DYNAMIC SPECTRUM MANAGEMENT FOR STANDARDIZED VDSL

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ABSTRACT

Dynamic spectrum management (DSM) improves the capacity utilization of twisted-pair cables by adapting the transmit power spectral density (PSD) of modems to the actual noise environment and channel conditions. Earlier proposed DSM algorithms do not take into account the standardized very high speed digital subscriber line (VDSL) constraints on the allowable transmit PSDs. However, VDSL modems support only restricted transmit PSD shapes resulting from the standardized power back-off (PBO) method, which is controlled by a small set of parameters. Furthermore, since all modems are currently using the same PBO parameters their bit rate performance is severely limited. In this paper, we show how to effectively exploit the standardized PBO concept for DSM to significantly boost bit rates. We also present a low complex DSM algorithm, the user unique PBO (UUPBO) algorithm, for calculating PBO parameters that are uniquely optimized for each modem.

Index Terms— DSL, optimization methods, signal processing, communication systems, information rates.

1. INTRODUCTION

Very high speed digital subscriber line (VDSL) technology 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. To deal with different network scenarios, current standardized VDSL systems use up to four frequency bands for each transmission direction.

Power back-off (PBO) is used in VDSL to solve the *near-far problem* in the upstream transmission direction [1]. With upstream PBO, modems located close to central office (CO) or cabinet reduce their transmitted power spectral densities (PSDs) in the upstream direction in order to improve the performance of modems located further away. Many PBO methods have been proposed for VDSL, see [1] and the references therein. However, after observing that many PBO methods can be described by a certain desired *received* PSD, the standardization bodies have agreed to use the 'reference PBO' method [1, 2]. A parameterized reference PSD is defined in this PBO method for each upstream band. In the current VDSL standards, the PBO is a requirement and the actual parameters used for the reference PBO were established by Schelstraete [1] and Oksman [2].

Deploying standardized PBO parameters in VDSL systems severely limit performance, since they are optimized for a worst-case noise environment and predefined bit rates. In this paper we will show how the capacity utilization of the twisted-pair cables can be improved if the PBO parameters are individually optimized for each modem by taking into account the actual network topology. Thus, we can perform DSM with the already standardized generation of VDSL systems. Furthermore, from simulations we conclude that shaping PSDs according to PBO parameters is sufficient for DSM.

The rest of the paper is organized as follows: Section 2 gives some preliminaries concerning PSD shaping in VDSL and our defined bit rate relation; Section 3 describes the optimization problem we aim to solve; Section 4 presents a new algorithm to solve the optimization problem of Section 3; Section 5 shows some simulation results; and Section 6 summarizes the major findings in this paper.

2. PRELIMINARIES

The reference PSD, as defined for PBO in the VDSL standards, determines the maximum recieved PSD and is a parameterized function of frequency. Although almost any shape of the reference PSD is possible to realize with discrete multitone (DMT) modulation, it has been agreed [1, 2] to select the reference PSD model (expressed in dBm/Hz) as

$$\mathcal{P}_u^{\mathrm{R}}(f) = \alpha + \beta\sqrt{f}, \quad \text{[dBm/Hz]} \tag{1}$$

where frequency f is given in MHz, and α and β are the parameters which 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. It is also standardized that independent reference PSDs should be assigned to each upstream band. In addition, modems need also adhere to a maximum allowed transmit PSD, $\mathcal{P}^{\max}$. Hence, the transmit signal PSD of a particular user u in subcarrier n is determined (in linear scale) by

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$$\mathcal{P}_u^n = \min\left\{\frac{\mathcal{P}_u^{n,\text{R}}}{\mathcal{H}_{uu}^n}, \mathcal{P}_u^{n,\max}\right\}, \quad (2)$$

where $\mathcal{H}_{uu}^n$ denotes the squared magnitude of the channel and $\mathcal{P}_u^{n,\text{R}} = \mathcal{P}_u^{\text{R}}(f = n\Delta_f)$ with Δ_f denoting the subcarrier width.

2.1. Bit rate relations

Based on Shannon's capacity formula the number of total bits that can be reliably transmitted in a particular DMT symbol for VDSL is determined as

$$R = \sum_{n \in I} \log\left(1 + \frac{\mathcal{H}_{uu}^n \mathcal{P}_u^n}{\Gamma \mathcal{N}_u^n}\right), \text{ with} \quad (3)$$

$$\mathcal{N}_u^n = \sum_{\substack{v=1 \\ v \neq u}}^{U} \mathcal{H}_{uv}^n \mathcal{P}_v^n + \mathcal{P}_{u,V}^n, \quad (4)$$

where I denotes the set of subcarriers used in the upstream transmission direction; Γ is the signal-to-noise ratio gap; $\mathcal{N}_u^n$, $\mathcal{P}_u^n$, $\mathcal{P}_{u,V}^n$ denote the PSD of user u in subcarrier n of noise, transmit signal, and the sum of background and alien noises, respectively; $\mathcal{H}_{uv}^n$ is the squared magnitude of far-end crosstalk (FEXT) coupling from user v to user u. The effect of the near-end crosstalk (NEXT) noise vanishes, since we assume all VDSL systems use D-FDD, the same band plan, and work fully synchronized.

The bit rate that can be delivered to each user depends on the selected band plan, network topology (insertion losses and FEXT couplings), background noise level, and the PSDs of the other VDSL systems deployed on the same cable bundle. To this end each user is assigned a bit rate share or priority value (p_u), respectively, which specifies how much of the total upstream cable capacity shall be assigned to the particular user u. This concept is the same as the one described in [3]. Hence, the relation between the user priorities and bit rates is specified as

$$\frac{R_1}{p_1} = \frac{R_2}{p_2} = \ldots = \frac{R_U}{p_U}, \text{ with } \sum_{u=1}^{U} p_u = 1. \quad (5)$$

If the user u is not transmitting, then $p_u = 0$ and this users is removed from (5) . The priority values are derived from the bit rates which we aim to deliver to each user relative to the total bit rate as: $p_u = \widetilde{R}_u / \sum_{u=1}^{U} \widetilde{R}_u$, where $\widetilde{R}_u$ denotes the desired bit rate of user u. Our aim is to use these user priority values p_u to find the desired operating point (*i.e.*, the bit rates of all users) since the quantities represented by these parameters are always related through (5).

3. OPTIMIZATION GOAL

The optimization goal is to 'jointly' maximize the bit rates for all users under the constraint that the bit rates should satisfy the predefined relations in (5). Without this constraint, users close to the CO would achieve very high bit rates at the cost of the distant users. To be standard compliant the transmit PSD of each user is selected to have the shape determined by (2). Thus, the transmit PSD, P_u, in each upstream transmit band is determined by α and β. We denote this set by $\Phi_u = \{(\alpha_{1,u}, \beta_{1,u}), \ldots, (\alpha_{SB,u}, \beta_{SB,u})\}$, where the subscript SB denotes the number of upstream subbands. The optimization problem can now be formulated as:

$$\underset{\Phi_1,\ldots,\Phi_U}{\text{maximize}} \sum_{u=1}^{U} R_u, \quad (6a)$$

$$\text{subject to:} \frac{R_1}{p_1} = \frac{R_2}{p_2} = \ldots = \frac{R_U}{p_U}, \quad (6b)$$

$$\mathcal{P}_u^n = \min\left\{\frac{\mathcal{P}_u^{n,\text{R}}}{\mathcal{H}_{uu}^n}, \mathcal{P}_u^{n,\max}\right\}, \ \forall\, u, \forall n \in I \quad (6c)$$

$$\sum_{n \in I} \mathcal{P}_u^n \leq T_u^{\max}, \ \forall\, u, \quad (6d)$$

where $T_u^{\max}$ denotes the maximum total power constraint for user u.

Let us assume for a moment that the constraint (6b) is removed from the optimization problem (6). With this assumption, as shown in [4], the optimization in (6) can be rewritten as an optimization problem where the objective is to maximize the sum of weighted bit rates:

$$\underset{\Phi_1,\ldots,\Phi_U}{\text{maximize}} \sum_{u=1}^{U} w_u R_u, \quad (7a)$$

$$\text{subject to:} \mathcal{P}_u^n = \min\left\{\frac{\mathcal{P}_u^{n,\text{R}}}{\mathcal{H}_{uu}^n}, \mathcal{P}_u^{n,\max}\right\}, \ \forall\, u, \forall n \in I \quad (7b)$$

$$\sum_{n \in I} \mathcal{P}_u^n \leq T_u^{\max}, \ \forall\, u, \quad (7c)$$

where w_u denotes the weighting value (or short: 'weight') assigned to user u. Without loss of generality, the weights can be selected such that $\sum_{u=1}^{U} w_u = 1$. We increase the bit rate of user u compared to the bit rates of the other users by increasing its w_u. For certain weights which satisfy the bit rate relations defined in (6b) the solution of optimization problem (7) is equivalent to the solution of optimization problem (6).

4. OPTIMIZATION ALGORITHM

To solve the optimization problem (6), we propose an algorithm, that we *call* user unique PBO (UUPBO), which consists of three levels of nested iterations, see Algorithm 2. The outer level, see Section 4.1, searches for weights, w_u, until the bit rate relations in (6b) are satisfied. The middle level, see Section 4.2, solves (7) and it uses dual decomposition, which applies Lagrange multipliers to deal with the constraints. Thus, in this level we search for Lagrange multipliers, λ_u, which satisfy the total power constraint (7c) and the constraint (7b).

The inner level, see Section 4.3, searches the sets of PBO parameters, Φ_u, which maximize the sum bit rates in (7a). In the following the task of each level will be described.

4.1. Outer Level

For a set of weights, a set of bit rates is found which lies on the hull of the bit rate region. The bit rate region for U user is U-dimensional. Since the hull of bit rate region in multi-user spectrum management is convex [4], there exists only one set of weights which maximizes (7) and satisfies the bit rate relations defined in (6b). Therefore, the task at hand is now to find a method to calculate the optimal weighting values that satisfies (6b).

For a two-user case the bisection algorithm is used to find the appropriate values of weights based on the following search criteria: if $\frac{R_1}{p_1} < \frac{R_2}{p_2}$, w_1 is increased otherwise it is decreased; and $w_2 = 1 - w_1$, due to assumption $\sum_{u=1}^{U} w_u = 1$. For cases with more than two users we use the pseudo-code of Algorithm 1, which emulate the behavior of the bisection search.

Algorithm 1 Outer level – updating weights when $U > 2$

Calculate $\frac{R_1}{p_1}, \dots, \frac{R_U}{p_U}$
Calculate $\sigma_u = \textbf{\textit{sign}} \left(\frac{R_u}{p_u} - \frac{1}{U} \sum_{u=1}^{U} \frac{R_u}{p_u} \right), \forall u$
Update $w_u = w_u + \Delta w_u \sigma_u, \forall u$
If $w_u \leq 0$ replace it with a small positive non-zero value
Normalize $w_u = \frac{w_u}{\sum_{u=1}^{U} w_u}, \forall u$ to satisfy $\sum_{u=1}^{U} w_u = 1$
Replace $\Delta w_u = \frac{\Delta w_u}{2}$ when the sign of σ_u changes between two iterations

4.2. Middle Level

Given the outer level, as defined above, all users weights are kept fixed on this level. The so-called Lagrangian is defined by incorporating the total power constraint from (7c) into the object function (7a)

$$L = \sum_{u=1}^{U} w_u R_u + \sum_{u=1}^{U} \lambda_u \left(T_u^{\max} - \sum_{n \in I} \mathcal{P}_u^n \right). \tag{8}$$

From the theory of the Lagrange functions it is known that the Lagrange multiplier will be selected such that either the total power of user u satisfies $\sum_{n \in I} \mathcal{P}_u^n = T_u^{\max}$ or $\lambda_u = 0$. By collecting the terms that belong to the same subcarrier it can be shown that (8) can be written as

$$L = \sum_{n \in I} L^n + \sum_{u=1}^{U} \lambda_u T_u^{\max}, \tag{9}$$

where L^n is the Lagrangian on subcarrier n and is given by

$$L^n = \sum_{u=1}^{U} w_u R_u^n - \sum_{u=1}^{U} \lambda_u \mathcal{P}_u^n. \tag{10}$$

Now the optimization problem (7) can be written as

$$\underset{\Phi_1, \dots, \Phi_U}{\text{maximize}} \;\; L(\mathbf{w}, \boldsymbol{\lambda}, \Phi_1, \dots, \Phi_U), \tag{11a}$$

$$\text{subject to: } \mathcal{P}_u^n = \min \left\{ \frac{\mathcal{P}_u^{n,\mathrm{R}}}{\mathcal{H}_{uu}^n}, \mathcal{P}_u^{n,\max} \right\}, \forall u, \forall n \in I, \tag{11b}$$

where $\mathbf{w} = [w_1, \dots, w_U]$ and $\boldsymbol{\lambda} = [\lambda_1, \dots, \lambda_U]$. A method to search for the optimal Lagrange multipliers is as follows: First, the Lagrange multipliers of all users are initialized to $\lambda_u = 2^m$, where $m \in 0 \cup \mathbf{Z}^+$. For the set of PBO parameters, Φ_u, calculated in the inner level, the transmit PSD of user u is calculated as in (6c). Depending on used power the following steps are taken: as long as $\sum_{n \in I} \mathcal{P}_u^n > T_u^{\max}$ the Lagrange multiplier of user u is updated by $\lambda_u = 2\lambda_u$. Thereafter, the bisection is used to search for the appropriate value of λ_u within the range $\lambda_u^{\min} = 0$ and $\lambda_u^{\max} = \lambda_u$, until the total power constraint in (6d) is satisfied with a predefined accuracy. The Lagrange multipliers, λ_u, are iterated many times among all users until there is no more change in the transmit PSDs of the users.

4.3. Inner Level

In this function the transmit PSDs and bit loadings of all users are calculated. Thus, for each user u a set of PBO parameters, Φ_u, is searched, which maximizes (11a) under the constraint (11b). Since the Lagrange function in (11a) is neither convex nor concave with respect to the power allocations, an exhaustive search is used to find the appropriate values of PBO parameters. To reduce the computation time, in current version of the algorithm, α values are kept fixed and set equal to the maximum PSD constraint (in dBm/Hz) for each subband. Thus, only optimized β values need to be searched. In addition to the maximum transmit PSD mask constraint, we can also define a minimum transmit PSD mask constraint, $\mathcal{P}_u^{\min}$. If not given by the standard it can be set equal to the background noise level; thus, $\mathcal{P}_u^{\min} = \mathcal{P}_{u,V}$. Based on the maximum and minimum transmit PSD values on each subband sb and the definition of the reference PSD in (2), the maximum and minimum β values for each subband are calculated (in dBm/Hz) as

$$\beta_u^{sb,\max} = \max \left\{ \frac{10 \log_{10} \left(\mathcal{H}_u(f) \right)}{\sqrt{f}} \right\}, \tag{12a}$$

$$\beta_u^{sb,\min} = \min \left\{ \frac{10 \log_{10} \left(\mathcal{H}_u(f) \right) - \mathcal{K}}{\sqrt{f}} \right\}, \tag{12b}$$

where $\mathcal{K} = 10 \log_{10} \left(\max \left\{ \mathcal{P}_u^{\max}(f) \right\} \right) - 10 \log_{10} \left(\min \left\{ \mathcal{P}_u^{\min}(f) \right\} \right)$ and f is restricted to the frequencies within the subband sb. Thus, the optimum value of β_u^{sb} lies in the interval $[\beta_u^{sb,\min}, \beta_u^{sb,\max}]$. The optimal value of β_u^{sb} in the given interval is searched exhaustively with a predefined search step $\Delta\beta$. For each value of β_u^{sb} the bit loading within the given subband is calculated as in (6.1) and the Lagrangian L^{sb} for the subband sb is calculated by

$$L^{sb} = \sum_{n \in I^{sb}} L^n, \tag{13}$$

where I^{sb} denotes the set of subcarriers within the subband sb and L^n is defined in (6.11).

Algorithm 2 User Unique PBO (UUPBO) Algorithm

Preset values: $p_u, w_u = \frac{1}{U}, \Delta w_u = \frac{1}{2U}; \forall u$
Outer Level
repeat
  $\mathbf{R}$ = ***CalcRates***$(\mathbf{w})$, where $\mathbf{R} = [R_1, \ldots, R_U]$
  Update $(\mathbf{w})$ according to Algorithm 1
until bit rates satisfy (6b) with some predefine accuracy

CalcRates function {*Middle Level*}
Initialize: $\boldsymbol{\lambda}$= $[\lambda_1, \ldots, \lambda_U]$ and $\mathcal{P}_u$, $\forall u$
repeat
  for $u = 1$ to U **do**
    Calculate Noise $\mathcal{N}_u$ for $n \in I$ as in (4)
    repeat
      $[\Phi_u, R_u]$= ***CalcPBOBitloading***$(u, \mathcal{N}_u, \mathbf{w}, \boldsymbol{\lambda})$
    until (7c) is satisfied or $\lambda = 0$
  end for
until the PSDs of all users have reach a desired accuracy

CalcPBOBitloading function {*Inner Level*, for fixed α's}
for $sb = 1$ to SB {number of subbands} **do**
  Calculate $\beta_u^{sb,\min}$ and $\beta_u^{sb,\max}$ as in (12)
  for $\beta_u^{sb} = \beta_u^{sb,\min}$ to $\beta_u^{sb,\max}$ with step $\Delta\beta$ **do**
    Initialize:$L^{sb,\max} = -\infty$
    Calculate $\mathcal{P}_u^{\mathrm{R}}$ and $\mathcal{P}_u$ as in (1) and (2), respectively
    $L^{sb} = 0$
    Calculate L_{sb} as in (13)
    if $L^{sb} \geq L_{sb}^{\max} = -\infty$ **then**
      $L^{sb,\max} = L^{sb}$
      Update β_u^{sb} and $\mathcal{P}_u$ values
    end if
  end for
end for

5. SIMULATION RESULTS

Simulation parameters are taken according to ETSI VDSL standard. Thus, we use $\Gamma = 12.3\,\mathrm{dB}$ as the SNR gap, cable TP100, and the band plan 997, which uses two upstream bands. We assume a network scenario with two users located at 600 m and 1200 m from a remote cabinet or a central office. Furthermore, for all simulations we have set: $\mathcal{P}_u^{\max} = 55$ [dBm/Hz] and $T_u^{\max} = 11.5$ [dBm].

The performance of the UUPBO algorithm is compared with iterative spectrum balancing (ISB) algorithm as presented in [5] and PBO parameters as given in the ETSI VDSL standard. From the simulation results in Fig. 1, we see that UUPBO and ISB algorithms show nearly equivalent performance.

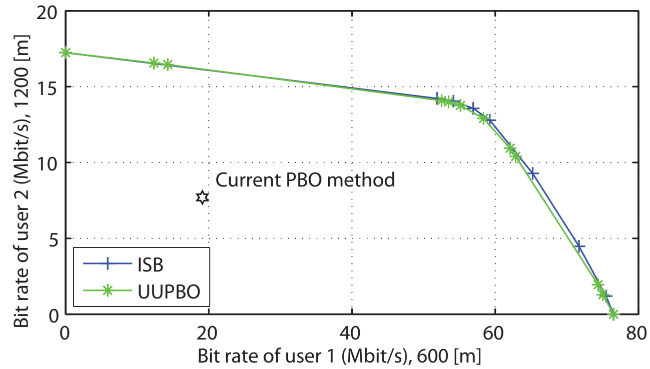

Fig. 1. Comparison of the rate regions between UUPBO and ISB algorithms for two users.

6. CONCLUSIONS

In this paper we showed how the capacity utilization of twisted-pair cables is improved if the standardized PBO parameters are individually optimized for each VDSL modem by taking into account the actual network topology. We also presented an efficient DSM algorithm, the user unique PBO (UUPBO) algorithm, for calculating transmit PSDs which follows standardized PBO constraints. Simulations showed that UUPBO significantly boost performance compared to the standardized PBO and achieves equivalent performance as the earlier proposed iterative spectrum balancing algorithm while still keeping to the VDSL standards.

7. REFERENCES

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