Upstream Power Control for Digital Subscriber Lines Based on Role Game Approach

Pavlina Koleva[1], Oleg Asenov[2] and Vladimir Poulkov[3]

Abstract – **In this paper an Upstream Power Control (UPC) algorithm for Digital Subscriber Lines (DSL) is introduced based on a game theoretic approach of the users in the subscriber loop. A Nash equilibrium power control policy for optimal throughput for the DSL users based on a role game scenario is introduced. The simulation results show that by proper appropriation of the roles of groups of active users in the DSL cable, a maximum of the utility functions for a maximum number of users, could be achieved, keeping the crosstalk under a given limit.**

Keywords – **Digital Subscriber Lines, Game theory, Upstream Power Control.**

I. INTRODUCTION

Power control (PC) is an important issue in interference limited multiuser systems, such as the very-high-bit-rate Digital Subscriber Lines (DSL). In these systems, the user's performance depends not only on its own power allocation, but also on the power of all other users and the generated crosstalk interference. The system design involves the estimation of a performance trade-off among the users [1-3].

Power control in DSL systems differs from the PC problem in wireless systems. The DSL transmission environment does not vary over time, but the DSL loops are frequency selective. The DSL systems suffer from a near–far problem which arises when two transmitters located in different distances attempt to communicate with the same Central Office (CO) at the same time. The interference coming from the closer transmitter overwhelms the signal from the transmitter that is farther from the CO. Thus optimal power control schemes need to optimize the total amount of power allocated to each user. For overcoming this problem, algorithms with varying performance and complexity based on power back-off schemes and dynamic spectrum management approaches exist, such as iterative water-filling algorithms, multiuser greedy algorithms, optimal spectrum balancing, etc. In many cases these algorithms are not considering fairness among the users and are in favor of the shorter lines or have a suboptimal performance. In other cases good performance algorithms use high computational complexity [1,3].

Recently game theoretical approaches have appeared studying the power control problem for wireless networks [4-7]. PC algorithms based on the concept of competitive optimality, or strictly competitive games are proposed in [8,9].

In this paper we propose an UPC algorithm based on a role game scenario where different roles to the subscribers are appropriated depending on the distance to the CO, their requested service (transmission speed and bandwidth), cross-talk (activity of other users in the lines), etc.

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II. TOPOLOGY OF THE DSL PLANT AND ENVIRONMENT

DSL technology refers to a family of technologies that provide digital broadband access over the local telephone network. The major problem with this technology is the crosstalk, generated among the lines operating in the same cable bundle. The crosstalk deteriorates the total Signal-to-Noise ratio, thus influencing the overall quality of service performance especially with multimedia services [10].

A very general local loop plant topology is shown in Fig. 1. The CO in a dense populated area can serve thousands of users. The distribution of the subscriber loop is carried in segments of feeder cable. A DSL binder can consist of up to 100 subscriber lines bundled together. Because of their close proximity, the lines create electromagnetic interference into each other, thus causing Near-end crosstalk (NEXT) and Far-end crosstalk (FEXT) noise (Fig. 2).

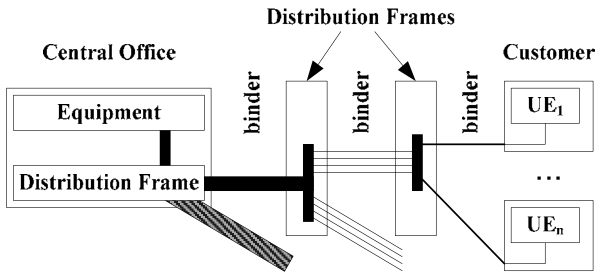

Fig. 1. Topology of a telephone digital local loop plant

The DSL environment is a multiuser environment, because the background noise in the loop is typically small and the system performance is limited by the crosstalk interference. A DSL local loop plant can be modeled as a Gaussian interference channel. In this case this is a multiple transmitter and receiver system, with interference as shown in Fig. 3. The channel from user to user in Fig. 3 is modeled as a frequency-selective channel, whose transfer function in the frequency domain is denoted as $H_{ij}(f)$, where $0 \le f \le Fs$, $Fs = 1/2Ts$ and Ts is the sampling rate.

In addition to the crosstalk interference, each receiver also experiences additive background noise, whit Power-Spectral-Density (PSD) σ. The power allocation for each transmitter must satisfy a power constraint:

$$\int_0^{Fs} P_i(f)df \le P_i \tag{1}$$

The achievable data rate for each user is:

$$R_i = \int_0^{Fs} \log_2\left(1 + \frac{P_i(f)\left|H_{ii}(f)\right|^2}{\Gamma\left(\sigma_i(f) + \sum_{j\neq i} P_i(f)\left|H_{ji}(f)\right|^2\right)}\right)df \tag{2}$$

where Γ denotes the SNR-gap.

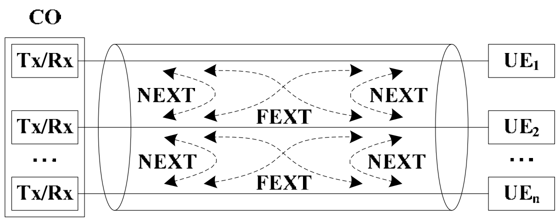

Fig. 2. DSL crosstalk environment

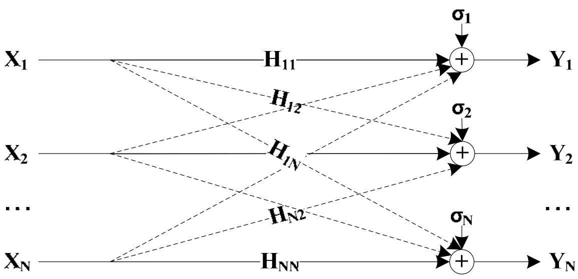

Fig. 3. Gaussian interference network

Objective of the system design is to maximize "jointly" the rates subject to the power constraints (1). For each transmitter, increasing its power at any frequency increases its own data rate, but this also increases its interference into other users. In a local loop topology with different line lengths and the transmitters at the CO transmitting with the same PSD, due to the difference in line attenuation, the FEXT caused by the shorter lines severely affects the upstream transmission and the performance of the long lines. To remedy this power and spectral compatibility problem, the short lines must reduce their upstream PSD. This reduction of the upstream transmit PSD is known as upstream power back-off (UPBO) [11, 12].

Several major UPBO control algorithms have been proposed for VDSL, such as the constant power back-off, the reference length, the multiple reference length, the equalized-FEXT, the reference noise method [12]. All of them require the power or noise spectrum of the short loops to comply with a reference loop or noise. These approaches are relatively simple to implement, because they only require each loop to adjust its power spectrum according to a reference, and do not require any knowledge of the network configuration, activity or QoS of users. With more complex network scenarios more sophisticated power control and allocation methods must be implemented.

III. Role Game Approach for Power Allocation

In [8] is stated that the majority of crosstalk experienced by a user comes from only a subset of lines within the binder. Such lines are referred as major or dominant crosstalkers and typically correspond to neighboring pairs of a particular line within the binder. In binders whose constituent lines have significantly different lengths near-end users cause significantly more crosstalk than far-end users since the signals of far-end users attenuate before crosstalk coupling occurs. For these reasons large performance gain could be achieved by cancelling crosstalk from dominant crosstalkers.

In [9] the concept of the worst-case interference (WCI) is introduced and the achievable rate of a single so-called "victim" modem in the presence of the WCI from other interfering lines in the same binder group is analyzed. The WCI problem is studied from a game-theoretic viewpoint. The objective is to bound the impact that multiuser interference can have on this victim modem, thereby determining whether service may be guaranteed. Nash equilibrium in this game is interpreted as characterizing a worst-case interference as an optimal response (power-allocation policy) to it.

We use a similar concept to introduce a role game approach for a Nash equilibrium power control policy that could ensure an optimal throughput for the DSL binders, or UEs formed in groups depending on the distance from the CO. The proposed approach is a power control scheme in which groups of DSL lines and their UEs are assigned different roles determined by the distance from the CO, the required service (throughput), crosstalk generated, activity, etc. The different roles are selected so as to achieve the optimum level of user satisfaction. The level of satisfaction is defined by their utility functions. Each role is modeled by the following equation:

$$Role_i(DSL_i) = \left\{ XT\left(\sum_{j=1}^{k} UEA_j\right), UEDis_i, MAX\left[uf_i(T_i, p_i, XTL_n)\right]\right\} \tag{3}$$

where, $XT(\Sigma UEA_j)$ is the crosstalk as a function of users' activity in the bundle (current bundle load), $UEDis_i$ is UE_i distance from the CO, uf_i is the utility function derived by user i, T_i is the throughput, p_i is the upstream power level for UE_i and XTL_n is the crosstalk limit in the bundle.

Based on the UE role model defined in equation (3) the role game approach is applied between the different groups of subscribers. The goal of the role game is to ensure maximum of the utility function for a maximum number of UEs, keeping the crosstalk in the bundle under a given limit. Without loss of generality the value of the Key Performance Indicator (KPI) for a given UE could be represented as the ratio between the throughput that the UE could achieve with his current allowable power level and bandwidth, and the required throughput that is necessary for a given role to have the necessary quality of performance. In this case maximum of the UE's utility function will be obtained when KPI=1. We assume that the user will be satisfied when he has such a role which ensures his KPI to lie in the interval:

$$1+\Delta \geq KPI \geq 1-\Delta \tag{4}$$

Here Δ is an acceptable deviation in the quality of performance. This deviation is a function of the number of roles. If the KPI is out of this interval for a given UE, the latter will be appropriated a role, away from the maximum of his utility function. So the choice of the value of Δ is a trade-off between the granularity of the roles and performance.

Let's consider a simple game scenario with three groups of users **X**, **A** and **B**, located at a different distance from the CO (Fig.4). They are considered as 3 group players in the game. The number of the UEs in each of the groups is equal and is 20. The goal of the power control mechanism is to ensure the KPIs of all of the UEs in the groups to be in the interval defined above and not to exceed a given limit of the crosstalk. Let's assume that an UE depending on his role generates some corresponding crosstalk to the other DSL lines in the bundle when his KPI=1, defined as $RoleXtalk_k$. The total crosstalk that all the UEs in a group could generate at a given time when they have achieved maximum of their utility functions (KPI=1) is defined through a relative parameter called "*additional XTalk*", dependent on the number of UE and their roles. The PC mechanism is performed in several steps.

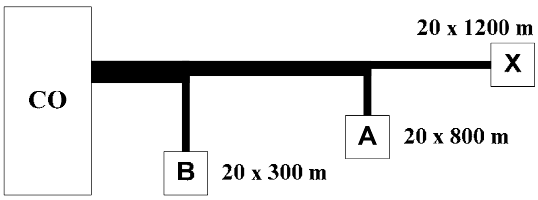

Fig. 4. Game scenario with three groups of users

In the beginning, this parameter is estimated for each group, i.e. $AddXTalk(Slot_i,Group_j)=SUM(RoleXTalk_k)$. The group which generates the maximum additional noise is appointed as master group and its estimated $AddXTalk(Slot_i,Group_j)$ is considered as reference. If this reference is under the admissible crosstalk limit all the UEs in the master group will receive the required upstream power. The PC mechanism is applied in such a way, that the UEs in this group will receive the required roles ensuring their KPI to be equal to 1. The other two groups will be considered as slave groups. This means that the number and activity of the UEs and the rank of their corresponding roles in the group contributes the corresponding group to become master.

In the next step, the PC algorithm sets the upstream power for the UEs located in the slave groups in such a way that their KPIs lie within the interval (4). The upstream power of each of the UEs located in these groups is determined as follows. The necessary power to ensure the required throughput for the requested role from the UE in the case of no crosstalk is estimated. Then the PC mechanism allows increase of the power of the UE to a level, which is necessary to compensate the "*additional XTalk*" introduced by the master group. The resulting KPI from the slave group is close but always less than 1, as the "*additional XTalk*" from the UEs in the neighboring slave groups is not compensated. Further, the $AddXTalk(Slot_i,Group_j)$ generated from each group is calculated. If the $AddXTalk(Slot_i,Group_j)$ in one of the slave groups becomes higher than the one in the master, this slave group is appointed master. This means that the number and activity of the UEs and the rank of their corresponding roles in one of the slave groups has become higher than the ones in the current master and a new master group is appointed.

a)
b)
c)
d)

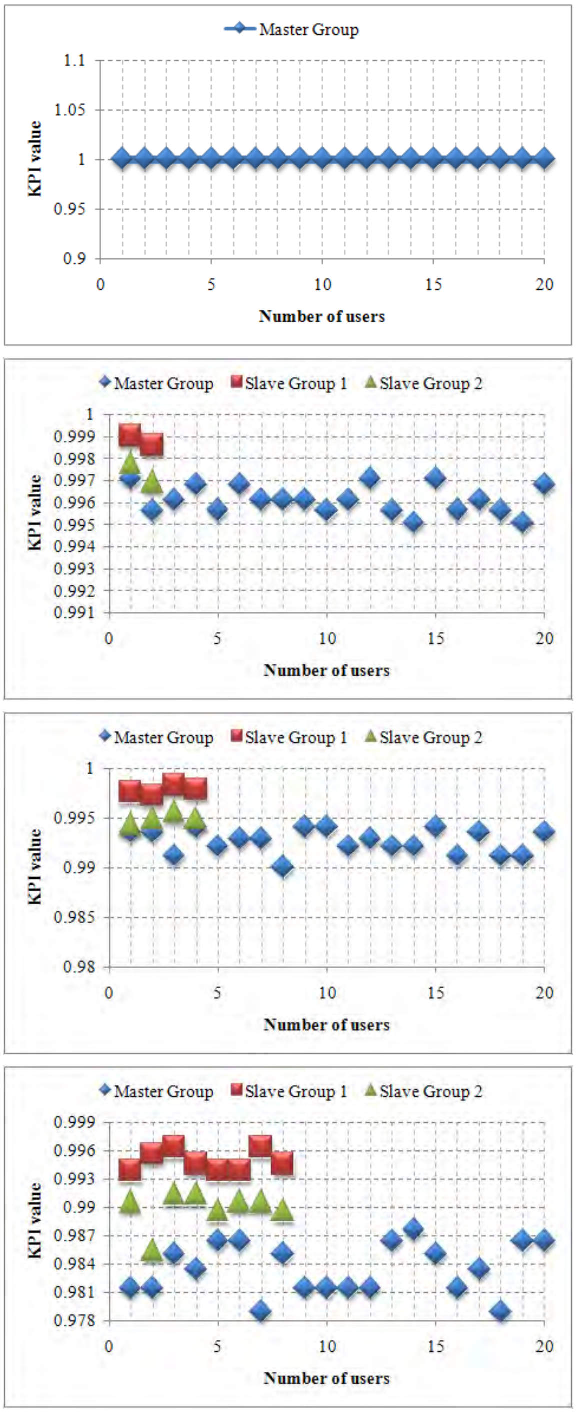

Fig. 5. KPI calculations for the role game algorithm

With the increase of the number and the rank of the requested roles in the slave groups, a tendency for the decrease of the users KPIs in the master group is expected. If the number of the users and/or the rank of their roles are relative low to those in the master group, with high probability the resulting deviation of the KPI of the UEs in the master group will lie within the interval (4). Then the power control mechanism in the CO will not take any action to change the upstream power of the UEs. This could be seen from the results from the simulations of the algorithm shown in Fig. 5. Let's accept that Δ is 0.1, there are 20 active UEs in group **X**, requiring randomly different ranks of roles, and no UEs are active in the other two groups. Thus the parameter $AddXTalk(Slot_i,Group_j)$ is maximum for this group and the latter is appointed as master. All of its UEs receive KPI=1, as shown in Fig. 5a. Following, the KPI of the users is calculated in case when in the slave group a number of 2, 4 and 8 UEs become active – Fig. 5b, c and d. It could be seen that the deviation of the KPIs of the users in the master group are within the interval (4).

In the limited case, of a small difference of the parameter $AddXTalk(Slot_i,Group_j)$ between the current master group and one of the slave groups, it is probable that part of the UE's KPI become less than 0.9 if additional UEs become active.

In such a case the reference crosstalk level of the master group is memorized and the power level of the UEs with least KPI is increased selectively up to the value KPI=1. A new reference $AddXTalk(Slot_i,Group_j)$ in the master group is obtained. The necessary power compensation in the slave groups is calculated for the "*additional crosstalk*" parameter from the master group based on the information from the previous slot, without taking into consideration the increase of the power of some of the UEs in the master group. This will lead to a decrease in the resulting KPI of the UEs in the slave groups. When the KPI of an UE from a slave group becomes less than 0.9, the power control scheme calculates the new reference $AddXTalk(Slot_i,Group_j)$ level and recalculates the individual power of their UEs and respective KPIs.

When changing the reference level of the parameter $AddXTalk(Slot_i,Group_j)$ it is obligatory to check if the limit of the allowable crosstalk level is reached. If so, the system changes into mode "*role decrementing*". This is a case when the master group cannot ensure maximum of the utility functions of all of his users and the PC mechanism will start lowering the rank of the roles of some of the UEs, thus giving them less throughput to keep the crosstalk below the limit. The criteria for role decrementing (applying a role of lower KPI) for part of the UEs, could be different. The system goes out of the mode "*role decrementing*" in two cases: change of the reference group or if the crosstalk falls below 95% of the allowable limit.

IV. Conclusion

This paper introduces an approach for PC for DSL based on defining roles of the subscribers within a subscriber network. The results show that optimal average throughput could be achieved, keeping the crosstalk interference under a given limit. On the other hand applying such a dynamic role appropriation algorithm fairness concerning the upstream power allocation among the subscribers in a DSL environment is achieved.

Acknowledgement

This work was supported in part by the Grant DDVU 02/13/17.12.2010 "Public and Private Multimedia Network Throughput Increase by Creating Methods for Assessment, Control and Traffic Optimization" of the Bulgarian Science Fund and by the Technical University of Sofia under Grant 121PD0068-07/2012 "Cognitive Approaches for Power and Interference control in New Generation Telecommunication Networks"

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