ENERGY EFFICIENT POWER BACK-OFF MANAGEMENT FOR VDSL2 TRANSMISSION

Tomas Nordström, Driton Statovci, and Martin Wolkerstorfer

Telecommunications Research Center Vienna (FTW.),
Donau-City-Straße 1, A-1220 Vienna, Austria
Emails:{nordstrom, statovci, wolkerstorfer}@ftw.at

ABSTRACT

Recently energy saving has become an important issue also for wired communication. In this paper we investigate the potential of using power back-off (PBO) as a means to achieve higher energy efficiency. Based on a global energy optimisation formulation we derive an energy efficient PBO (EEPBO) algorithm. Through simulation we compare EEPBO with continuous bit-loading to the near-optimal energy efficient spectrum balancing (EESB) algorithm and an integer bit-loading version of EEPBO with energy efficient iterative spectrum balancing (EEISB).

By restricting the search to practical levels of PBO parameters instead of optimizing the bit-loading on each and every carrier separately we see a significant reduction in computational complexity. It also means that EEPBO is already supported by current VDSL2 systems. Still, even after restricting the spectrum to what the PBO in VDSL2 allows we can show, through simulations, that EEPBO achieves the same level of energy efficiency as the near-optimal methods. This high performance and low-complexity together with standard compliance makes EEPBO a very attractive choice for future energy efficient transmission in VDSL2.

1. INTRODUCTION

In the last few years more energy efficient or "greener" information and communication technology has been high priority for both industry and governments all over the world. For example, since July 2006 an "EU Code of Conduct on Energy Consumption of Broadband Equipment" [1] exists with the goal to half the expected electricity consumption of broadband equipment by 2015. The major part of broadband equipment today is based on digital subscriber line (DSL) technology. The latest addition to this family is an updated version of very high-speed DSL (VDSL), known as VDSL2 [2]. A VDSL2 system 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. As FDD is used the DSL systems' performance is typically restricted by the far-end crosstalk (FEXT) interference.

For distributed DSL scenarios modems further out suffer from a near-far problem where all modems close to the deployment point disturb the already attenuated signals from modems far out. This problem is especially pronounced for higher frequencies, and therefore VDSL systems, due to higher FEXT couplings at higher frequencies. Thus, for VDSL[1] a power back-off (PBO) concept is standardized for use in the upstream transmission direction. In earlier papers [3, 4] we have described how to optimize the PBO parameters to achieve best performance (in bitrate), while in this paper we will look at optimizing PBO parameters for energy efficiency.

In all VDSL systems the line-driver power consumption is a large part, between 30 and 60 %, of the overall system power consumption. Together with an almost linear relation between line-driver power consumption and transmit power it is clear that reducing transmit power will reduce the overall power and therefore energy consumption. Therefore it is expected that many of the dynamic spectrum management (DSM) methods will help to reduce power consumption as they are designed to reduce interference among the users [6]. Recently it was shown that there is a benefit from optimizing directly for energy efficiency, using the energy-efficient spectrum balancing (EESB) algorithm [7], instead of getting an indirect power reduction through standard DSM methods, like optimal spectrum balancing (OSB) [5], which in fact try to maximize rate. This was further expanded in [9] where a family of energy efficient DSM algorithms, EEOSB, EEISB, and EEIWF were presented. These algorithms are modified versions of OSB, ISB, and IWF that minimize total power instead of maximizing rate.

In this paper we will add one new member to this family of energy efficient algorithms by looking at the only DSM method currently available in all VDSL systems, i.e., using upstream PBO. The performance of the resulting energy efficient power back-off (EEPBO) algorithm is then compared to the optimal or near-optimal companions in the family of energy efficient DSM algorithms.

In the next section we will introduce our system model, standardized power back-off, and our problem formulation. Then in Section 3 we describe our energy efficient PBO (EEPBO) algorithm. This is followed by Section 4 where we simulate EEPBO and compare its performance to other energy efficient DSM algorithms. Finally in Section 5 we summarize the paper and draw our conclusions on using EEPBO to improve energy efficiency in DSL.

2. SYSTEM MODEL AND PROBLEM FORMULATION

For DSL transmission over unshielded twisted-pair cables the lines interfere with each other through cross-talk. Discrete multi-tone (DMT) is currently the favored modulation

[1] In this paper we will use VDSL as a generic term for both first and second generation of VDSL.

scheme and allows to perform efficient resource allocation, in bits and power, over the carriers and thus in frequency. The latest DSL technology, very high speed digital subscriber line (VDSL), can utilize frequencies up to 30 MHz and uses digital frequency division duplex (D-FDD) to split the utilized bandwidth between downstream and upstream directions. By assuming synchronisation we may model the C carriers as orthogonal subchannels and obtain a far-end crosstalk limited system. To relax the demand for synchronisation the carriers are grouped and current standardized VDSL systems use between two and four frequency bands for each transmission direction.

In terms of channel information we assume to have access to the magnitudes of all crosstalk couplings at least at the collocated side. We also restrict the permitted coordination to the spectrum level and crosstalk is hence treated as noise at the receiver side. In the following users, subbands and carriers are identified by the sets of indices $\mathscr{U} = \{1,\dots,U\}$, $\mathscr{S} = \{1,\dots,SB\}$ and $\mathscr{C} = \cup_{s=1}^{SB}\mathscr{C}_s = \{1,\dots,C\}$, respectively, where $\mathscr{C}_s$ contains the carrier indices in subband s, and SB denotes the number of subbands. Under Gaussian-noise approximation and two-dimensional signal constellations the achievable rate per DMT-symbol for user $u \in \mathscr{U}$ on carrier $c \in \mathscr{C}$ is thus given by

$$r_c^u(\mathbf{p}_c) = \log_2\left(1 + \frac{H_c^{uu} p_c^u}{\Gamma(\sum\limits_{i\in\mathscr{U}\setminus u} H_c^{ui} p_c^i + N_c^u)}\right), \quad (1)$$

where $\mathbf{p}_c = [p_c^1,\dots,p_c^U]^T$ and p_c^u is the power spectral density (PSD) on carrier c for user u. We have denoted the squared magnitudes of the direct channel transfer coefficient of user u by H_c^{uu} and the cross-channel transfer coefficient from user i to user u by H_c^{ui}, respectively. We further utilize the SNR-gap to capacity Γ and write the total background noise power spectral density on carrier c and line u as N_c^u.

By reformulation of (1) and using vector notation the per-carrier power allocation for a certain number of bits $\mathbf{b}_c = [b_c^1,\dots,b_c^U]^T$ loaded by the users on carrier c can be expressed as

$$\mathbf{p}_c = (\mathbf{I} - \mathbf{F}^c)^{-1}\mathbf{v}^c, \quad (2)$$

where $\mathbf{F}^c$ is an irreducible, nonnegative matrix with entries

$$F_{uj}^c \triangleq \begin{cases} 0, & \text{if } u = j, \\ \dfrac{\Gamma H_c^{uj}(2^{b_c^u}-1)}{H_c^{uu}}, & \text{otherwise,} \end{cases} \quad (3)$$

and

$$\mathbf{v}^c \triangleq \left[\frac{\Gamma(2^{b_c^1}-1)N_c^1}{H_c^{11}},\dots,\frac{\Gamma(2^{b_c^U}-1)N_c^U}{H_c^{UU}}\right]^T. \quad (4)$$

This formulation will later be used in the problem description.

2.1 Standardized Power Back-off

Power back-off (PBO) is used in VDSL to solve the *near-far problem* in the upstream transmission direction [8] where modems closer to the deployment point reduce their transmit power. Currently the standardized method to shape the PSD is to use a so called reference PSD that determines the maximum received PSD and is a parameterized function of frequency. For a VDSL system there is a reference PSD for each upstream subband. Thus, the transmit PSD, p_c^u, $c \in \mathscr{C}_s$ in each subband s for user u is determined by the values of two parameters: α_s^u and β_s^u. We denote these variables by $\Phi^u = \mathsf{X}_{s\in\mathscr{S}}\Phi_s^u$ or $\Phi_s = \mathsf{X}_{u\in\mathscr{U}}\Phi_s^u$, where $\Phi_s^u = \{\alpha_s^u, \beta_s^u\}$ and X denotes the Cartesian set product. The reference PSD is shaped (expressed in dBm/Hz) according to

$$p_{\mathrm{R\_dBm}}^u(f_c, \Phi_s^u) = -\alpha_s^u - \beta_s^u\sqrt{f_c},\ \forall c \in \mathscr{C}_s \quad (5)$$

where f_c denotes the carrier frequency given in MHz. The standard also limits the α values to be in the range $[40\dots80.95]$ in steps of 0.01 and β in the range $[0\dots40.95]$ in steps of 0.01 (all in dBm/Hz).

Currently $\Phi_s^u, \forall u \in \mathscr{U}, \forall s \in \mathscr{S}$ are usually optimized for maximizing the weighted sum-rate [4] or reach [8].

2.2 Problem Formulation

The overall optimization goal is to "jointly" minimize the weighted sum of power used by all users in a cable bundle, while satisfying predefined target bitrates. The problem formulation also contains practical aspects like PSD masks and potential use of discrete bit-loading. Thus, we pose the global optimization problem as

$$\underset{\Phi_1,\dots,\Phi_{SB}}{\text{minimize}} \quad \sum_{u\in\mathscr{U}} w_u \sum_{\substack{s\in\mathscr{S},\\ c\in\mathscr{C}_s}} p_c^u(\Phi_s) \quad (6a)$$

$$\text{subject to} \quad \sum_{\substack{s\in\mathscr{S},\\ c\in\mathscr{C}_s}} b_c^u(\Phi_s) \geq R_u,\ \forall u \in \mathscr{U}, \quad (6b)$$

$$\text{where,}\ \forall u \in \mathscr{U}, \forall s \in \mathscr{S}, \forall c \in \mathscr{C}_s,$$

$$\tilde{p}_c^u(\Phi_s^u) = \min\{\frac{10^{p_{\mathrm{R\_dBm}}^u(f_c,\Phi_s^u)/10}}{H_c^{uu}}, p_c^{u,\max}\}, \quad (6c)$$

$$\tilde{r}_c^u(\Phi_s) = r_c^u(\tilde{\mathbf{p}}_\mathbf{c}(\Phi_s)), \quad (6d)$$

$$b_c^u(\Phi_s) = \begin{cases} \tilde{r}_c^u, & \text{if continuous,} \\ \min\{\lfloor \tilde{r}_c^u(\Phi_s)\rfloor, B^{\max}\}, & \text{if integer bit-loading,} \end{cases} \quad (6e)$$

$$\mathbf{p}_c(\mathbf{b}_c(\Phi_s)) = (\mathbf{I} - \mathbf{F}^c)^{-1}\mathbf{v}^c, \quad (6f)$$

with $B^{\max}$ denoting the assumed maximum number of loaded bits per carrier and we used the definition of F_{uj}^c and $\mathbf{v}^c$ in (3) and (4) respectively. Besides complying with the reference PSD, modems also need to adhere to a maximum allowed transmit PSD $p_c^{u,\max}$, *cf.* (6c). Line (6e) models the use of continuous valued or integer bit-loading at the transmitter, while in (6f) we compute the (unique) power-allocation for it. The problem further includes weights $w_u, u \in \mathscr{U}$, being restricted to the open simplex $w_u > 0$, $\sum_{u\in\mathscr{U}} w_u = 1$. Finally, R_u is the target-rate for user u in [bits/DMT-symbol]. The total transmit energy $f_s^{-1}\sum_{u\in\mathscr{U}}\sum_{c\in\mathscr{C}} p_c^u$, where f_s denotes the DMT-symbol frequency, is only a scaled version of our objective and hence minimized by the optimum of (6). The optimization problem (6) can be extended in a straightforward way to deal with the constraints on the PBO parameter values, Φ_s, as specified in Section 2.1.

3. ENERGY EFFICIENT POWER BACK-OFF (EEPBO)

Optimization problem (6) is in general nonconvex and the parameters Φ_s are coupled among the subbands due to constraint (6b). To alleviate the exponential complexity of exhaustive parameter search in the number of subbands we relax the target-rate constraints in (6b) to obtain *SB* independent subband problems. Based on this, a dual optimization problem to (6) is written as

$$\underset{\boldsymbol{\lambda}}{\text{maximize}}\ \underset{\Phi_1,\ldots,\Phi_{SB}}{\text{minimize}}\ \sum_{s\in\mathscr{S}} L_s(\Phi_s,\boldsymbol{\lambda}) \tag{7a}$$

$$\text{subject to}\quad \lambda_u \ge 0,\ \ \forall u \in \mathscr{U}, \tag{7b}$$
$$\text{Constraints } (6c)-(6f),$$
$$\forall u\in\mathscr{U}, \forall s\in\mathscr{S}, \forall c\in\mathscr{C}_s.$$

where the partial objective is defined as

$$L_s(\Phi_s,\boldsymbol{\lambda}) = \sum_{u\in\mathscr{U}_s}\left(w_u \sum_{c\in\mathscr{C}_s} p_c^u(\Phi_s) + \lambda_u\big(R_u - \sum_{c\in\mathscr{C}_s} b_c^u(\Phi_s)\big)\right). \tag{8}$$

Since the problem (7) is also in general nonconvex in Φ, we propose a heuristic approach for solving it as summarized in Algorithm 1. We call our algorithm energy-efficient PBO (EEPBO), since it minimizes the energy consumption of modems for a given set of bitrates by only searching for optimized PBO parameters. EEPBO pursues an iterative approach over users in the similar fashion as energy efficient iterative spectrum balancing (EEISB) [9]. For each user u and subband s a set of PBO parameters, Φ_s^u, is calculated that minimizes the partial objective (8) under the constraints (6c) - (6f).

In a particular user iteration, c.f. function CalcPBOBitload, for each subband s we use the Nelder-Mead simplex algorithm [10] to search for the optimized PBO parameters that minimize the partial objective (8). This procedure is repeated for each subband. The Nelder-Mead algorithm does not accept constraints on PBO parameters, Φ_s, however, the VDSL standards specify limits as discussed in Section 2.1. To overcome this problem we use the *extended-value extension* [11] of the partial objective, L_s, where the value of L_s is defined to be infinity outside the feasible region.

The main complexity of EEPBO and EEISB can be found in how often the partial objective is evaluated. For EEPBO the number of iterations depend on the number of subbands (2-4) multiplied with the number of Nelder-Mead search steps. In our simulations we have found that the number of search steps always stays below 50. Thus, for EEPBO there are between 100 and 200 iterations. This should be compared to the complexity of EEISB for which the number of iterations depends on the number of active carriers (1000-2000) multiplied by the maximum allowed number of bits per carrier, $B^{\max}$ (typically 15). Thus, we find EEISB two orders of magnitude more complex than EEPBO.

As we will show by simulation, EEPBO has slightly worse performance compared to EEISB in terms of power necessary to support a given set of bitrates. There is however a trade-off between computation power and transmit power. Computation power may in fact become a significant factor in energy consumption when the transmit PSDs are updated regularly, *e.g.*, in order to exploit traffic variability. Thus, EEPBO becomes even more attractive in terms of energy efficiency when transmit PSDs have to be updated often.

Algorithm 1 Energy Efficient PBO (EEPBO) Algorithm

Preset values: $p_c^u\ \forall u,c$ and w_u, R_u; $\forall u$

Initialize: $\boldsymbol{\lambda} = [\lambda_1,\ldots,\lambda_U]$
repeat
  for $u = 1$ to U **do**
    repeat
      $\left[\Phi^u, \sum_{c\in\mathscr{C}} b_c^u\right]$=***CalcPBOBitload***$\left(u, \mathbf{w}, \lambda_u, \Phi^i, \forall i\in\mathscr{U}\right)$
      Update λ_u { *e.g.* use bisection}
    until the target rate for user u is achieved, cf. (6b)
  end for
until convergence of $\boldsymbol{\lambda}$

Function ***CalcPBOBitload***
for $s = 1$ to SB {number of subbands} **do**
  Set search starting point $\bar{\Phi}_s^u$ {*e.g.* $\{60, 20\}$}
  $[L_s, \Phi_s^u]$ = ***NelderMead***$\left(@\textbf{\textit{PartialObjective}}, \bar{\Phi}_s^u\right)$
  Calculate $b_c^u\ \ \forall c\in\mathscr{C}_s$ as in (6e)
end for

Function L_s =***PartialObjective*** $\left(u, \mathbf{w}, \lambda_u, \Phi^i, \forall i\in\mathscr{U}\right)$
if α_s^u and β_s^u outside the allow domain **then**
  $L_s = \infty$
else
  Calculate L_s as in (8) using (6c) - (6f)
end if

4. COMPARATIVE SIMULATIONS

For ease of comparison we will restrict our simulations to a VDSL scenario as shown in Figure 1 with two users located at 300 m and 600 m distance from the deployment point, respectively. The simulation parameters were chosen according to the ETSI VDSL standard [12], with an SNR-gap $\Gamma = 12.8$ dB and two transmission bands as defined in band plan 997. The cable used is TP100, and the background noise comprised of ETSI VDSL noise A added to a constant noise floor at -140 dBm/Hz.

4.1 Comparison to EESB

Energy efficient spectrum balancing (EESB) is a continuous, distributed algorithm for energy efficient DSM as presented in [7]. This heuristic and low-complexity algorithm shows near-optimality for a wide range of scenarios and will be used as a reference when evaluating the performance of EEPBO.

For the two selected user scenarios simulated we have

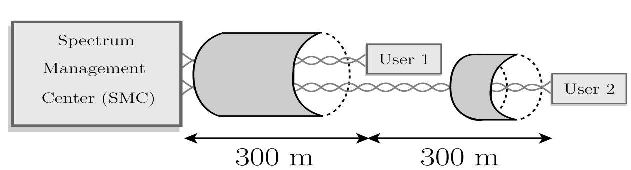

Figure 1: 2-User xDSL Scenario.

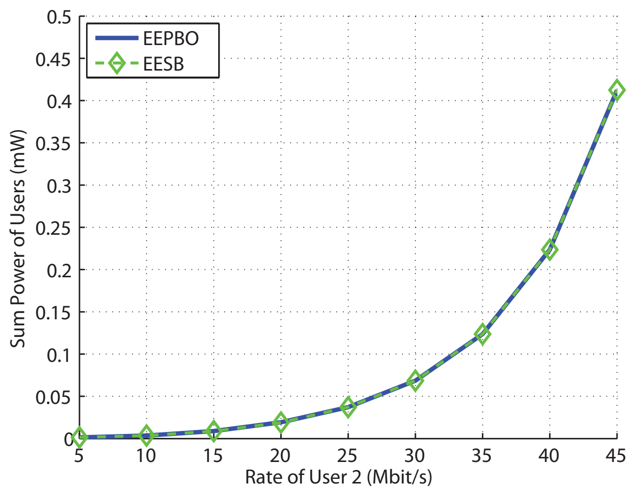

Figure 2: Sum-power transmitted for EEPBO and EESB when $R_1 = 25$Mbits/s and R_2 varies between 5 and 45 Mbits/s.

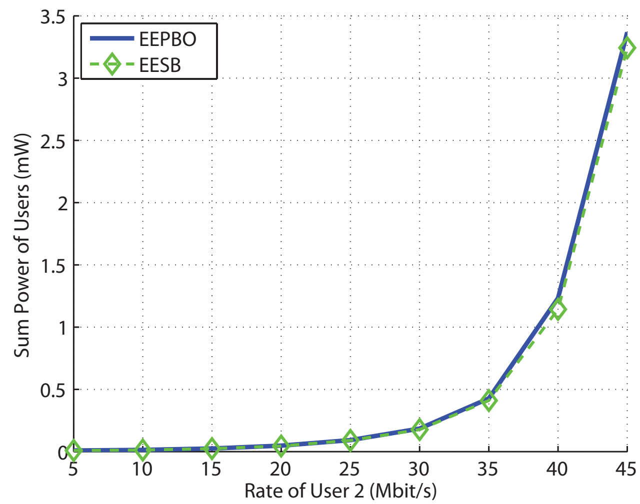

Figure 4: Sum-power transmitted for EEPBO and EESB when $R_1 = 45$ Mbits/s and R_2 varies between 5 and 45 Mbits/s.

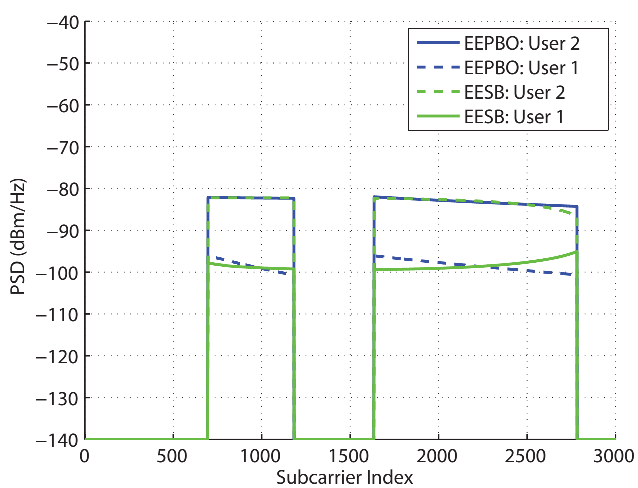

Figure 3: PSD's for EEPBO and EESB when R_1 and R_2 transmits 25 Mbit/s each.

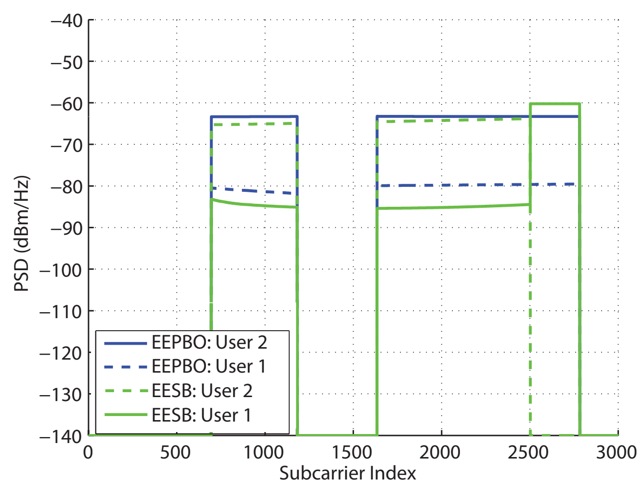

Figure 5: PSD's for EEPBO and EESB when R_1 and R_2 transmits 45 Mbit/s each.

evaluated the sum power of the two users when the first user's target rate R_1 is fixed at 25 and 45 Mbit/s and the second user's target rate R_2 varies between 5 and 45 Mbit/s in steps of 5 Mbits/s. In Figure 2 we show the case when R_1 is fixed at 25 Mbits/s. The corresponding PSDs when both users transmit at 25 Mbit/s are shown in Figure 3. We see that for the case when both target rates are moderate (at 25 Mbit/s each) the EEPBO and EESB perform almost identically.

If we instead increase the target rate for R_1 to 45 Mbit/s, which is close to the maximum feasible for this two-user scenario, we see in Figure 4 that the difference in performance between EEPBO and EESB increase slightly. A reason for this can be observed in Figure 5 where EESB now selects a partial frequency division multiplex between the users, while EEPBO do not have this freedom and thus loses in efficiency.

We also performed simulations on these scenarios using fixed α values and only optimizing the β values, as done in [4] when optimizing for rate. In this case, however, we saw a significantly lower performance of the EEPBO algorithm. This strengthen our opinion that optimizing energy efficiency is more difficult than the optimization of rates and therefore it is natural that EEPBO needs the additional freedom to change the α values in order to achieve the same performance as EESB.

4.2 Comparison to EEISB

Real VDSL2 modems do not implement continuos bit-loading, instead they use integer bit-loading. Therefore, we have also simulated a bit-loading version of EEPBO which we will denote EEPBO$^{\#}$. To make a fair comparison we will compare EEPBO$^{\#}$ to EEISB [9] that also uses integer bit-loading. EEISB uses iterations over the users to alleviate some of the complexity issues that exist in the optimal EEOSB [9].

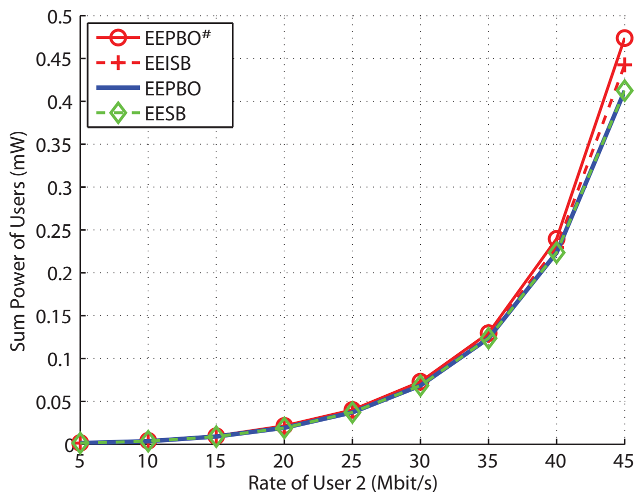

Figure 6: Sum-power transmitted for EEPBO# and EEISB when $R_1 = 25$ Mbits/s and R_2 varies between 5 and 45 Mbits/s.

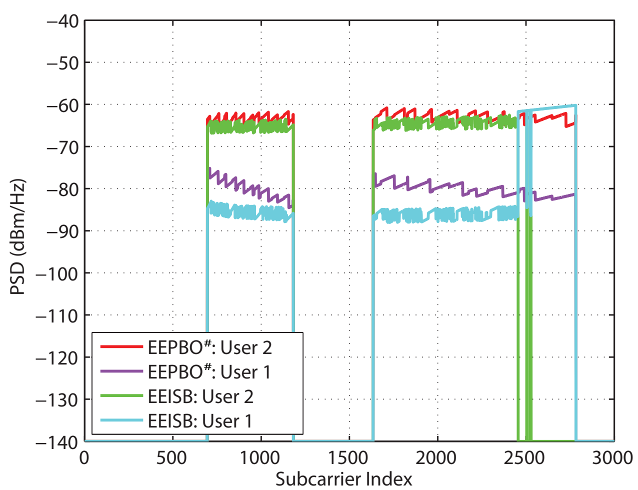

Figure 7: PSD's for EEPBO# and EEISB, which uses integer bit-loading, when R_1 and R_2 transmits 45 Mbit/s each.

In Figure 6 we compare EEPBO# and EEISB when R_1 is fixed at 25 Mbits/s and R_2 varies between 5 and 45 Mbit/s. Due to integer bit-loading there is a slightly higher sum-power for EEPBO# and EEISB compared to EEPBO and EESB (cf. Figure 2) but otherwise they show identical behavior. The PSDs used by EEPBO# and EEISB when both users transmit at 45 Mbit/s are shown in Figure 7.

5. CONCLUSIONS

In this paper we have introduced the energy efficient power back-off (EEPBO) algorithm as a new member of the growing family of energy efficient spectrum management methods. From simulations we see that EEPBO suffers no significant performance loss compared to methods optimizing the bit-loading on each carrier separately. Thus, making EEPBO a very attractive approach for increasing the energy-efficiency in current digital subscriber lines since it has low complexity and the PBO concept is already standardized and available in today's VDSL2 modems.

6. ACKNOWLEDGMENT

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