DYNAMIC UPSTREAM POWER BACK-OFF FOR MIXTURES OF VECTORED AND NON-VECTORED VDSL

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ABSTRACT

Far-end crosstalk severely degrades upstream rates in mixtures of vectored and non-vectored Very high-speed Digital Subscriber Loops (VDSL). As replacement of non-vectored VDSL systems by vectored VDSL systems is expected to be gradual, a crucial problem is the upstream rate optimization of vectored lines while maintaining the rate targets of non-vectored lines. To address this problem, this paper describes an algorithm that selects suitable Upstream Power Back-Off parameters for the vectored and the non-vectored lines. The algorithm has much lower computation requirements compared to Optimal Spectrum Balancing (OSB), yet simulation results show that the achievable vectored rates are very close to the OSB theoretical limits.

***Index Terms*—**Digital subscriber line, dynamic spectrum management, upstream power back-off, vectored VDSL

1. INTRODUCTION

Very high-speed Digital Subscriber Loop (VDSL) systems [1] are degraded in the upstream direction by crosstalk from shorter loops coupling into longer loops. This well-known effect, which resembles the "near-far" problem in wireless communications, can be mitigated through the application of Upstream Power Back-Off (UPBO) [2], [3].

Vectored VDSL systems use crosstalk cancellation to improve performance in the downstream and upstream directions [4]. In a deployment with all lines operating in vectored VDSL mode, crosstalk has only marginal effects on performance. But in practice, replacement of non-vectored VDSL systems by vectored VDSL systems is expected to be gradual, and mixtures of vectored and non-vectored VDSL systems will be present in access networks for many years [5]. For the *downstream* direction, Dynamic Spectrum Management (DSM) techniques for reducing the impact of crosstalk from the non-vectored lines to the vectored lines have been previously described in [5], [6], [7].

This paper proposes a DSM technique to improve performance in the *upstream* direction for mixtures of vectored and non-vectored VDSL. The technique relies on the UPBO feature of VDSL [1], but requires a Spectrum Management Center (SMC) [8] to compute and configure the UPBO parameters of the vectored and non-vectored lines. Compared to Optimal Spectrum Balancing (OSB) [9], the proposed technique has much lower computation and configuration requirements. As opposed to Mixed-binder Multi-level Water-filling [10], the method of this paper requires no changes to current VDSL [1] or vectored VDSL [4] standards.

The rest of this paper is organized as follows. Section 2 briefly reviews the system model and formulates the problem. The solution is described in Section 3, while simulation results are provided and discussed in Section 4. Section 5 generalizes the proposed solution to multiple vectored user groups. Finally, conclusions are drawn in Section 6.

2. SYSTEM MODEL AND PROBLEM FORMULATION

Fig. 1 shows the system model used in this paper for investigating the co-existence of vectored and non-vectored VDSL. There are N_1 lines of various lengths connected to a vectored VDSL access node and operating in vectored VDSL2 mode [4]. There are also N_2 lines of various lengths connected to a non-vectored (legacy) VDSL access node and operating in VDSL2 mode [1]. The two access nodes are co-located, and the $N_1 + N_2$ lines are part of the same copper cabling over a certain length, thus experiencing Far-End Crosstalk (FEXT). These two access nodes are connected to an SMC, which is capable of programming all physical-layer control parameters of the $N_1 + N_2$ lines [8].

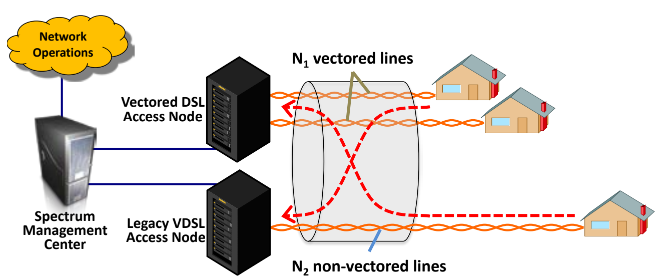

Fig. 1. Mixed deployment of vectored and non-vectored VDSL: N_1 lines use vectored VDSL and N_2 non-vectored lines use VDSL.

The system model of Fig. 1 corresponds to a deployment plan for gradual replacement of non-vectored VDSL equipment. The results obtained with this system model are also applicable to the case of a single vectored VDSL access node (no legacy VDSL access node), but with N_1 lines connected to vectoring-enabled Customer Premises Equipment (CPE), and N_2 lines to non-vectored (legacy) CPE.

Traditionally, non-vectored VDSL systems employ the UPBO feature from the VDSL2 standard [1] to mitigate the level of upstream FEXT from shorter loops to longer loops. UPBO limits the upstream transmit PSD mask of user (line) k to a reference PSD compensated for loop-attenuation:

$$p_k(n) = \underbrace{-\alpha - \beta(f_n)^{0.5}}_{\text{reference PSD}} + \underbrace{\ell_k(f_n)^{0.5}}_{\text{loop-attenuation compensation}} \text{(dBm/Hz)}, \qquad (1)$$

where $p_k(n)$ represents the maximum transmit PSD that user k can allocate to the n^{th} subcarrier, ℓ_k denotes the electrical length of user k, and f_n represents the n^{th} subcarrier frequency in MHz; α and β are configurable UPBO parameters with the following constraints: $40 \le \alpha \le 80.95$, $0 \le \beta \le 40$. After α and β have been specified, each user applies UPBO independently. UPBO requires no coordination among users and no knowledge of the crosstalk channel. Typically, the values of α and β are fixed for the users in the entire network, and are chosen based on the desired performance goals. An efficient method to optimize α and β for a given upstream rate target is presented in [11].

The loop mixture of vectored and non-vectored VDSL in Fig. 1 leads to crosstalk effects different from those with only non-vectored VDSL. FEXT is greatly reduced among vectored lines, but remains among non-vectored lines, and between non-vectored and vectored lines. In general, the upstream rate target of vectored lines is expected to be substantially higher than that of non-vectored lines.

These observations suggest that using common values of α and β for both vectored and non-vectored lines is not the best solution, and that performance gains can be achieved by applying different α and β to each of the vectored and non-vectored groups of lines. This paper proceeds to describe an algorithm executed by an SMC to compute values α_1 and β_1 for UPBO on the N_1 vectored lines, provided that α_2 and β_2 have been selected for UPBO on the N_2 non-vectored lines.

3. DYNAMIC UPSTREAM POWER BACK-OFF

Consider a DSL network where all the lines originally used non-vectored VDSL with an optimized UPBO configuration (α_2, β_2) to achieve the target upstream rate R_2 [11]. Now N_1 lines are upgraded to vectored VDSL as shown in Fig. 1. An upstream power control algorithm for the mixture of vectored and non-vectored VDSL is next described. This algorithm, implemented by an SMC, determines the UPBO configuration values, α_1 and β_1, to be used by the set of N_1 vectored lines given R_2 and (α_2, β_2) as inputs. The other loop-mixture information that the algorithm accepts as inputs: the maximum loop length, L_1, and the number of lines, N_1, of the set of vectored lines, and the maximum loop length, L_2, and the number of lines, N_2, of the set of non-vectored lines. It is expected in general that L_1 is shorter than or equal to L_2.

The search for α_1 (or for β_1) uses simulation to compute the upstream data rates of the vectored and non-vectored lines. Computing the data rates requires the use of a crosstalk model for an assumed binder group. The N_1 vectored lines and the N_2 non-vectored lines are randomly assigned within the binder, and their rates are then estimated. A large number, M, of Monte-Carlo runs is executed with different random assignments, and data rates are recorded for each run. The results are $M \times N_1$ data rates of vectored lines and $M \times N_2$ data rates of non-vectored lines. If all the $M \times N_2$ data rates of non-vectored lines are equal to or larger than R_2, then the UPBO values (α_1, β_1) used by the set of vectored lines are declared feasible, and the minimum among the $M \times N_1$ data rates of vectored lines is saved as R_1. The search continues for α_1 (or for β_1) with a goal to achieve a higher value for R_1. A slightly different implementation of the algorithm seeks to maximize the worst-case p^{th} percentile of the $M \times N_1$ vectored rates instead of the minimum value. The algorithm is next described for a loop mixture $\mathcal{M}(\mathcal{M}_{\mathcal{V}}, \mathcal{M}_{\mathcal{L}})$ where $\mathcal{M}_{\mathcal{V}}$ and $\mathcal{M}_{\mathcal{L}}$ stand for the sets of vectored and non-vectored lines, respectively.

Algorithm 1 Determine UPBO configuration for $\mathcal{M}_{\mathcal{V}}$

inputs:
  L_1, L_2, maximum loop lengths in $\mathcal{M}_{\mathcal{V}}$, $\mathcal{M}_{\mathcal{L}}$, resp.
  N_1, N_2, numbers of users in $\mathcal{M}_{\mathcal{V}}$, $\mathcal{M}_{\mathcal{L}}$, resp.
  R_2, target rate in $\mathcal{M}_{\mathcal{L}}$
  (α_2, β_2), pre-optimized UPBO parameters for all lines in $\mathcal{M}$ to achieve R_2 before $\mathcal{M}_{\mathcal{V}}$ upgraded to vectored VDSL
outputs:
  (α_1, β_1), optimized UPBO parameters for $\mathcal{M}_{\mathcal{V}}$
procedure:
  let $\mathcal{M}'(\mathcal{M}'_{\mathcal{V}}, \mathcal{M}'_{\mathcal{L}})$ be a loop mixture obtained from
    extending the N_1 lines in $\mathcal{M}_{\mathcal{V}}$ to loop length L_1
    extending the N_2 lines in $\mathcal{M}_{\mathcal{L}}$ to loop length L_2
  $\alpha_1 \coloneqq \alpha_2$; $\alpha_{11} \coloneqq \alpha_2$;
  $\beta_1 \coloneqq \beta_2$; $\beta_{11} \coloneqq \beta_2$;
  $R_1 \coloneqq -\infty$; $R_{11} \coloneqq 0$;
  while $(R_{11} > R_1 + \varepsilon)$ **do**
    $\alpha_1 \coloneqq \alpha_{11}$; $\beta_1 \coloneqq \beta_{11}$; $R_1 \coloneqq R_{11}$
    find $\alpha_{11} \in [\alpha_1, 80.95]$ that
      maximizes the minimum rate R_{11} in $\mathcal{M}'_{\mathcal{V}}$
      when (α_{11}, β_1) are applied to $\mathcal{M}'_{\mathcal{V}}$,
      when (α_2, β_2) are applied to $\mathcal{M}'_{\mathcal{L}}$, and
      subject to all rates in $\mathcal{M}'_{\mathcal{L}} \ge R_2$
    find $\beta_{11} \in [0, \beta_1]$ that
      maximizes the minimum rate R_{11} in $\mathcal{M}'_{\mathcal{V}}$
      when $(\alpha_{11}, \beta_{11})$ are applied to $\mathcal{M}'_{\mathcal{V}}$,
      when (α_2, β_2) are applied to $\mathcal{M}'_{\mathcal{L}}$, and
      subject to all rates in $\mathcal{M}'_{\mathcal{L}} \ge R_2$

The algorithm has two important components. First, the loop topology is simplified to make the vectored line lengths all equal to L_1, and the non-vectored line lengths equal to L_2. This new mixture is denoted by $\mathcal{M}'(\mathcal{M}'_{\mathcal{V}}, \mathcal{M}'_{\mathcal{L}})$. Second, an iterative procedure is followed to determine the values of α_1 and β_1. The initial values of α_1 and β_1 are the same as the corresponding values, α_2 and β_2, of the non-vectored lines. A new value for α_1, and then a new value for β_1 are determined in each iteration such that the new value of α_1 is always larger than or equal to the previous value, and the new value of β_1 is always smaller than or equal to the previous value. These updated α_1 and β_1 favor the higher frequencies and penalize the lower frequencies, so that the (shorter) vectored lines will cause less interference on the (longer) non-vectored lines that mostly utilize the lower frequencies for transmission. Each iteration monotonically increases the minimum (or the worst-case p^{th} percentile) among the upstream rates of the vectored lines. The iterations stop when the rate improvement becomes insignificant (or zero).

The simplification of mixture topology is an important step that achieves the following: first, it simplifies the crosstalk model for the assumed binder group. Second, it leads to a choice of (α_1, β_1) that can be used with (α_2, β_2) by any mixture to support the optimized vectored rate R_1 and the non-vectored rate target R_2, provided that the maximum loop length of the N_1 vectored lines is equal to or less than L_1, and the maximum loop length of the N_2 non-vectored lines is equal to or less than L_2. This claim is formally described and proved in Lemma 1.

Lemma 1. *In Algorithm 1, if $\mathcal{M}'_{\mathcal{V}}$ and $\mathcal{M}'_{\mathcal{L}}$ can achieve R_1 and R_2, respectively, by using (α_1, β_1) in $\mathcal{M}'_{\mathcal{V}}$ and (α_2, β_2) in $\mathcal{M}'_{\mathcal{L}}$, then $\mathcal{M}_{\mathcal{V}}$ and $\mathcal{M}_{\mathcal{L}}$ can achieve R_1 and R_2, respectively, by using (α_1, β_1) in $\mathcal{M}_{\mathcal{V}}$ and (α_2, β_2) in $\mathcal{M}_{\mathcal{L}}$.*

Proof: Suppose (α_1, β_1) and (α_2, β_2) are used for the lines in $\mathcal{M}_{\mathcal{V}}$ and $\mathcal{M}_{\mathcal{L}}$, respectively. The FEXT channel model [12] states that the upstream interference signal power transmitted from user j and received by user k at the n^{th} subcarrier is

$$\underline{\mathrm{FEXT}}_{k,j}(n) = \delta \cdot d_{k,j} \cdot (f_n)^2 \cdot p_j(n) \cdot |h_j(n)|^2 \quad (\mathrm{mW}), \quad (2)$$

where δ is a constant, $d_{k,j}$ means the overlapping loop length between user j and user k, f_n denotes the n^{th} subcarrier frequency, $p_j(n)$ stands for the maximum transmit PSD that user j can allocate to the n^{th} subcarrier, and $h_j(n)$ represents the direct channel coefficient of user j at the n^{th} subcarrier. The overlapping loop lengths $d_{k,j}$ can only become smaller when the loop topology is transitioned from $\mathcal{M}'$ to $\mathcal{M}$. Moreover, $p_j(n) \cdot |h_j(n)|^2$ is always the same in $\mathcal{M}'$ and $\mathcal{M}$ because of the UPBO loop-attenuation compensation term in (1). Thus, $\underline{\mathrm{FEXT}}_{k,j}(n)$ for $\mathcal{M}$ is always smaller than or equal to that for $\mathcal{M}'$; every user has a signal-to-noise ratio in $\mathcal{M}$ larger than or equal to that in $\mathcal{M}'$, which proves the claim. □

Algorithm 1 can be executed by an SMC to compute the UPBO configurations used by the vectored and non-vectored lines. The algorithm is dynamic in the sense that the resulting UPBO parameters depend on the binder characteristics, and different parameters are applied to lines with different rate targets. Moreover, Algorithm 1 only needs to be executed infrequently for the expected topology profile (L_1, L_2, N_1, N_2) and the non-vectored rate target R_2. This is very different from OSB [9], which produces a solution very specific to the detailed loop characteristics with prohibitively-high computation costs. Simulation results in Section 4 demonstrate that the achievable vectored rates of Algorithm 1 are similar to those of OSB with the same non-vectored rate targets.

4. SIMULATION RESULTS

The simulation parameters used in this section are listed in Table 1.

TABLE 1. SIMULATION PARAMETERS

Parameter	Value
VDSL2 profile; system upstream PSD mask	17a; Annex A EU-32
Background noise	-140 $^{\mathrm{dBm}}/_{\mathrm{Hz}}$, AWGN
Target noise margin	9 dB
Net coding gain	4.2 dB
SNR gap for uncoded QAM	9.8 dB
Max number of bits per subcarrier	15 bits
Number of runs per Monte-Carlo simulation	1000 times

4.1. Comparison with OSB

Algorithm 1 optimizes the UPBO configuration of the vectored lines, all of the same length, subject to the constraint that the non-vectored lines, all of the same length, attain the rate target R_2. Table 2 compares the 1% worst-case vectored rates achieved by Algorithm 1 and by OSB for random mixtures of 12 vectored lines and 12 non-vectored lines. The results show that the rates achievable by Algorithm 1 are within 98% of the rates achievable with OSB when the non-vectored lines operate at 10Mbps.

TABLE 2. 1% WORST-CASE VECTORED RATES (MBPS) WITH NON-VECTORED RATES TARGETED AT 10MBPS

12 vectored 500m + 12 non-vectored 700m			12 vectored 600m + 12 non-vectored 700m		
Algorithm 1	OSB	Ratio	Algorithm 1	OSB	Ratio
24.56	**25.02**	98.2%	**19.97**	**20.25**	98.6%
UPBO parameters from Algorithm 1: (α_1, β_1) = (72, 10) (α_2, β_2) = (51, 19)			UPBO parameters from Algorithm 1: (α_1, β_1) = (74, 10) (α_2, β_2) = (51, 19)		

4.2. Sensitivity to Number of Lines

Algorithm 1 assumes a simplified loop mixture dependent on N_1 and N_2, the numbers of vectored and non-vectored lines, respectively. Therefore, it is important to investigate the sensitivity of the resulting UPBO parameters and data rates with respect to N_1 and N_2.

To study this question, four different mixtures are considered with the loop-length distributions specified in Table 3. Mixtures 1 and 2 contain vectored lines with maximum length shorter than 500m, and non-vectored lines with maximum length equal to 700m. According to Lemma 1, Mixture 1 is able to achieve the target rate 10Mbps for the non-vectored VDSL using (α_1, β_1) = (72, 10) and (α_2, β_2) = (51, 19) as shown in Table 2. Mixture 2 has a larger number of lines upgraded to vectored VDSL, but is assumed to use the same UPBO parameters as Mixture 1. Fig. 2 shows the 1% worst-case vectored and non-vectored rates for the lines of Mixtures 1 and 2. The chart shows that the vectored lines of Mixture 2 have similar 1% worst-case performance to the vectored lines of Mixture 1, and that the non-vectored lines always meet their target rate of 10Mbps. This suggests that the UPBO parameters do not need to be recomputed every time the mixture of vectored and non-vectored lines changes.

A similar analysis is made for Mixtures 3 and 4 using $(\alpha_1, \beta_1) = (74, 10)$ and $(\alpha_2, \beta_2) = (51, 19)$, which are values computed by Algorithm 1 for 12 vectored lines at 600m co-existing with 12 non-vectored lines at 700m (see Table 2). Fig. 3 again shows that the 1% worst-case rates are similar between Mixtures 3 and 4.

TABLE 3. LOOP-LENGTH DISTRIBUTIONS
(#-VECTORED LINES/#-NON-VECTORED LINES PER LOOP LENGTH)

#-vectored lines/#-non-vectored lines	300m	433m	566m	700m
Mixture 1: 12 vec. + 12 non-vec.	6/3	6/3	–/3	–/3
Mixture 2: 16 vec. + 8 non-vec.	8/1	8/1	–/3	–/3
Mixture 3: 12 vec. + 12 non-vec.	4/3	4/3	4/3	–/3
Mixture 4: 15 vec. + 9 non-vec.	5/2	5/2	5/2	–/3

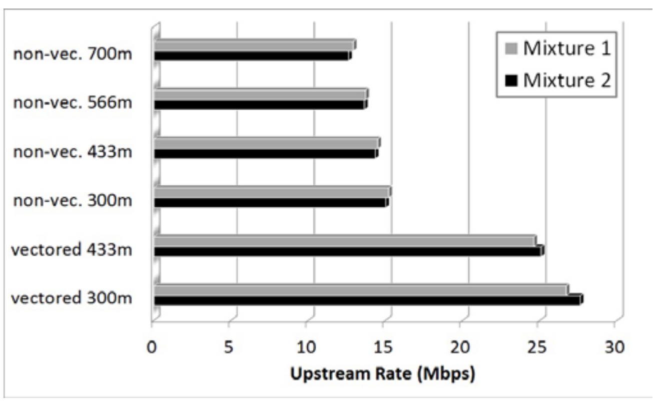

Fig. 2. 1% worst-case upstream vectored and non-vectored rates; Mixtures 1 & 2 use $(\alpha_1, \beta_1) = (72, 10)$ and $(\alpha_2, \beta_2) = (51, 19)$.

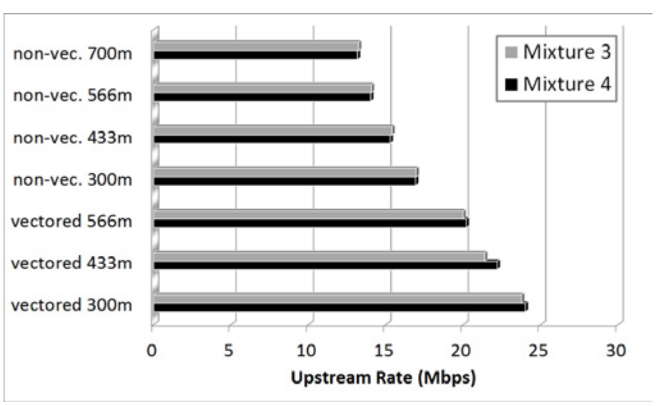

Fig. 3. 1% worst-case upstream vectored and non-vectored rates; Mixtures 3 & 4 use $(\alpha_1, \beta_1) = (74, 10)$ and $(\alpha_2, \beta_2) = (51, 19)$.

5. GENERALIZATION TO MORE THAN TWO USER GROUPS

Algorithm 1 can be generalized to take account of multiple vectored user groups. For example, in addition to the group of non-vectored lines, there can be one group of vectored lines with a lower requirement for upstream vectored rates (called "long-vectored"), and a second group of vectored lines with a higher requirement for upstream vectored rates (called "short-vectored"). In this case, the rate target constraints are individually configured for the group of non-vectored lines and for the group of long-vectored lines. The optimization procedure in Algorithm 1 can thus be extended to account for multiple rate target constraints. An example is next presented.

The loop mixture comprises 6 short-vectored lines at 300m, 6 long-vectored lines at 600m, and 12 non-vectored lines at 700m. From Lemma 1 and Table 2, using the UPBO parameters $(\alpha_1, \beta_1) = (74, 10)$ for the 12 vectored lines and $(\alpha_2, \beta_2) = (51, 19)$ for the 12 non-vectored lines can achieve vectored rates of at least 20Mbps and non-vectored rates of at least 10Mbps. Algorithm 1 can be extended to optimize the UPBO configuration for the 6 short-vectored lines, while imposing the rate target constraints of 20Mbps and 10Mbps for the long-vectored and non-vectored lines, respectively. The final optimized UPBO parameters are $(\alpha_0, \beta_0) = (80, 5)$ for the short-vectored lines. Table 4 compares the 1% worst-case short-vectored rates achievable by OSB and by applying (α_0, β_0), (α_1, β_1), (α_2, β_2) for the short-vectored, long-vectored, and non-vectored lines, respectively; the generalized Algorithm 1 attains a rate within 92% of the OSB rate.

TABLE 4. 1% WORST-CASE SHORT-VECTORED RATES (MBPS) WITH LONG-VECTORED AND NON-VECTORED RATES TARGETED AT 20MBPS AND 10MBPS, RESPECTIVELY.

6 short-vectored 300m + 6 long-vectored 600m + 12 non-vectored 700m		
Generalized Algorithm 1	OSB	Ratio
35.98	**38.89**	92.5%

UPBO parameters from Algorithm 1:
short-vectored $(\alpha_0, \beta_0) = (80, 5)$
long-vectored $(\alpha_1, \beta_1) = (74, 10)$
non-vectored $(\alpha_2, \beta_2) = (51, 19)$

6. CONCLUSIONS

This paper presented a DSM algorithm that mitigates the impact of upstream FEXT in mixtures of vectored and non-vectored VDSL. The algorithm simplifies a mixture topology and then applies optimization to derive the UPBO configurations for the vectored and non-vectored VDSL. The resulting spectrum configurations achieve upstream vectored rates very close to those achieved through OSB, while meeting the upstream rate targets of the non-vectored lines. Finally, the proposed methodology is fully standard-compliant, and has low computation and configuration requirements.

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