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Energy-Efficient DSL using Vectoring

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***Abstract*—A multi-user signal coordination scheme known as Vectoring will play a crucial role in next generation digital subscriber lines (DSL). Previous studies have demonstrated that vectoring increases the bitrate of DSL systems due to its ability to mitigate the interference. In this work we show how Vectoring improves the energy-efficiency of DSL over state-of-the-art spectrum balancing methods. In addition we investigate the impact of channel-state information errors and low-complexity implementations on the performance of Vectoring. We find that Vectoring yields large energy savings in terms of line-driver power consumption even under high channel estimation errors.**

I. Introduction

Reducing the total power consumption of telecommunication devices has recently become a main target for information and telecommunication technology (ICT) researchers. In 2006 the "EU Code of Conduct on Energy Consumption of Broadband Equipment" set the goal to halve the energy consumption of broadband equipment by 2015 [1]. With this objective in mind, *energy-efficient* dynamic spectrum management (DSM) level-2 algorithms have been designed and analyzed in [2] [3].

Vectoring, also referred to as vectored digital subscriber lines (DSL) transmission, was introduced in [4] [5] and represents the highest level (level-3) of DSM [6]. Vectoring coordinates the signals between users and can theoretically, assuming perfect channel knowledge, completely cancel the crosstalk between DSL lines. It is performed at the receiver side in the upstream transmission and at the transmitter side in the downstream transmission as DSL modems are only collocated at the central office (CO) or cabinet side.

However, in practical DSL systems perfect channel knowledge can not be assumed due to channel estimation errors. The effect of channel estimation errors in multi-carrier systems were investigated in [7] for the single-user case. This analysis was extended in [5] to the multi-user case, assuming linear crosstalk cancelation based on QR decomposition. The analysis in [5] shows that channel estimation errors result in residual crosstalk which can be treated as noise, and a detection bias which can be modeled by a decrease in minimum distance between constellation points. In [8] a simplified performance evaluation of a linear diagonalizing precoder based vectoring systems is presented considering errors in the estimated channel magnitude only.

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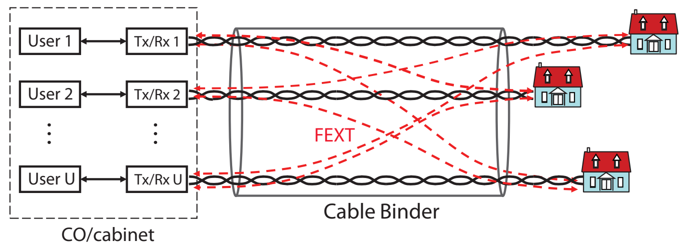

Fig. 1. DSL system topology with a cable binder shared by different users.

In the present study we focus on two linear crosstalk cancelation schemes, the linear Zero-Forcing (ZF) canceler [9] applied to upstream crosstalk cancellation, and the Diagonalizing Precoder (DP) [10] used for crosstalk precompensation in downstream communications. This choice of low-complexity Vectoring implementations is motivated by the near-optimal performance they achieve in low-bandwidth systems [9], [10].

Our main contributions can be summarized as follows. Considering a multi-user environment, we study the effects of channel estimation errors in high-bandwidth vectored DSL systems based on the ZF canceler and the DP for upstream and downstream communication, respectively. We perform an error analysis under imperfect channel state information (CSI), considering both, errors in magnitude *and* phase. We will show how Vectoring can be used to reduce the line-driver (LD) energy consumption of DSL systems and discuss at which rates and up to what level of channel estimation error a Vectoring system is more "energy-efficient" than current crosstalk-limited non-vectored DSL systems.

The rest of the paper is organized as follows. In Section II the used system and crosstalk models will be introduced. Based on these we derive error and performance models in Section III. Simulation results comparing Vectoring to current non-vectored systems in terms of rate-region, LD power consumption, and the achievable energy-per-bit are presented in Section IV. Our conclusions are summarized in Section V.

II. System Model

A multi-user DSL environment is considered, consisting of U interfering subscriber lines sharing a single cable binder as shown in Figure 1. We will assume that modems are co-located at the CO or street cabinet side in order to perform joint signal processing, whereas they may be distributed at the customers'

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side. We further assume all DSL systems are synchronized and based on discrete multi-tone (DMT) modulation, where near-end crosstalk (NEXT) is avoided by the use of frequency-division duplexing (FDD), *e.g.*, the so-called *Zipper* technique [11]. Consequently one obtains a far-end crosstalk (FEXT) limited system and the received symbol vector $\mathbf{y}_k \in \mathbb{C}^U$ on tone k can be written as

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{x}_k + \mathbf{n}_k, \tag{1}$$

where $\mathbf{x}_k \in \mathbb{C}^U$ denotes the vector of transmitted symbols, $\mathbf{n}_k \in \mathbb{C}^U$ indicates the vector of additive received noise including thermal noise, impulse noise, and radio-frequency interference. $\mathbf{H}_k \in \mathbb{C}^{U\text{x}U}$ represents the channel frequency response matrix on tone k with $h_k^{u,m} \triangleq [\mathbf{H}_k]_{u,m}, \quad \forall u,m \in \mathcal{U} = \{1,\ldots,U\}$. Hence, $h_k^{u,u}$ is the direct channel frequency response while $h_k^{u,m}$ is the crosstalk channel frequency response from the "disturber" line m to the "victim" line u. Distinguishing the interference and noise signals, the received symbol on line u and tone k is equivalently given by

$$y_k^u = h_k^{u,u} x_k^u + \sum_{m \neq u} h_k^{u,m} x_k^m + n_k^u, \tag{2}$$

From here on we will only consider the independent per-subcarrier channels and therefore in the following for simplicity we omit the index k.

A. FEXT Channel Model

As a crosstalk model we will use the common "99% worst-case crosstalk model" [12] where the cross-channel magnitude is given as

$$|H_{\text{FEXT}}(f,L,U)|^2 = U^{0.6} K_{\text{FEXT}} f^2 L |H_D(f,L)|^2, \tag{3}$$

where $H_D(f,L)$ is the direct channel magnitude, f is the frequency in [MHz], L is the loop length in [feet]([km]) and $K_{\text{FEXT}} = 8 \cdot 10^{-20} (K_{\text{FEXT}} = 10^{-19.5})$ is a constant given for North American (European) cables. In [13] a parametric stochastic FEXT model was presented where the coupling phase is modeled separately from the magnitude. The phase of the cross-channel coefficients is approximately linear like the phase of the direct channel $\phi_D(f,L)$ but with different slope, and it is modeled as [13]

$$\phi_{\text{FEXT}}(f,L) = \phi_D(f,L) \cdot \phi_0, \tag{4}$$

where ϕ_0 is a Gaussian random variable with mean $\mu_{\phi_0} \approx 1.3$ and variance $\sigma_{\phi_0} \approx 0.09$. Based on [13] and measurements done in [14], we model the phase of the direct channel as

$$\phi_D(f,L) = -\alpha \cdot f \cdot L, \tag{5}$$

where $\alpha = 0.03$ and L is the loop length in [m]. Summarizing, the models in (3), (4) and (5) have been used to characterize the crosstalk channel in our simulations.

III. Performance Modeling under Channel Estimation Errors

As mentioned in the introduction, we base our implementation of Vectoring on the crosstalk cancelation schemes proposed in [9] and [10], respectively. In [8] a simplified performance evaluation is presented for DP in downstream communications, where only deterministic errors in the estimated channel magnitude are considered. Next we present error models for Vectoring under imperfect CSI in upstream and downstream transmission, respectively, considering errors in magnitude *and* phase. We denote the estimated channel matrix on a specific tone as $\mathbf{H_{est}} \in \mathbb{C}^U$, $h_{\text{est}}^{u,m} \triangleq [\mathbf{H_{est}}]_{u,m}$. The resulting estimation error matrix is given by

$$\mathbf{E} \triangleq (\mathbf{H} - \mathbf{H_{est}}),$$

where $e_{i,j} \triangleq [\mathbf{E}]_{i,j}$ and the real channel can thus be written as

$$\mathbf{H} = \mathbf{H_{est}} + \mathbf{E}.$$

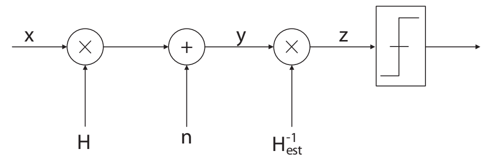

Fig. 2. Upstream signal model.

A. Upstream error model

Figure 2 shows the signal model on a particular subcarrier for upstream communication using ZF cancelation [9]. We define the inverse of the estimated channel matrix as $\mathbf{G} = \mathbf{H_{est}}^{-1}$, thus the symbol vector $\mathbf{z} \in \mathbb{C}^U$ after crosstalk cancelation is given by

$$\begin{aligned} \mathbf{z} = \mathbf{G} \cdot \mathbf{y} &= \mathbf{G} \cdot (\mathbf{H} \cdot \mathbf{x} + \mathbf{n}) \\ &= \mathbf{G} \cdot (\mathbf{H_{est}} + \mathbf{E}) \cdot \mathbf{x} + \mathbf{G} \cdot \mathbf{n} \\ &= \mathbf{G} \cdot \mathbf{H_{est}} \cdot \mathbf{x} + \mathbf{G} \cdot \mathbf{E} \cdot \mathbf{x} + \mathbf{G} \cdot \mathbf{n} \\ &= \mathbf{x} + \mathbf{G} \cdot \mathbf{E} \cdot \mathbf{x} + \mathbf{G} \cdot \mathbf{n}. \end{aligned} \tag{6}$$

Equivalently, the received symbol for user u can be written as

$$z_u = x_u + \sum_{j,i \in \mathcal{U}} \left([\mathbf{G}]_{ui} [\mathbf{E}]_{ij} x_j \right) + \sum_{i \in \mathcal{U}} [\mathbf{G}]_{ui} n_i. \tag{7}$$

Assuming that the estimation error matrix $\mathbf{E}$, the vector of transmitted symbols $\mathbf{x}$, and the noise vector $\mathbf{n}$ are statistically independent and zero mean, we can compute the variance of the received symbol z_u as

$$\mathcal{E}\left\{|z_u|^2\right\} =$$

$$= \mathcal{E}\left\{\left| x_u + \sum_{j,i \in \mathcal{U}} \left([\mathbf{G}]_{ui} [\mathbf{E}]_{ij} x_j \right) \right|^2\right\} + \mathcal{E}\left\{\left| \sum_{i \in \mathcal{U}} [\mathbf{G}]_{ui} n_i \right|^2\right\} \tag{8a}$$

$$= p_u + \sum_{j,i \in \mathcal{U}} |[\mathbf{G}]_{ui}|^2 \cdot \delta_{ij} \cdot p_j + \sum_{i \in \mathcal{U}} |[\mathbf{G}]_{ui}|^2 \cdot \sigma_n, \tag{8b}$$

where $p_i \triangleq \mathcal{E}\left\{|x_i|^2\right\}$ is the variance of the transmitted symbol of user i, $\delta_{ij} \triangleq \mathcal{E}\left\{\left|[\mathbf{E}]_{ij}\right|^2\right\}$ is the estimation error

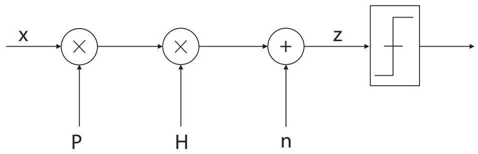

Fig. 3. Downstream signal model.

variance and $\sigma_n \triangleq \mathcal{E}\left\{|n_i|^2\right\}$ is the variance of the noise symbols vector $n_i, \quad \forall i \in \mathcal{U}$. The term $\sum_{j,i\in\mathcal{U}} |[\mathbf{G}]_{ui}|^2 \cdot \delta_{ij} \cdot p_j$ can be interpreted as a residual crosstalk term due to the channel estimation errors, while the last term in (8b) is an increased noise variance caused by the zero-forcing canceler as discussed in [15]. We define the normalized channel estimation error in $[\%]$ used in our simulations as

$$\xi = \frac{\delta_{ij}}{\left|h_{\text{est}}^{ij}\right|^2}. \qquad (9)$$

B. Downstream error model

Figure 3 shows the signal model on a particular subcarrier for downstream communication using the linear *Diagonalizing Precoder (DP)* [10]. The precoding matrix is given as

$$\mathbf{P} = \mathbf{G}\cdot\mathbf{D} = \mathbf{G}\cdot \text{diag}\{h_{\text{est}}^{11}, \ldots, h_{\text{est}}^{uu}, \ldots, h_{\text{est}}^{UU}\}, \qquad (10)$$

where diag$\{\ldots\}$ denotes a matrix within elements in brackets are on its main diagonal. The received symbols vector $\mathbf{z} \in \mathbb{C}^U$ follows as

$$\begin{aligned}\mathbf{z} = \mathbf{H}\cdot(\mathbf{P}\cdot\mathbf{x}) + \mathbf{n} &= (\mathbf{H_{est}} + \mathbf{E})\,(\mathbf{G}\cdot\mathbf{D})\cdot\mathbf{x} + \mathbf{n}\\ &= \mathbf{D}\cdot\mathbf{x} + \mathbf{E}\cdot\mathbf{G}\cdot\mathbf{D}\cdot\mathbf{x} + \mathbf{n}. \qquad (11)\end{aligned}$$

Equivalently, the received symbol for user u can be written as

$$z_u = [\mathbf{D}]_{uu}\,x_u + \sum_{j,i\in\mathcal{U}} [\mathbf{E}]_{ui}\,[\mathbf{G}]_{ij}\,[\mathbf{D}]_{jj}\,x_j + n_u \qquad (12)$$

Under the same assumptions on statistical independence the variance of the received signal z_u can be written as

$$\mathcal{E}\left\{|z_u|^2\right\} = |h_{\text{est}}^{uu}|^2\cdot p_u + \sum_{j,i\in\mathcal{U}} \delta_{ui}\cdot\left|[\mathbf{G}]_{ij}\,h_{\text{est}}^{jj}\right|^2\cdot p_j + \sigma_n. \qquad (13)$$

The second term on the right side in (13) can be interpreted as a residual crosstalk term due to the channel estimation errors.

C. Achievable bitrate formulas

In DSL systems without crosstalk cancellation the theoretically achievable bitrate of user u on tone k assuming perfect CSI is given by [12]

$$r_u = \log_2\left(1 + \frac{|h^{u,u}|^2 p_u}{\Gamma(\sum_{m\in\mathcal{U}\setminus u} |h^{u,m}|^2 p_m + \sigma_n)}\right), \qquad (14)$$

where Γ is the SNR-gap to capacity. An upper-bound on the achievable bitrate of a Vectoring system is hence computable by removing the crosstalk terms as

$$r_u^{\text{ideal}} = \log_2\left(1 + \frac{|h^{u,u}|^2 p_u}{\Gamma\sigma_n}\right), \qquad (15)$$

Based on (8b) the achievable bitrate under imperfect channel estimation of a Vectoring system using a ZF canceler can be written as

$$r_u^{\text{ZF}} = \log_2\left(1 + \frac{p_u}{\Gamma(\sum_{j,i\in\mathcal{U}} |[\mathbf{G}]_{ui}|^2\,\delta_{ij}p_j + \sum_{i\in\mathcal{U}} |[\mathbf{G}]_{ui}|^2\,\sigma_n)}\right), \qquad (16)$$

where a residual crosstalk term and an increased background noise term are present in the denominator. Based on (13) the achievable bitrate under channel estimation errors of a Vectoring system using DP is given by

$$r_u^{\text{DP}} = \log_2\left(1 + \frac{|h_{\text{est}}^{u,u}|^2\,p_u}{\Gamma(\sum_{j,i\in\mathcal{U}} \delta_{ui}|\,[\mathbf{G}]_{ij}\,h_{\text{est}}^{jj}|^2 p_j + \sigma_n)}\right), \qquad (17)$$

where similarly as in the ZF canceler the denominator includes a residual crosstalk term. Furthermore, the multiplication with the precoding matrix **P** results in an SNR reduction [15] which has to be considered during the power allocation process. The expressions in (16) and (17) will be used in the next section for performance evaluation of Vectoring systems.

IV. Simulations

In this section we present performance evaluation results comparing Vectoring systems under imperfect channel estimation to non-vectored DSL systems using DSM under perfect channel estimation, *i.e.*, we focus our analysis on phase errors which do not impact non-vectored systems. Conclusions on these experiments are further supported by more extensive simulations provided in [16]. We use simulation parameters according to the VDSL2 standard ITU G.993.2 [17] with profile 30a, spectral mask definition B7-10 and a maximum transmitted power of $14.5\,$dBm. Furthermore, the ETSI-VDSL-Alien Noise model A [18] has been added to background noise at $-140\,$dBm/Hz. We compare our *energy-efficient Vectoring (EEVectoring)* implementation with the well-known *Iterative Spectrum Balancing (ISB)* algorithm[1] [19]. When not explicitly mentioned otherwise we also use these spectrum management schemes to optimize the Vectoring performance under the residual crosstalk due to channel estimation errors. This way of performance evaluation will be referred to as "error consistent" (VectoringEC). A second, pessimistic way of evaluation is to regard the effect of the error *after* performing the single-user bitloading for all users and subsequently flooring the bitrates on each tone to the next-lower integer value ("VectoringFloor").

[1] Differently from [19] we perform a bisection search over multipliers and a line-search over the bitrates. The (non-discrete) bit-allocation of ISB is then floored and a greedy bit-adaptation applied as in [20] for rate-maximization or as in [21] for power minimization.

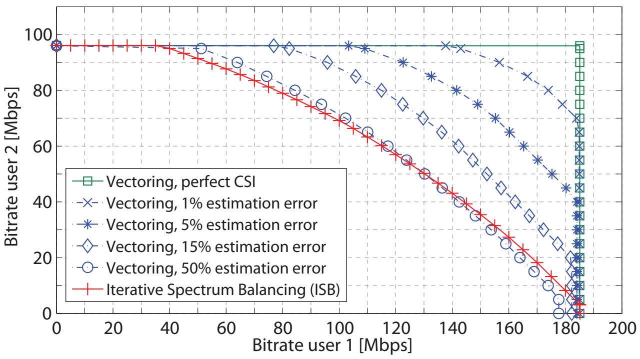

Fig. 4. Upstream rate region with partial CSI in a 2-user distributed scenario with modems located at 300 m and 600 m distance.

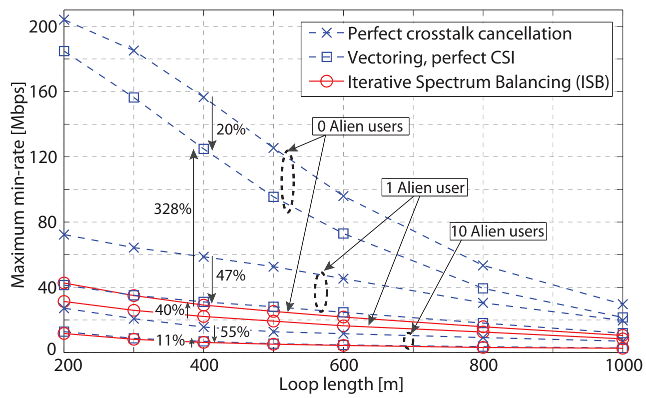

Fig. 5. Per-user bitrate in distributed 10-user upstream scenarios for different loop lengths and number of alien VDSL2 disturbers.

A. Rate maximization under channel estimation errors

Figure 4 shows the rate region achieved in a 2-user distributed upstream scenario with modems located at 300 m and 600 m distance from the deployment point, respectively. An increase of the channel estimation error decreases the rate region for the Vectoring system. Furthermore, considering 50 % of error in channel estimation the rate region of Vectoring and spectrum balancing almost overlap. Similar results and conclusions have been found in the corresponding downstream scenario. Even the single-user rates are affected by the error due to the "self-interference" present in the error models in (8b) and (13), *cf.* Figure 4. Increasing the number of users at 600 m distance in the upstream case to 14 and varying the error between 1 % and 50 % reduces the single-user rate of the shorter line under Vectoring between 0.2 % and 20 % compared to a non-vectored system.

Next we analyze the impact of alien disturbers not included in the Vectoring group, where we assume that these VDSL2 disturbers transmit with power levels according to the spectral mask constraints. Figure 5 shows the impact of these alien users in terms of the per-user bitrate for 10-user distributed upstream scenarios. Scenarios for a loop length of l m were generated by locating 4 lines at $l-100$ m, 3 lines at l m, and 3 lines at $l+100$ m. The gap between the perfect crosstalk cancellation scheme and the Vectoring with perfect CSI is

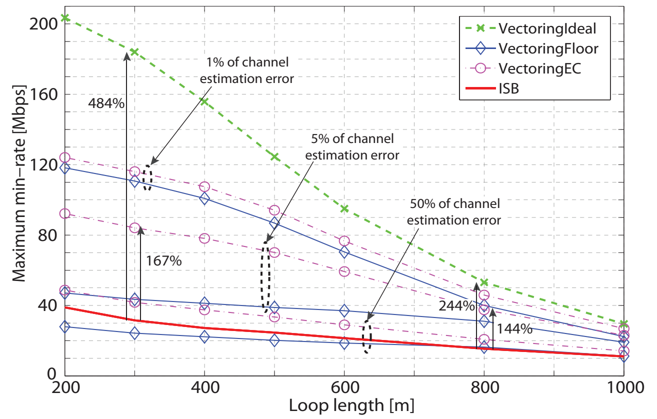

Fig. 6. Per-user bitrate in co-located 10-user upstream scenarios for different loop lengths and channel estimation errors.

due to the noise enhancement causes by the ZF canceler. For example, in the scenario with a $l = 400$ m loop length increasing the number of alien users this gap increases from 20 % with no alien users to 47 %, and 55 % with 1, and 10 alien users, respectively. In the same scenario the achievable bitrate improvement by using ZF based Vectoring compared to ISB decreases from 328 % without alien users to 40 % and 11 % if 1 and 10 alien users are present in the system, respectively. In Figure 6 we show per-user rates for co-located 10-user upstream scenarios. For short, 300 m long loops it is possible to increase the bitrates by more than 400 % assuming perfect CSI. This percentage decreases to 167 % if we consider 5 % of channel estimation error. For 800 m long loops the gain in bitrates is only 244 % and 144 % with and without perfect CSI, respectively. The gap for short loop lengths is smaller in the 2-user case [16] due to the lower crosstalk levels which impact only the spectrum balancing performance. The error in channel estimation degrades the performance of Vectoring, being comparable to that of spectrum balancing when a 50 % error in channel estimation is considered.

B. Energy minimization under channel estimation errors

The objective here is to understand how much energy can be saved by using Vectoring compared to ISB and how the channel estimation error impacts this relation. We cannot establish the power consumption related to the computation needed by using Vectoring. However, we will calculate a limit up to which Vectoring can be still considered energy-efficient. For this purpose we adopt the line-driver (LD) model in [22] to map between transmit power and line-driver power consumption. In Figure 7 we study a distributed 10-user downstream scenario where 4, 3, and 3 users are located at 300 m, 450 m, and 600 m distance from the deployment point, respectively. We plot the LD sum-power as a function of the target rates (up to the max-min rates) for different percentages of channel estimation error. We find that on the ISB rate region border it is possible to save almost 50 % of energy by using Vectoring even when 1 % of channel estimation error is assumed. The gain decreases however when moving inside the ISB rate

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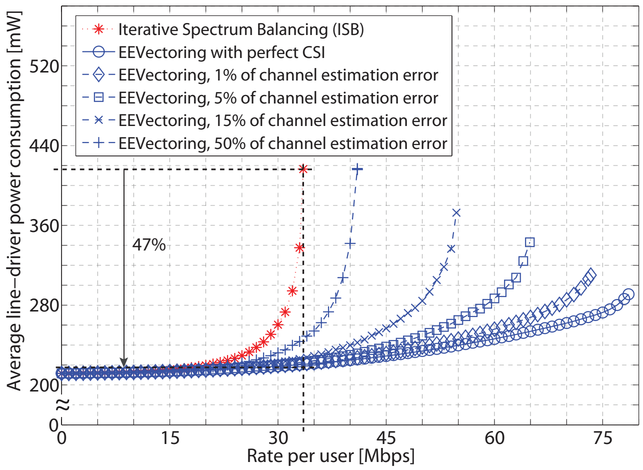

Fig. 7. Line-driver power consumption in a distributed 10-user downstream scenario with partial CSI and target rates evaluated in steps of one Mbps.

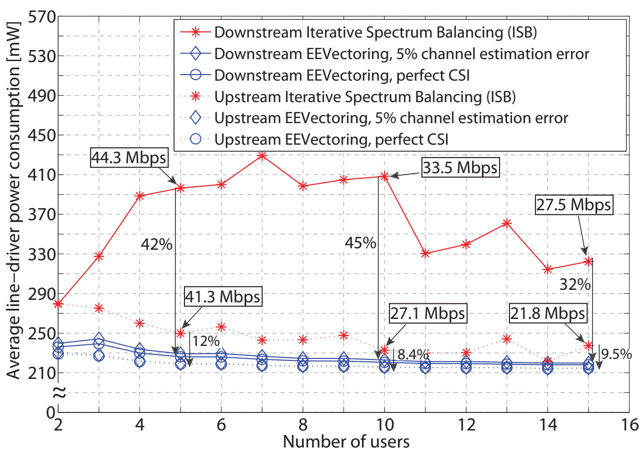

Fig. 8. Average line-driver power consumption at max-min rates for spectrum balancing under imperfect CSI with users distributed at 300 m, 450 m, and 600 m distance.

region. In the corresponding upstream scenario we find that the gain in LD power consumption is lower (only 12 %). This can be explained by the higher crosstalk levels in upstream frequency bands which tendentiously limits the transmit power spectral density (PSD) levels on shared tones at the max-min rate, while the use of large power levels on exclusively used tones is constrained by the spectral mask. Figure 8 shows the LD energy consumption as a function of the number of users for both, upstream and downstream scenarios. Users are distributed at 300 m, 450 m, and 600 m distance, where we generated different scenarios by iteratively adding users to these distances. We compare spectrum balancing to Vectoring at the max-min rates (*i.e.*, on the rate region border) achieved by spectrum balancing. As these max-min rates are lower compared to the maximum achievable max-min rates using Vectoring the curves related to Vectoring with perfect and partial CSI almost overlap, *cf.* also Figure 7. In both, upstream and downstream transmissions the maximum achievable rate decreases under spectrum balancing if the number of users is increased due to the increase of crosstalk interference. Due

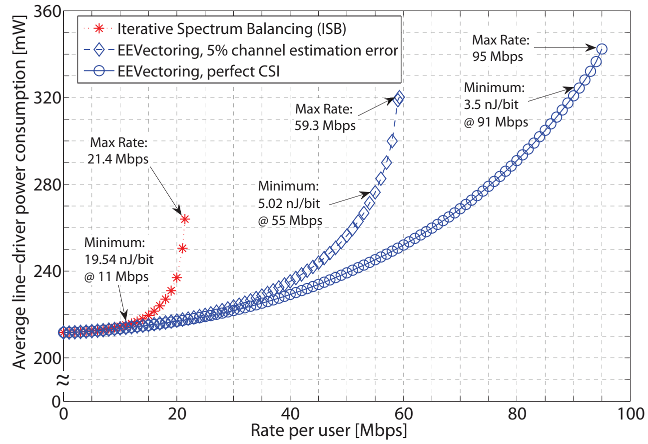

Fig. 9. Average line-driver power consumption at max-min rates for spectrum balancing in a co-located 10-user upstream scenario with 600 m long loops. Rates which resulted in the minimum energy-per-bit are marked.

to the higher upstream crosstalk levels mentioned above the energy savings by Vectoring are more evident in downstream scenarios than in upstream. Confirming the results in the 10-user example in Figure 7 we can conclude that by using Vectoring the LD power consumption can be reduced by around 50 % (or approximately 200 mW) in downstream links, while in upstream this gain is around 12 % (approximately 28 mW).

So far we have considered the energy savings by Vectoring on the spectrum balancing rate region boundary. However, as Vectoring promises higher rates, another meaningful energy-efficiency metric is the energy consumed by the LD per transmitted bit. In Figure 9 we again show the LD power consumption as a function of the target rate, this time for a co-located 10-user upstream scenario with loop lengths of 600 m. Searching exhaustively all target rates on a grid of 1 Mbps step-size we marked the rates which resulted in the minimum energy-per-bit. We see that while this minimum (on the search grid) is rather close to the max-min rates in the case of Vectoring, in case of spectrum balancing it appears at approximately half of its max-min rate. This can be explained by the crosstalk under which a non-vectored system suffers, which strongly influences the energy-per-bit when increasing the bitrate. The illustrated minima in Figure 9 correspond to a gain by Vectoring compared to spectrum balancing of 82 % and 74 % in terms of energy-per-bit, respectively, depending on whether we assume no or 5 % estimation error. In Figure 10 we generalize these results to various 5 and 10-user upstream scenarios by varying the loop lengths, showing the improvement in energy-per-bit by using Vectoring. This improvement decreases with increasing loop lengths or with decreasing the number of users, *cf.* Figure 10. Similarly, the corresponding results for downstream transmission show lower gains by Vectoring due to lower crosstalk levels as explained above. Concluding, considering typical loop lengths (up to 600 m) Vectoring appears to be over 50 % more energy-efficient in terms of energy-per-bit than spectrum balancing, even if 5 % of channel estimation error are considered.

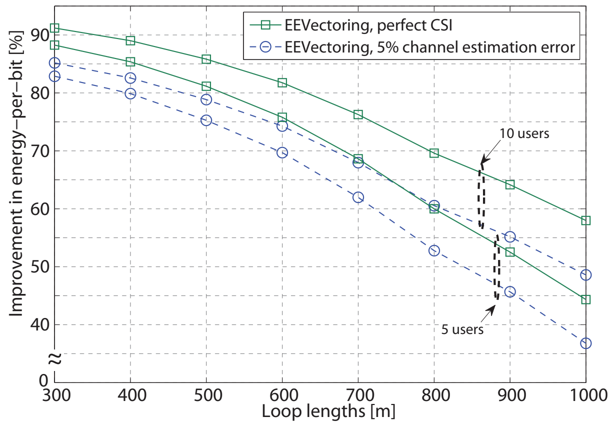

Fig. 10. Improvement in energy-per-bit by Vectoring compared to spectrum balancing for co-located 5 and 10-user upstream scenarios.

C. Future Work

As we considered the 99 % worst case FEXT magnitude model [12] our estimated performance gain by crosstalk cancelation compared to spectrum balancing is an overestimate, especially in scenarios with a large number of users. As future work we plan the use of measured cable data or more realistic channel models such as the stochastic MIMO model in [13]. However, we emphasize that such a model necessitates Monte Carlo simulations for performance evaluation. Furthermore, we have computed the power and bit allocations considering an average noise term due to the channel estimation error. This approximation is similar to the common approach for modeling crosstalk noise, *cf.* Section II-A. An alternative evaluation method is again to make a Monte Carlo simulation considering different combinations of error and data signal realizations. Also, in this work we have quantified energy efficiency in terms of LD power consumption. However, models of the energy consumed for the additional computations and memory usage by Vectoring are needed for a complete analysis of the energy efficiency of Vectoring.

V. Conclusions

We have investigated the potential savings in line-driver power consumption by using Vectoring in multi-user digital subscriber line (DSL) networks compared to a spectrum optimized non-vectored system. We have shown that Vectoring with up to 5 % of channel estimation errors improves the energy efficiency in terms of the line driver energy consumption per bit by more than 45 % in various typical 10-user VDSL2 scenarios. This gain decreases with increasing loop lengths or decreasing the number of DSL lines. The savings in line driver power consumption by Vectoring for max-min rates under the non-vectored system were found to be below 50 %, decreasing with an increasing channel estimation error. In this sense, for a vectored system to be considered more energy-efficient than a non-vectored system using spectrum balancing its additional power consumption for computation and memory must lie below approximately 200 mW, depending on the model in [22] and the network topology.

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