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CONTRIBUTION

TITLE: **DSM Level 2 Band-Preference using Penalty Tables**

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ABSTRACT

This contribution presents a nearly-distributed Level 2 DSM method for the bit-loading as well as the bit- and gain-swapping procedures of DMT DSL based on the concept of band-preference. Politeness is achieved by using rate-penalty tables along with existing bit-loading algorithms (such as Levin-Campello) to limit the interference caused to weak users in the network. When the "politeness" indication is on (i.e. the "maximum SNR margin mode" a.k.a. "margin-cap mode," or "band-preference" is on), some bands of the DMT DSL are given preferential treatment during the loading and swapping procedures, while other bands are associated with a penalty. Results show that the proposed method can achieve near-optimal performance. Limited, infrequent information sent by a spectrum management center (SMC) is sufficient to generate the rate-penalty tables. This contribution is provided for information only.

1. Introduction

The Level 2 band-preference concept allows current DSL performance (including future Level 1 DSM performance) to be tremendously improved, with reasonable complexity that is within the scope of current standards. The spectrum management center (SMC) imposes politeness on users who transmit too much power in frequency bands that are critical to the performance of other users in the network. This problem of interference-management by appropriately shaping the power-spectral-densities (PSDs) of the users is referred to as spectrum balancing [1]. For loops of equal length, the iterative water-filling (IWF) algorithm [2] can achieve close to optimal spectrum balancing performance. The distributed IWF method can obtain significant gains over impolite present-day DSLs; however, it does not provide the full improvement when the loops have significantly different lengths. The optimal bound for spectrum balancing was presented in [3], however its exponential complexity in the number of users as well as the need for centralized bit-swapping make it infeasible for practical implementation. The band-preference that was proposed in [4] enables a practical way to achieve the full gains of spectrum balancing, with performance close to the optimum.

A companion contribution [5] presents a distributed band-preference method that utilizes the “politeness” indication from the SMC, which has been known as “band-preference, margin-cap mode, or maximum SNR margin mode,” and also another method based on a modification to the IWF procedure using additional water-level scaling factors. The present contribution presents an alternate band-preference method that utilizes rate-penalty tables. The rate-penalty table measures the amount of bits that a user loses in a tone or frequency band when another user transmits more power in that tone/band. Similar to the methods presented in [5], the rate-penalty based method can be implemented with low complexity using limited information that is sent to the modems by the SMC. A re-use of some unused fields in VDSL2 can be used to pass this limited information as mentioned in [5]. These algorithms enable a practical realization of the Level 2 DSM potential.

The complete description of the algorithms is provided in the appendix. The main body of the contribution presents the results for an upstream VDSL example.

2. Performance Results for VDSL and Discussion

Figure 1 illustrates the basic band preference concept as in [5] for upstream VDSL. This example has been well studied in DSM

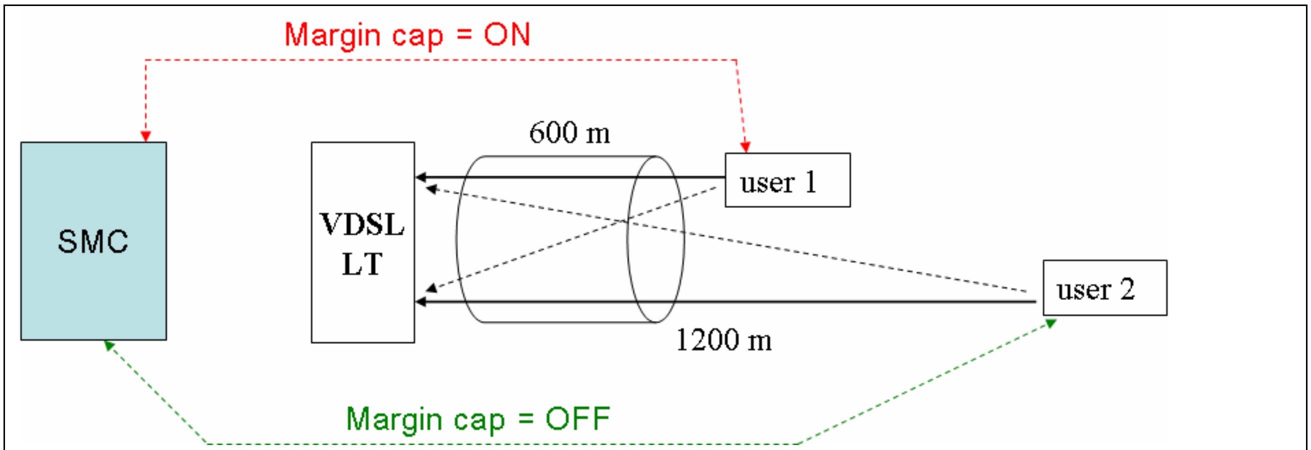

Figure 1 – illustration of SMC setting margin cap on for extra politeness from user 1.

and corresponds to a situation where Level 2 DSM can provide an enlarged set of possible data rates for both users (see Annex C of the DSM Report [6]).

When the “politeness” indication (labeled as “margin cap”) in the figure is off, user 2 simply performs normal bit-loading as in current DSLs. On the other hand, user 1 sees that the “politeness” indication has been turned on by the SMC and hence uses a modified loading procedure. Identification of the strong and weak users (such as users 1 and 2 respectively) is performed by the SMC based on the observation of the lines.

As described in detail in the appendix, a rate-penalty table is used by user 1 during the bit-loading process. The SMC could either centrally compute the rate-penalty table and send it to the modem, or the modem could simply be provided with parameters that enable it to compute the rate-penalty table on its own.

Figure 2 presents the achievable rate region obtained using different spectrum balancing methods for the upstream VDSL situation of Figure 1. The rate region describes the achievable pairs of data rates for the two users in the presented example. Figure 1 clearly shows that the rate-penalty-based band-preference algorithm (also referred to as SBLC) almost achieves optimal performance (given by OSB). In fact, there is almost no difference between the two rate regions. This observation is further validated by comparing the PSDs in Figures 3(a) and (b). Significant improvements over the IWF algorithm can be achieved using the SBLC algorithm, while maintaining its practicality and adaptability. The presented band-preference method can also be employed to compute the scaled water-levels for the method presented in [5], instead of using it directly for bit-loading. Subsequent execution of the BPSM algorithm of [5] will result in the same performance as SBLC in Figure 2.

Since the rate-penalty tables only need to be infrequently communicated to the modems, there may be certain existing VDSL2 MIB fields that would not be in simultaneous use that could be used for distribution of the rate-penalty table information. For example, the virtual noise (VN) field will not be used when the "politeness" mode is on, since VN will lead to increased user powers and hence, will cause more interference in the network and is opposite to the politeness requirement. Instead, such fields can be better used to send the rate-penalty information that helps achieve optimal performance. Alternately, the rate-penalty table can be computed locally at the modem using some "reference line" parameters (see appendix) that are sent by the SMC. The rate-penalty table can also be formed using lesser information albeit with a performance loss similar to the DBPSM method in [5]. For example, such basic information could be about which frequency bands are to be given preference during bit-loading. A fully autonomous approach for the presented band-preference method (SBLC), similar to the DBPSM method, is also possible.

3. Conclusions

A band-preference method based on rate-penalty tables has been presented that achieves close to optimal Level 2 DSM performance. Both ADSL and VDSL2 results have been presented. Results have been presented only for the 2-user case for simplicity and for comparison with OSB (whose complexity exponentially increases for more than 2 users). More complicated situations can be investigated for the rate-penalty-based band-preference method. The rate-penalty table in a sense acts like bit-caps on some bands, thus limiting the interference to other users. The bit- and gain-swapping procedures can still be implemented in a distributed manner and centralized swapping is avoided in the presented band-preference method. Such band-preference methods enable the full realization of Level 2 DSM potential in DMT DSLs such as VDSL2. This contribution is provided for information only.

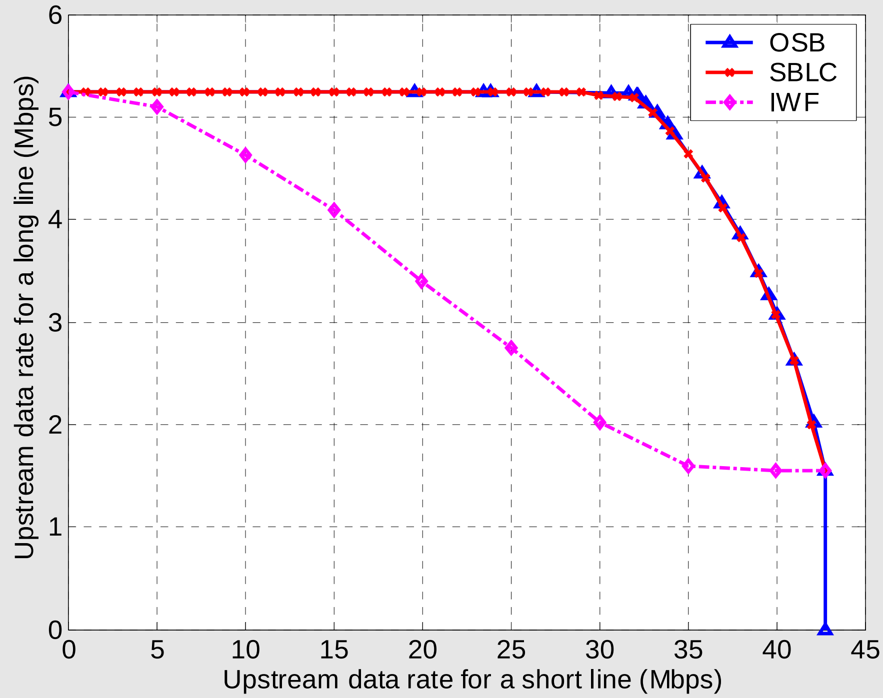

Figure 2 – Performance of various methods for the situation of Figure 1.

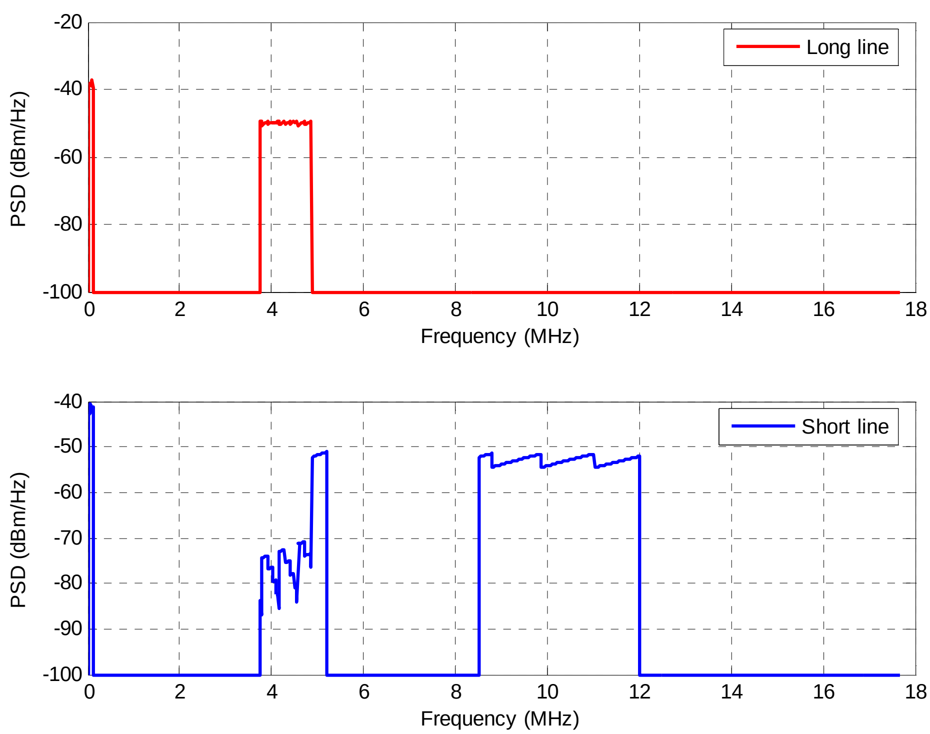

Figure 3(a) – OSB spectra for Figure 1 when R_{short} = 35 Mbps.

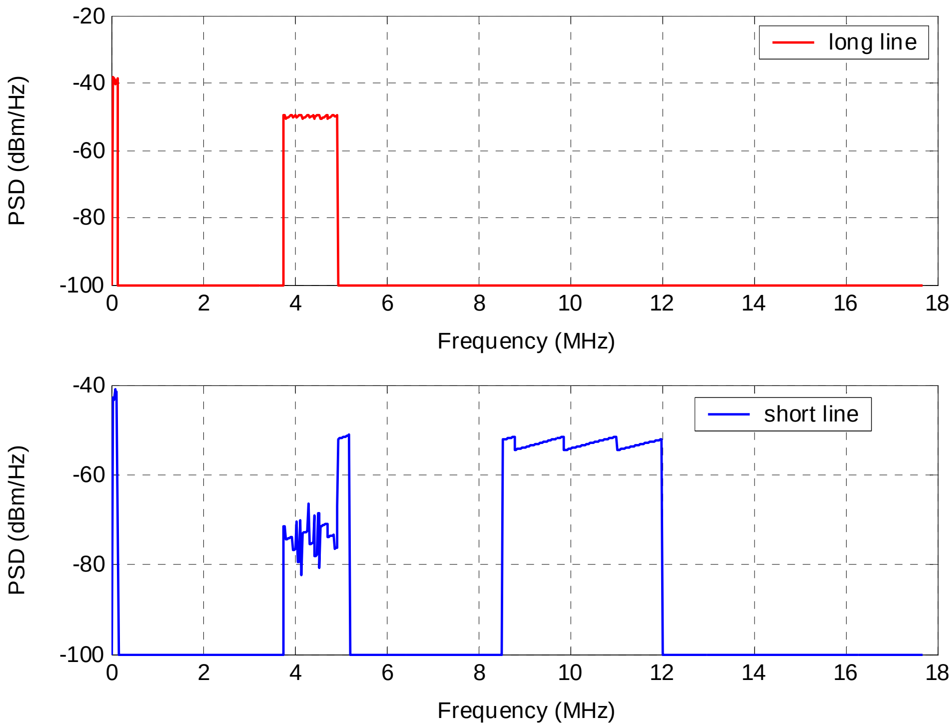

Figure 3(b) – SBLC spectra for Figure 1 when R_{short} = 35 Mbps.

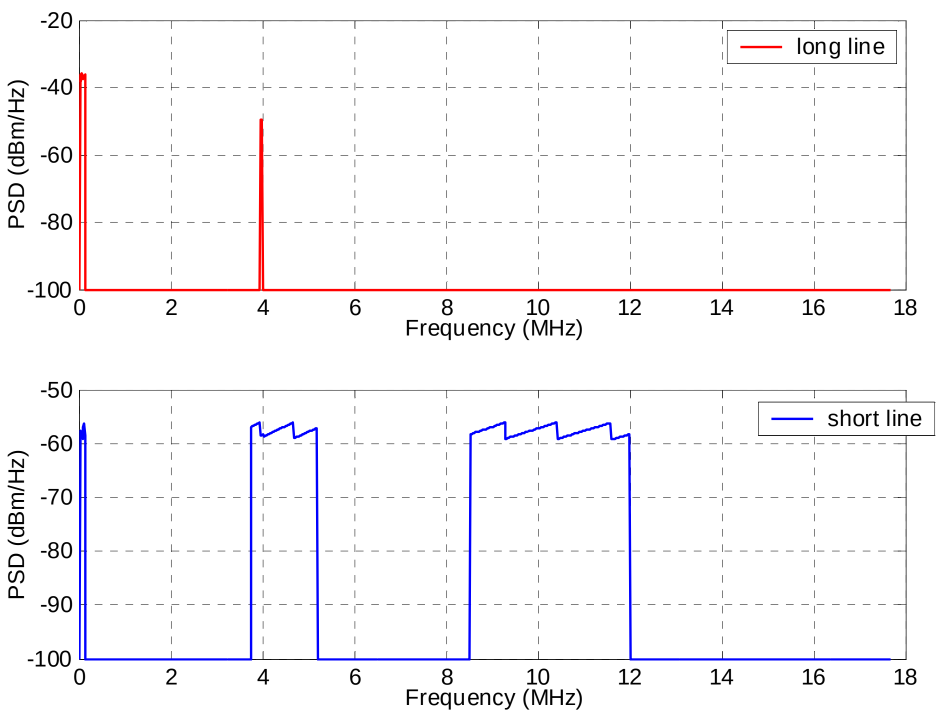

Figure 3(c) – IWF spectra for Figure 1 when R_{short} = 35 Mbps.

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Distributed, Adaptive Bit-loading for Spectrum Optimization in Multi-user Multicarrier Systems

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***Abstract*— This paper presents a discrete bit-loading algorithm for multi-user multicarrier systems with application to spectrum balancing in digital-subscriber-lines. The algorithm can be implemented in a distributed manner using limited information that is sent to modems by a spectrum management center (SMC). The SMC first classifies users as strong and weak. Strong users then form a rate-penalty table that is used along with the Levin-Campello bit-loading algorithm to limit the interference to weak users. Simulation results show that the proposed algorithm can achieve near-optimal performance. Moreover, the structure of the algorithm enables easy implementation of polite bit and gain adaptation procedures without the need for executing the entire bit-loading algorithm again.**

I. Introduction

Optimization of spectra among multiple users is an important component of modern communication systems. One example is the digital-subscriber-line (DSL) network where Level 2 Dynamic Spectrum Management (DSM) methods [1][2] (also known as spectrum balancing) optimize the spectra of users to reduce interference. For example, the distributed Iterative water filling (IWF) algorithm [3] obtains significantly higher data-rates than currently-used static spectrum management methods. However, IWF is sub-optimal in near/far scenarios such as upstream VDSL and central-office (CO)/remote-terminal (RT) mixed-binder downstream situations[1].

Optimal Spectrum Balancing (OSB) provides the optimal solution to the spectrum balancing problem [4]. However, its exponential complexity in the number of users and centralized nature make it prohibitive for practical implementation. Iterative Spectrum Balancing (ISB) [5][6] reduces the complexity but is still centralized. Unlike OSB and ISB, a continuous bit-loading method called SCALE was presented in [7] by applying a convex relaxation technique to spectrum balancing. With SCALE as a starting point, [8] employs a greedy method to generate a discrete bit-loading for use in practical systems.

In pursuit of a more distributed but near-optimal solution, the band preference methodology was proposed in [9] where modems independently perform waterfilling based on the power-spectral-density (PSD) masks or water-level scaling factors [10] provided by the spectrum management center (SMC). Autonomous Spectrum Balancing (ASB) [11] is also a distributed algorithm where information about a typical line in the network is initially passed from the SMC to the modems, which then independently perform their optimization.

[1]Refer to Fig. 1. A fiber-fed RT causes severe crosstalk to a user served by a CO, while the RT user does not experience much interference from CO.

Previous work on spectrum balancing has not considered adaptation to slow channel/noise variations by adjusting the bits and energies (or gains) of the subchannels[2], which is very important since the spectra are optimized for a specific channel and noise situation. Such variations could be caused by other DSLs in the binder turning on/off, changing temperature and soil conditions, or simply other non-crosstalk noise sources that vary with time. In the single-user case, the optimal discrete bit-loading algorithm known as Levin-Campello (LC) [12][13] allowed for easy adaptation [14]. Although [15][16] extended the LC algorithm to the multi-user case, the extension is centralized and not amenable to bit and gain changes.

This paper uses the LC algorithm along with a rate-penalty table to reduce the amount of interference caused by strong users to weak users. The penalty table represents the reduction in the data rate of the weak user when the strong user adds more bits to a subchannel. This table is formed using information sent by the SMC to the modems. An important contribution is the development of bit and gain adaptation procedures that are polite toward weak users using the proposed framework.

The remainder of the paper is organized as follows. The system model and problem formulation are described in Section II. The distributed discrete bit-loading algorithm is presented in Section III. Bit- and gain-adaptation are discussed in Section IV. Simulation results showing the performance of the bit-loading algorithm are presented in Section V. Finally, the paper is concluded in Section VI.

II. System Model and Problem Definition

A multi-user multicarrier system with N subchannels and U users is considered with one transmitter and receiver for each user. Assuming there is no intercarrier interference and that the users are synchronized, the channel can be modeled as N parallel and independent subchannels, each of which is an interference channel with U users. Such a model can be applied independently to the upstream and downstream of a DSL system that employs frequency-division duplexing, or may be applied in a full-duplex DSL system by treating the upstream and downstream as separate interfering users.

On subchannel n, the magnitude-square of the direct channel of user u is denoted as $H^n_{u,u}$, while the magnitude-square of the crosstalk channel from user v to user u is given by $H^n_{u,v}$. The background noise at user u's receiver on subchannel

[2]Such adjustment is referred to as bit/gain-swapping in DSL.

n is assumed to be Gaussian with zero mean and energy σ_u^n. Denoting the energy transmitted by user v on subchannel n as $\mathcal{E}_v^n$, the channel signal-to-interference-plus-noise ratio (SINR) of user u on subchannel n is expressed as

$$g_u^n = \frac{H_{u,u}^n}{\sum_{v \neq u} \mathcal{E}_v^n H_{u,v}^n + \sigma_u^n}. \tag{1}$$

Denoting the smallest incremental unit of information that can be transmitted as β bits (typically $\beta = 1$), the number of bits for user u on subchannel n can be expressed as

$$b_u^n = \beta \Big\lfloor \frac{1}{\beta} \log_2 \Big(1 + \frac{\mathcal{E}_u^n g_u^n}{\Gamma} \Big) \Big\rfloor, \tag{2}$$

where Γ is the gap to capacity of the code plus the noise margin used for protection against unexpected noise. The data-rate for user u is then given by

$$R_u = \sum_{n=1}^{N} b_u^n. \tag{3}$$

Users in the network are classified as strong and weak by the SMC. For example, in near-far situations, the near user will typically be the strong user and the far user will be the weak user. In general, the classification can be based on the acutal network topology and channel/noise conditions. The general goal of spectrum balancing is to allow weak users in the network to maximize their data-rates, while strong users try to achieve their target data-rates, causing minimal interference to the weak users. Mathematical formulation of this problem is convenient when target data-rates are fixed for $K-1$ users and the data-rate of the K^{th} user is to be maximized. The algorithm presented in this paper can be applied directly to the general goal, while the latter specific problem will be considered to compare the performance with OSB. The constraints for each user u include a total energy limit $\mathcal{E}_u = \sum_{n=1}^{N} \mathcal{E}_u^n \leq \mathcal{E}_u^{\text{tot}}$, a PSD mask $\mathcal{E}_u^n \leq C_u^n, \ \forall n$, and a maximum bit-cap for each subchannel $b_u^n \leq \bar{b}, \ \forall n$. A bit-cap that varies among the users and subchannels can be easily incorporated into the proposed algorithm.

III. The Distributed Discrete Bit-loading Algorithm

A. Energy Table

Each user u in the network measures the channel SINR $g_u^n, \ \forall n$. Using (2), the minimum energy required for loading b_u^n bits on subchannel n is

$$\mathcal{E}_u^n(b_u^n) = \frac{\Gamma}{g_u^n} \big(2^{b_u^n} - 1 \big). \tag{4}$$

The incremental energy to transmit b_u^n bits on subchannel n for user u is then defined as

$$e_u^n(b_u^n) = \begin{cases} \mathcal{E}_u^n(b_u^n) - \mathcal{E}_u^n(b_u^n - \beta) & \text{if } b_u^n > \beta \\ \mathcal{E}_u^n(b_u^n) & \text{if } b_u^n = \beta \end{cases} \tag{5}$$

$$= \frac{\Gamma}{g_u^n} 2^{b_u^n} \big(1 - 2^{-\beta} \big). \tag{6}$$

An incremental energy table such as Table I is formed by each user, which indicates the amount of energy required to load an extra β bits on subchannel n. When no more bits can be loaded on a subchannel because of violation of the PSD mask or bit-cap, the incremental energy is set to ∞. Such an incremental energy table is used in the optimal LC algorithms for single-user discrete bit-loading. While the gap to capacity is almost constant for many practical codes over a wide range of signal-to-noise-ratios (SNRs), there can be some deviation in practice based on the constellation size and type of code used. An advantage of the LC-based approach is that the energy table can be determined exactly by the modem based on the constellation and code that are used, instead of using the gap approximation [12].

TABLE I

Incremental Energy Table for User u with $\beta = 1$

6	$e_u^1(6)$	∞	∞	$\cdots$	∞
5	$e_u^1(5)$	∞	$e_u^3(5)$	$\cdots$	∞
4	$e_u^1(4)$	$e_u^2(4)$	$e_u^3(4)$	$\cdots$	∞
3	$e_u^1(3)$	$e_u^2(3)$	$e_u^3(3)$	$\cdots$	∞
2	$e_u^1(2)$	$e_u^2(2)$	$e_u^3(2)$	$\cdots$	$e_u^N(2)$
1	$e_u^1(1)$	$e_u^2(1)$	$e_u^3(1)$	$\cdots$	$e_u^N(1)$
b_u^n / n	1	2	3	$\cdots$	N

B. Rate-penalty Table

The SMC provides strong users with information about a reference line, which represents a typical weak line in the network. This concept was used in [11] to develop the ASB algorithm. The parameters of the reference line could be that of the weakest line in the network or could just be a suitable set of parameters that the SMC determines based on the network scenario. Let the reference line's noise and crosstalk channel from user u to the reference line on subchannel n be denoted by σ_{ref}^n and α_{ref}^n respectively, where both quantities are normalized by the direct channel of the reference line divided by the gap. The SMC additionally provides the nominal energy allocation E_{ref}^n of the reference line, which may simply be the PSD mask or may be obtained by water-filling with the nominal background noise. This information is used to form a rate-penalty table $B_{\text{pen},u}^n(b_u^n)$, which indicates the reduction in bits for the reference line (or weak user) when strong user u loads b_u^n bits on subchannel n. Formally, for $b_u^n = 1, \ldots, \bar{b}$, the penalty table is defined as

$$\begin{aligned} B_{\text{pen},u}^n(b_u^n) = \min \Big(\bar{b}, \beta \Big\lfloor \frac{1}{\beta} \log_2 \Big(1 + \frac{E_{\text{ref}}^n}{\sigma_{\text{ref}}^n} \Big) \Big\rfloor \Big) - \\ \min \Big(\bar{b}, \beta \Big\lfloor \frac{1}{\beta} \log_2 \Big(1 + \frac{E_{\text{ref}}^n}{\mathcal{E}_u^n(b_u^n) \alpha_{\text{ref}}^n + \sigma_{\text{ref}}^n} \Big) \Big\rfloor \Big), \end{aligned} \tag{7}$$

and the incremental penalty table is defined as

$$B_{\text{inc},u}^n(b_u^n) = \begin{cases} B_{\text{pen},u}^n(b_u^n) - B_{\text{pen},u}^n(b_u^n - \beta) & \text{if } b_u^n > \beta \\ B_{\text{pen},u}^n(b_u^n) & \text{if } b_u^n = \beta \end{cases}. \tag{8}$$

$B_{\text{inc},u}^n$ measures the weak user's incremental loss of bits caused by adding one bit to the strong user u. Table II shows

TABLE II

INCREMENTAL RATE-PENALTY TABLE FOR USER u WITH $N = 10$, $\beta = 1$

6	1	0	1	1	1	0	0	0	0	0
5	0	1	1	0	0	0	0	0	0	0
4	0	0	0	1	0	1	0	0	0	0
3	1	1	0	0	1	0	0	0	0	0
2	0	0	1	1	0	0	0	0	0	0
1	0	0	0	0	1	1	0	0	0	0
b_u^n / n	1	2	3	4	5	6	7	8	9	10

an example of an incremental rate-penalty table. The shaded regions will be explained later.

C. Bit-loading Algorithm

The fixed-margin (FM) and rate-adaptive (RA) LC algorithms form an important part of the proposed spectrum balancing algorithm that is hereafter referred to as Spectrum Balancing Levin-Campello (SBLC). RA LC (Algorithm 1) maximizes the data-rate subject to a energy constraint. The FM version, which minimizes the energy subject to a target data-rate, is obtained by replacing the stopping criteria in step 4 of the RA LC algorithm with $e_u^m(b_u^m+1) = \infty$ or $R_u \geq R_u^{\text{target}}$.

In the SBLC algorithm, the SMC first classifies the users as strong or weak. Weak users simply execute FM LC if they are provided with a target data-rate, otherwise they execute RA LC. Strong users will try to attain their data-rate target while causing minimum amount of penalty to the weaker users. The users execute their algorithms independently until their PSDs converge. If the SMC classifies all users to be weak, then the users effectively participate in an IWF procedure.

Algorithm 1 Rate-adaptive (RA) LC algorithm for user u

1: Initialization: Form the incremental energy table $e_u^n,\ \forall n$. Set $\mathcal{E}_u^n \leftarrow 0,\ b_u^n \leftarrow 0,\ \forall n$. Therefore, $\mathcal{E}_u = 0$ and $R_u = 0$.
2: **loop**
3: Set $m \leftarrow \arg\min_n e_u^n(b_u^n+1)$
4: **if** $e_u^m(b_u^m+1) = \infty$ or $(\mathcal{E}_u + e_u^m(b_u^m+1)) > \mathcal{E}_u^{\text{tot}}$ **then** stop **else**
6: $b_u^m \leftarrow b_u^m + 1,\ \mathcal{E}_u \leftarrow \mathcal{E}_u + e_u^m(b_u^m+1),\ R_u \leftarrow R_u + 1$

The strong user u forms the rate-penalty tables $B_{\text{pen},u}^n$ and $B_{\text{inc},u}^n$ using the parameters of the reference line. Subchannels on which no rate-penalty is caused to the reference line $\mathcal{N}_{np} \subseteq \{1, \ldots, N\}$ are identified. For example, columns 7, 8, 9, and 10 of Table II correspond to $\mathcal{N}_{np}$. More formally, no rate-penalty means the entire column of the $B_{\text{inc},u}^n$ table is zero. FM LC is first executed on $\mathcal{N}_{np}$. If the target data-rate is not met, then the remaining subchannels $\mathcal{N}_p =\subseteq \{1, \ldots, N\} \backslash \mathcal{N}_{np}$ become candidates for energy allocation. The FM LC algorithm is executed again to obtain additional data-rate with a modified energy table $\tilde{e}_u^n$, where $\forall n \in \mathcal{N}_p,\ b = 1, \ldots, \bar{b}$

$$\tilde{e}_u^n(b) = \begin{cases} e_u^n(b) & \text{if } B_{\text{pen},u}^n(b) = 0 \\ \infty & \text{if } B_{\text{pen},u}^n(b) \neq 0 \end{cases}. \tag{9}$$

The first FM LC run using $\mathcal{N}_{np}$ completely avoids overlapping the strong user's PSD with that of the weak user, while the second FM LC run using $\mathcal{N}_p$ tries to reach the target data-rate by loading on the overlapping tones but without penalizing the reference line. For example, the light-shaded cells in Table II show the bit-loading achieved by the two FM LC runs. If these two passes are not sufficient to meet the target data-rate, then the strong user has no option but to cause penalty to the reference line. However, the penalty is minimized by considering the following procedure. First, the subset $\mathcal{N}_{p,\min} \subseteq \mathcal{N}_p$ of subchannels having the minimum incremental rate-penalty are considered. For these subchannels, the number of bits Δb that could be loaded before the next penalty is caused is computed. The subchannels with maximum Δb are denoted by $\mathcal{N}_{p,\min}^{\Delta b_{\max}}$, where the maximum value is $\Delta b_{\max}$. Essentially for the same amount of penalty caused, subchannels where the maximum number of bits can be loaded by the strong user are selected as candidates. For these subchannels, the remaining rate-penalty $B_{\text{rem},u}^n$ that could be caused is calculated as

$$B_{\text{rem},u}^n = \sum_{b=b_u^n+1}^{b_{\max,u}^n} B_{\text{inc},u}^n(b), \tag{10}$$

where $b_{\max,u}^n$ is the maximum number of bits that can be loaded on subchannel n by user u.

The subset of subchannels $\mathcal{N}_{p,\text{rem}} \subseteq \mathcal{N}_{p,\min}^{\Delta b_{\max}}$ having the minimum remaining penalty $B_{\text{rem},u}^n$ is then considered (shown in dark shade in Table II). Among $\mathcal{N}_{p,\text{rem}}$, the subchannel m for which the reference line's channel SNR is smallest is chosen. User u then loads an extra bit on subchannel m. The intuition is that since the reference line spends a lot of energy to load bits on subchannels with low channel SNR, the strong user can add more bits in such a subchannel if the remaining penalty is small. This could be beneficial to the weak user, which then utilizes its energy more efficiently in subchannels with better channel SNR and lower interference. The penalty procedure stops when the target data-rate is met. Since the total energy constraint may have been violated during the polite bit allocation, the final routine moves bits from subchannels with the highest incremental energies to those with the lowest incremental energies until the energy constraint is satisfied. Algorithm 2 summarizes the procedure for the strong users.

Algorithm 2 SBLC Algorithm for Strong User u

1: Generate $B_{\text{pen},u},\ B_{\text{inc},u}$, and identify $\mathcal{N}_{np},\ \mathcal{N}_p$
2: Perform FM-LC on $\mathcal{N}_{np}$
3: **if** $R_u < R_u^{\text{target}}$ **then**
4: Continue FM-LC on $\mathcal{N}_p$ with modified $\tilde{e}_u^n$ (9)
5: **while** $R_u < R_u^{\text{target}}$ **do**
6: Identify $\mathcal{N}_{p,\text{rem}}$. Choose $m \in \mathcal{N}_{p,\text{rem}}$ with minimum channel SNR for the reference line.
7: **if** $e_u^m(b_u^m+1) \neq \infty$ **then** $b_u^m \leftarrow b_u^m + 1,\ R_u \leftarrow R_u + 1$
8: **else** remove subchannel m from $\mathcal{N}_{p,\text{rem}}$
9: **while** $\sum_{n=1}^N \mathcal{E}_u^n > \mathcal{E}_u^{\text{tot}}$ **do**
10: $m \leftarrow \arg\max_n e_u^n(b_u^n+1),\ p \leftarrow \arg\min_n e_u^n(b_u^n+1)$
11: $b_u^m \leftarrow b_u^m - 1,\ b_u^p \leftarrow b_u^p + 1$

The convergence properties of SBLC are beyond this short paper's scope. However, the algorithm can be verified to converge very quickly in simulations. The structure of SBLC has a complexity advantage over the ASB algorithm for discrete bit-loading. ASB for each user consists of a nesting of two loops - one to achieve the target data-rate and the other to meet the energy constraint. Within the nested loop, it requires the evaluation of a Lagrangian corresponding to each integer bit-loading on each tone. SBLC avoids nested loops and does not require an exhaustive search over the bit-loadings.

IV. Adaptation to Channel/Noise Variations

The SBLC algorithm allows for easy adaptation to changes in the channel SINR through the exchange of bits and energies between subchannels. An equal margin policy is usually adopted since the performance of a multicarrier system depends on the bit-error-rate of the worst subchannel. Such equal margin imposition may be the choice of the SMC that is not dynamic in terms of the speed of line-condition changes.

A. Polite Identification of Bit-swaps

Swapping of bits can be determined in a similar manner to current systems that treat each user independently. If all users are classified by the SMC as weak, i.e., they are effectively running IWF, then traditional methods to determine bit- and gain-swaps may be sufficient to reach a new equilibrium point. In near-far situations, the same argument holds separately between the weak users, and between the strong users.

Adaptation by weak users will typically not affect the strong users. On the other hand, strong users should be polite toward the weak users in their adaptation. If bit-swapping is performed among subchannels that are already used, then other users will not see an increase in their interference since there is no energy increase in the subchannels. However, if a bit is to be added to a subchannel that previously carried no bits, then a rate-penalty may be caused to the weak user since it will experience more interference because of the extra energy used by the strong user on that subchannel. Polite addition of bits to new subchannels can be achieved by using the rate-penalty table. Using steps 6 to 8 of Algorithm 2, the strong user can determine the subchannel where the bits are to be added, while causing minimal penalty to the weak user.

B. Polite Identification of Gain-swaps and Power-increase

Fine gain (or energy) scaling is typically used to aid bit-swapping and equalize the margin across subchannels. If the noise of the strong user changes, then the margin may drop below the target value prompting the modem to swap bits and energies, and even increase the total power. In current systems, bits would be moved to subchannels with the lowest incremental energy so that the maximum margin can be achieved with minimum power-increase. However, this may not be polite towards weak users. Instead, strong users should try to adapt while causing minimum harm to weak users. The penalty table can be used to achieve politeness as follows:

Algorithm 3 Polite Power-increase by Strong User

1: Remove bits and energies from subchannels that are below the target margin
2: Execute steps 6 to 11 of Algorithm 2 until the target data-rate is met
3: Implement appropriate bit/gain-swaps and power-increase

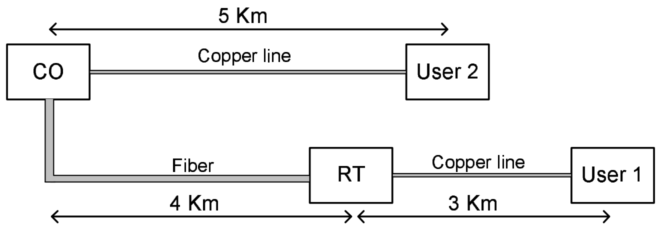

Fig. 1. Simulation Setup - ADSL CO/RT scenario

V. Simulation Results and Discussions

An ADSL downstream CO/RT scenario (Fig. 1) was simulated to evaluate the performance of SBLC. For comparison with the computationally complex OSB, only two users are considered. The simulation parameters are summarized in Table III. The noise is a combination of -140 dBm/Hz AWGN along with Noise A, which is a mixture of 16 ISDN, 4 HDSL, and 10 ADSL disturbers. The SBLC algorithm converged within 3 iterations among the users. A discrete-bit loading version of IWF was also simulated where the FM LC algorithm was executed by the RT user, and the RA LC algorithm was executed by the CO user until convergence.

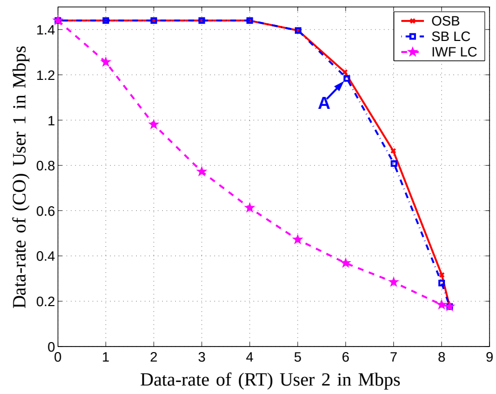

Fig. 2. Comparison of rate region achieved by SBLC with OSB and IWF

Figure 2 compares the rate region of SBLC with those

TABLE III
SIMULATION PARAMETERS

No. of subchannels	256	Subchannel Width (KHz)	4.3125
Bit-cap	15	Coding Gain (dB)	3
Symbol Rate (KHz)	4	Max Power (dBmW)	20.4
Target Margin (dB)	6	PSD Mask (dBm/Hz)	−38.5
Uncoded Gap (dB)	9.8	Line Gauge	24

obtained by OSB and IWF. The rate region of SBLC is very close to that of the optimal OSB. The PSDs in Fig. 3 further verify the closeness. The stronger RT user fully utilizes the higher frequency band and then loads bits in the lower frequencies while causing minimum penalty to the weaker CO user. This enables SBLC to obtain huge gains over IWF and very close performance to OSB.

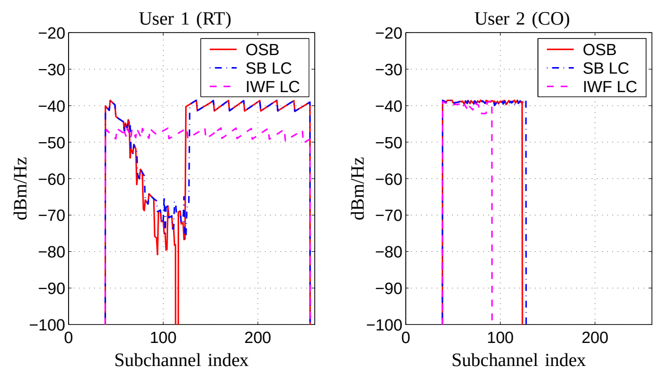

Fig. 3. Energy allocation of SBLC, OSB, and IWF when R_1=6 Mbps

VI. Conclusions

A distributed, low-complexity discrete bit-loading algorithm called SBLC was presented for spectrum balancing in multi-user multicarrier systems. The SBLC algorithm can be easily implemented by simply using an additional rate-penalty table and extra checks along with the LC algorithm. The proposed algorithm could be used to either perform distributed bit-loading or efficiently determine the water-level scaling factors for band preference. Simulation results demonstrated that near-optimal performance can be achieved by the SBLC algorithm. Moreover, procedures to determine bit- and gain-swaps were developed to ensure politeness toward the weaker users. Such adaptation capability to changes in the channel and noise conditions is a unique advantage of the proposed algorithm.

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