimal case arrangement*. Second, binder management is not implemented; the simulated lines are randomly assigned to positions in the binder. This is the *average case* in which operators do not perform binder management. In the third setup, each line in each quad is assigned to a different operator. As in this setup the average distance to non-controlled lines is minimized, it is considered as the *worst case* and establishes a lower bound on the vectoring performance.

We have simulated three cable mapping scenarios: dominant, non-dominant and balanced. In the dominant scenario, one of the providers has control over the majority of the lines, i.e., $N_1 > N_2$; the non-dominant scenario is the opposite, i.e., $N_1 < N_2$, whereas in the balanced case both systems have control over the same number of lines, i.e., $N_1 = N_2 = 25$.

V. SIMULATION RESULTS

We use the *percent loss (PL)* [17] as an indicator for comparing benefits of vectoring in the different scenarios. The PL quantifies the proportion of Single-line Data Rate (SDR), i.e., the achievable data rate of a single line in absence of FEXT, that cannot be attained by a vectoring system. It is defined as

$$PL = 100\% \cdot \left(\frac{SDR - VDR}{SDR} \right), \tag{9}$$

where VDR is the vectored data rate.

A. Impact of binder management

Figure 2 depicts the mean PL with respect to the line length of the vectored lines in balanced, dominant and non-dominant scenarios for downstream transmission. In order to obtain the average performance as seen by a user with given line length, we have repeated our simulations 100 times, whereby each time new line lengths were drawn from a length distribution described in [18]. FEXT channel gains were calculated using the characterized model. This approach allows us to reproduce the empirical evaluation for 100 different binders containing services with non-collocated CPE transceivers. The comparative results between the best case, i.e., when binder management is applied, and the random pair-allocation, shows that the performance of both vectored systems is independent of the pair allocation adopted within the binder. This means that exercising binder management does not improve the vectoring performance in non-cooperating scenarios since the allocation does not affect on average the performance.

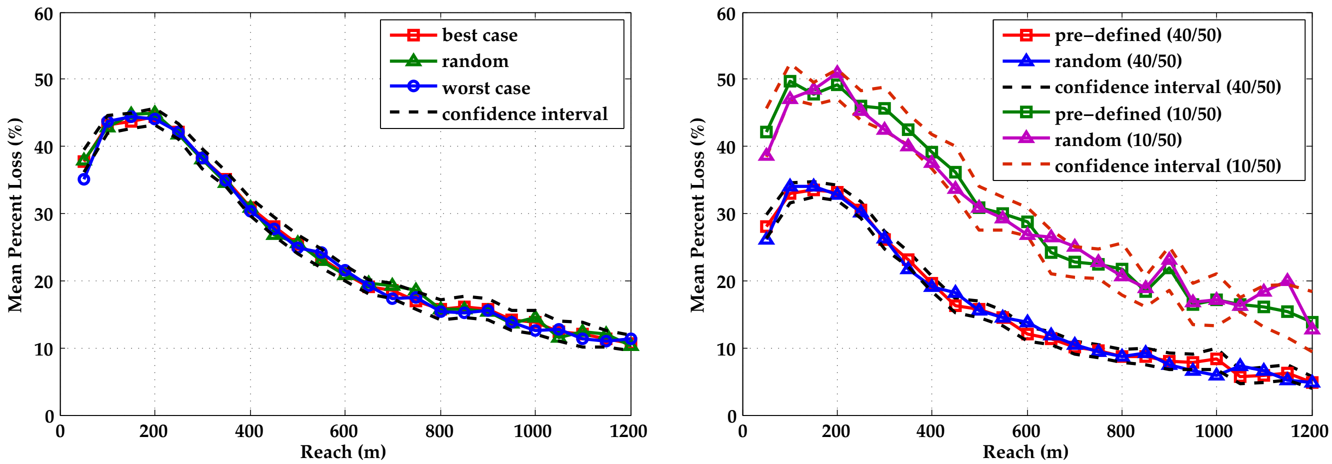
An interesting observation is made in the balanced scenario results. The performance of lines controlled by each system is not affected by the assumed worst case allocation even though the controlled lines suffer strong interference from the nearby uncontrolled lines. However, not only the magnitude of the interference determines the capacity of the vectored systems given by (7), but also the transmit power limited by the scaling factor β_k^{DP} of the DP operation. We have thus carried out a deeper analysis of the effective FEXT magnitude dispersion, which determines the vectoring performance.

B. FEXT magnitude dispersion

Figure 3 depicts the mean fraction of FEXT magnitude that every inter-pair relationship contributes to the total FEXT magnitude along the frequency. This value indicates that the two strongest groups of interfering pairs are located at the nearby sub-binders and quads. Notice that these values refer to the cumulative interference generated by the entire group of lines. The mean interference per line is the ratio between the depicted values and the number of interfering lines at the respective hierarchical level. An estimation of the mean magnitude contribution per line, along the frequency and at every level is given in Table III. Taking these values into account and considering that in the worst case allocation the lines of every system are equally distributed within the binder, each

TABLE III
INTERFERENCE CONTRIBUTION PER LINE

Relationship	$\lvert H_{FEXT}\rvert^2$/ line(%)
Intra-quad	12.8
Inter-quad near	5.6
Inter-quad far	3
Inter-binder near	1.9
Inter-binder far	0.7



(a) Balanced system performance.

(b) Dominant and non-dominant systems performance.

Fig. 2. Downstream Percent Loss (PL) for balanced, dominant and non-dominant scenarios. Figure (a) shows the performance of two vectoring systems with 25 controlled lines each one. Figure (b) depicts the results for dominant and non-dominant vectoring systems controlling 40 and 10 lines, respectively. 95% confidence intervals are plotted for the random arrangement; their values for worst and best cases are similar and are omitted to improve visibility.

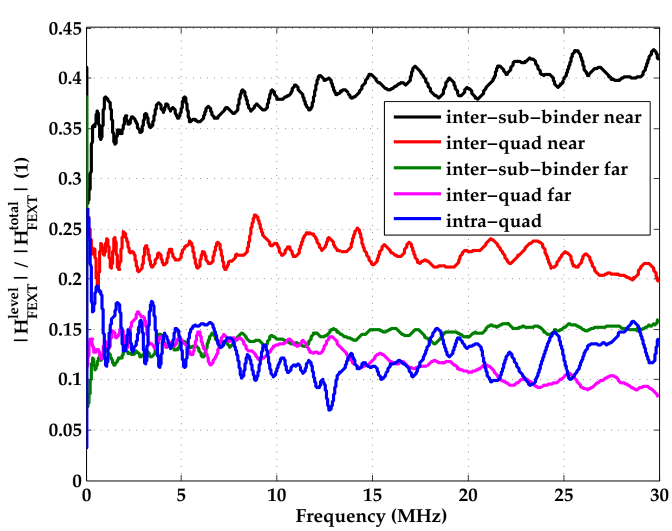
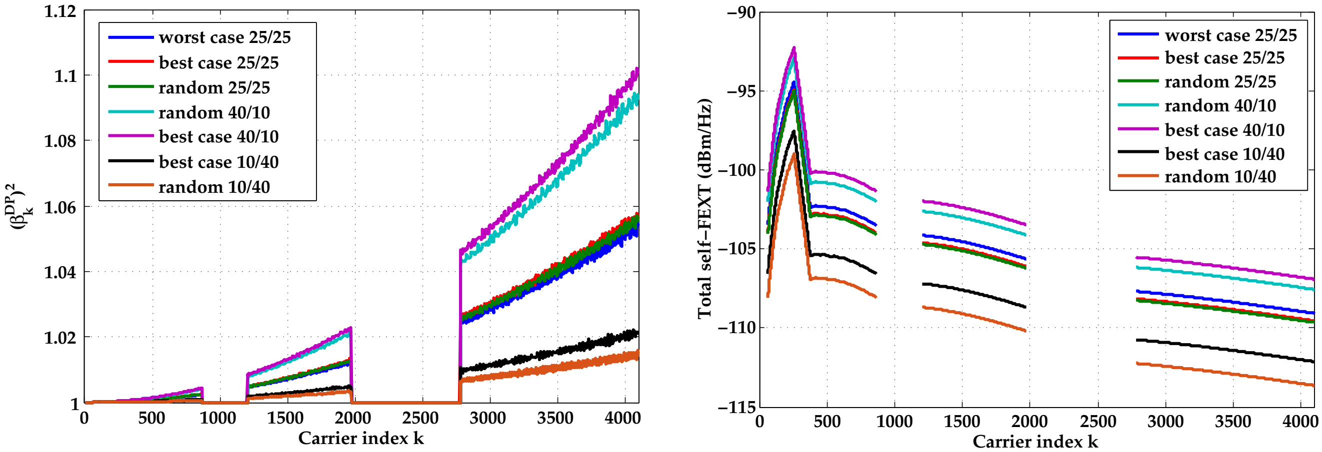


Fig. 3. Mean FEXT magnitude fraction of inter-pair relationships in a fully-occupied 50-pair binder. Inter-sub-binder and inter-quad near-neighbors concentrate about 60% of the interference magnitude.

vectoring system is statistically exposed to the same self- and alien- FEXT magnitude. On the other hand, in the best case arrangement, each system has total control over lines within two near sub-binders (20 lines) and equally share another (5 lines each). Therefore, they can compensate the inter-quad interference in most of the controlled lines and partially cancel the near inter-binder interference, which constitute most of the interference according to Figure 3. However, the self-FEXT also increases because of the proximity of controlled lines, which has a cost in the transmit power when the precoding operation is applied.

Regarding the transmit power of the precoded signal, it is limited by the scaling factor β_k^{DP} defined in (6). From its definition, β_k^{DP} is determined by the insertion loss of the vectored lines, i.e., the diagonal entries of the channel matrix $\mathbf{H_k}$, and the self-FEXT channel gains, i.e., the out-of-diagonal entries of the channel matrix. Since we seek to compare the impact of binder management with random allocations, only the relative position of vectored lines within the binder is modified. Therefore, the diagonal terms remain invariant in both cases and the value of β_k^{DP} is determined by the self-FEXT channel gains. Figure 4 shows the mean (over the iterations) of the squared values of β_k^{DP} and the total mean self-FEXT power (particularly considering 300 m lines). Notice that the value of β_k^{DP} is close to unity for the first band tones, suggesting a high degree of diagonal dominance in the channel matrix [10]. However, two facts are important to remark regarding the two upper bands: (1) the value of $(\beta_k^{DP})^2$ progressively increases, revealing loss of the diagonal dominance degree due to the stronger self-FEXT magnitude in high frequencies for short loops, and (2) the value is higher for larger vectoring group sizes (implying higher self-FEXT magnitude), showing a strong correlation with the corresponding self-FEXT magnitude depicted in Figure 4b. Therefore, if vectored lines are located in neighboring positions to minimize the interference caused by alien systems (from the non-controlled lines), the self-FEXT magnitude increases as well as the scaling factor β_k^{DP}. Although the values of the random and systematic/best allocation scaling factors are not notably different in the balanced scenario, the difference between random and best case allocations is significant in dominant and non-dominant scenarios.

According to our simulation results, the systematic mapping of lines within the cable binder also leads to a reduction in alien-FEXT. However, this is counteracted by the requirement that the transmit power has to be reduced in the vectoring setup by a factor of $(\beta_k^{DP})^{-2}$, and thus we found only limited



(a) Scaling factor.

(b) Self-FEXT magnitude.

Fig. 4. Scaling factor of the Diagonalizing Precoder (DPC) and total self-FEXT magnitude of vectored lines (considering $300\,\mathrm{m}$ lines) at every tone for balanced, dominant and non-dominant systems. The lower $(\beta_k^{DP})^2$ values of random allocations are determined by the corresponding lower values of self-FEXT power.

benefits in such scenarios.

C. Vectoring implementation gain

Although the presented results predict a low impact of binder management on vectored systems performance, the evaluation of the performance according to the degree of dominance within a binder allows us to estimate in which cases it remains advantageous for an operator to deploy vectoring in partially controlled systems. Figure 5 compares the performance indicators of vectored and non-vectored systems for different number of controlled lines within a 50-pair binder for three representative lengths. The gain that is obtained by deploying vectoring is given by the difference between the corresponding curves. However, the economic feasibility of upgrading DSL infrastructure with vectoring is ultimately a matter of upgrading costs that are not considered here.

In non-dominant systems, the evaluation shows that the maximum attainable gain is about 9% for the short, medium and long length ranges ($300\,\mathrm{m}$, $550\,\mathrm{m}$ and $1050\,\mathrm{m}$, respectively). The scenario is much more favorable for the dominant provider or vectoring unit, especially in the short and medium loop lengths ranges in which the gain can reach about 30% and 25% if 45 lines are controlled.

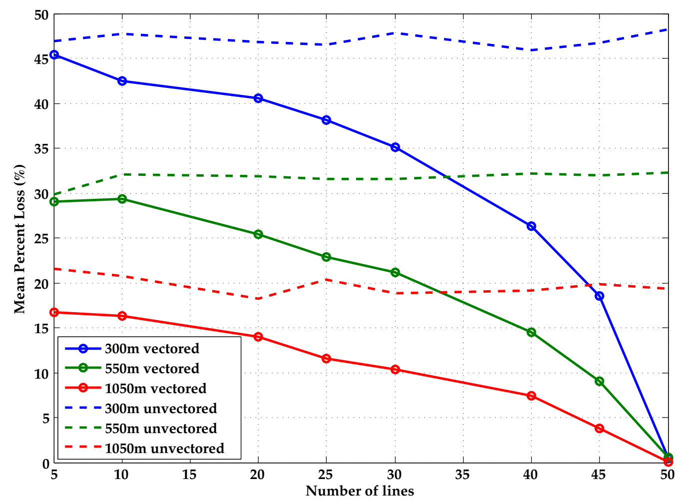


Fig. 5. Vectored and non-vectored systems performance for different number of controlled lines. The difference between dashed and solid curves is the gain obtained by vectoring in terms of the proximity to the FEXT-free performance.

VI. Conclusions

In this paper we have evaluated binder management as a means to minimize FEXT interference in VDSL2 vectoring systems. We are the first to quantify the achievable gains arising from careful mapping of lines to providers when a fraction of the lines is controlled by the same vectoring unit.

Our extensive simulation results based on a new 50-pair binder model show that the implementation of binder management does not offer significant benefits in partially controlled cable binders. Our FEXT channel characterization jointly with the simulations results indicate that the reduction of alien-FEXT magnitude often used as an argument for supporting binder management techniques is often counteracted by an equivalent decrease in transmit power due to vectoring operations. Therefore, the attainable vectoring gain does not depend on the line positions within the cable binder, but solely more on the number of lines that a provider controls within it, i.e., the provider degree of dominance in the network. Further benefits may be realized through the implementation of non-linear vectoring schemes, but we presume that their increased algorithmic complexity would not justify the limited performance gains. Hence, we argue that dynamic spectrum management (DSM) techniques and virtual unbundling are more suitable options to be deployed in partially controlled scenarios.

References

[1] C. Leung, S. Huberman, K. Ho-Van, and T. Le-Ngoe, "Vectored DSL: Potential, implementation issues and challenges," *Commun. Surveys Tuts.*, vol. 15, no. 4, pp. 1907–1923, Fourth Quarter 2013.

[2] *Self-FEXT cancellation (vectoring) for use with VDSL2 transceivers*, Rec. ITU-T G.993.5, International Telecommunication Union Std., April 2010.

[3] Euro. Parliament and Council, "Regulation no 2887/2000 on unbundled access to the local loop," *Official Journal of the European Communities*, vol. 4, no. L 336, pp. 4–8, December 2000.

[4] K. Kerpez, J. Cioffi, S. Galli, G. Ginis, M. Goldburg, and M. Mohseni, "Compatibility of vectored and non-vectored VDSL2," in *Proc. IEEE Conference on Information Sciences and Systems (CISS)*, Princeton, NJ, March 21–23 2012.

[5] A. Colmegna, S. Galli, and M. Goldburg, *Methods for supporting vectoring when multiple service providers share the cabinet area (white paper)*. ASSIA Inc., 2012.

[6] "Techniques to mitigate uncancelled crosstalk on vectored VDSL2 lines," Broadband Forum, Tech. Rep. TR-320. Issue 1, March 2014.

[7] G. Ginis, M. Goldburg, and J. Cioffi, "The effects of vectored DSL on network operations," *Journal of Telecommunications Management*, vol. 3, no. 2, pp. 107–117, July 2012.

[8] "An overview of G.993.5 vectoring," Broadband Forum, Tech. Rep. MR-257. Issue 2, March 2014.

[9] G. Ginis and J. M. Cioffi, "Vectored transmission for digital subscriber line systems," *IEEE J. Select. Areas Commun.*, vol. 5, no. 4, pp. 1085–1104, June 2002.

[10] R. Cendrillon, G. Ginis, E. V. den Bogaert, and M. Moonen, "A near-optimal linear crosstalk precoder for downstream VDSL," *IEEE Trans. Commun.*, vol. 55, pp. 860–863, 2007.

[11] *Cable reference models for simulating metallic access networks*, Permanent Document ETSI STC TM6, European Telecommunications Standards Institute Std., June 1998.

[12] *Test Procedures for digital subscriber line (DSL) transceivers*, G.996.1, International Telecommunication Union Std., February 2006.

[13] M. Sorbara, P. Duvaut, F. Shmulyian, S. Singh, , and A. Mahadevan, "Construction of a DSL-MIMO channel model for evaluation of FEXT cancellation systems in VDSL2," in *Proc. IEEE Sarnoff Symposium*, April 2007, pp. 1–6.

[14] *Multiple-Input Multiple-Output Crosstalk Channel Model*, ATIS-0600024, Alliance for Telecommunications Industry Solutions Std., 2011.

[15] W. Xu, C. Schroeder, and P. A. Hoeher, "A stochastic MIMO model for far-end crosstalk in VDSL cable binders," in *Proc. IEEE International Conference on Communications*, 2009.

[16] G. Maierbacher and M. Leibiger, "Access- und Inhouse Netze in Deutschland - ein Erfahrungsbericht zu Twisted-pair Kabelmessungen," in *Proc. 20. ITG-Fachtagung Kommunikationskabelnetze*, Cologne, NRW, Germany, December 10-11 2013.

[17] "Testing of G.993.2 self-FEXT cancellation (vectoring)," TR-249 Issue 1, Broadband Forum, Tech. Rep. TR-249. Issue 1, March 2014.

[18] J. Maes, M. Guenach, M. B. Ghorbel, and B. Drooghaag, "Managing unvectored lines in a vectored group," in *Proc. IEEE Globecom - Symposium on Selected Areas in Communication*, Atlanta, GA, USA, December 9–13 2013.