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A dynamic spectrum management algorithm in VDSL systems

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Abstract: A modified iterative water-filling algorithm is proposed in which power from only those subcarriers of the near end user are reduced, which has the worst effect on bit rates of far end users. The power back off from these subcarriers is done by reducing power spectral masks at respective subcarriers. The results after simulating the proposed algorithm give significant performance advantages in terms of data rate over the traditional iterative water-filling algorithm. These results approach the performance of highly complex optimal spectrum management algorithms while maintaining the complexity of the traditional iterative water-filling algorithm.

Key words: Digital subscriber line, dynamic spectrum management, iterative water-filling, optimal spectrum balancing, coding scheme

1. Introduction

In digital subscriber line (DSL) systems, crosstalk is created among a bundle of twisted copper pairs due to the effect of an electromagnetic coupling [1–3]. In a very high bit rate digital subscriber line (VDSL), data transmission is done at higher frequencies. At these higher frequencies crosstalk, a most significant factor that is 10–20 dB higher than the background noise, degrades the performance of the system. During data transmission in the upstream direction, the near end user declines the bit rates of far end users by creating far end crosstalk. This is called the 'near-far' problem and is shown in Figure 1 [4,5]. In order to reduce the effect of crosstalk several dynamic spectrum management (DSM) algorithms were proposed in the literature, which dynamically allocate transmit power spectral densities (PSDs) to achieve the maximum data rate for each user [6–15]. There are two approaches for implementing DSM. One is centralized, in which a central agent is required for the full knowledge of the network. Centralized DSM algorithms like optimal spectrum balancing (OSB) and iterative spectrum balancing give optimal solutions at the cost of higher complexity. The next approach is called distributive, which is fully autonomous with low complexity [16]. Iterative water-filling (IWF) is the first distributed algorithm with autonomous implementation at low computational complexity [17,18].

The IWF algorithm gives suboptimal performance. Many distributed algorithms have already been proposed in the literature, like successive convex approximation for low complexity (SCALE), selective iterative water-filling (SIW), and autonomous spectral balancing (ASB). All these distributed algorithms have some drawbacks. In SCALE, central coordination is required. The ASB algorithm does not give optimal solutions and SIW has high complexity compared to IWF [6,8].

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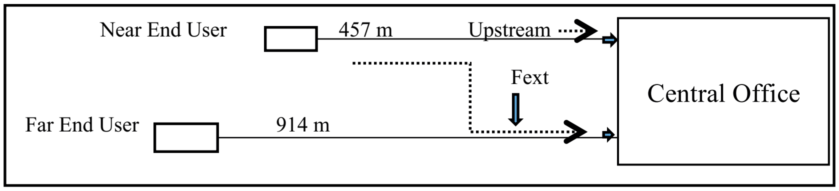

Figure 1. 'Near-far' problem in upstream direction.

This paper proposes a modified IWF algorithm that approaches an optimal solution by maintaining complexity as that of the traditional IWF algorithm. The performance of the traditional IWF algorithm is suboptimal because of inefficient use of bandwidth. The bandwidth efficiency is increased by the proposed algorithm by decreasing the power from those subcarriers of the near end user, which have the most effect on the bit rates of far end users.

The present paper is organized as follows: Section 2 describes the system model, followed by the spectrum optimization problem in Section 3. Section 4 discusses the IWF algorithm, followed by the proposed algorithm in Section 5. Section 6 discusses the numerical results. Section 7 provides some concluding remarks.

2. System model

A DSL system model with N, $(1 \leq n \leq N)$ users, each having K, $(1 \leq k \leq K)$ parallel independent subcarriers, is considered [3,6,16]. The DSL channel [16] can be expressed independently for each subcarrier as:

$$\mathbf{Y}_k = \mathbf{H}_k \mathbf{X}_k + \mathbf{Z}_k, k = 1, \ldots.., K \tag{1}$$

where $\mathbf{H}_k$ denotes an $N \times N$ channel matrix on subcarrier $k.H_k^{nm}(n \neq m)$ is an element of the channel matrix that represents crosstalk from transmitter m to receiver n on subcarrier $k.\mathbf{X}_k = [x_k^1, x_k^2, \ldots . x_k^N]^T$ denotes the transmitted signal at subcarrier k for all users. $\mathbf{Z}_k$ and $\mathbf{Y}_k$ represent an AWGN vector and received signal vector on subcarrier k, respectively [6,16]. The structure is the same for both as that of the transmitted signal vector. The transmit PSD of user n on subcarrier k is defined by $P_k^n = \varepsilon \left\{ |x_k^n|^2 \right\} / \Delta f$, where $\varepsilon \{.\}$ represents the mean value and $\Delta f = 4.3125$ kHz denotes spacing among subcarriers [6]. The vector that contains the PSD of user n on all subcarriers is defined as $P^n = [P_1^n,\ P_2^n, \ldots P_K^n]$. The signal to noise ratio (SNR) [6,9] of user n on subcarrier k is expressed as:

$$SNR_k^n = \frac{|H_k^{nn}|^2 P_k^n}{\sigma_k^n + \sum_{n \neq m}^{n} H_k^{nm} P_k^m} \tag{2}$$

where $\sigma_k^n = \varepsilon \left\{ |Z_k^n|^2 \right\} / \Delta f$ denotes the noise PSD of user n at subcarrier k. The practical data rate [6,17] of the Gaussian interference channel shown in Figure 2 at some acceptable error probability P_e is defined as:

$$b_k^n = log_2 \left(1 + \frac{SNR_k^n}{\Gamma} \right) \tag{3}$$

where Γ is the SNR gap whose selection depends on error probability P_e and the coding scheme [4,5]. For a two-dimensional QAM system having a bit error rate (BER) of 10^{-7}, the gap Γ [10,16] is calculated by the following formula:

$$\Gamma = 9.8 + \gamma_m - \gamma_c (\text{dB}) \tag{4}$$

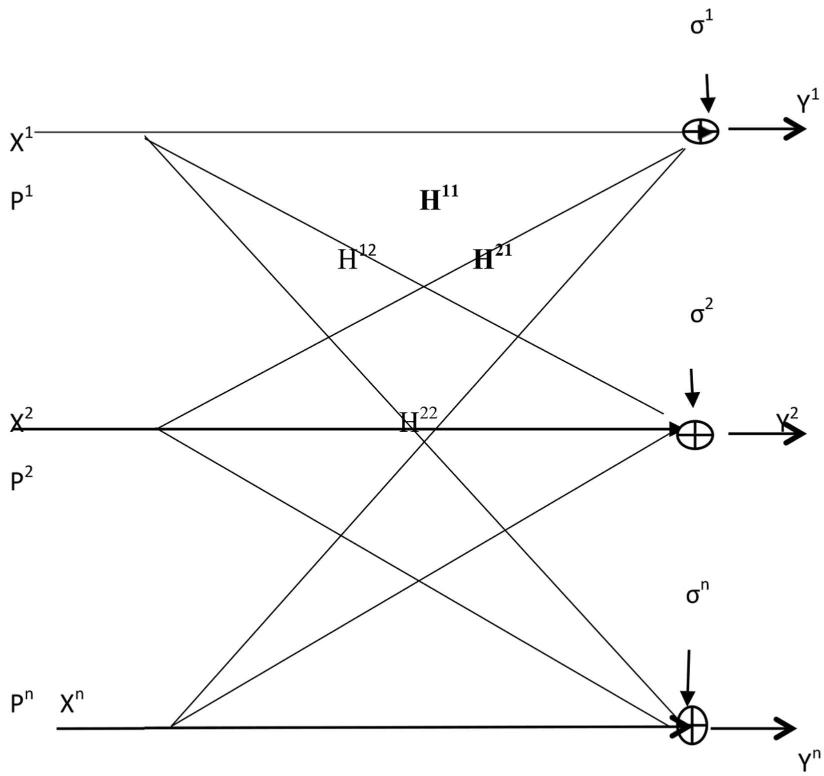

Figure 2. A Gaussian interference channel.

where γ_m and γ_c denote performance margin and coding gain, respectively. The achievable data rate [6,16] of user n is given as:

$$R^n = f_s \sum_{k=1}^{K} b_k^n \tag{5}$$

where f_s denotes symbol rate. Several limitations exist while transmitting power for each user. The first limitation is the maximum power that can be allocated to user n, denoted as $P^{n,total}$. Another one is the maximum power that can be allocated to subcarrier k of user n, denoted as $P_k^{n,max}$. The power limitations [16] are summarized as:

$$\sum_{k=1}^{K} P_k^n \leq P^{n,total} \text{ and } 0 \leq P_k^n \leq P_k^{n,max} \tag{6}$$

3. Spectrum optimization problem

In order to remove 'near-far' problem, the near end user decreases its transmit PSD in such a way that the disturbance to the far end users becomes minimum. This method of reducing power is called upstream power back off (UPBO) [19–23]. In DSM, several algorithms for UPBO have been proposed. In order to resolve this 'near-far' problem, a traditional IWF DSM algorithm is used in VDSL networks [6,10,11,14,17,24]. All bit rate combinations of different users are achieved and then represented by the rate region [6,25]. Different DSM algorithms are then compared with each other through the rate region. Every DSM technique has an objective to find the optimal transmit spectra in order to maximize the data rate of all users in the DSL network [24]. The optimization problem [8,16] is formulated as:

$$\underset{P^1,........P^N}{maximize} R^n \tag{7}$$

Subject to $R^m \geq T^m$, $m \neq n$

$$\sum_{k=1}^{K} P_k^n \leq P^{n,total}, 0 \leq P_k^n \leq P_k^{n,max}, \forall n, \forall k.$$

This problem tries to maximize the data rate of user n with a constraint of achieving minimum data rate T^m at user m, which is different from user n. This data rate maximization is done subject to the condition of constraints on total transmit power of user n, i.e. $P^{n,total}$, as well as the maximum power on subcarrier k of user n, i.e. $P_k^{n,max}$ [16,24].

4. IWF algorithm

In the IWF algorithm, each user greedily tries to achieve a maximum data rate until an optimal Nash equilibrium (NE) point is not reached [24]. A two-stage looping is present in this algorithm. A NE point is achieved in the first stage by performing water-filling in a sequential manner. The water-filling [24] is given in Eq. (8):

$$p_k^n = \left[\frac{1}{\varepsilon^n} - \frac{\Gamma(\sum_{m \neq n}^{N} |H_k^{nm}|^2 p_k^m + \sigma_k^n)}{|H_k^{nn}|^2 p_k^n} \right]^+ \tag{8}$$

where $\frac{1}{\varepsilon^n}$ denotes the level of water-filling and $[x]^+ = \max\ (0,\ x)$. A rate region is plotted by different combinations of bits rates that can be achieved in each pair of cables within the binder by the water-filling process [6]. In order to get different data rate combinations, the total available power of the near end user is decreased in a successive manner by some constant value until the bit rate becomes zero. Any of the available data rate combinations can be treated as the target rate. In the next stage, the total power allocated to each user is adjusted in such a way that each user can achieve its target rate [24]. The symbol δ is used as a constant for incrementing or decrementing the total allocated power to each user. The algorithm works well with parameter ε, which is taken as 10% of the target rate.

5. The proposed algorithm

In the proposed algorithm, a new power back off technique is used in order to enhance the data rate of both the near and the far end user. In this algorithm, power back off is done from selected subcarriers of the near end user, not like IWF. In the traditional IWF algorithm, power back off is done from all subcarriers. In order to select the subcarriers, a learning method is used. The PSDs of near and far end users in the case of the IWF algorithm are shown in Figure 3. This gives information about the maximum power allocating subcarriers of each user. These maximum power allocating subcarriers of each user are divided into two frequency bands: C (3.75 MHz to 5.2 MHz) and D (8.5 MHz to 10 MHz). In the proposed algorithm, the target data rate of near and far end users is taken from any of the achieved bit rate combinations from the IWF rate region shown in Figure 4.

Initialize $P^{n,total} = P^{n,max}$, $\delta > 0$, $\varepsilon > 0$, $p_k^n = 0, \forall k, \forall n$

While $R^n > T^n$, $\forall n$

Repeat

For each *n* do

For each subcarrier *k* do

Apply water filling algorithm to all subcarriers and allocate them total power $P^{n,total}$.

end

End

Until a desired accuracy is obtained

Set R^n as the resultant data rate.

For each *n* do

If $R^n > T^n + \varepsilon$ **set** $P^{n,total} = P^{n,total} - \delta$;

If $R^n > T^n + \varepsilon$ **set** $P^{n,total} = P^{n,total} + \delta$;

If $P^{n,total} > P^{n,max}$ **set** $P^{n,total} = P^{n,max}$;

End

End while

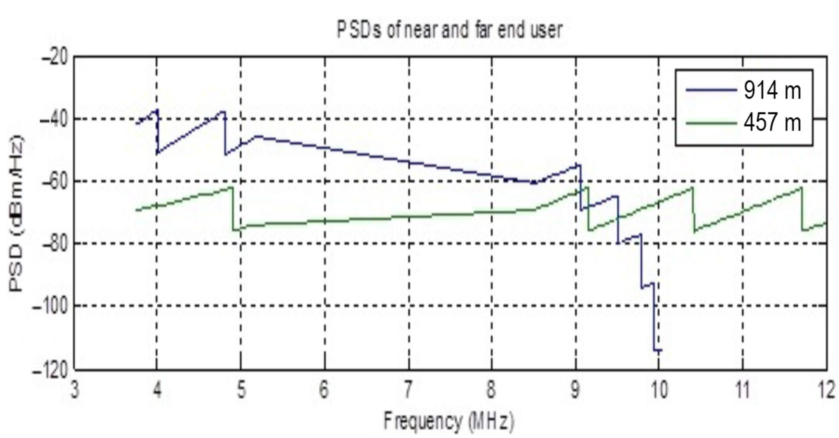

Figure 3. Upstream PSDs of near and far end users.

Initialize $\delta > 0$, $\varepsilon > 0$, $p_k^n = 0, \forall k, \forall n$

Apply IWF algorithm to subcarrier k of user n and obtain the initial spectral mask $p_k^{n,max}$.

While $R^n > T^n, \forall n$

Repeat

For each *n* do

For each subcarrier *k* do

Apply water filling algorithm to all subcarriers and allocate them total power $P^{n,total}$ and spectral mask $p_k^{n,max}$.

End

End

Until a desired accuracy is obtained

Set R^n as the resultant data rate.

For each *n* do

If $R^n > T^n + \varepsilon$ then

$p_k^{n,max} = p_k^{n,max} / \delta, k \in C, D$

End

End

End

The target data rate in the proposed algorithm is achieved by power back off from those subcarriers of the near end user that come in frequency bands C and D only. The proposed algorithm first applies IWF to subcarriers of each user. The IWF algorithm converges at a NE point and the PSDs at this point are taken as initial spectral masks. In the next step, water-filling is done by taking power constraints for user n as well as for each subcarrier k of user n. The water-filling algorithm runs until the convergence is not reached. If the obtained data rate of any user becomes higher than its target data rate, the power is back off by a factor δ from those subcarriers that come under band C and D. Now the proposed algorithm converges at a different improved NE point.

5.1. Complexity

The traditional IWF algorithm consists of two loops, where the outer loop cycles through the inner loop for all users. The water-filling is performed by the inner loop for the nth user over all the K subcarriers until a convergence criterion is reached. The complexity of the traditional IWF algorithm is found to be in the order of $O(KN)$ [6]. Similar operations are performed in the proposed algorithm, which gives complexity of the same order as the traditional IWF. On the other hand, OSB is a fully centralized algorithm with a large amount of messages passing between the users and the spectrum management center. OSB is impractical to implement due to its high complexity in the order of $O\left(Ke^N\right)$.

6. Numerical results

The FDD band plan 998 is adopted for VDSL upstream transmission [6,26,27]. Two separate upstream bands, i.e. 3.75–5.2 MHz and 8.5–12 MHz, are reserved under this band plan [27]. It is optional to use the 30–138 kHz frequency band, and 26-gauge (0.4 mm) copper wires (twisted) are used in the VDSL upstream transmission test case. A symbol rate $f_s = 4$ kHz with subcarrier spacing $\Delta_f = 4.3125$ kHz and $\delta = 3$dB have been considered during simulation [6]. A noise margin of 6 dB and a coding gain of 3 dB give an SNR gap $\Gamma = 12.8$ dB for an error probability of 10^{-7} [6,28–30]. A maximum transmit power of 11.5 dBm is applied for each modem with the background noise $\sigma_k^n = -140$ dBm/Hz. The rate region plot of the proposed algorithm, traditional IWF, and the OSB algorithm for a 2-users test case is shown in Figure 4. The target data rate of 10 Mbps by the far end user is achieved by utilizing its total transmitted power of 11.5 dBm, whereas the near end user achieves a data rate of 20 Mbps by reducing its total transmitted power from 11.5 dBm (maximum allowable) to –10.6 dBm, which is denoted by point A in Figure 4. The PSDs of the near and far end users in the case of traditional IWF are shown in Figure 3. In the proposed algorithm, a data rate of 44.5 Mbps is achieved by the near end user while maintaining a target data rate of 10 Mbps by the far end user denoted by point B in Figure 4. This data rate is achieved by the near end user by reducing its maximum allowable power of 11.5 dBm to –10.7 dBm. The proposed algorithm, like OSB, offers a data rate of 44.5 Mbps, which is more than twice the rate of 20 Mbps for the near end user in traditional IWF. The obtained data rate of the near end user in the proposed algorithm is much higher than that of traditional IWF. The rate region of the proposed algorithm approaches that of the OSB algorithm.

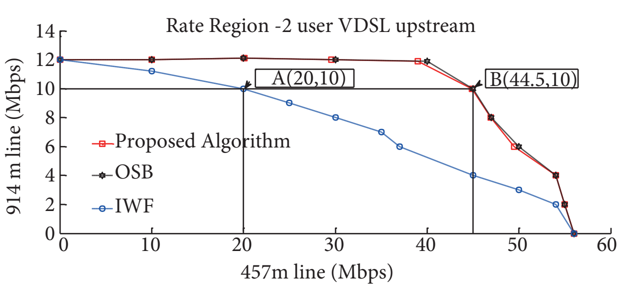

Figure 4. Rate region of 2 users in VDSL upstream.

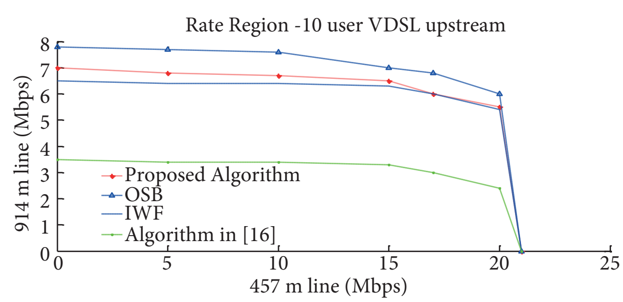

Figure 5. Rate region of 10 users in VDSL upstream.

In the multiuser upstream data transmission case, 5 users are located at 457 m and another 5 are at 914 m from a central office. Figure 5 shows the rate region obtained by these two groups of users by applying different spectral management algorithms. It is clear from Figure 5 that the proposed algorithm achieves a significant performance advantage in terms of data rate even in the multiuser case, similar to the 2-user case.

7. Conclusion

This paper introduced an improved IWF algorithm that removes the 'near-far' problem in VDSL upstream transmission. In the proposed algorithm, this 'near-far' problem is reduced by power back off from only those subcarriers of the near end user that have a worst effect on bit rates of far end users. The power back off from these subcarriers is done by reducing power spectral masks at these subcarriers. The simulation results show that the proposed algorithm approaches the rate of the OSB algorithm and maintains a distributive nature and complexity the same as that of the traditional IWF algorithm.

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