Performance Evaluation of the Cable Bundle Unique Power Back-Off Algorithm

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Abstract. The latest digital subscriber line (DSL) technology, VDSL2, used for broadband access over twisted-pairs, promises up to 100 Mbit/s for both transmission directions on short loops. Since these systems are designed to operate in a far-end crosstalk (FEXT) limited environment, there is a severe performance degradation when deployed in distributed network scenarios. With power back-off (PBO) the network operators attempt to protect modems deployed on long loops by reducing the transmit power of the short ones. However, currently very little guidance has been given to operators on how to set and optimize the parameters for PBO. In this paper we explore one promising method, the cable bundle unique PBO (CUPBO), which optimizes these parameters according to the actual situation in the cable with regard to noise and network topology. Using real VDSL systems and cables we show that CUPBO algorithm achieves a significant increase in performance compared to the case when one naively takes the PBO values given in the VDSL standard.

Keywords: DSL, VDSL, Power back-off, Optimization, Demonstrator.

1 Introduction

The latest addition to the digital subscriber line (DSL) family is an updated version of very high-speed DSL (VDSL), known as VDSL2 [6]. It can utilize frequencies up to 30 MHz and theoretically deliver up to 100 Mbit/s in both upstream (toward the network) and downstream (toward the customer) directions. Similar to ADSL, VDSL2 is based solely on discrete multi-tone modulation (DMT) and uses frequency division duplex (FDD) in order to avoid near-end crosstalk (NEXT) noise between VDSL systems. However, in contrast to ADSL, VDSL uses the 'Zipper' transmission scheme [4], also known as digital FDD, which allows for greater flexibility in how the frequencies can be divided between the downstream and upstream directions.

VDSL can be deployed from local exchanges/central offices as well as street cabinets. As the bit rate is very much dependent on the line lengths (line attenuations), it is expected that the majority of the VDSL systems will be deployed from cabinets installed in streets or in apartment buildings. In the following we will use the term cabinet to represent the network side.

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A determining factor for the performance of VDSL is crosstalk noise between twisted-pairs in a cable bundle. Since VDSL is using FDD we only need to consider far-end crosstalk (FEXT). Very early in the standardization of VDSL researchers from BT [7] noted that "FEXT is not reciprocal". This means that the FEXT from one line into another might differ significantly compared to the FEXT caused by the latter into the first one. This is particularly pronounced for the so-called near-far problem, as illustrated in Fig. 1, where the modems in the upstream direction that are closer to the cabinet disturb modems located further out in the network.

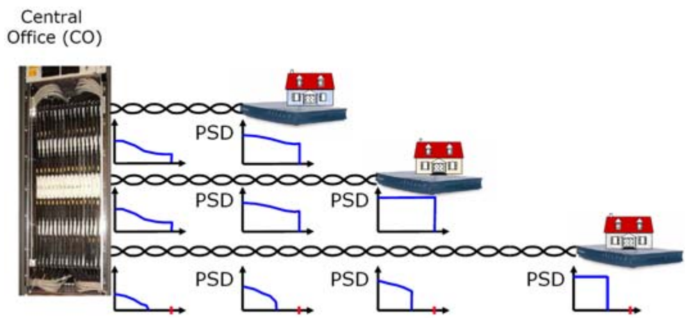

Fig. 1. A distributed DSL scenario which illustrates the near-far problem and a power back-off (PBO) solution in the upstream transmission direction. PSD denotes the power spectral density.

The natural solution to this near-far problem is a reduction of transmit power on the modems closer to the cabinet as shown in Fig. 1, which is known as power back-off (PBO). Many PBO methods were proposed for VDSL, as described by Schelstraete in [3] and the references therein. In the end it was agreed on using the so-called 'reference PBO' method [3]. In this method a desired *received* power spectral density (PSD) is defined as parametrized *reference* PSD for each upstream band. However, the VDSL standard(s) gives little or no guidance to an operator on how to establish 'good' PBO parameters for its particular network and customers. The optimal PBO parameters depend on the topology of the access network, cable characteristics, the mixture of DSL systems, and the type of services (bit rates) that operators want to offer to their customers.

In earlier papers we have identified three *levels* of PBO parameter optimization:

- Regional PBO (RPBO) [2], where the PBO parameters are optimized for a region, e.g. Europe, or a country, e.g. Austria, based on statistical cable models and a predefined set of bit rates;
- Cable bundle unique PBO (CUPBO) [5], where the PBO parameters are optimized for a particular cable bundle; and
- User unique PBO (UUPBO) [1], where the PBO parameters are optimized for each line separately.

For CUPBO and UUPBO the optimization of the PBO parameters depends on the actual situation in a particular cable bundle. We have shown in [1,5] that they give similar performance in comparison to the best schemes proposed for dynamic spectrum management (DSM).

In this paper we will describe our results from implementing CUPBO on real VDSL2 modems connected to a flexible cable plant built for testing distributed network topologies.

The rest of the paper is organized as follows: Section 2 outlines some basic concepts related to standardized PBO for VDSL systems. Section 3 describes the cable bundle unique power back-off (CUPBO) algorithm with the main focus on strategies used to measure (estimate) the parameters required for implementation in practical systems. Then follows a section presenting the developed demonstrator platform used for evaluating the performance of the CUPBO algorithm. In Section 5 we present and evaluate the performance and Section 6 summarizes the major findings of this paper.

2 Standardized Upstream Power Back-Off for VDSL Systems

To solve the near-far problem in DSL access networks many PBO methods have been proposed. For an extensive description of the PBO methods for VDSL systems the reader is referred to [3,8] and the references therein.

The VDSL standards define PBO based on a reference PSD, which is a parametrized function of frequency. Although in principle any shape of PSD could have been selected for the aim of PBO, during the standardization process it has been agreed on using the following reference PSD model:

$$\mathcal{P}_{\mathrm{REF\_dBm}}(f) = -\alpha - \beta\sqrt{f}, \qquad [\mathrm{dBm/Hz}], \tag{1}$$

where α and β are the PBO parameters to be determined. The frequency f is given in MHz. This shape was selected for ease of implementation and it furthermore simplifies the search for optimal PBO parameters. The VDSL standards allow independent reference PSDs for each upstream band. However, the allowable values of the PBO parameter α range from 40 dBm/Hz to 80.95 dBm/Hz in steps of 0.01 dBm/Hz and of parameter β range from 0 dBm/Hz to 40.95 dBm/Hz in steps of 0.01 dBm/Hz [9]. These ranges have been thought to be sufficient for all potential VDSL2 deployment scenarios.

In addition, modems need also adhere to a maximum allowed transmit PSD, $\mathcal{P}^{\max}$, the so-called PSD mask. Hence, the transmitted PSD of a particular user u in subcarrier n is given by

$$\mathcal{P}_u^n = \min\left\{\frac{\mathcal{P}_{\mathrm{REF}}^n}{\mathcal{H}_{uu}^n}, \mathcal{P}_u^{n,\max}\right\}, \tag{2}$$

where $\mathcal{H}_{uu}^n$ denotes the squared magnitude of the *direct* channel and $\mathcal{P}_{\mathrm{REF}}^n = \mathcal{P}_{\mathrm{REF}}(f = n\Delta_f)$ with $\Delta_f = 4.3125$ kHz being the subcarrier width. From Eq. (2) we see that $\mathcal{P}_{\mathrm{REF}}$ actually represents the maximum received PSD on any line.

Different optimization strategies have been proposed to determine the optimized values of α and β. The optimization criterion used by Schelstraete in [3] and Statovci *et. al.* in [2] is the minimization of the maximum difference in the loop reach, achieved with collocated modems without PBO and modems using PBO that are distributed in a way to represent the worst-case noise environment. The PBO parameters are usually optimized to protect multiple bit rates (services), which results in not protecting some modems deployed in long loops as illustrated in Fig. 1. Contrarily, the CUPBO algorithm uses the maximization of the minimum bit rate as its optimization criterion [5].

3 Description of the Cable Bundle Unique Power Back-Off Algorithm

One significant feature of the CUPBO algorithm is that it can be implemented in VDSL modems without imposing any changes to the current standards. It finds an optimized set of PBO parameters by taking into account the parameters that characterise the actual network topology, such as line attenuations, noise environment, and FEXT couplings. We denote this set by $\Phi = \{(\alpha_1, \beta_1), \ldots, (\alpha_{SB}, \beta_{SB})\}$, where the subscript SB denotes the number of upstream bands. In the following we describe the methods used to measure the actual noise environment and what we call the *normalized* FEXT couplings. The algorithm also requires the knowledge of the actual line attenuations, but as this is already measured by currently deployed VDSL modems we will not further analyze it here.

3.1 Parameter Estimation for CUPBO

Under the assumption that two-dimensional signal constellations are used, based on Shannon's formula, the bit rate of a particular user u per DMT symbol can be expressed as

$$R_u = \sum_{n \in I} \log_2 \left(1 + \frac{\mathcal{H}_{uu}^n \mathcal{P}_u^n}{\Gamma \mathcal{N}_u^n} \right), \tag{3}$$

where I denotes the set of subcarriers used in the particular transmission direction, in our case upstream; Γ is the gap approximation to Shannon capacity [10]; $\mathcal{P}_u^n$ and $\mathcal{N}_u^n$ are the PSDs of transmitted signal and total noise, respectively, of user u in subcarrier n. All VDSL systems measure the PSD of the total noise; thus, the sum of all noises, since this information is also required for bit-loading. The total noise that is experienced by user u on carrier n consists of background noise, $\mathcal{P}_{u,\mathrm{BGN}}^n$, and FEXT noise, $\mathcal{P}_{u,\mathrm{FEXT}}^n$, originating from the other users sharing the same cable bundle, i.e,

$$\mathcal{N}_u^n = \mathcal{P}_{u,\mathrm{FEXT}}^n + \mathcal{P}_{u,\mathrm{BGN}}^n. \tag{4}$$

Current VDSL systems do not differentiate between various noise sources, but they only consider the total noise. However, we can control the PSD levels of

FEXT noise by controlling the transmit PSDs and, as can be seen in Eq. (3), thereby indirectly also the performance of VDSL systems.

In this paper, we assume that the background noise, $\mathcal{P}_{u,\mathrm{BGN}}^n$, also comprises the alien noise that originates from other non-VDSL modems and the noise from unknown sources, such as impulse noise and radio frequency interference (RFI) for example. The NEXT noise can be neglected, since we are assuming fully synchronized VDSL systems that use the digital FDD transmission scheme.

The FEXT noise of a particular user u is given by

$$\mathcal{P}_{u,\mathrm{FEXT}}^n = \sum_{\substack{v=1 \\ v \neq u}}^{U} \mathcal{H}_{uv}^n \mathcal{P}_v^n, \tag{5}$$

where $\mathcal{H}_{uv}^n$ denotes the squared magnitude of FEXT coupling from user v to user u on subcarrier n.

It is clear that in order to be able to calculate the FEXT noise, the individual FEXT couplings are needed. However, these are not measured by the current VDSL systems. Still, by exploiting some nice properties of standardized PBO it is possible to overcome this problem.

First, we observe that by a suitable selection of $\mathcal{P}_{\mathrm{REF}}$ we can ensure that received PSDs on all lines are the same and equal to the reference PSD. Under this assumption the transmit PSD of user v is given by $\mathcal{P}_v^n = \mathcal{P}_{\mathrm{REF}}^n / \mathcal{H}_{vv}^n$ and the FEXT noise in Eq. (5) can then be written as

$$\mathcal{P}_{u,\mathrm{FEXT}}^n = \sum_{\substack{v=1 \\ v \neq u}}^{U} \frac{\mathcal{H}_{uv}^n}{\mathcal{H}_{vv}} \mathcal{P}_{\mathrm{REF}}^n. \tag{6}$$

By holding $\mathcal{P}_{\mathrm{REF}}$ fixed we can now define the *normalized* FEXT coupling for each user as

$$\mathcal{H}_{u,\mathrm{FEXT}}^{n,\mathrm{norm}} = \sum_{\substack{v=1 \\ v \neq u}}^{U} \frac{\mathcal{H}_{uv}^n}{\mathcal{H}_{vv}^n} = \frac{\mathcal{P}_{u,\mathrm{FEXT}}^n}{\mathcal{P}_{\mathrm{REF}}^n}. \tag{7}$$

Thus, the *normalized* FEXT couplings can easily be estimated by each modem based on a given $\mathcal{P}_{\mathrm{REF}}^n$ and the measured PSDs of the FEXT noise. Rewriting Eq. (4) the FEXT noise can be calculated as

$$\mathcal{P}_{u,\mathrm{FEXT}}^n = \mathcal{N}_u^n - \mathcal{P}_{u,\mathrm{BGN}}^n. \tag{8}$$

After the normalized FEXT couplings are estimated, based on Eq. (6) and (7), the total noise is calculated as

$$\mathcal{N}_u^n = \mathcal{P}_{\mathrm{REF}}^n \mathcal{H}_{u,\mathrm{FEXT}}^{n,\mathrm{norm}} + \mathcal{P}_{u,\mathrm{BGN}}^n. \tag{9}$$

Thus, we take into account the actual FEXT couplings rather than assuming a model for them.

3.2 Optimization Strategies

After experimenting with different optimization strategies for CUPBO algorithm, as described in [5], the maximization of the minimum bit rate (among the modems included in the optimization process) is considered to be the most robust approach. Furthermore, since maximizing the bit rates independently in each band also maximizes their sum, the optimization by CUPBO can independently be done for each transmission band. Thus, the optimization problem for the i-th band can be formulated as

$$\underset{\alpha_i,\beta_i}{\text{maximize}} \left(\min_u \{R_{u,i}\} \right) \tag{10a}$$

subject to:

$$\alpha_{\min} \leq \alpha_i \leq \alpha_{\max} \tag{10b}$$

$$\beta_{\min} \leq \beta_i \leq \beta_{\max}, \tag{10c}$$

where $R_{u,i}$ denotes the bit rate of user u in the i-th upstream band, I_i denotes the set of subcarriers used in that particular band, and $\alpha_{\min}$, $\alpha_{\max}$, $\beta_{\min}$, and $\beta_{\max}$ denote the minimum and maximum values of α and β as specifed in Section 2. Taking the transmit PSD mask constraint into account, the bit rate of a particular user u in the i-th band per DMT symbol during the optimization is approximated by

$$R_{u,i} = \sum_{n \in I_i} \log_2 \left(1 + \frac{\mathcal{H}_{uu}^n \mathcal{P}_u^n}{\Gamma \left(\mathcal{P}_{\text{REF}}^n \mathcal{H}_{u,\text{FEXT}}^{n,\text{norm}} + \mathcal{P}_{u,\text{BGN}}^n \right)} \right), \tag{11}$$

where the transmit PSD, $\mathcal{P}_u^n$, for a give set of PBO parameters is calculated as in Eq. (2).

The above approximation can be interpreted as follows: During the search for the optimal PSD parameters we can not guarantee that $\mathcal{P}_{\text{REF}}$ is not restricted by $\mathcal{P}^{\max}$. If this happens the calculated bit rates will be an underestimate of the real bit rates, since the reference PSD represents the highest possible received PSD and thus the total noise is overestimated. This means that the PBO parameters are optimized towards higher noise levels than the modems in fact are experiencing.

3.3 Optimization Algorithm

The pseudo-code of the CUPBO algorithm, which solves the optimization problem in Eq. (10) is listed as Algorithm 1. The core of the CUPBO is based on the Nelder–Mead simplex search [11], which finds the optimized α and β for each upstream band.

In practice an operator typically wants to offer a predefined minimum bit rate. If this minimum bit rate is not supported, we remove the user with the lowest bit rate and rerun the optimization process. We repeat this step until the minimum predefined bit rate is achieved. Using this procedure, operators will be able to offer a predefined service to the largest number of users possible.

Algorithm 1. Cable bundle unique PBO (CUPBO) algorithm [5]

1: Select suitable $\mathcal{P}_{\text{REF}}$ so that the best estimate of Eq. (7) is achieved
2: Calculate the normalized FEXT couplings for each line using Eq. (7)
3: **for** $i = 1$ *to* SB **do**
4: $\quad \Phi_i = [\alpha_i, \beta_i]$ $\quad \{Starting\ values\}$
5: $\quad$ **repeat**
6: $\quad\quad \Phi_i =$ ***NelderMead***(@***RateCalcMin***, Φ_i),
7: $\quad$ **until** the specified accuracy has been reached
8: $\quad$ **if** the longest line is not using the current band for transmission **then**
9: $\quad\quad$ Exclude it from the optimization and go to step 4
10: $\quad$ **end if**
11: **end for**

12: ***Function*** $R^{\mathbf{min}} =$ ***RateCalcMin***(Φ_i)
13: Calculate $R_{u,i}$ for all lines according to Eq. (11)
14: Calculate $R^{\min} = \min_u\{R_{u,i}\}$

4 Description of the Demonstrator Platform

In order to evaluate the performance of our PBO and DSM algorithms in real modems and real cables we have developed a versatile testbed consisting of a VDSL2 DSLAM and modems, four 200 m rolls of 10 pair 0.6 mm cables and a connection board. A photo of the setup is shown in Fig. 2. The cable used is an Austrian 10 pair 'layered' cable based on 5 star-quads and 0.6 mm wires, with model number F-02YHJA2Y. This is the typical cable deployed from cabinets to the customers in Austria. In a distributed scenario like the one considered in this paper the FEXT will vary significantly between different lines. In Fig. 6 and 7 are plotted the actual normalized FEXT couplings as measured by modems during the CUPBO parameter estimation.

With the connection board we can set up many distributed scenarios with modems placed at loop lengths of 200, 400, 600, or 800 m away from the DSLAM. For the experiments described in this paper we connected one modem at 200, one at 400 and one at 600 m, with FEXT coupling lengths of 200 and 400 m.

The VDSL2 systems used for these experiments were provided by Infineon Technologies Austria AG and consist of a line card that acts as a DSLAM and four VDSL2 CPE units. We control the DSLAM using simple object access protocol (SOAP) calls from Matlab running on a separate computer.

4.1 Implementation Details

When implementing CUPBO in real systems there are few practical details worth noting. First, we describe how to select $\mathcal{P}_{\text{REF}}$ and then how to use the total noise measurements to estimate the background noise as well as the normalized FEXT couplings, cf. Eq. (7) and (8).

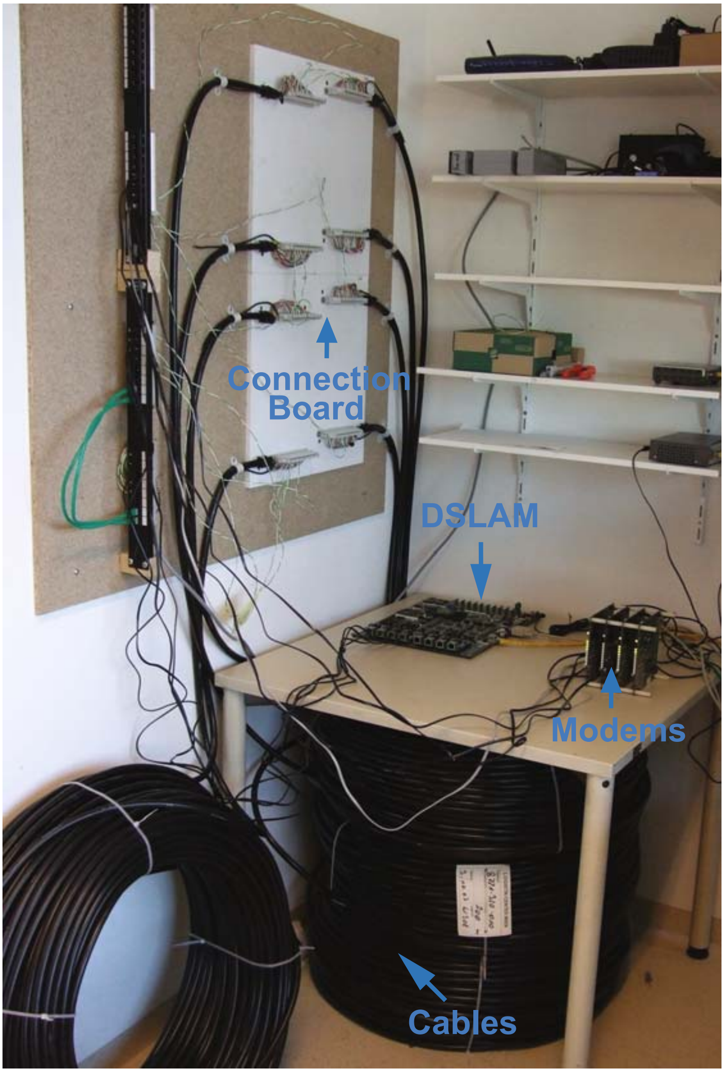

Fig. 2. The VDSL2 demonstrator platform

As mentioned in Section 3, $\mathcal{P}_{\mathrm{REF}}$ (independent for each band) should be selected so that the received PSDs on all lines are the same. This selection is crucial for accurate parameter estimation. The suitable $\mathcal{P}_{\mathrm{REF}}$ is this that compensates for the highest attenuation on any line while still not violating the maximum transmit PSD mask. At the same time $\mathcal{P}_{\mathrm{REF}}$ should be above the PSD of background noise. For short loops both conditions are always satisfied. If we cannot satisfy both criteria, we simply select $\mathcal{P}_{\mathrm{REF}}$ to be some dB (e.g. 10 dB) above the PSD of background noise.

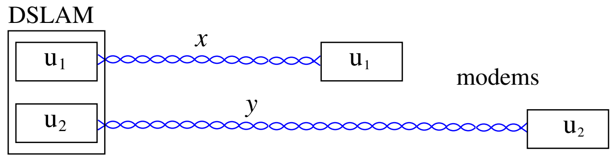

Fig. 3. Network scenario with two users, where x and y denote the loop lengths

The background noise of each user u, $\mathcal{P}^n_{u,\mathrm{BGN}}$, is estimated by initializing the modems in turn; that is, one modem is going into show time while the others are silent. In this case the total noise measured by the modems in fact represents the true background noise. After these steps all modems simultaneously go into the show time with a reference PSD, $\mathcal{P}_{\mathrm{REF}}$, selected as described above. During this phase the measured total noise, $\mathcal{N}^n_u$, is used (after subtraction of the background noise) to estimate the normalized FEXT couplings.

5 Performance Evaluation and Discussions

We will compare the performance of CUPBO against three other configurations: PBO disabled (NoPBO), standardized PBO parameters (StdPBO), and what we call *exhaustive* CUPBO (ExhCUPBO). In the exhaustive CUPBO the optimized PBO parameters are calculated using the modems 'in the loop' during the search. Thus, we use the true bit rates that are achieved by the modems using a particular PBO parameter set in the *Nelder-Mead* simplex search (replacing line 13 in Algorithm 1). It is worth mentioning that exhaustive CUPBO should not be deployed in practical systems, since it is very time consuming and requires a large number of modem restarts for each set of PBO parameters tested. We have implemented it just to prove that our developed strategy for estimating the normalized FEXT couplings and the total noise, cf. Eq. (9), works well in practice.

The performance of the CUPBO algorithm is evaluated in different network scenarios with two and three users. All simulations are performed for the bandplan 998–Annex B–profile 12b (Name 998-M2x-NUS0, Table B-6, [6]), which has two upstream bands. We have selected the standardized PBO parameters for Noise F as defined in the ETSI VDSL standard [12], since they show the best performance in our demonstration platform among all standardized PBO parameters.

5.1 Performance Evaluation for the Two-User Case

The network scenario for the two-user case is shown in Fig. 3. We have evaluated the performance under the following configurations. Scenario A: loop lengths of 200 and 400 m; Scenario B: loop lengths of 400 and 600 m; and Scenario C: loop lengths of 200 and 600 m. The twisted-pairs for the three loops were selected randomly out of the ten twisted-pairs in each section of our cable. The attenuations

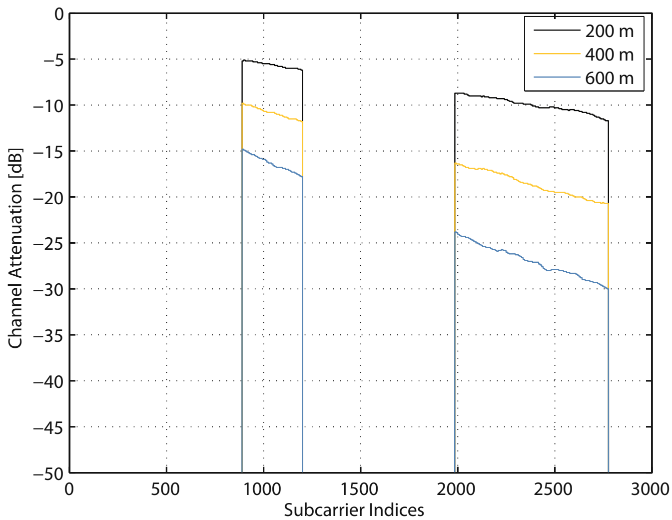

Fig. 4. Channel attenuations for loop lengths of 200, 400, and 600 m

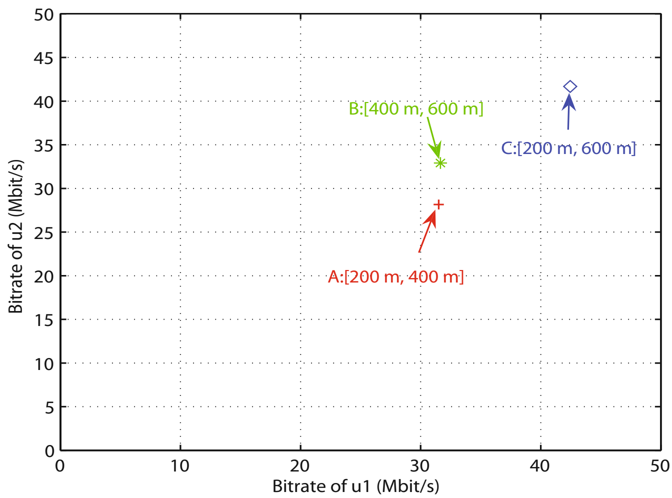

Fig. 5. Bit rates supported by the CUPBO algorithm for three network scenarios with two users shown in Fig. 3. Scenario A: loop lengths of 200 and 400 m; Scenario B: loop lengths of 400 and 600 m; and Scenario C: loop lengths of 200 and 600 m

of these loops as they have been measured by the modems, i.e., including also the attenuation on the analog front-end, are plotted in Fig. 4.

Fig. 5 shows the bit rates supported by the CUPBO algorithm for all three network scenarios. Some results can be considered surprising and counter-intuitive. We are for instance achieving lower bit rates in Scenario A that has shorter

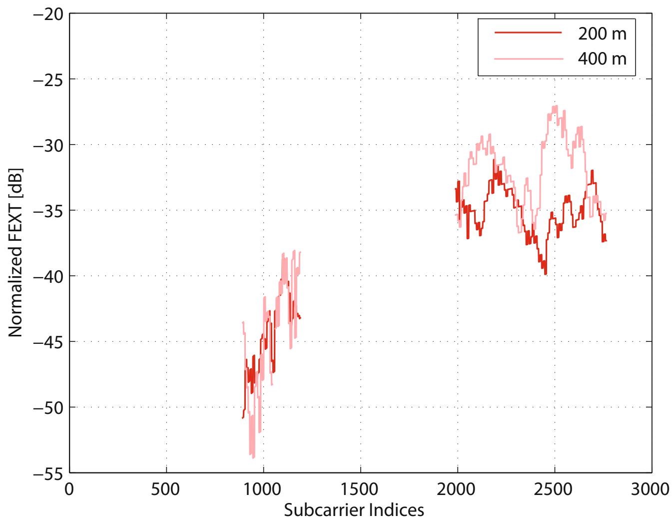

Fig. 6. Normalized FEXT couplings for network Scenario A: Loop lengths of 200 and 400 m

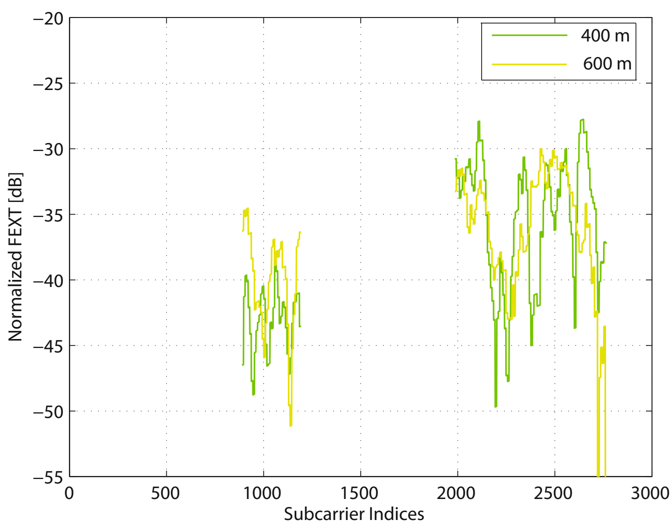

Fig. 7. Normalized FEXT couplings for network Scenario B: Loop lengths of 400 and 600 m

loop lengths (lower attenuations) than in Scenario B and C that have longer loop lengths (higher attenuations). However, based on Eq. (11), we can conclude that the bit rates of users not only depend on the levels of channel attenuations, but also on the levels of normalized FEXT couplings and the PSD levels of background noise.

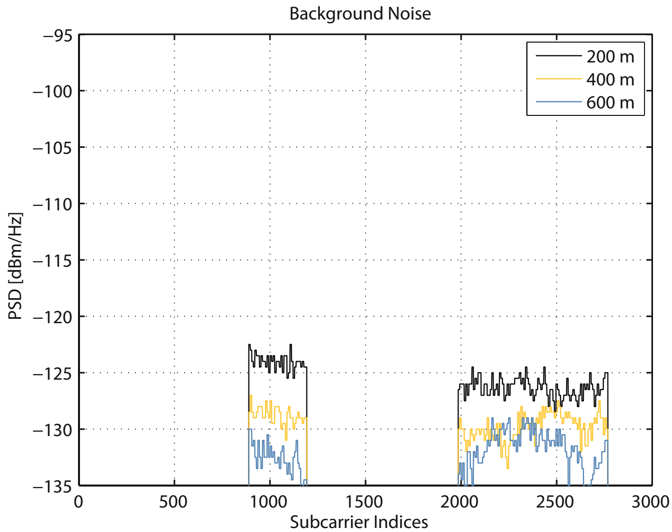

Fig. 8. PSDs of background noise for lines of 200, 400 and 600 m

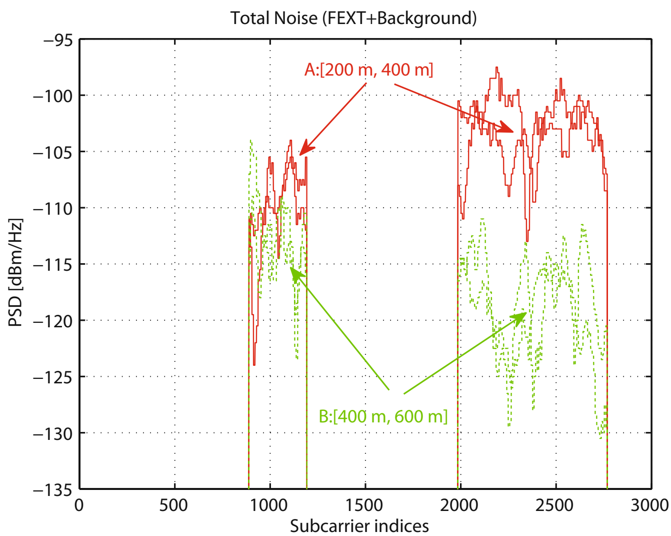

Fig. 9. PSDs of total noise for Scenario A and B after PBO parameter optimization

Fig. 6 and 7 show the normalized FEXT couplings for two out of the three network configurations which, as expected, are different between various lines. Fig. 8 shows the PSDs of background noise for three lines, which surprisingly are *very* different from each other (up to 11.5 dB difference). We can see in the plots in Fig. 6 and 7 that the lines in Scenario A have higher averaged

Table 1. Users' supported bit rates for Scenarios A, B, and C as well as for PBO disabled (NoPBO), standardized PBO (StdPBO), exhaustive CUPBO (ExhCUPBO), and CUPBO

	Users' bit rates in Mbit/s			
	NoPBO	StdPBO	ExhCUPBO	CUPBO
User	Scenario A			
u_1	36.1	19.2	30.7	31.2
u_2	23.1	22.6	28.6	27.8
User	Scenario B			
u_2	41.1	16.0	32.0	31.7
u_3	24.0	22.2	31.9	32.7
User	Scenario C			
u_1	53.9	21.2	42.9	42.7
u_3	27.5	24.2	41.6	41.4

Table 2. CUPBO performance comparison versus NoPBO, StdPBO, and ExhCUPBO

	Bit rate gain/loss(-) in %		
Scenario	NoPBO	StdPBO	ExhCUPBO
A	20.1	45.0	−3.00
B	32.0	98.5	−0.56
C	50.2	95.0	−0.52

normalized FEXT couplings than the lines in Scenario B. Furthermore, PSD-levels of background noise for Scenario A are higher than for Scenario B as can be seen in Fig. 8, which also results in high levels of total noise for Scenario A as shown in the plots in Fig. 9. This also explains why for Scenario A we achieve the worst performance in terms of supported bit rates. With similar analysis we can also justify the bit rates achieved for the other network scenarios.

Table 1 summarizes the achieved bit rates for three network scenarios and various schemes. Table 4, in the appendix, summarizes the PBO parameters as calculated by the CUPBO and ExhCUPBO for the bit rates shown in Table 1. In Table 2 we compare the performance of CUPBO versus NoPBO, StdPBO, and ExhCUPBO. Since we have selected the maximization of minimum bit rate as the optimization criterion, we have also performed the comparisons for the minimum bit rates supported by the modems. The performance improvements of CUPBO compared to NoPBO and StdPBO are in the range from 20% to 98.5%, which are similar to those achieved by simulations in [5]. We see larger improvements over StdPBO than over NoPBO. This is due to the fact that standardized PBO parameters are optimized for a reach of above one kilometer (above three kilofeet) and for twenty VDSL systems, which both are not encountered in our selected network configurations. CUPBO suffers only a loss of 0.5% to 3% compared to ExhCUPBO.

5.2 Performance Evaluation for the Three-User Case

We have also evaluated the performance for a network scenario with three users with the loop lengths of 200 , 400 , and 600 m, which actually are the same loops used in the network scenario with two uses. Table 3 summarizes the achieved bit rates and compare the performance of CUPBO versus NoPBO, StdPBO, and ExhCUPBO. Table 4, in the appendix, summarizes the PBO parameters as calculated by the CUPBO and ExhCUPBO for the bit rates shown in Table 3.

CUPBO achieves performance improvements of 28.4% and 36.3% compared to NoPBO and StdPBO, respectively, which are again similar to those achieved by simulations in [5]. Furthermore, for this network scenario CUBPO suffers a loss with respect to the minimum bit rate of less than 0.1% compared to ExhCUPBO.

Table 3. CUPBO performance comparison versus PBO disabled (NoPBO), standardized PBO (StdPBO), and exhaustive CUPBO (ExhCUPBO)

	Users' bit rates in Mbit/s			
User	NoPBO	StdPBO	ExhCUPBO	CUPBO
u_1	35.7	18.8	25.7	25.7
u_2	22.8	20.5	29.7	29.9
u_3	20.0	22.0	27.9	26.3
Minimum bit rate	20.0	18.8	25.7	25.7
CUBPO gain in %	28.4	36.3	< -0.1	-

5.3 Further Discussions

It should be noted that the methodology and the CUPBO concept in general can equally well be deployed in the downstream direction. Downstream power back-off is only necessary when operators mix deployment of VDSL systems from the local exchange and cabinet in the same cable bundle. This leads to large performance degradations on all lines; therefore, operators should avoid such deployments. Due to this we do not expect that downstream power back-off will in practice be an important issue.

6 Conclusions

In this paper we have evaluated the performance of the cable bundle unique power back-off (CUPBO) algorithm on real VDSL2 modems and real cables. The test setup has been connected in four different distributed network scenarios with modems placed at 200, 400, and 600 m. We have found that the CUPBO algorithm achieves significant improvements in terms of upstream bit rates over the case when no power back-off (PBO) is used. Compared to the PBO parameters as specified in VDSL standards we have seen even larger performance improvements. This reduction in performance when using the PBO parameters as suggested by standards stems from the fact that they are very conservative and actually optimized for situations when modems are deployed at much longer loop lengths than encounter in our network configurations. Therefore, we expect that telecom operators will significantly improve the performance of their VDSL systems (i.e., potentially double the upstream bit rates) by using CUPBO.

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Appendix

In this appendix we summarize optimized PBO parameters as calculated by the CUPBO and exhaustive CUPBO (ExhCUPBO) for network configurations with two and three users for the bit rates shown in Table 1 and Table 3, respectively.

Table 4. Optimized PBO parameters for the two-user case (Scenarios A, B, and C) as well as the three-user case for CUPBO and ExhCUPBO

Set of PBO parameters in dBm/Hz (c.f. Sections 2 and 3)	
CUPBO	ExhCUPBO
$\{(\alpha_1, \beta_1), (\alpha_2, \beta_2)\}$	$\{(\alpha_1, \beta_1), (\alpha_2, \beta_2)\}$
Scenario A (two-user case)	
$\{(40.00, 11.41), (69.57, 0.39)\}$	$\{(55.20, 5.35), (52.95.5.43)\}$
Scenario B	
$\{(45.48, 12.42), (70.50, 4.16)\}$	$\{(46.15, 12.60), (57.88, 8.56)\}$
Scenario C	
$\{(50.83, 9.45), (40.00, 12.39)\}$	$\{(52.41, 7.36), (40.00, 12.24)\}$
Three-user case	
$\{(45.80, 12.73), (76.85, 0.04)\}$	$\{(45.30, 12.84), (62.84, 4.66)\}$