Distributed & Centralized Power Control Algorithms for Very High-Speed Digital Subscriber Lines (VDSL) Upstream Transmission

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Abstract— **Very High-Speed Digital Subscriber Lines upstream transmission suffers from strong far end crosstalk (FEXT) by the shortest lines in a multiuser communication environment. This problem called "Near-Far Effect" drastically reduces the upstream capacity on the longer lines. Power control algorithms effectively handle this problem and maximize the achievable data rate region, given an average power constraint for each user. This paper examines distributed and centralized power control algorithms and compares their performance in a frequency selective multiuser interference channel considering VDSL upstream transmission environment.**

I. INTRODUCTION

Digital Subscriber Lines (DSL) is a local access technology that brings high speed data connection to home via ordinary telephone twisted pairs. VDSL is the latest and the most advanced member in the family of DSL. The DSL transmission environment is traditionally thought of as a single user environment because each user is connected to the central office via a pair of dedicated wires (see Fig.1). However, a central office typically serves hundreds of thousands of homes, and twisted pairs from different homes are bundled together on the way to central office. In the bundled environment, because of the physical proximity, the twisted pairs emit electromagnetic interference into each other. Such interference is called crosstalk and is a major issue in DSL systems. DSL experience two types of crosstalk: near end crosstalk (NEXT) generated by transmitter on the same side of the receiver and far end crosstalk (FEXT) generated by transmitter on the opposite side of the receiver. For this reason, the DSL environment is more accurately modeled as a multiuser environment.

The effect of crosstalk on the performance of DSL systems is more severe in a distributed topology where loops carrying the DSL signals significantly vary in length and thus give rise to "Near-Far Effect" (see Fig.2) as in case of code division multiple access (CDMA) wireless systems. In CDMA near far problem arises when the user close to the base station limits the performance of the user far from the base station without power control. In DSL if the transmit power spectral densities (PSDs) of all the users are the same in the upstream direction, the far end crosstalk (FEXT) from a short loop is larger than that from a long loop. The excessive crosstalk from the short loop thus reduces the data rate of the long loop, which is already smaller than the data rate of the short loop even in the absence of crosstalk because the loop attenuation increases as the loop length increases.

Power control of DSL systems like in CDMA can be quite useful in mitigating crosstalk resulting from near far effect. But the power control in DSL differs in two important aspects from that in wireless systems.

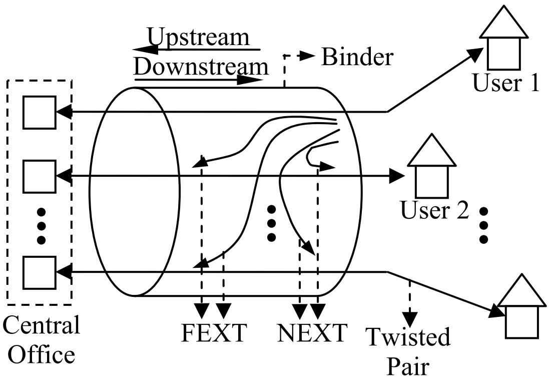

Fig.1. DSL Crosstalk Environment

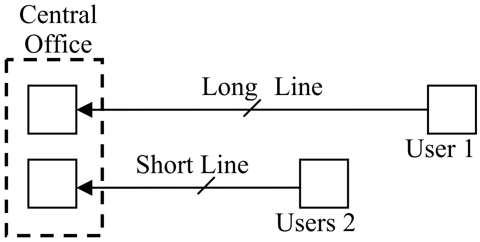

Fig.2. VDSL Upstream Transmission Environment

First, although DSL transmission environment varies from line to line, it does not vary over time. Fading and mobility are not the issues. Consequently, the assumption of perfect channel knowledge is realistic and is made here. On the other hand, unlike the usual flat-fading assumption in wireless, the DSL lines are severely frequency selective. Thus the optimal power scheme needs to consider not only the total amount of power allocated to each user, but also the allocation of power over frequencies. Nevertheless, power control schemes designed for wireless systems [2] [3] can still provide considerable insight.

This paper investigates the performance of two power control algorithms for VDSL upstream transmission. A distributed power control (DPC) algorithm iterative waterfilling (IWF) [6][7] and a centralized power control (CPC) algorithm based on multiuser discrete bit loading [8][9] have been considered. The organization of this paper is as follows. Section II introduces the system model and formulates the problem mathematically. Section III reviews DPC algorithm IWF. Section IV presents CPC algorithm and Section V compares the performance of both the algorithms. Finally, concluding remarks are given in Section VI.

II. SYSTEM MODEL AND PROBLEM FORMULATION

Here we examine the power control problem in a FEXT limited DSL system such as VDSL. The level of the FEXT PSD can be much higher especially at high frequency than that of the background noise PSD since VDSL provides a service for short subscriber loops. It is assumed that the FDD is used to suppress NEXT and that the transmitters or the receivers in the same bundle are not coordinated and thus model an interference channel.

Discrete multi-tone (DMT) modulation divides the frequency selective channel into N independent ISI free sub channels, each of which is an interference channel of M users. Without interference cancellation, the signal to interference plus noise ratio (SINR) of the user i in subchannel n is expressed as

$$S_i(n) = \frac{H^2_{i,i}(n)P_i(n)}{N_i(n) + \sum_{j=1, j\neq i}^{M} H^2_{i,j}(n)P_j(n)} \tag{1}$$

Where $P_i(n)$ and $N_i(n)$ are the signal power and the background noise power of user i in the subchannel n, respectively. $H_{i,i}(n)$ represents the direct channel gain of user i in the sub channel n while $H_{i,j}(n)$ represents the crosstalk channel gain from user j to user i. Assuming that all the transmitted signals and background noises are Gaussian, the number of bits transmittable with quadrature amplitude modulation (QAM) is approximated by

$$b_i(n) = \log_2\left(1 + \frac{S_i(n)}{\Gamma}\right) \tag{2}$$

Where Γ is the signal to noise ratio (SNR) gap that depends on the probability of symbol error, the noise margin, and the coding gain. The data rate of user i is then

$$R_i = \frac{1}{T_s}\sum_{n=1}^{N} b_i(n) \tag{3}$$

Where T_s is a symbol period. A rate region is defined as the union of all the rate sets $(R_{1,}R_{2,}.........., R_N)$ that can be achieved while satisfying the following power constraints:

$$P_i \leq P_{\max,i} \quad \text{for } i=1,2,\ldots\ldots,M \tag{4}$$

where

$$P_i = \sum_{n=1}^{N} P_i(n) \tag{5}$$

and $P_{\max,i}$ is the maximum power for user i.

The main problem of interest is to develop an algorithm that maximizes data rate given a power constraint for each user.

$$\text{maximize } \sum_{i=1}^{M} R_i \tag{6}$$

$$\text{subject to } \sum_{i=1}^{M} P_i \leq P_{\max}$$

where $P_{\max}$ is the maximum possible power sum. This problem is called rate sum maximization problem (RSMP) in the optimization theory. The problem can also be formulated as power sum minimization problem (PSMP) in which we

$$\text{minimize} \sum_{i=1}^{M} P_i \tag{7}$$

$$\text{subject to } \sum_{i=1}^{M} R_i \geq R_{\text{target}}$$

where $P_i = \sum_{n=1}^{N} P_i(n)$ is the power of user i and R_{target} is the target rate sum.

III. DISTRIBUTED POWER CONTROL ALGORITHM

RSMP or PSMP can be solved using distributed or centralized rate and power control algorithms. A distributed power control algorithm iterative waterfilling (IWF) has been purposed in [6][7], which addresses the RSMP problem. The goal is to achieve a set of target rates for all users. The adaptive algorithm runs in two stages. The inner stage takes a set of power constraints for each user as the input and derives the competitively optimal power allocation and its associated data rate as output. It is accomplished through IWF such that with a fixed total power constraint for each user, the first user updates its power allocation by deriving a water filling spectrum while regarding all other user's crosstalk as noise. Waterfilling is then successively applied to the second user, third user etc., until the process converges. Fig. 3 illustrates the distributed power control algorithm based on IWF. The outer stage finds the optimal total power constraint for each user. The outer procedure adjusts each user's power based on the outcome of the inner iterative waterfilling. If a user's data rate is below its target rate, its power is increased by δ, unless this exceeds the power constraint. If a user's data rate is much above its target data rate, its power is decreased by δ. If the data rate is only slightly above the target rate, its power remains unchanged. The outer procedure converges when the target rates is achieved.

To truly implement distributed power control algorithm, each user must know its target data rate *a prior*. It is important for the target rates to be within the achievable rate region, otherwise some or all the users would operate with negative margin. Unfortunately, the set of achievable target rates cannot be determined distributively. Some centralized agent or spectrum management center (SMC) with full knowledge of direct and crosstalk channel transfer functions must decide, by running through all possible total possible power constraints, which sets of target rates can be deployed in DSL bundle. However this can be done during initialization (loop planning stage) and also need not to be repeated because of the slow varying nature of the DSL channel. IWF offers an opportunity for different loops in a binder to negotiate the best use of frequency with each other. Thus each loop has an incentive to move away from frequency bands where interference is strong and concentrate on the frequency bands that it can most efficiently utilize.

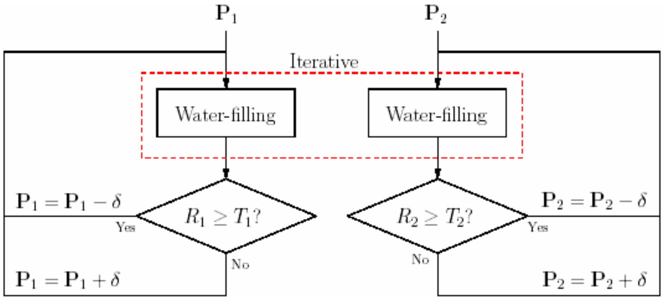

Fig.3. DPC using Iterative Waterfilling

IV. CENTRALIZED POWER CONTROL ALGORITHM.

A centralized power control algorithm can be implemented by assuming that there exists a SMC that knows the channel gains and noise power spectral densities (PSDs) of all users. For DSL both the channel gains and noise PSDs can be estimated quickly because of the slow variation of channels. The SMC determines the achievable rate region with the power control algorithm and transmits the information on the power allocation to each user. For multiuser power control, the multiuser bit loading algorithm in [8] can be used. Although the original multiuser bit loading algorithm allocates the power of all users with the aim of minimizing the total power for a given target rate sum, the algorithm should be modified to attempt to solve the following weighted power sum minimization problem (WPSMP)

$$\text{minimize} \sum_{i=1}^{M} w_i P_i \tag{10}$$

$$\text{subject to} \sum_{i=1}^{M} R_i \geq R_{\text{target}}$$

where $P_i = \sum_{n=1}^{N} P_i(n)$ is the power of user *i*, R_{target} is the target rate sum and w_i is the positive power weight of user *i*.

The objective of WPSMP is minimizing the weighted power instead of the power sum. To solve the WPSMP, we use the following generalized multiuser discrete bit-loading algorithm:

1) Initialization:

For all users and all subchannels, calculate the cost to transmit one bit.

2) Bit-Loading Iterations:

Repeat the following until a desired rate-sum is achieved.

a) Increase one bit in the user and subchannel pair (*i*,*n*) where adding one bit requires the minimum cost among all available subchannels and users.

b) Update the cost to increase one bit of user *i* in subchannel *n*.

We define the cost function to increase one bit in subchannel *n* for user *i* as the weighted incremental power sum:

$$J(n,i) = \sum_{j=1}^{M} w_j \Delta P_{j,i}(n) \tag{11}$$

Where $\Delta P_{j,i}(n)$ is the incremental power of user *j* to add one bit to user *i*. With this cost function, the multiuser bit loading algorithm allocates bit and power using greedy algorithm [8]. To apply the multiuser bit loading algorithm to the power control problem, the bit loading iterations should stop if power constraint (4) is violated. Thus the target rate sum in the WPSMP is essentially determined by power constraint (4). Since the power constraint is violated by only those users whose powers are allocated faster than others, the multiuser bit loading algorithm may not allocate all the power $P_{\max,i}$ for all users. The amount of power assigned to each user can be determined by the power weights. If the weight w_i of user *i* is reduced, the cost function is less influenced by the power increase of user *i*, resulting in the faster allocation of the power of user *i*. Consequently, more power is assigned to user *i* with reduced weight w_i. On the other hand, less power is assigned to user *i* by raising the weight of user *i*. The amount of power assigned to each user is also controlled by the weights since the data rate is determined by the amount of power used.

The algorithm [9] can be described as follows:

1) Initialization: let the weight $w_i = w_{i,initial}$, for *i*=1,...*M*
2) Power Allocation: Allocates power over all frequency sub channels and users using the multiuser bit loading algorithm with given power weights.
3) Assigning a new weight:
   a) If the data rate of user *i* needs to be increased, reduce w_i by setting $w_i = {}^{w_i}\!/\!_{\zeta}$
   b) If the data rate of user *i* needs to be decreased, raise w_i by setting $w_i = w_i \zeta$
   c) Repeat the power allocation with the new weight until a desirable rate set is achieved.

With the power constraint in (4), the power control algorithm does not know a priori whether a certain target rate set is achievable or not. Thus, it necessary for SMC to draw the achievable rate region using the multiuser bit loading algorithm with the various weights and decide the desirable rate for each user. The SMC then completes the rate and power control process by commanding each modem to adopt bit and power allocation to desirable rate set.

V. PERFORMANCE

We now examine the performance of both the DPC and CPC algorithms for VDSL upstream transmission scenario. For all simulations we use 26 AWG lines and the simulation parameters are taken from [10]. The algorithms are applicable to any DSL system whose performance is limited by FEXT. We simulate VDSL upstream transmission (Near Far Scenario) with four users located at 3000 ft from the central office and four users are located at 2000 ft from the central office. The maximum power is 14.5 dBm with the SNR gap of 12 dB. The number of bits in each subchannel are limited to be less than or equal to 11. FDD bandplan is used for the upstream frequency bands. The crosstalk noise model A is used to generate crosstalk from other services. Fig. 4 shows the achievable rate regions associated with the DPC and CPC algorithms. Since the data rates of users at the same distance from central office are almost the same, we took the average of data rates of the users with the same loop length to draw the rate regions in two dimensions. As can be seen the centralized power control algorithm gives much higher data rates for all users than the DPC algorithm.

VI. CONCLUSIONS

This paper examined the power control problem in a frequency selective interference channel and suggests a centralized algorithm for VDSL upstream transmission. SMC is required for this algorithm to achieve direct and crosstalk channel gains. The CPC algorithm enlarges the rate region achieved by the DPC.

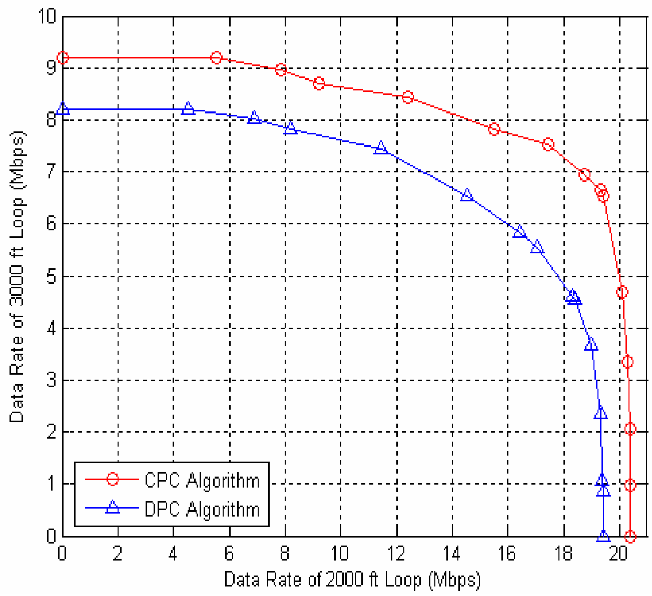

Fig. 4. Rate region of four 3000 ft loops and four 2000 ft loops

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