Fairness Tradeoff Analysis during VDSL2 Network Migration – Simulation and Testbed Results

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Abstract—Vectoring very high speed digital subscriber line 2 (VDSL2) lines will coexist with legacy VDSL2 lines during copper access network migration. Without the ability of legacy lines to cooperate for crosstalk channel estimation, Vectoring lines may still suffer from crosstalk noise. We study the spectral protection of Vectoring lines by dynamic upstream power back-off (UPBO) and provide a multiobjective methodology for fairness optimization between legacy and Vectoring lines. Extensive simulation and exemplary testbed results with up to 20 lines illustrate the tradeoff in mean-rate offered to network operators, as well as the effect of various fairness definitions.

I. INTRODUCTION

The latest deployed generation of digital subscriber lines (DSL), Vectoring very-high-speed DSL 2 (VDSL2), is capable of canceling in-domain self-crosstalk and achieves multi-user data-rates beyond 100 Mbps per line over few hundred meters [1]. However, during technology migration legacy and Vectoring VDSL2 lines will coexist in the network. When the legacy lines are not providing the required minimum Vectoring functionality for pilot-based channel estimation [2], Vectoring lines potentially still suffer from uncanceled crosstalk noise with an enormous detrimental impact on performance [3], even in the non-unbundled scenario considered in the following. This problem is especially present in upstream transmission (from user to the network) as the modems are distributed and may not be property or under the control of the operator.

We study the problem of optimizing fairness among lines by controlling the crosstalk noise through upstream power back-off (UPBO) [4], [5] in migration scenarios with a mixture of Vectoring and legacy VDSL2 lines. Our contributions are:

a) A novel multiobjective heuristic based methodology for spectrum management through UPBO parameter optimization, providing the network operator decision support through a diverse set of available performance tradeoffs.

b) The experiment-based comparison of numerous fairness metrics for DSL network migration. Such scalar metrics are important for reducing the number of objectives for tractability of optimization and ease of visualizing results, and for automatically analyzing the impact of the optimization in numerous scenarios. These metrics are based on well-known definitions from literature [6], [7], but also include two novel metrics, one modifying the energy-efficiency metric in [8], and one generalizing the metric in [7] to groups of users.

c) Simulation results on performance gains achievable by dynamic UPBO in mixed legacy/Vectoring VDSL2 networks.

d) Exemplary testbed results with 10 and 20 lines confirming the effectiveness of UPBO seen in simulations.

The article is organized as follows: In Section II we review related work in the field of DSL on mixed legacy/Vectoring VDSL2 networks, on the role of UPBO in Vectoring VDSL2, and on MOO based spectrum balancing (SB). In Section III we describe the system and performance models as well as optimization formulation and algorithms. Simulation results for (deterministically or randomly generated) representative distributed scenarios, as well as testbed results in two scenarios are provided in Section IV, before concluding in Section V.

II. RELATED WORK

A. Mixed Legacy and Vectoring VDSL2 Networks

In [9] the effect of legacy crosstalk on Vectoring lines under a zero-forcing generalized decision feedback equalizer has been analyzed. Algorithms for canceling alien crosstalk in upstream transmission have been proposed in [10], [11]. Differently, in this article we assume a low-complex and in practice deployed linear zero-forcing canceler and no (e.g., SNR-based [2, App. III]) channel estimation functionality between Vectoring and legacy lines. Substantial Vectoring gains despite the presence of non-Vectoring lines are still feasible through SB [12]. Applications of SB for mixtures of Vectoring and non-Vectoring VDSL2 in upstream and downstream direction can be found in [9], [13]. While in [13] a Vectoring minimum-rate maximization is targeted, in [9] the weighted sum-rate of legacy lines is the objective, both, subject to target-rate constraints for the remaining lines. In [14] dynamic line management is considered, e.g., for mixtures of Vectoring and legacy lines in downstream transmission served by a single operator but connected to different access nodes – the suggested methods include maximum-margin limitation for Vectoring lines, maximum power-spectral-density (PSD) limitation for legacy lines, and rate-capping for both line-types. For mixtures of legacy and Vectoring lines in downstream transmission, techniques such as the SNR-based channel estimation method in [2, App. III] or the pilot-based method in [15], and even commercial realizations [16] are available.

Differently, in this work we focus on upstream scenarios with lines served by a single access node and operator, and the
fairness tradeoff among groups of users. Parts of the modems are assumed “non-Vectoring-friendly”, i.e., differently to the partial-Vectoring case [17] the selection of dominant disturbers is not feasible. This may be for instance the case when operators migrate to Vectoring without replacing all legacy VDSL2 modems or without upgrading them to a “Vectoring-friendly” [18] firmware.

B. Upstream Power Back-Off (UPBO) for Vectoring VDSL2

We utilize the standard-compliant [5] UPBO method [4] for upstream spectrum management, cf. [19] for a practical alternative method. While potentially detrimental [20], a mild UPBO setting for all-Vectoring scenarios has been suggested in [21, 22], for example motivated by channel information inaccuracies due to feedback interpolation or finite channel estimation time. UPBO is known to improve the performance in all-Vectoring DSL with residual crosstalk [23] (e.g., due to inaccurate Vectoring coefficients, partial Vectoring of dominant disturbers only, or subloop unbundling) and in partially Vectoring networks [17] with Vectoring-friendly [18] legacy lines. Note that dynamic UPBO optimization is limited to scenarios excluding unbundling, and may be performed on a per-line basis [24]. The authors in [17] conclude that there is no single UPBO parameter set that is optimal for all cases, which motivates their network-specific dynamic optimization.

Differently to previous work on UPBO, we focus on a) the specific VDSL2 migration use-case (i.e., no classical “near-far” scenario, but a protection of Vectoring lines against disturbance from legacy lines); b) the fairness tradeoff among user groups with potentially different UPBO parameters; and c) a global multiobjective optimization (MOO) methodology for setting UPBO parameters. Furthermore, the applied model of crosstalk from legacy into Vectoring lines incorporates the effects of the crosstalk cancellation technique.

C. Multiobjective Spectrum Balancing

For MOO, evolutionary heuristics have shown to be and efficient tool [25]. While these allow for black-box optimization, they are fairly limited in the number of optimization variables compared to nonlinear programming or even convex optimization. Hence, we opt for UPBO as a low-dimensional spectrum management approach. Note that our MOO formulation for spectrum management in DSL is different to that in [26]. In [26] MOO is applied to adapt the weights for weighted sum-rate maximizing coordinated multi-user SB. The main advantages of our methodology compared to that in [26] are the low complexity (using low-complexity single-user bit-loading based performance evaluation; no coordinated SB algorithm is required since we directly optimize the power allocation), realism of the simulation-based performance model (e.g., compared to analytical models), and applicability for non-convex problems in which the weighting method as applied in [26] does not guarantee to find all Pareto solutions [25, Ch. 1]. In fact, our simulation results indicate that the UPBO fairness-regions and rate-regions investigated in this article may indeed be non-convex.

III. UPBO OPTIMIZATION METHODOLOGY

We assume a mixed Vectoring and legacy VDSL2 network, employing frequency division duplexing and discrete multitone (DMT) modulation, which is assumed to be perfectly synchronized. This leaves us with the far-end crosstalk (FEXT) as the main performance limitation.

A. Performance Model

We assume a linear zero-forcing canceler applied to |U| Vectoring lines indexed by \( I = \{1, \ldots, |U|\} \), \( i(u) \in I \) denoting the index corresponding to Vectoring line \( u \in U \). We denote the channel for all lines and the subset of Vectoring lines on tone \( c \) by \( G_c^u \in \mathbb{C}^{|I| \times |U|} \) and \( G_c \in \mathbb{C}^{|I| \times |U|} \), respectively, and write the inverse as \( F_c^u = (G_c^u)^{-1} \) and direct channel gains as \( H_{u,u} = |G_{u,u}^c|^2, \forall u \in U \). We refer to [27] on the modeling of channel estimation errors. The number of loadable bits of user \( u \in U \) on tone \( c \in C \) is approximated by

\[
\tau_c^u(v) = \log_2 \left( 1 + \frac{H_{u,u}^c p_c^u(v)}{\Gamma(\sum_{j \in U} H_{u,j}^c p_c^j(v) + \sigma_u^c)} \right),
\]

where \( v \in \mathbb{R}^N \) are the \( N = (4 \cdot M) \) UPBO parameters \( \alpha \) and \( \beta \) for each of the \( M \) frequency bands for Vectoring and legacy lines, respectively, \( p_c^u(v) [\text{mW}] \) is the transmit power of user \( u \) on tone \( c \), while the crosstalk gains \( H_{u,j}^c \) among Vectoring lines \( u, j \in U \) are due to potential channel estimation errors, and crosstalk cancelation results in an increased noise \( \sigma_u^c \) compared to the additive white Gaussian background noise \( \bar{\sigma}_u^c \) on Vectoring lines \( u \in U \), while \( \sigma_u^c = \bar{\sigma}_u^c, \forall u \in U \) [27]. Additionally, the effective crosstalk gain from a legacy line \( j \in \bar{U} \) into a Vectoring line \( u \in U \) depends on its couplings into all Vectoring lines as \( H_{u,j} = H_{u,u}^c \cdot \tau_{j,u}^c \cdot \sum_{i \in U} |F_{i,j}^c|^2 |G_{i,j}^c|^2 \), while the crosstalk gains \( H_{u,j}^c = |G_{u,j}^c|^2 \) from Vectoring lines \( j \in \bar{U} \) into legacy lines \( u \in U \) are not impacted by Vectoring.

The transmit power \( p_c^u(v) \) is computed by discrete bit-loading under a maximum sum-power \( P_{\text{MAX}}^u \), a spectral mask \( \tilde{p}_c^u \), a limit on the number of loadable bits, and the transmit power limit \( (1/H_{u,u}^c) \cdot 10^{p_{\text{MAX}}^u/(10 \log_{10} M)} \), with received power limit \( p_{\text{MAX}}^c = -\alpha - \beta f_c \), where \( f_c \) is the frequency of tone \( c \) in [MHz], being imposed by the UPBO parameters \( \alpha \) and \( \beta \) associated with the spectral band containing tone \( c \). As in real systems bit-loading is performed independently among lines, where the maximum transmit power based crosstalk noise is assumed for deterministic performance evaluation. Note that this approach leads to a low-complexity performance evaluation per UPBO setting, and therefore enables the population-based global search scheme described in Section III-C. We use three methods for generating the channel \( G_c^u, c \in C \), in our simulations: a) the reproducible and commonly used worst-case crosstalk model and direct channel model1 “TP100” [29], with phase-models as summarized in [27], for simulations in Section IV-A; b) the model in a) modified by the stochastic crosstalk model in [30] in Section IV-B; and c) the channel information as provided by DSL equipment (direct and crosstalk

1We refer to [28] for a publicly available DSL simulator.
channel [31, Sec. 11.2.2.1] and background noise) for testbed results in Sections IV-C and IV-D.

We remark that in practical implementations the crosstalk channel among groups of lines is most likely unknown to operators, and hence needs to be approximated, e.g., based on known cable models, loop-lengths, and worst-case crosstalk models [32], or based on noise measurements [33, Ch. 3]. Alternatively, in [34] aggregated/normalized crosstalk coefficients among all lines have been estimated in a single step (joint reinitialization of all modems) by noise measurements reported by the modems. In [35] crosstalk coefficients are estimated in \(|U|\) steps based on single-input / multiple-output noise measurements. In [36] the lines are grouped into \(G\) subgroups, which reduces the number of crosstalk measurements needed for spectrum management to \(G \times |U|\). In summary, approximate aggregated/normalized crosstalk coefficients as need in our study are readily obtained by a straightforward extension of the scheme in [34] to multiple user-groups, requiring as many modem reinitializations as groups of lines.

B. Fairness Metrics

We define a set of nine rate and power fairness metrics partially adapted from literature which scalarize the performance of user-groups. This will in the next section allow us to analyze the tradeoff between the fairness metrics of Vectoring and legacy VDSL2 user-groups, respectively. We define a user’s sum-rate in \([\text{Mbps}]\) as \(s_u(v) = (R/10^6) \cdot \sum_{c \in C} R_c(v)\) and its transmitted sum-power in \([\text{mW}]\) as \(t_u(v) = \sum_{c \in C} P_{c,u}(v)\), where \(R\) is the DMT-symbol-rate. Furthermore, we specify three reference scenarios, that are a) the single-line case \([25]\), resulting in a sum-rate \(\frac{1}{|U|} \sum_{u \in U} s_u(v)\) and corresponding sum-power \(\frac{1}{|U|} \sum_{u \in U} t_u(v)\) \([\text{mW}]\); b) the rates when either only Vectoring lines or only legacy lines are active (the “group ideal point”), resulting in a sum-rate \(\frac{1}{|U|} \sum_{u \in U} s_u(v)\) and corresponding sum-power \(\frac{1}{|U|} \sum_{u \in U} t_u(v)\) \([\text{mW}]\); and c) the case when no coexistence measures through UPBO are taken in the multiuser network, resulting in a sum-rate \(\frac{1}{|U|} \sum_{u \in U} s_u(v)\) and corresponding sum-power \(\frac{1}{|U|} \sum_{u \in U} t_u(v)\) \([\text{mW}]\), \(u \in U\).

1) Fairness Definitions from Literature: A wide set of fairness metrics can be derived from the generic \(\alpha\)-rate-fairness [6], such as the system optimal rate fairness (ORF), \(f_{\text{ORF}}(U, v) = \frac{1}{|U|} \sum_{u \in U} s_u(v)\), proportional rate fairness (PRF), \(f_{\text{PRF}}(U, v) = \frac{1}{|U|} \sum_{u \in U} \log(s_u(v))\), maximum rate fairness (MRF), \(f_{\text{MRF}}(U, v) = \min_{u \in U}(s_u(v))\), and harmonic mean rate fairness (HMF), \(f_{\text{HMF}}(U, v) = (\frac{1}{|U|} \sum_{u \in U} s_u^{-1}(v))^{-1}\). Additionally we consider the similar metrics of geometric-mean-rate fairness (GMF), \(f_{\text{GMF}}(U, v) = (\prod_{u \in U} s_u(v))^{1/|U|}\), and balanced capacity fairness (BCF) [7], \(f_{\text{BCF}}(U, v) = \min_{u \in U}(\frac{s_u(v)}{s_{\text{min}}})\), where the latter metric incorporates the ideal point.

In [37] a “greening fairness index” has been proposed which takes the performance of the network before optimization into account, and leads us to a joint rate and power fairness (RPF) defined as \(f_{\text{GRF}}(U, v) = \frac{1}{|U|-1} \left( \frac{\sum_{u \in U} x_u}{|U|} \right)^2 - 1\), where \(x_u = \frac{s_u(v)}{d(t_u(v))}\).

2) Two Novel Fairness Metrics: We define a similar metric to BCF with relevance for network migration, obtained by exchanging the minimum by the mean and the normalization by the ideal point with with one by the group ideal point, resulting in a “balanced group fairness” (BGF) defined as

\[
f_{\text{BGF}}(U, v) = \frac{1}{|U|} \sum_{u \in U} \left\{ \frac{s_u(v)}{s_{\text{min}}} \right\}.
\]

Our second proposed metric is based on [8] where the power consumption \([\text{mW}]\) per \([\text{Mbps}]\) of data-rate and loop-length \([\text{km}]\) has been proposed as a metric for fixed broadband access networks, implicitly taking the operator objectives and reach into account. The hardware block in currently deployed DSL transceivers that is mainly affected by a transmit power reduction is the line-driver. Hence, in order to arrive at an analytical model for the metric in [8] we apply the simple parameterized class-AB line-driver model for VDSL2 (17 MHz) in [38], with the function mapping transmitted sum-power \(t_u\) to line-driver power consumption given by \(d(t_u) = 144.9 + 42.7 \cdot \sqrt{t_u} \text{ [mW]}\). Combining the wireline energy-efficiency metric with this power consumption model we define energy-efficiency fairness (EEF) as

\[
f_{\text{EEF}}(U, v) = \frac{\sum_{u \in U} s_u(v) \cdot L_u}{\sum_{u \in U} d(t_u(v))}.
\]

C. Optimization Formulation and Algorithms

Taking the EEF metric as an example, the fairness tradeoff between legacy and Vectoring lines is approached by maximizing the vector-valued fairness function \(f(v) = [f_{\text{GRF}}(U, v), f_{\text{ORF}}(U, v)]\), and is similarly defined for the other fairness metrics above. Our mutiobjective problem of fairness maximization in mixed Vectoring and legacy DSL networks is given as

\[
\min_{v \in \mathcal{V}} f(v)
\]

subject to \(s_u(v) \geq S_u, \forall u \in U\),

where \(S_u\) \([\text{Mbps}]\) denotes the minimum sum-rate for user \(u \in U\), and \(\mathcal{V}\) is the set of feasible UPBO parameter vectors obeying boundary constraints set by standards [39]. Other system constraints (maximum sum-power, power-spectral mask, bit-loading restrictions) are considered implicitly during bit-loading, cf. Section III-A.

For optimizing the constrained multiobjective problem in (4) we use the population-based evolutionary algorithm selected and parameterized in [40], based on a generalized form of differential evolution combined with tournament selection as the mating strategy, with a population size of 200 and a restriction on the run-time of 200 iterations.\(^2\) In the following sections we optimize the UPBO parameters separately for Vectoring and legacy lines on 3 spectral bands, yielding in total 12 optimization variables. The variables \(v\) are in \([\text{dBm/Hz}]\) as

\(^2\)This amounts to a run-time of approximately 14 minutes per optimization problem on the used Intel 8-core system at 3.2 GHz with 8 GB RAM.
searching in logarithmic scale is natural due to the logarithmic relationship between power and rate, cf. also the logarithmic variable transformation applied in [41] to an SB problem.

For comparison we additionally adapt the heuristic low-complexity combinatorial SB algorithm in [42]. It considers per-tone bit-loading subproblems and a linear master problem for ORF. Differently, for PRF the master problem is separable convex. The result of this algorithm is a single sum-fairness maximizing point on the tradeoff curve.

We remark that population-based global search approaches as the one presented in this article are most suitable for simulation-based/offline and/or multiobjective optimization. For the UPBO optimization with modems in the loop, local-search techniques [34] might be a suitable extension of this work.

IV. VDSL2 EXPERIMENT RESULTS

We assume a VDSL2 network with \( |\mathcal{U}| = 10 \) lines (in Section IV-D \( |\mathcal{U}| = 20 \) lines) among which the first half of the lines form a Vectoring group. Furthermore, we select a minimum rate of \( S_u^{\text{min}} = 1 \text{Mbps} \), band plan “998ADE17-M2x-A”, which uses bands US0 above POTS, US1, and US2, a total SNR gap of \( \Gamma = 12 \text{dB} \) (including 6 dB SNR margin), a maximum sum-power of \( P_u^{\text{max}} = 14.5 \text{dBm} \), a bit-cap of 15 bits, and perfect Vectoring channel estimation, \( \forall u \in \mathcal{U} \).

Furthermore, in simulations we use a flat background noise of \(-130 \text{dBm/Hz}\). Note however that, as remarked in [13], different lines may be configured differently in practice, e.g., with respect to their service profile, noise protection, etc. For comparison standard UPBO parameters as suggested in [29, Sec. 8.1.6] under “Noise F” are chosen. The channel models for the following sections were mentioned in Section III-A. The network topologies are deliberately selected to reflect migration scenarios, i.e., we make no distinction among Vectoring and legacy VDSL2 lines in terms of loop-lengths.

A. Simulation Results – Distributed Network Topology

A distributed scenario is generated by selecting the loop-lengths \( L_u \) of users \( u \in \mathcal{U} \) as \( L_1 = L_4 = L_7 = L_{10} = 200 \text{m} \), \( L_2 = L_5 = L_8 = 400 \text{m} \), and \( L_3 = L_6 = L_9 = 600 \text{m} \).

Figures 1 and 2 show the obtained fairness tradeoffs and sum-fairness maximizing solutions in terms of mean-rates for Vectoring and legacy lines, respectively. Differently, Figure 3 shows the fairness objective tradeoffs, where a normalization was applied based on maximum rates (the ideal point), minimum rates \( S_u^{\min}, u \in \mathcal{U} \), and corresponding transmit sum-powers by single-user bit-loading, and maximum per-user sum-powers. Objective functions not shown in Figures 1 and 3 lead to similar results as the regions under sum-rate maximization. However, different fairness metrics applied to the same rates may select different points under sum-fairness maximization. Metrics involving the transmit power (EEF and RPF) and MRF are not necessarily on the boundary (Pareto solutions) of the shown mean-rate tradeoff, and the tradeoffs provided by RPF are negligible, cf. Figure 1. Regarding Figure 2 we find that different sum-fairness maximizing solutions show diverse tradeoffs between the mean-rates of Vectoring and legacy lines. For instance, the group ideal rates for ORF favor the mean-rate of Vectoring lines. This is due to the
larger achievable rates by Vectoring lines, which are largely influenced by crosstalk and hence demand for a low mean-rate of legacy lines. In Figure 3 we show, additional to the tradeoff curves obtained by MOO, the sum-PRF and sum-ORF maximizing solutions obtained by SB [42], which are only marginally better than the corresponding UPBO solutions.

**B. Simulation Results – Random Network Topologies**

In this section we randomly generate network topologies by independently sampling the lines’ lengths from a log-normal distribution $Y = \exp(X), X \sim \mathcal{N}(\mu, \sigma^2)$, with parameters $\mu = 5$ and $\sigma = 0.7$ (resulting in a mean length of 190 m). Furthermore, differently to the previous section we use a stochastic crosstalk channel model [30]. The UPBO optimization results for all proposed fairness metrics on a set of 650 thereby generated scenarios are summarized in Table I based on a) the average ratio between mean-Vectoring and mean-legacy rates at the sum-fairness maximizing point; b) the network-wide mean rate; and c) the mean gain/loss in Vectoring/legacy mean-rates at sum-fairness maximizing UPBO settings. Note that the maximum gain in mean Vectoring rates as found under metric ORF amounts to 43 Mbps. As in the distributed example above the sum-fairness maximizing UPBO setting under the metrics BGF, and RPF lead to similar mean-rates as in the no-protection case, rendering them rather unsuitable for the spectral protection of Vectoring lines. Differently, the metrics BCF, MRF, ORF, HMF, GMF lead to the largest gains in mean Vectoring rates, with BCF and MRF incurring the largest losses in mean legacy VDSL2 rates.

**C. Testbed Results – Distributed 10-user Network Topology**

Next we compare results obtained from a Vectoring VDSL2 testbed with the distributed network topology described in Section IV-A, using 10-pair 0.6 mm cables typically deployed in the Austrian access network. Similarly as in Figure 2 for the model-based channel setup, in Figure 4 we compare the mean-rates obtained on our testbed for UPBO settings maximizing the sum-fairness between Vectoring and legacy lines. While the results are qualitatively similar, the lower crosstalk couplings in the studied cables leads to higher achievable mean-rates for legacy lines. As an exemplary result, compared to the standard UPBO settings the sum-rate maximizing (ORF) dynamic UPBO solution sacrifices 14.65 Mbps in mean legacy rates in order to boost the mean Vectoring rates by 21.9 Mbps.

**D. Testbed Results – Collocated 20-user Network Topology**

Our second testbed scenario consists of $|U| = 20$ collocated lines, with a mixture of 10 Vectoring modems (lines $u \in \{1, \ldots, 10\}$) and 10 legacy VDSL2 modems (lines $u \in \{11, \ldots, 20\}$), using a 250 m long Danish cable of type CU/SPPE/NAP/PAP/L+PE consisting of 20 pairs with 0.5 mm diameter. Figure 5 illustrates the achieved tradeoffs between the two groups of modems. Without UPBO the mean-line-rates of both modem groups are comparable (at around 40 Mbps). Under the settings optimized for maximizing the sum of mean-line-rates per group the mean Vectoring line-rates are boosted to 63.1 Mbps, which is close to the maximum line-rates supported by the modems, while the mean legacy line-rates drop to 10.1 Mbps. The UPBO parameters corresponding to the sum-rate maximizing point are detailed in Table II.

**V. CONCLUSIONS**

A multiobjective upstream power back-off (UPBO) optimization problem is proposed in order to arrive at a fair tradeoff between the data-rates of jointly deployed groups of Vectoring and legacy very-high speed digital subscriber line 2 (VDSL2) lines, respectively. The proposed multiobjective optimization methodology provides diversity in user rates while allowing for low-complexity performance calculations and realistic simulation-based system models. Simulation results as
well as exemplary tested experiments demonstrate that sum-fairness-maximizing UPBO and multiobjective optimization are valid decision support tools for network operators by providing a diverse set of network operation points.

REFERENCES


