An Efficient Multi-User Power Control Algorithm for DMT-based DSL Systems

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***Abstract*-This paper investigates the rate and power control problem in a frequency selective interference channel. Fixed Margin Iterative Water filling is applied to minimize the transmission power in multi-user DSL systems and also the overall high-quality service is guaranteed for all the users in the same binder. Through the simulation of VDSL and ADSL systems with new proposed standards, the common upstream power backoff problems and downstream RT/CO FEXT problems are overcome.**

***Index Terms*—DMT, ADSL, VDSL, iterative water-filling, fixed margin, interference channel, upstream power backoff, power control.**

Ⅰ. INTRODUCTION

Rate and power control is central problem to improve the performance of interference-limited multi-user communication systems. In these systems, each user's performance depends not only on its own power allocation, but also on the power allocation of all other users. In this paper the digital subscriber line (DSL) system is considered as a multi-user environment. The aim is to apply a power allocation scheme that is able to jointly optimize the performance of multiple DSL modems in the presence of mutual interference.

DSL is a multiuser environment because telephone lines induce crosstalk into each other and such interference is often the dominant noise source in a

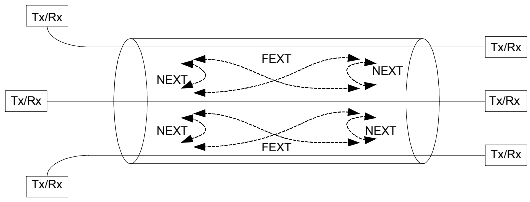

Fig. 1 The DSL Crosstalk Environment

loop. The near-far problem of wireless CDMA systems occurs also in DSL systems [1]. For example, the increasing VDSL users based on ONU emit strong inference into the VDSL users based on CO. And also DSL loops are severely frequency selective. Thus, a power allocation scheme needs to consider not only the total power allocated for each user, but also the allocation of power in each frequency. The applied algorithm in this paper can resolve the problems above.

The remainder of this paper is organized as follows. Section Ⅱ reviews the DSL environment system model. Section Ⅲ describes the Fixed Margin iterative water-filling algorithm. In section Ⅳ, the simulation results are given and accordingly the analysis is given for the practical problems. And conclusions are made in section Ⅴ.

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Ⅱ. THE DSL ENVIRONMENT AND SYSTEM MODEL

DSL modems use frequencies above the traditional voice band to carry high-speed data. The telephone channels are severely frequency selective. One way to combat intersymbol interference (ISI) is to use discrete multitone (DMT) modulation, which divides the frequency band into a large number of ISI-free subchannels and lets each subchannel carry a separate data stream. This paper considers the DMT modulation scheme as standardized for ADSL and VDSL.

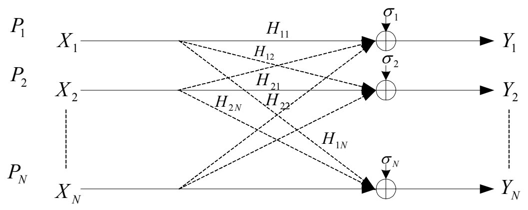

Fig. 2 A Gaussian interference network.

Because a great of subscriber lines are bundled together in a DSL binder, the lines create electromagnetic interference into each other, thus causing crosstalk noise (see Fig. 1). Near-end crosstalk (NEXT) refers to crosstalk created by transmitters located on the same side as the receiver. Far-end crosstalk (FEXT) refers to crosstalk created by transmitters located on the opposite end of the line. NEXT is usually much stronger than FEXT. Usually in DSL transmission systems FDD is used to avoid NEXT. Thus FEXT is the main crosstalk.

The DSL environment consists of multiple transmitters and multiple receivers interfering into each other as shown in Fig. 2. This model is usually referred to as an interference channel (IC). Although the unresolved problems about the capacity of IC, the aim here is to focus only on the problem of power allocation for each user.

Suppose that the entire system has *N* frequency tones, the signal-to-interference-plus-noise ratio (SINR) of user i in subchannel n is expressed as

$$SINR_i(n)=\frac{H_{i,i}^2(n)P_i(n)}{\sum_{j\neq i}H_{i,j}^2P_j(n)+N_i(n)}, \tag{1}$$

where $P_i(n)$ and $N_i(n)$ are the signal power and the background noise power of user i in subchannel n respectively. $H_{i,i}(n)$ represents the direct channel gain of user i in subchannel n, while $H_{i,j}(n)$ represents the crosstalk channel gain from user j to user i.

Assuming that all transmitted signals and background noises are Gausian, the reliably transmittable bit rate with QAM modulation under a certain bit error rate and coding scheme is then expressed as:

$$b_i(n)=\log_2\left[1+\frac{1}{\Gamma}\cdot\frac{H_{i,i}^2(n)P_i(n)}{\sum_{j\neq i}H_{i,j}^2P_j(n)+N_i(n)}\right], \tag{2}$$

Where Γ, SNR gap is the function of the target BER, noise margin and coding schemes [2].

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? The objective of the system design is to maximize the set of rates $(R_1,\cdots,R_M)$ subject to the power constraints

A rate region is defined as the union of all the rate sets $(R_1,\cdots,R_M)$ that can be achieved while satisfying the following power constraint:

$$P_i\le P_{\max,i}\quad \text{for}\quad i=1,\cdots,M, \tag{4}$$

where

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

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

Ⅲ. RATE AND POWER CONTROL USING IW FIXED MARGIN MODE

A. Iterative Water-filling

As we all know, water-filling is the optimal-power distribution algorithm for the single-user communication and provides the basis for the power and bit allocation schemes in most DMT based modems. Given the channel signal-to- noise ratio (SNR) information in the frequency domain SNR(*f*), the optimal spectrum (P(*f*)) maximizing the data rate is obtained by allocating more power to frequency bands with higher channel SNR. The single user water-filling procedure is given in [2].

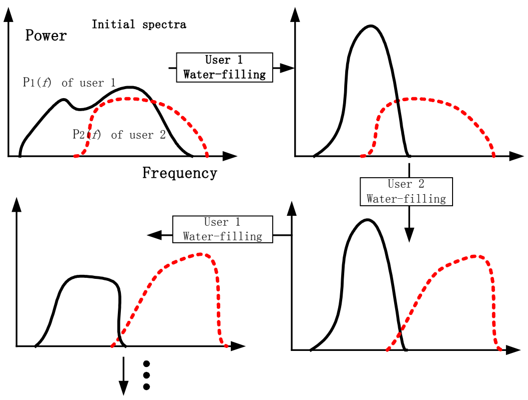

Fig. 3 Iterative Water-filling for two users

Iterative water-filling can be viewed as an extension of the water-filling process for a multi-user communication environment. This algorithm is based on formulating power allocation in the multi-user interference channel as a non-cooperative game, where each user adjusts its power allocation to maximize its own data rate, while regarding all other interference as noise. The conditions for existence and uniqueness of the Nash Equilibrium were given in [3], and also experimentally these conditions are satisfied for all the possible DSL channel environments that has been tested. Thus an iterative water-filling algorithm, where in every step each modem updates its PSD regarding all interference as noise, converges to the unique Nash equilibrium from any starting point.

Simply, the iterative water-filling process [4] for two users is illustrated in figure 3. We can see that at each step each user's spectrum moves away from the frequency region where strong interference exists. Thus better performance is realized step by step.

According to the descriptions above, iterative water-filling procedure is expressed in figure 4. Starting with any initial spectra, usually, the procedure will converge to a stationary point after 2 or 3 passes in practice.

In figure 4, L is the number of lines in the binder,

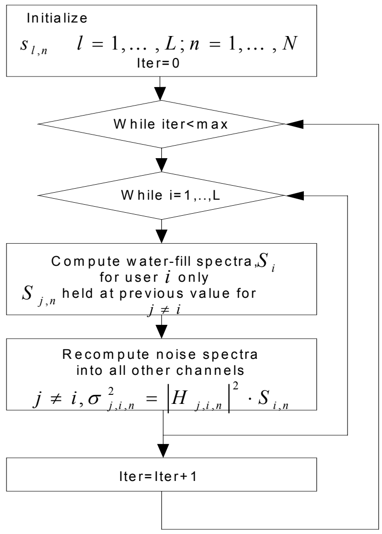

Fig. 4 The procedure of Iterative Water-filling

n is a tone index, j and i are the line indices that go from 1 to L. Also, $\left|H_{j,i}(n)\right|^2$ is the transfer function magnitude from line i to line j at tone n, while $S_i(n)$ is power spectral density at tone n of line i, and $\sigma^2_{j,i}(n)$ is the crosstalk noise on line j from line i on tone n.

B. Fixed Margin Mode

Fixed Margin (FM) mode of iterative water-filling is the one that uses only power needed to guarantee best overall use of the binder and is finding increasing use with the service providers who are desired to ensure all services perform as best as possible. Because the use of FM mode allows other systems that have insufficient margin to improve and also coordination is unnecessary as long as the attempted data rates are in the achievable rate region of iterative water-filling.

Any DSL modem that minimizes the transmit power necessary at a given fixed margin for a certain probability of BER to achieve the service-provider target data rate is said to operate with fixed-margin.

Power minimization of the fixed-margin DSL modem can be achieved theoretically by DSL power spectral density $S_{DSL}(n)$ at tone n that satisfies the equation

$$S_{DSL}(n)+\frac{10^{.95+\gamma_m-\gamma_c}}{\frac{|H(n)|^2}{S_{noise}(n)}} = \text{constant for all used tones} \qquad (6)$$

where $10^{.95+\gamma_m-\gamma_c}$ is the SNR-gap [5], γ_m is the fixed margin, γ_c is the coding gain of the receiver, $|H(n)|^2$ is the transfer function magnitude, and $S_{noise}(n)$ is the noise power spectral density at tone n. According to the principle of water-filling, the constant in (6) is determined by allocating non-negative psd or energy to the tones with highest ratio SNR. And also equation (6) above is solved until the desired data rate of the DSL transmission system is equal to data rate computed by

$$R = \Delta f \cdot \sum_{\text{used } n} \log_2\left(1+\frac{SNR(n)}{10^{.95+\gamma_m-\gamma_c}}\right) \qquad (7)$$

where Δf is the frequency range for every tone.

For the multi-user case, the power control algorithm proposed in [6] which is based on IW is applied here in order to obtain the minimized power for every user. The algorithm is composed of two stages.

The inner stage is to make sure that each user optimizes its power in order to maximize the rate**,** in which a specific total power constraint is given to each user and then water-filling is used to each user to maximize the total rate for the user under the given power constraint. This optimization for each user is performed iteratively until the power allocations of all the users converge to certain values.

The outer stage finds the optimal total power constraint for each user based on the given target rate. The outer procedure adjusts each user's power based on the output rates of the inner stage. When the resulting total rate for a certain user is smaller than the target rate for the user, the total power budget for that user is increased and the inner stage is run again. Likewise, when the total rate for a certain user needs to be decreased, the total power budget is reduced and the inner stage is run again. The outer stage converges only when the set of target rates is within the IW rate region.

The outer loop of the power control algorithm essentially attempts to find the minimum amount of power that is needed to support the target data rate. And also fixed margin is used here to ensure the service quality for all the users in the same binder. The algorithm above can be alternatively thought of as each user doing "fixed-margin-adaptive" water-filling [3] against each other. And also as long as the set of target rates are in the rate region, the algorithm above can be easy to implement in practical modems for the unnecessary centralized control.

Ⅳ. SIMULATION RESULTS

The performance of the fixed margin IW algorithm is considered in this section. Two realistic VDSL environments, upstream power backoff problem and RT/CO downstream FEXT problem, are tested. And finally RT/CO ADSL FEXT problem is considered.

A. VDSL Upstream Power Backoff Problem

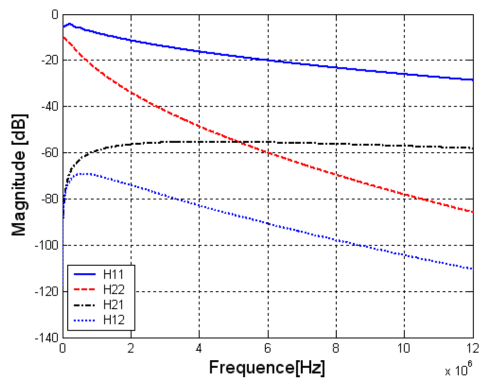

Fig.5. VDSL channel and crosstalk transfer function:3000ft vs 1000ft

Figure 5 shows the plots of channel and crosstalk transfer functions for two users located 3000ft and 1000ft away from CO, where $H_{i,j}(n)$ refers to the upstream transfer function from user j to user i. The twisted pairs are assumed to be 26 AWG, and the crosstalk transfer functions are computed using the well-known FEXT models [7].

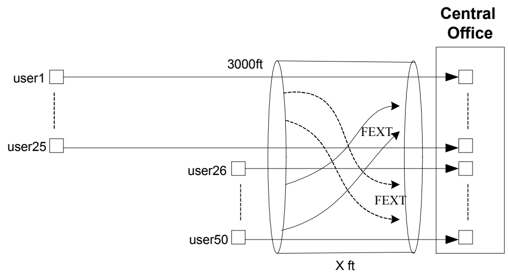

Fig6. Channel Topology for VDSL upstream power backoff with 50 lines in a binder (X =500-2000 ft)

The performance of IW fixed margin mode for a binder with 50 VDSL lines in Fig. 6 is tested. Twenty-five of the lines are at a distance of 3000 feet away from the CO, while the other 25 are at the a distance of X feet, where X varies between 500 and 2000 feet. The maximum transmission power of each modem is 11.5 dBm [7]. The North America 998 frequency plan [8] is used to separate upstream and downstream.

Table 1 shows the obtained data rates and minimized power allocation for each set of users based on the given target rates. X, the length of the short group users, is equal to 1000 feet in this case. The data rates for each set of 25 users are the same, thus the data rates in table 1 stand for 25 short or long user's data rates. Using the algorithm described in part Ⅲ, we can see that the target rates can be obtained approximately and accordingly the minimized power can also be got as long as the target rates are in the rate region.

To make sure that the selected target rates are in the rate region, it is necessary to obtain the rate region. The fixed margin IW rate region can be obtained by performing the inner stage described in part Ⅲ for all the possible combinations of power constraints for each user. Also for the data rates for each set of 25 users are the same, so the rate region can be depicted as two-dimensional. Fig. 7 shows the fixed margin IW VDSL upstream rate regions for Channel Topology in fig. 6. The outermost curve corresponds to the topology with 25 lines at 500 ft and 25 lines at 3000 ft. The next two ones correspond to the topology with 1000 ft versus 3000 ft and with 2000 ft versus 3000 ft respectively. For example, with 25 lines at 500 ft and the other 25 lines at 3000 ft, it is possible to achieve 25

TABLE 1. OBTAINED DATA RATES AND MINIMEZED POWER ALLOCATION FOR EACH SET OF USERS BASED ON THE GIVEN TARGET RATES FOR VDSL POWER BACKOFF PROBLEM.

Target Rate(Mbps)		Obtained Rate(Mbps)		Minimized Power (dBm)	
1000 feet	3000 feet	1000 feet	3000 feet	1000 feet	3000 feet
12Mbps	10Mbps	12.37Mbps	10.25Mbps	-30.5dBm	11.5dBm
16Mbps	8Mbps	16.81Mbps	8.14Mbps	-28.5dBm	3.5dBm
22Mbps	6.5Mbps	23.54Mbps	6.75Mbps	-22.5dBm	0.5dBm
25Mbps	2Mbps	25.82Mbps	2.14Mbps	-11.5dBm	-8.5dBm

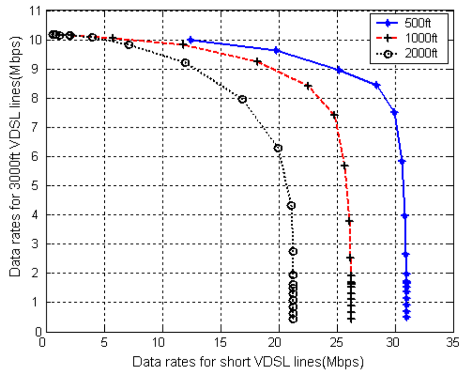

Fig7. Fixed margin iterative water-filling upstream rate regions in VDSL: 3000 versus various lengths (fig. 6 Channel Topology).

Mbps in 500 ft loops and 8.9 Mbps in 3000 ft loops, or 30 Mbps on 500 ft loops and 7.5 Mbps on 3000 ft loops. The data rate trade-offs in the rate regions imply the possibility of supporting different classes of service on the same binder.

B. VDSL RT/CO Downstream FEXT Problem

A problem feared by service providers in potential deployment of FTTCab (Fiber to the cabinet) VDSL is that it's serious downstream FEXT into FTTEx (Fiber to the exchange office) VDSL. In fact, The data rate of VDSL users from FTTEx is decreased dramatically without power control. This section investigates some trade-offs between FTTCab VDSL and FTTEx VDSL when using fixed-margin iterative water-filling.

Fig 8. shows the channel topology for FTTEx-based VDSL versus FTTCab -based VDSL with 50 lines in a

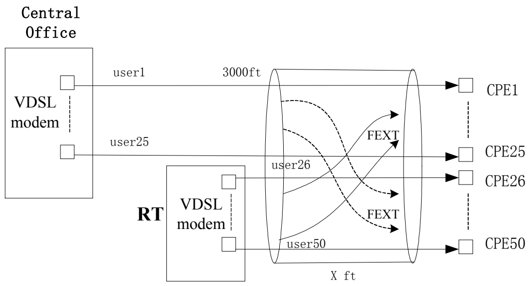

Fig8. Channel Topology for FTTEx-based VDSL versus FTTCab -based VDSL with 50 lines in a binder (X =500-2000 ft)

binder. The simulation parameters are similar to those of section 4.2 except that the maximum transmission power for FTTCab modems and FTTEx modems are 11.5 dBm and 14.5 dBm [9] respectively. And also the North America 998 frequency plan is used to separate upstream and downstream. A fixed margin 6 dB and coding gain 5.5 dB are considered.

Also the obtained data rates and minimized power allocation for each set of users are given in Table 2 based on the given target rates. X is also equal to 1000 feet in this case. Approximately we can obtain the rate that is desired and accordingly the minimized power can also be got. Fig. 9 shows the achievable fixed margin IW VDSL downstream rate regions for Channel Topology in fig. 8. For example, the rates 58 Mbps, 49.5 Mbps and 42 Mbps can be obtained for FTTCab VDSL 500ft, 1000ft and 2000ft respectively when 3000ft FTTEx VDSL transmits at 25 Mbps. According to the rate regions, service providers can provide various kinds of rates on the same binder.

C. ADSL RT/CO Downstream FEXT Problem

Finally, the common RT/CO ADSL FEXT problem is investigated in this section. The increasingly installed ONU, which is located close to customer homes in order to enlarge the service area, induces that the RT-based ADSL emits strong downstream interference into the CO-based ADSL. Actually the CO-based ADSL.can't work without power control

Fig. 10 shows the channel topology, which consists of 25 CO-based 15000 ft ADSL lines and 25 RT-based 5000 ft ADSL lines in the same binder and fig.11

TABLE 2. OBTAINED DATA RARTES AND MINIMIZED POWER ALLOCATION FOR EACH SET OF USERS BASED ON THE GIVEN TARGET RATES FOR VDSL RT/CO DOWNSTREAM FEXT PROBLEM.

Target Rate(Mbps)		Obtained Rate(Mbps)		Minimized Power (dBm)	
3000 feet	1000 feet	3000 feet	1000 feet	3000 feet	1000 feet
33Mbps	35Mbps	33.98Mbps	35.22Mbps	11.5dBm	-20.5dBm
28Mbps	45Mbps	28.16Mbps	45.91Mbps	7.5dBm	-13.5dBm
20Mbps	50Mbps	20.34Mbps	51.18Mbps	0.5dBm	-7.5dBm
14Mbps	51.5Mbps	14.56Mbps	52.15Mbps	-1.5dBm	-1.5dBm

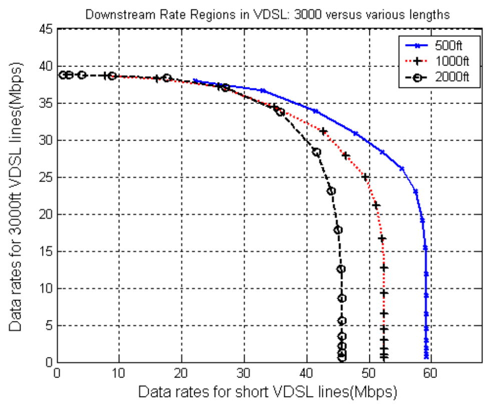

Fig 9. Fixed margin iterative water-filling downstream rate regions in VDSL: 3000 versus various lengths (fig. 8 Channel Topology).

illustrates the channel and crosstalk transfer functions for this topology. And also fig. 12 illustrates the rate region for channel topology in fig. 10 using the fixed margin IW algorithm. In this case, we only consider a downstream frequency band of ADSL from 138 kHz to 1.104 MHz. And also a fixed margin 6 dB and coding gain 5.5 dB are considered. The rate tradeoff between the short and long users can also be obtained. For example, 5.9 Mbps in 5000 ft loops and 3.1 Mbps in 15000 ft loops.

Ⅴ. CONCLUSIONS

This paper examined the rate and power control problem in a frequency-selective interference channel. Based on competitive optimality, the Fixed Margin iterative water-filling algorithm allows the lines to negotiate the best use of power and frequency with each other. Without centralized control, it is easier to implement in practice and also the minimized power constraints for multi-user modems can be obtained in order to approximately satisfy the given target rate. By applying it to the VDSL upstream backoff scenario, the performance is improved and also the ADSL or VDSL downstream RT/CO FEXT problems can be resolved by the rate tradeoff between them.

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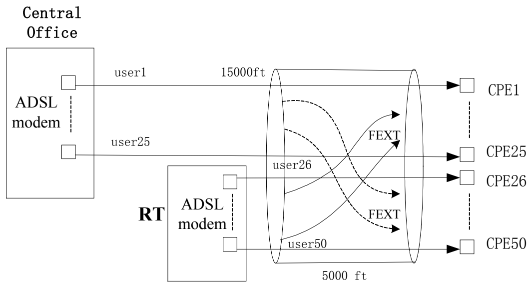

Fig. 10. Channel Topology for CO-based ADSL (15000 ft.) versus RT-based ADSL (5000 ft.) with 50 lines in a binder.

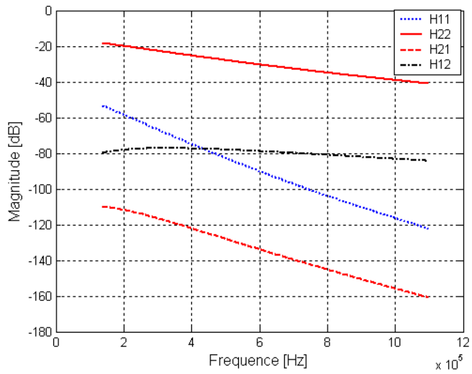

Fig.11. ADSL channel and crosstalk transfer function: 15000ft vs 5000ft

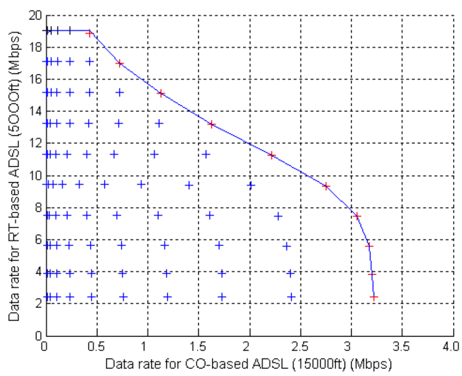

Fig12. Fixed margin iterative water-filling downstream rate region in 15000ft. CO-located ADSL versus 5000ft. RT-located ADSL (fig. 10 Channel Topology).