ADAPTIVE RESOURCE ALLOCATION IN MULTIUSER FDD-DMT SYSTEMS

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ABSTRACT

The performance of multiuser digital subscriber line (DSL) systems is constrained by crosstalk noise. This becomes especially noticeable in DSL systems that use high frequencies as in very high speed DSL (VDSL), since the crosstalk increases with frequency. To minimize the performance losses due to the crosstalk the users should coordinate and optimize their spectra with the aim of jointly maximizing the bit rates of all users. However, the multiuser DSL environment is modelled as a Gaussian interference channel and the rate region for this channel model is still an unsolved problem in information theory. This problem, for multiuser frequency division duplex discrete multi-tone (FDD-DMT) systems, is solved in a suboptimal way by our proposed Normalized-Rate Iterative Algorithm (NRIA). The NRIA determines optimized down- and upstream subcarrier allocations for the bundle and implicitly performs power control and power allocation for all users. In this paper we show, by simulation, that this algorithm achieves a significant performance improvement over existing standardized upstream power back-off (UPBO) and spectra plans in VDSL.

1. INTRODUCTION

Currently, each DSL modem runs independently from all other modems, and they are designed assuming the worst-case noise scenario and statistically 99% worst-case crosstalk couplings regardless of the actual network environment. The data rates achieved are therefore far below what is possible. Furthermore, when dimensioning networks it is assumed that all disturbers are collocated at the same place as the disturbed modem at the network termination (NT) and line termination (LT) sides. Thus, the near-far problem [3, 7] that arises due to the distributed topology of DSL access networks is ignored completely. To solve the near-far problem in VDSL for the upstream transmission direction the modems located near the central office (CO) or cabinet reduce their transmit power spectral density (PSD) masks. This reduction of transmit PSD mask in the upstream direction is known as UPBO.

An obvious extension for future DSL is to consider the cable bundle as a multiuser channel. Analysis has shown that substantial performance improvement can be achieved by applying coordination and joint signal processing among the modems in a bundle [8]. Throughout this paper the term performance improvement is used to describe the increasing of bit rates that can be delivered to users. Joint signal processing is not always possible, because due to the unbundling process [6] either the modems are allocated in different physical locations or the access to the physical-layer signals between the incumbent local exchange carrier and different competitive local exchange carriers will not be allowed. Still, it is possible to improve the system performance when we analyze the systems as transmitting over a Gaussian interference channel [2] and optimize the user spectra jointly. Unfortunately, for this channel the rate region is an unsolved problem in information theory [2]. The rate region characterizes all possible data rate combinations among all users subject to the power constraints [7]. It was shown by Yu et. al. [7] that performance can be improved when optimizing the spectra of all users jointly by using an iterative water-filling algorithm. Their proposed algorithm can be implemented distributively, but it does not consider the problem of down- and upstream subcar-

rier allocation; instead it supposes that they are known and fixed. The convergence of the algorithm is, furthermore, only ensured if the set of target bit rates of all users are achievable, which has to be determined *a priori*.

In [1] we have proposed the "Normalized-Rate Iterative Algorithm" (NRIA), which solves the rate region problem in a Gaussian interference channel for multiuser FDD-DMT systems in a suboptimal way. NRIA determines an optimized down- and upstream subcarrier allocation for the bundle and implicitly it performs power control and power allocation for all users. Our algorithm does not need to know *a priori* the set of target bit rates since we estimate the target bit rate adaptively in every iteration. NRIA can be implemented only in a central agent that has a full knowledge of all channel transfer and crosstalk coupling functions.

This paper proceeds as follows: In the next section we present the NRIA. In Section 3 we show the simulation results and compare the performance of NRIA to the existing standardized static spectra and UPBO used in VDSL. In Section 4 we draw some conclusions.

2. NORMALIZED-RATE ITERATIVE ALGORITHM

DSL systems that use the DMT modulation technique divide the transmission bandwidth into many subcarriers and in these subcarriers they adaptively perform power allocation with the water-filling algorithm [8]. In current systems the down- and upstream subcarriers are fixed, as they are designed as a single user system. In multiuser FDD-DMT systems, to achieve the best performance we need to consider the down- and upstream subbcarrier allocation as well as power allocation of the used subcarrier with the aim of jointly maximizing the bit rates of all users. To simplify this problem we assume FDD over all users and perfect synchronization among all users. When these assumptions are satisfied for the systems that need to be optimized, there is no self far-end crosstalk (self-FEXT), meaning no FEXT noise from the systems of the same type. The alien noise is the noise that comes from the other systems. In the following the alien near-end crosstalk (NEXT) and FEXT noises are considered as background noise.

NRIA is suboptimal for two reasons: to make the algorithm tractable we have constrained it to search in a reduced space for subcarrier allocation; and it is based on Yu's iterative water-filling [9], which finds the competitively optimal power allocation solutions, which are, for the Gaussian interference channel, not globally optimal [7].

Our algorithm has two main phases: *initialization* and *iteration*. The iteration phase is further divided into two stages: *an inner stage* and *an outer stage*.

The inner stage, for fixed subcarrier allocation, calculates the sets of down- and upstream supported bit rates and implicitly performs power control and power allocation for all users. The inner stage is based on Yu's [9] iterative water-filling algorithm, with the target bit rate estimated adaptively in every iteration. To do this we have defined a normalized supported bit rate, which is calculated as a supported bit rate of a user u divided by the user priority α_u. The normalized supported bit rate $\overline{R}$, the supported bit rates R, and

priory α for all users are related by Eq. (1),

$$\overline{R}_1 = \frac{R_1}{\alpha_1} = \overline{R}_2 = \frac{R_2}{\alpha_2} = \ldots = \overline{R}_U = \frac{R_U}{\alpha_U}; \quad \sum_{u=1}^{U} \alpha_u^{DS} = 1, \quad (1)$$

where U is the number of users.

For each iteration i a target bit rate is estimated. We will use the linear least squares estimator [5] to calculate this bit rate because we cannot make *a priori* any probabilistic assumptions about the down- and upstream supported bit rates of all users. Thus, the target bit rate is calculated as the mean value of the normalized supported bit rates in the last m iterations multiplied by user priority α_u. The algorithm works well using $m = U$. However, performance improvement sometimes is achieved when m is increased. To achieve the best performance and the fastest convergence m should be updated adaptively.

Due to the estimation of the target bit rate in every iteration, the user order over which we iterate becomes important for the algorithm's performance. It is quickly realized that the users should be arranged first in decreasing priority order and then within the same priority group, they should be arranged in decreasing line-attenuation order. We perform this ordering independently for each transmission direction.

The water-filling algorithm used in the inner stage is a modified version of the fixed-margin water-filling algorithm [8]. In our case we do not know *a priori* if the target bit rate can be supported for a given maximal power allowed to be used. Therefore we have modified the fixed-margin water-filling algorithm as follows: if the target bit rate can be supported, then only the power needed to support this given bit rate is used; otherwise the maximum allowed power is used and the supported bit rate is calculated.

The outer stage searches for the subcarrier allocation in the down- or upstream directions. In principle, each subcarrier should be allocated in the direction of highest average channel-gain-to-noise ratio. However, the noise is unknown *a priori* because it depends on the power allocation of all other users.

In our algorithm the subcarrier allocation starts with the initial values calculated as follows: the bandwidth from N subcarriers is partitioned into K subbands with an equal number of subcarriers per subband. The subbands are allocated in the down- and upstream directions in succession. A binary search within the subbands for the down- or upstream subcarrier allocation is performed by simultaneously moving either all downstream right side edges as in Fig. 1 (an example with four subbands) or all downstream left side edges (simultaneously over all users, since we have FDD with the same subcarrier allocation for all users) until the equation

$$\sum_{u=1}^{U} R_u^{DS} = a \sum_{u=1}^{U} R_u^{US}, \quad (2)$$

is satisfied to a desired accuracy. In Eq. (2) U is the number of users, R_u^{DS} and R_u^{US} are down- and upstream supported bit rates of a user u, and a is the asymmetry parameter between the sum of down- and upstream supported bit rates of all users.
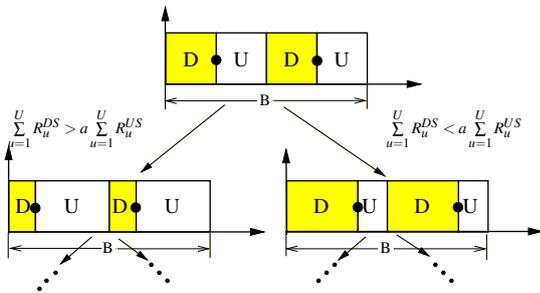

Figure 1: Searching for subcarrier allocation.

The algorithm for the general case is presented below:
Initialization phase:
I) For a given number of subcarriers N, the number of subbands is initialized to $K = 2^b$, where b can take one of the following values: $1, 2, \ldots, log_2 N$. The sets of subcarriers for the upstream w^{US} and downstream w^{DS} directions are initialized from the initial allocation of the K subbands.
II) Set the downstream PSD mask P_u^{DS} and upstream PSD mask P_u^{US} of all users to zero.
III) Initialize the sets of user priorities for the downstream $\{\alpha_1^{DS}, \ldots, \alpha_U^{DS}\}$ and upstream $\{\alpha_1^{US}, \ldots, \alpha_U^{US}\}$ directions, together with the asymmetry parameter a.
IV) The users are first arranged in decreasing priority order. Then users within the same priority group are arranged in decreasing line-attenuation order. The ordering is performed independently for both transmission directions.
V) Set the initial target bit rates $\tilde{R}_{Target}^{DS}$ and $\tilde{R}_{Target}^{US}$ to infinity.
VI) Set the parameters m^{DS} and m^{US} (which specify the last m normalized supported bit rates used to calculate the target bit rate for a given transmission direction) to user-selected values.
Iteration phase:
1. Repeat (outer stage).
2. Set the downstream iteration counter to $i^{DS} = 1$.
3. Repeat (downstream inner stage).
4. Repeat for all users u (in the same order as in IV).
5. Calculate the noise for the set of subcarriers w^{DS} at the NT side. For a given user u in subcarrier n it is calculated as:

$$N_{u,n}^{NT} = \sum_{\substack{t=1 \\ t \neq u}}^{U} \left| H_{tu,n,FEXT}^{NT} \right|^2 P_{t,n}^{DS} + P_{n,BG}. \quad (3)$$

6. The target bit rate is calculated as follows: (for $i^{DS} = 1$, R_{Target}^{DS} is equal to the initial value in V):

$$\tilde{R}_{Target}^{DS} = \frac{\alpha_u^{DS}}{r} \sum_{k=i^{DS}-r}^{i^{DS}-1} \overline{R}_k^{DS}, \quad (4)$$

where $r = \begin{cases} i^{DS} - 1 & \text{if } i^{DS} \leq m^{DS} \\ m^{DS} & \text{if } i^{DS} > m^{DS}. \end{cases}$

7. Apply modified fixed-margin water-filling to user u for the target bit rate calculated in Step 6 and defined $P_{u,max}^{DS}$. As a result the supported bit rate R_u^{DS} and the corresponding PSD mask $\hat{P}_u^{DS}$ of the user u are found.
8. Update the downstream PSD mask of user u: $P_u^{DS} = \hat{P}_u^{DS}$
9. The downstream normalized supported bit rate in iteration i^{DS} is calculated as:

$$\overline{R}_{i^{DS}}^{DS} = \frac{R_u^{DS}}{\alpha_u^{DS}}.$$

10. Increase the downstream iteration counter $i^{DS} = i^{DS} + 1$.
11. Go to (4). Repeat for all users.
12. Go to (3). Repeat until the desired accuracy on the downstream supported bit rate of all users is reached.
13. Repeat Steps 2 to 12 for the upstream direction.
14. Depending on the down- and upstream supported bit rates of all users, and the asymmetry constraint a the subband edges are moved (*c.f.*, Fig. 1). Then the set of subcarriers for the downstream w^{DS} and for the upstream w^{US} direction are calculated for the next outer stage iteration.
15. Go to (1). Repeat until the desired (a)symmetrical accuracy is achieved in Eq. (2) or the maximal number of combinations have been examined.

By using a linear least square estimate of the target bit rate, which is a nonlinear function of power allocation of all users, it is possible for the NRIA algorithm to converge to the point that the sum of the bit rate of all users is lower than can be achieved

in reality. Fortunately, these cases can always be recognized since none of the modems use the maximal allowed power, which is determined either by the PSD mask or the total power constraint, or both of them. In such cases a "small" performance improvement is achieved when the last m values of $\overline{R}$ are increased by some amount, let us say $\Delta\overline{R}$. We do not analyze this problem further here because of space limitations.

3. SIMULATION RESULTS AND DISCUSSION

In this section we present the simulation results and compare the performance of our algorithm to standardized static spectra and UPBO in VDSL. In our simulation scenario, shown in Fig. 2, all systems are deployed from the cabinet. The simulation parameters are based on the ETSI VDSL standard [4] for 4096 subcarriers. The main simulation parameters are given as follows. NRIA does not need a PSD mask constraint, since a total power constraint alone is a sufficient to control the maximal power allowed to be used by the modems. However, for a fair comparison the maximum PSD mask constraint is set to -60 dBm/Hz for all simulations. Simulations are performed under the ETSI 99% worst-case FEXT coupling model, the diamond-marked line in Fig. 3, and for the measured FEXT coupling of a 0.4 mm cable with 50 pairs (vendor identification: F02YHJA2Y 50x2x0.4). Fig. 3 shows the equal level FEXT (EL-FEXT) couplings of all fifteen twisted pairs used, which are selected randomly from the 50 possible pairs. The insertion losses per unit length in all twisted pairs of our cable are very similar, as Fig. 4 shows. Therefore, for all simulations we assume that all twisted pairs have equal insertion loss per unit length and we use the model shown in Fig. 4. Moreover, to take into account the alien noise at both the NT and LT sides, in addition to the background noise, we have also added the alien ETSI VDSL noise A model [4]. The parameters for the standardized VDSL UPBO are selected for this type of noise as defined in [4]. The subcarrier allocation for ETSI VDSL are: $w^{DS} = \{32\text{--}695, 1182\text{--}1634\}$ for the downstream and $w^{US} = \{696\text{--}1181, 1635\text{--}2782\}$ for the upstream directions. All simulations with our algorithm are performed for $K = 8$, $m^{DS} = 50$, and $m^{US} = 50$. Furthermore, for a fair comparison we use the same spectrum in all simulations: so we only use subcarriers from 32 to 2782 with our algorithm, but we have performed a binary search for optimal subcarrier allocation within the $K = 8$ subbands. In all simulations we use the bit loading algorithm with maximal number of bits per subcarrier set to fifteen.
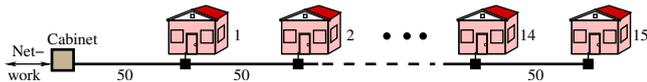
Figure 2: Simulation Scenario. The maximum loop length is 750 m (for user 15).

By deploying adaptive resource allocation, the performance of DSL systems improve due to the search for optimized spectra allocation rather than the use of standardized fixed spectra. Using existing crosstalk couplings to calculate the noise instead of assuming the 99% worst-case coupling models also improves the performance. Thus, we first consider the VDSL performance improvement when the measured FEXT couplings shown in Fig. 3 are used rather than assume the 99% worst-case FEXT coupling as is current practice. The curves in Fig. 5 show the supported bit rates of all users when VDSL static spectra and UPBO are used. During the simulation, to calculate the self-FEXT noise at the input of each modem for the 99% worst-case FEXT coupling, we use the FSAN noise calculation method [4]. Although the FEXT couplings between the lines are different we have not performed pair selection, but we have deployed the VDSL systems in the twisted pairs randomly. It can be seen from the curves in Fig. 5 that substantial increases in the supported bit rates are achieved, when the measured FEXT couplings are used to calculate the noise. The increased supported bit rates are higher in the downstream than in the upstream
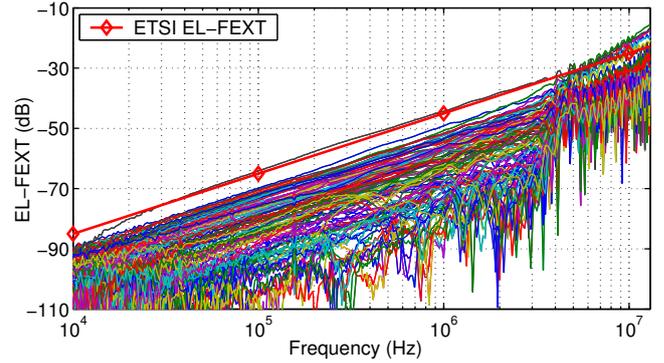
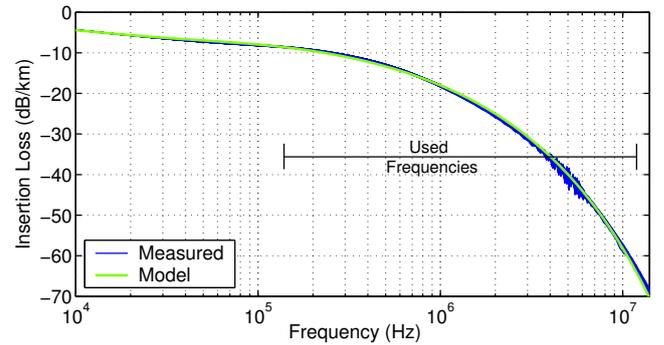Figure 3: Measured EL-FEXT values between fifteen pair of a 0.4 mm cable with 50 pairs.

Figure 4: Measured insertion loos of all 50 pairs and the model used for simulation.

direction, because all VDSL modems in the downstream direction transmit with the maximal allowed PSD masks. In the upstream direction the modems disturb each other due to the near-far problem, but they transmit with some form of "optimized" spectra calculated by the UPBO algorithm. Although the transmit signals of users 11, 12, and 13 for both transmission directions are attenuated more than the transmit signals of users 8, 9, and 10, they support higher bit rates. This is as a result of lower FEXT coupling levels between the twisted pairs on which the user 11, 12, and 13 are deployed and the other twisted pairs used by other VDSL systems. The same holds true for users 14 and 15. Thus, the insertion loss alone is not the optimal parameter to determine the level of transmit PSD masks as is done in the current standardized VDSL UPBO.
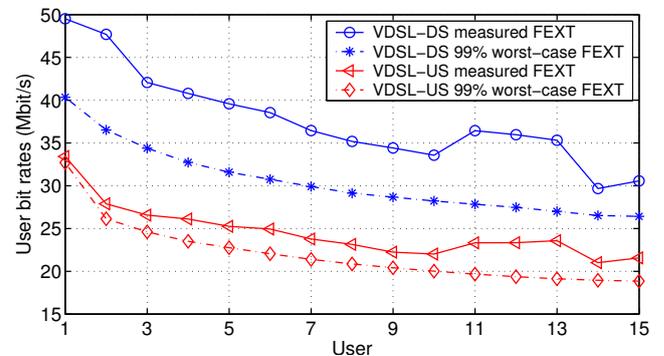
Figure 5: VDSL supported bit rates for 99% worst-case and measured FEXT couplings.

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The main drawback of using static transmit spectra is that the allowed spectra are optimized for some "reference" network scenarios and these optimized spectra are not optimal for any real network scenario. Furthermore, due to the use of the static spectra the maximal bit rates which can be delivered to the users are fixed, no matter what their needs are. For the scenario shown in Fig. 2 only the VDSL bit rates shown in Fig. 5 can be supported. For instance, if there is a need to deliver equal bit rates to all users and equal down- and upstream bit rates then the bit rate that can be delivered to all users is determined by the smallest supported bit rate, in our case the bit rate of user 14 in upstream that is approximately 21.5 Mbit/s (or the bit rate of user 15 in the upstream direction that is approximately 19 Mbit/s when the 99% worst-case FEXT coupling is assumed).

When we apply the equal down- and upstream bit rates constraint to our proposed NRIA, thus, $a = 1$, for the simulation scenario in Fig. 2 approximately 33 Mbit/s can be delivered to all users as shown in Fig. 6. This figure also shows that for VDSL fixed spectra the upstream supported bit rates are approximately half of the downstream supported bit rates. Thus, if we set the asymmetry parameter in NRIA to $a = 1.5$ then bit rates of approximately 39 and 26 Mbit/s can be delivered to all users in the down- and upstream directions, respectively. Increases in the supported bit rates are achieved as a results of a "more appropriate" subcarrier and power allocations, as found by NRIA, to serve the needs of all users in comparison to the fixed VDSL spectra. The subcarrier and power allocations for some users in VDSL and NRIA cases when the asymmetry constant is $a = 1.5$, are shown in Fig. 7 and Fig.8, respectively. The PSD masks have a non-smooth shape due to using a bit-loading algorithm to perform power allocation. Bit-loading algorithms constrain the number of bits that can be transmitted on subcarriers to an integer.
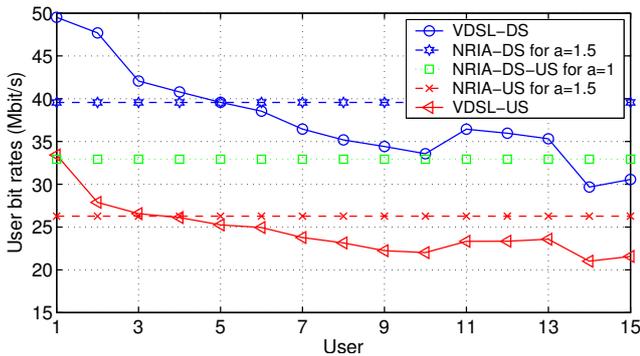

Figure 6: Comparison of user supported data rates of VDLS to NRIA when the sum of user upstream bit rates is half of the sum user downstream bit rates (thus $a = 1.5$) and when they are equal (thus $a = 1$). For all simulations the measured FEXT couplings are used.

4. CONCLUSIONS

In this paper we have shown that significant performance improvement can be achieved in DSL systems when the cable resources are shared adaptively among the users. By using our Normalized-Rate Iterative Algorithm (NRIA) each user is able to optimize the allocation of power according to the actual interference situation and use a minimum of power to achieve his or her own particular needs. We have shown by simulations that the NRIA significantly improves the performance of all users in a distributed VDSL scenario compared to the use of standardized upstream power back-off and static spectrum allocation.
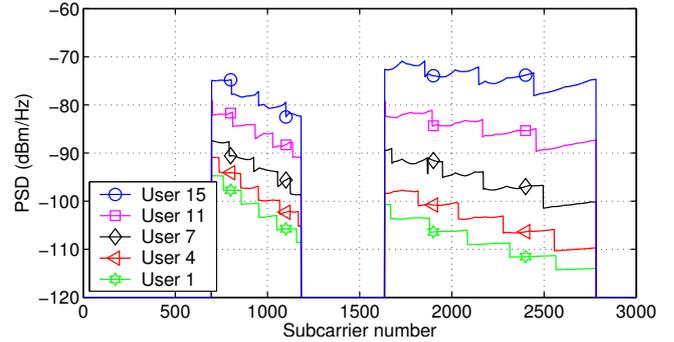
5. ACKNOWLEDGMENTS

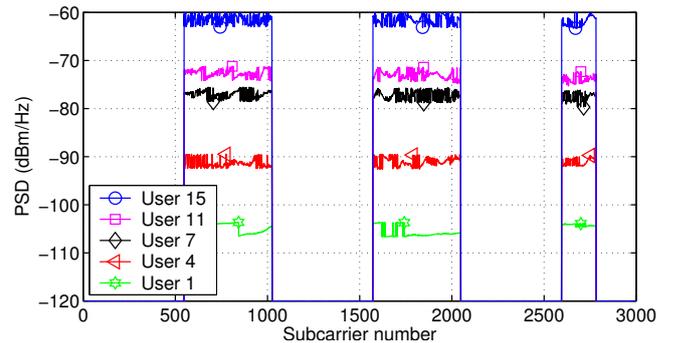Figure 7: VDSL upstream transmit PSD masks of user 1, 4, 7, 11, and 15 for static spectra and UPBO .

Figure 8: NRIA upstream transmit PSD masks of user 1, 4, 7, 11, and 15.

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