15th European Signal Processing Conference (EUSIPCO 2007), Poznan, Poland, September 3-7, 2007, copyright by EURASIP

VDSL POWER BACK-OFF PARAMETER OPTIMIZATION FOR A CABLE BUNDLE

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ABSTRACT

To better utilize the capacity of the twisted-pair access networks, operators deploying very high-speed digital subscriber line (VDSL) systems need accurate parameters for power back-off (PBO). However, VDSL standards give almost no guidance on how these parameters should be established for a particular network. In this paper we present a new technique for optimizing PBO parameters for a cable bundle, which is based on the Nelder–Mead simplex search algorithm. In this way each operator can easily calculate PBO parameters that match its actual access network down to the individual cable bundle. Using the properties of the PBO, as defined in the VDSL standard, we show how a normalized *FEXT coupling can replace the knowledge of the individual couplings during the optimization of the PBO parameters. By simulations based on measured cable data we show that our approach using cable bundle unique PBO (CUPBO) achieves a significant improvements compared to the performance achieved with the ordinary PBO.*

1. INTRODUCTION

In recent years, telecom operators showed a strong interest in improving the capacity utilization of their twisted-pair access networks. Therefore, they have introduced a sequence of digital subscriber line (DSL) technologies with an ever increasing performance as for example symmetric high-speed DSL (SHDSL), asymmetric DSL (ADSL), and ADSL2+. The DSL technology with the highest performance is the very high-speed DSL (VDSL) that can utilize frequencies up to 30 MHz. Similar to ADSL, VDSL is based on discrete multitone modulation (DMT). Furthermore, it uses frequency division duplex (FDD) in order to avoid near-end crosstalk (NEXT) noise between VDSL systems. However, by using a 'Zipper' transmission scheme [1] (also known as digital FDD), VDSL is much more flexible in how the frequencies can be divided between the downstream (toward the customer) and upstream (toward the network) directions. Recently, an updated version of VDSL, known as VDSL2, has been released. In VDSL2 up to four frequency bands can be used for each transmission direction.

A determining factor for the performance of VDSL is crosstalk noise between twisted-pairs in a cable bundle. This is particularly pronounced for the so called near-far problem, as illustrated in Figure 1, where the modems in the upstream direction that are closer to the central office (CO) or cabinet disturb modems located further out in the network. The solution to this problem involves some form of length dependent power back-off (PBO) [2]. By using PBO, modems located close to the central office (CO) or cabinet reduce their transmitted power spectral densities (PSDs) in order to improve the performance of modems located further away. In standardized VDSL the required PBO method is 'reference PBO' [2]. With this method a desired *received* PSD is defined as a parameterized reference PSD for each upstream band. The actual parameters proposed by the VDSL standards were established by Schelstraete [2] and Oksman [3] using single user worst-case noise scenarios. Another approach to find the optimized parameters for different protected rates, which uses Nelder–Mead simplex search, was presented by Statovci *et al.* in [4] where they also introduced the concept of virtual modems.

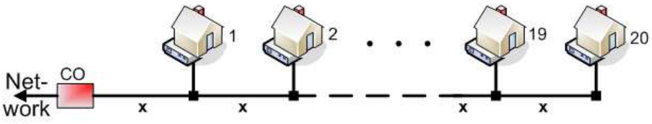

Figure 1: A DSL scenario with near-far crosstalk problems in the upstream direction.

All of the above mentioned methods try to optimize the PBO reference PSD for a region or a country. In order to separate this level of optimization from other more localized we refer to it as ordinary PBO. Two additional levels of PBO can be identified: cable bundle unique PBO (CUPBO), where the PBO parameters are optimized for a particular cable bundle; and user unique PBO (UUPBO), where the PBO parameters are optimized for each line separately. UUPBO was explored in [5] where it was shown that the capacity utilization can be significantly improved.

In this paper we want to explore the possibility to do CUPBO. That is, we want to optimize a set of PBO parameters, which are unique for a particular cable bundle. Utilizing the property that all received PSDs are the same when using the reference PBO we show how a normalized FEXT coupling can replace the knowledge of the complete FEXT couplings, which are difficult to obtain, during the optimization of the PBO parameters. With these optimized PBO parameters we then achieve a significant performance increase for actual deployed cables compared to the worst case design currently in use. The CUPBO can be applied to both single carrier and DMT systems; however, to simplify the description for this paper we will only consider DMT modulation.

The rest of the paper is organized as follows: Section 2 gives some basic concepts concerning PBO and PSD shaping in standardized VDSL. In section 3, rate and crosstalk (FEXT) calculations are presented as well as a procedure that shows how to calculate the FEXT noise without knowing the individual FEXT couplings between the lines. Section 4 describes the optimization strategies used to calculate the optimized PBO parameters. Also two algorithms for solving the optimization problems are presented. Section 5 shows some simulation results used to evaluate the proposed approaches and Section 6 summarizes the major findings of this paper.

2. PRELIMINARIES

The VDSL standards define the PBO based on the reference PSD that is a parameterized function of frequency. During the standardization process it has been agreed, although in principle any shape for PSD could have been selected, to use the following reference PSD model (expressed in dBm/Hz):

$$\mathcal{P}_{\text{REF\_dBm}} = \alpha + \beta\sqrt{f}, \qquad [\text{dBm/Hz}], \tag{1}$$

where f is given in MHz, and α and β are the parameters that are free to be determined. In currently deployed VDSL systems the reference PSD is the same for all users and it is optimized to maximize the reach for a given set of bit rates under a worst-case noise environment. Independent reference PSDs are assigned for each upstream band.

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

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

where $\mathcal{H}_{uu}^n$ denotes the square magnitude of the channel and $\mathcal{P}_{\text{REF}}^n = \mathcal{P}_{\text{REF}}(f = n\Delta_f)$ with $\Delta_f = 4.3125\,\text{kHz}$ denoting the subcarrier width. Therefore, taking into consideration (2), $\mathcal{P}_{\text{REF}}$ in fact represents the maximum received PSD on any line.

3. RATE AND CROSSTALK CALCULATIONS

Looking at a cable bundle, the bit rate of a particular user u 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 a particular transmission direction, in this case upstream; Γ is the gap approximation to Shannon capacity; $\mathcal{P}_u^n$ and $\mathcal{N}_u^n$ are the PSDs of transmitted signal and received noise, respectively, of user u in subcarrier n. The total noise that is experienced by user u is a sum of background noise $\mathcal{P}_{u,\text{BGN}}^n$ and FEXT noise originating from all other users sharing the same bundle. It is given by:

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

The background noise $\mathcal{P}_{u,\text{BGN}}^n$ comprises also the alien noise that arises from the other non-VDSL modems. The NEXT noise can be neglected, since we are assuming fully synchronized VDSL systems that use digital FDD transmission scheme.

The FEXT noise of a particular user u is given by:

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

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

With a suitable selection of $\mathcal{P}_{\text{REF}}$ we can ensure that received PSDs on all lines are the same and equal with the reference PSD. Under this assumption $\mathcal{P}_v^n = \mathcal{P}_{\text{REF}}^n/\mathcal{H}_{vv}^n$ and the FEXT noise can then be written as:

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

Now by holding $\mathcal{P}_{\text{REF}}$ fixed we can define for each user the *normalized* FEXT coupling as:

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

The total noise can now be expressed as:

$$\mathcal{N}_u^n = \mathcal{P}_{\text{REF}}^n \mathcal{H}_{u,\text{FEXT}}^{n,\text{norm}} + \mathcal{P}_{u,\text{BGN}}^n. \tag{8}$$

In an initial phase (with $\mathcal{P}_{\text{REF}}$ fixed) we can estimate $\mathcal{H}_{u,\text{FEXT}}^{n,\text{norm}}$, since we can assume that each modem estimates both the background noise, $\mathcal{P}_{u,\text{BGN}}^n$, and total noise, $\mathcal{N}_u^n$, with a high accuracy.

A simple method to estimate the background noise and total noise is as follows. The background noise, $\mathcal{P}_{u,\text{BGN}}^n$, can be estimated during the initialization phase by sensing the line when the modems are not transmitting. After this step all modems start transmitting with the PBO enabled such that the received PSDs on all lines are equal to the reference PSDs, $\mathcal{P}_{\text{REF}}$. During this phase the same method that is used for the bit-loading algorithms to estimate the total noise, $\mathcal{N}_u^n$, can also be applied here.

The bit rate for every user (line) after substituting (8) into (3) can be written as:

$$R_u = \sum_{n\in I} \log_2\left(1 + \frac{\mathcal{P}_{\text{REF}}^n}{\Gamma\left(\mathcal{P}_{\text{REF}}^n \mathcal{H}_{u,\text{FEXT}}^{n,\text{norm}} + \mathcal{P}_{u,\text{BGN}}^n\right)}\right). \tag{9}$$

Thus, the bit rate of each user depends only on the received reference PSD, $\mathcal{P}_{\text{REF}}$, which is the same for all users, the background noise level and the topology of the network that is quantified by $\mathcal{H}_{u,\text{FEXT}}^{n,\text{norm}}$.

4. OPTIMIZATION ALGORITHMS

To calculate PBO parameters various optimization criteria have been proposed. For the ordinary PBO, the optimization criteria used in [2, 4] 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 the way to represent the worst-case noise environment. For this kind of PBO the parameters are usually optimized to protect multiple bit rates (services). A new scheme to set-up the network scenario which better represents the worst-case noise environment is introduced in [4].

Another optimization criteria, used by Statovci *et al.* [5] for UUPBO, is to maximize the sum of weighted bit rates. For this approach the optimal weighting values depend on the predefined *relative* target bit rates. However, for the calculation of noise during the optimization the individual FEXT couplings between all lines are needed.

We have considered two optimization criteria for CUPBO: maximizing the sum of weighted bit rates and maximizing the minimum bit rate. After experimenting with various network scenarios, we have recognized that both approaches show similar performance, but for the first approach we have in addition to determine the appropriate weighting values. Hence, we decided to use the maximization of the minimum bit rate as optimization criteria for CUPBO. The aim is to find α and β for each transmit band that are the same for all users. 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.

For CUPBO we neither assume a full knowledge of FEXT couplings to calculate the noise as in [5] nor use the worst-case noise environment as in ordinary PBO [2, 4]. Instead, we will use the normalized FEXT couplings as described in Section 3 to calculate the noise during the optimization process.

According to the standards, independent reference PSDs can be assigned to each upstream band. Furthermore, for standardized VDSL it is reasonable to assume that the total power constraint is equal to the integration of the PSD mask over the used subcarriers. With this assumption the optimization can be done independently for each upstream band, since maximizing the bit rates independently for each band also maximizes their sum. Thus, the optimization problem for 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:

$$\mathcal{P}_u^n = \min\left\{\frac{\mathcal{P}_{\text{REF}}^n}{\mathcal{H}_{uu}^n}, \mathcal{P}_u^{n,\max}\right\}, \quad \forall\, u, \forall n \in I_i, \tag{10b}$$

where $R_{u,i}$ denotes the bit rate of user u in i-th band and I_i denotes the set of subcarriers used in a particular upstream band. Taking the PSD mask constraint into the account, the bit rate of a particular user u in i-th band during the optimization is calculated by

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

To solve the optimization problem (10) we use the Nelder–Mead simplex algorithm as described in [4]. During this search, as it is done in an off-line process, we can not guarantee that $\mathcal{P}_{\text{REF}}$ is not restricted by $\mathcal{P}^{\max}$. If this happens the calculated bit rates will underestimate 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.

One important point to note is that if the line with highest attenuation can not transmit in the band being optimized, we exclude it from the optimization process. We proceed in this fashion until a line is found that can use that particular band. This procedure and the algorithm to solve the optimization problem (10), is presented in Algorithm 1. In practice it is common that an operator wants to offer a predefined minimum bit rate. With the proposed algorithm it can happen that this minimum is not achieved. If this is the case, we remove the line with the lowest bit rate from the optimization process. We repeat this until the minimum predefined bit rate is achieved. Using this procedure, operators can offer a predefined service to the largest amount of users possible.

Algorithm 1 Optimization Algorithm

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

12: Function $y$ = RateCalcMin($\Phi_i$)
13: Calculate $R_{u,i}$ for all lines according to (11)
14: Calculate $R^{\min} = \min_u\{R_{u,i}\}$
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In the core of this algorithm we need, in each optimization step, to find the minimum rate of all users, $R^{\min} = \min_u\{R_{u,i}\}$. In order to reduce complexity (as in computations and data exchange needed) as well as gaining some additional insights to what is determining the optimal PBO parameters we will now derive an approximate $R^{\min}$, denoted $\widetilde{R}^{\min}$.

There are two factors that will determine $\widetilde{R}^{\min}$: the line with the highest attenuation (typically the longest line) and the line with the highest normalized FEXT coupling (typically *not* the longest line). As line with the highest normalized FEXT coupling is select the line that experience the maximum value when summing $\mathcal{H}_{u,\text{FEXT}}^{n,\text{norm}}$ (calculated according to (7)) over all subcarriers of a particular band. The combination of these two factors can be seen as a *virtual line* that will have the lowest rate $\widetilde{R}^{\min}$ according to (11) than any other user in the bundle. That is, in Algorithm 1 the operations in line 13 and 14 are replaced by a single bit rate calculation of $\widetilde{R}^{\min}$. The complexity of this approach is lower compared to the original algorithm, since there is neither need to calculate the bit rate for each user nor to find a minimum bit rate among the users.

Both strategies represent a form of dynamic spectrum management (DSM). According to the DSM levels definitions as in [6], our proposed algorithms belong to DSM level 1. There was no need for worst-case crosstalk coupling modeling as in [4] because we used the *normalized* FEXT coupling approach. In this way we are optimizing PBO parameters for a particular cable bundle. Furthermore, the loop lengths are known in advance. Thus, we applied different optimization criteria than the one presented in [4]. The schemes proposed here differ from the UUPBO method presented in [5] by not defining the user unique rates and by not requiring any knowledge about the individual FEXT crosstalk couplings between the lines.

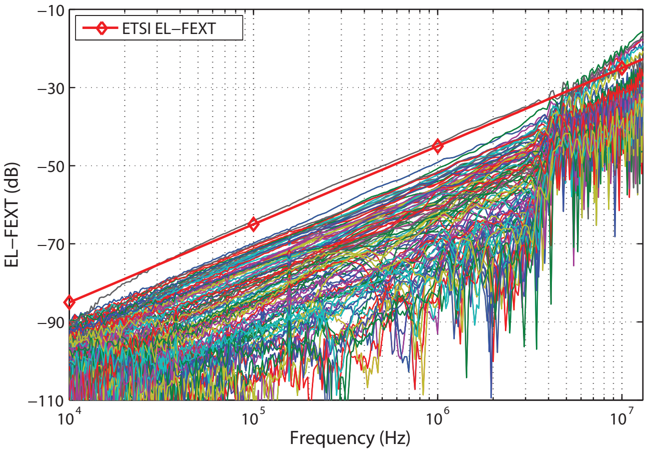

Figure 2: Measured EL-FEXT values, normalized to 1 km, between twenty pairs of a 0.4 mm cable with 50 pairs.

5. SIMULATION RESULTS AND DISCUSSIONS

In order to evaluate the performance of the algorithms presented in Section 4 some simulations were performed. Simulation parameters are taken according to ETSI VDSL standard [7]. Thus, we use $\Gamma = 12.3\,\mathrm{dB}$ as the SNR gap, and the band plan 997, which uses two upstream bands.

We are considering 20 equally spaced modems indexed from 1 to 20, where 1 denotes the user closest to the CO and 20 the most distant user, as shown in Figure 1. Furthermore, the maximum PSD mask constraint is set to $-60\,\mathrm{dBm/Hz}$ for all simulations. Simulations were performed for the measured FEXT couplings of a 0.4 mm cable with 50 pairs (vendor identification: F02YHJA2Y $50 \times 2 \times 0.4$). Figure 2 represents equal level FEXT (EL-FEXT) couplings of all twenty pairs used, which are selected randomly from 50 possible pairs. The insertion losses per unit length in all twisted pairs of our cable are very similar as can be seen in Figure 3. Therefore, we assume for all simulations that all twisted pairs have the same insertion loss per unit length. Moreover, to take into account the alien noise, in addition to the background noise at $-140\,\mathrm{dBm/Hz}$, we have also added the ETSI VDSL Noise E [7]. For the first set of experiments we are considering two network topologies: in the first one we assume a distance between modems of $x = 25\,\mathrm{m}$ and in the second one a distance of $x = 50\,\mathrm{m}$. Thus, the longest lines considered are 500 m and 1000 m, respectively. For the second simulation scenario, the normalized FEXT couplings seen on every line in the bundle are illustrated in Figure 4.

Figure 5 shows the bit rates obtained for both scenarios and both optimization strategies. The results are also compared with bit rates obtained when the standardized PBO parameters are used. We see that for the scenario with $x = 25\,\mathrm{m}$, all modems get significant higher bit rates, since now the parameters are optimized for this particular scenario. The improvement for the line with the lowest bit rate is above 40 %. Likewise the improvement of the minimum rate for the scenario with $x = 50\,\mathrm{m}$ is almost 20 %. However, bit rates of the modems close to the CO are slightly reduced, because the optimization algorithm is focusing on the maximization of the minimum bit rate.

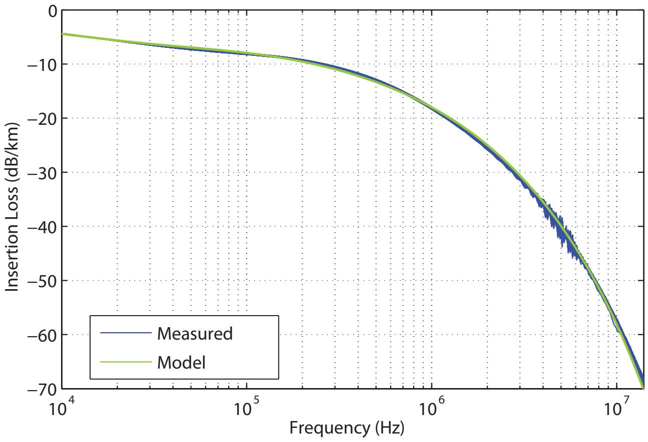

Figure 3: Measured insertion loss, at 1 km, of all 50 pairs and the model used for simulation.

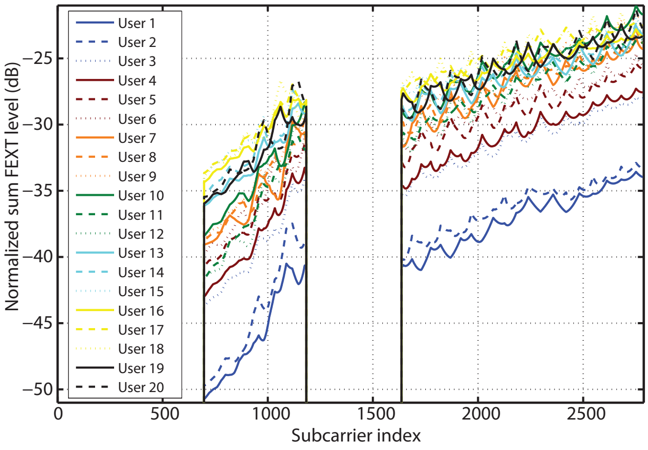

Figure 4: Normalized FEXT couplings for the network scenario in Figure 1 with $x = 50\,\mathrm{m}$

Comparing both optimization algorithms that we proposed, from Figure 5 it is obvious that the concept of virtual line represents a good approximation to the maximization of the minimum bit rate procedure. It can be further noted that the results for both optimization strategies are overlapping when $x = 25\,\mathrm{m}$. There is only a small deviation for the longest line. For scenario with $x = 50\,\mathrm{m}$, the maximization of the minimum bit rate strategy in general shows better performance. However, the minimum bit rates of both algorithms are very similar. It can be concluded that the concept of virtual line is a good approximation of maximization of minimum bit rate strategy.

If an operator is not satisfied with the achieved rates in the bundle they can exclude the longest line from the optimization process and optimize the bundle for a shorter line. We show in Figure 6 the attained bit rates when distance between the modems was set to 50 m and the bundle was optimized by forming the virtual line with attenuations from different lines, namely 20, 19, 17, 15. If a shorter loop is used to form the virtual line then the bit rates on the loops that are closer

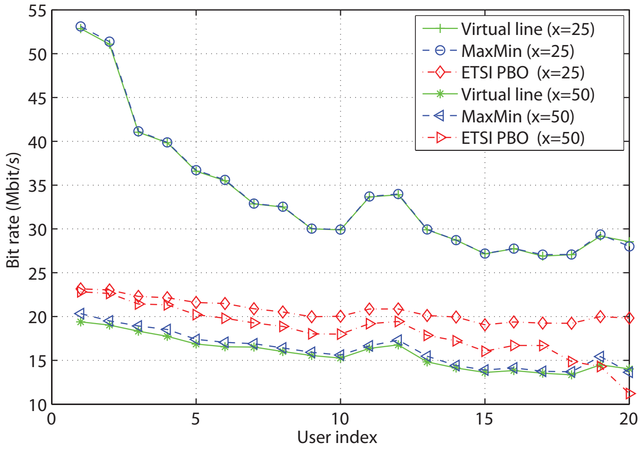

Figure 5: Simulation results obtained from both proposed optimization algorithms as well as for ETSI standardized PBO parameters.

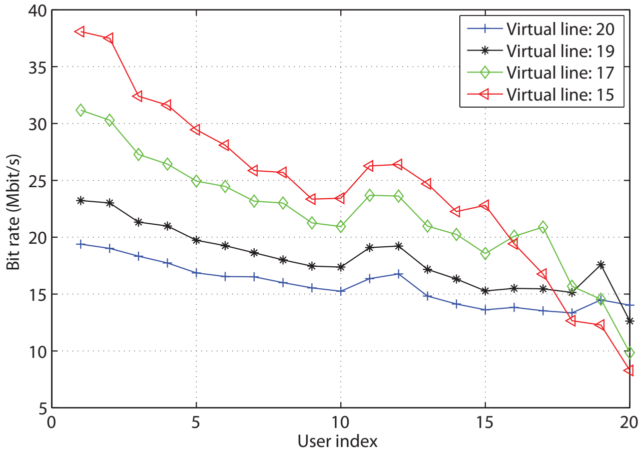

Figure 6: Achieved bit rates when virtual line is formed with line 20, 19, 17, and 15 with $x = 50$m.

to the CO are increased. Improvements in minimum bit rates for the virtual lines 19, 17, and 15 compared to the virtual line 20 are 11 %, 33 %, and 36 %, respectively. That is, an operator can select per cable bundle for which bit rates the power back-off parameters are optimized.

Figure 7 shows the bit rate gain in percentage, of maximization of minimum bit rate and virtual line optimizations versus ETSI PBO parameters, for the distance between users in the range from 10 to 75 m. One can see that the largest improvements are achieved for short and long cables. For the medium length cables the improvements are lower, which is due the fact that the standardized PBO parameters are optimized for medium length cables.

6. CONCLUSIONS

In this paper we have presented a technique for optimization of the upstream power back-off (PBO) parameters that are unique for a cable bundle. This cable unique PBO (CUPBO) optimization approach gives an operator the opportunity to optimize VDSL performance according to an actual network situation. By using the property of VDSL reference PBO where all received PSDs are the same we showed how a *normalized* FEXT coupling can replace the knowledge of the complete FEXT couplings during the optimization of the PBO parameters. By optimizing the PBO parameters for an actual cable bundle we achieve a significant performance increase compared to the worst case design used in standardized VDSL systems. As demonstrated by simulations these improvements are in the range of 5 % up to more than 80 %. In addition we presented a method where an operator can set an arbitrary minimum bit rate toward which the PBO parameters are optimized.

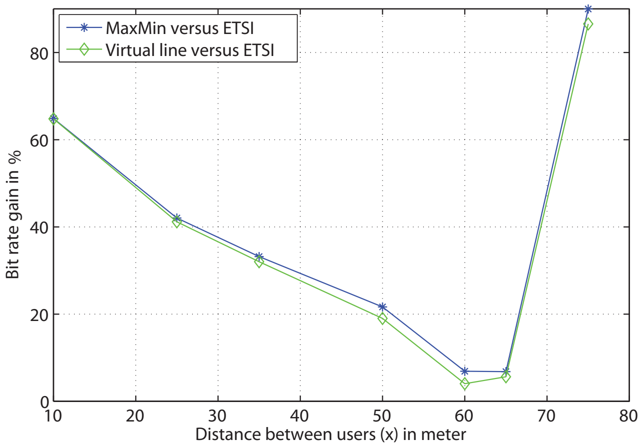

Figure 7: Rate gain in percentage of maximization of minimum bit rate and virtual line optimizations versus ETSI PBO parameters.

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