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Subchannel Allocation on Multiple *pDSL* Lines

Th. Antonakopoulos and N. Papandreou

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Theodore Antonakopoulos
Dept. Electrical Engineering & Computers Technology
University of Patras, 26500 Rio - Patras, Greece
E-mail: antonako@ee.upatras.gr

Nikolaos Papandreou
Research Academic Computer Technology Institute
61 Riga Feraiou Str., 26100 Patras, Greece
E-mail: npapandr@cti.gr

***Abstract*— The *pDSL* technology is used for providing multiple, high-speed broadband links over power lines in the indoor environment. This work addresses the problem of bandwidth allocation between the various links of a *pDSL* network and proposes an algorithm for determining the allocation of the various subchannels during network activation and periodically during the normal network operation. The paper also demonstrates the performance of the proposed algorithm using an illustrative example.**

I. Introduction

The *pDSL* networking concept provides high speed broadband communications using indoor power-lines by forming a set of 'point-to-point', high-speed links between a *pDSL* gateway and multiple *pDSL* devices [1]. The *pDSL* communications environment has to use various dynamic mechanisms for confronting the main impairments of power-line (PLC) channels [2], [3]. An initial approach on the necessary procedures for improving the performance of such a communications environment, including channel training techniques and adaptation of bandwidth allocation to the underlying transmission conditions, was discussed in [1]. In this work, we extend the initially presented ideas by presenting a new bandwidth allocation algorithm (in terms of fixed-bandwidth subchannels), using a more formal approach and more quantitative criteria for deciding on the bandwidth allocation under specific loading conditions.

The indoor power grid behaves as a time-varying multipath fading channel, where several frequency bands may become temporarily unsuitable for transmission on each *pDSL* link. These unsuitable subchannels are not necessarily the same on all links and in many cases, a subchannel that exhibits strong attenuation in a *pDSL* link, demonstrates good transmission conditions on another *pDSL* link. In a *pDSL* network, a point-to-point link between each *pDSL* device and the *pDSL* gateway is established on non-overlapping frequency bands. Each link is bidirectional with suitable upstream (from the device to the gateway) and downstream (from the gateway to the device) allocated bandwidth, depending on the application specified data rates. As the network loading conditions change, new frequency bands become unsuitable, in other frequency bands the SNR changes significantly and other previously useless frequency bands become appropriate for transmission. Once the quality of each subchannel in all links is identified, proper selection of the transmission parameters, such as bandwidth allocation and bit loading, can be performed.

Optimization of the bandwidth allocation procedure is a challenging task, especially since the medium displays both frequency and time varying characteristics that differ on each *pDSL* link. Distribution of the available bandwidth, divided in a number of subchannels, should be based on the expected bandwidth demand on each transmission direction of a particular link and the quality of each subchannel for supporting reliable communications.

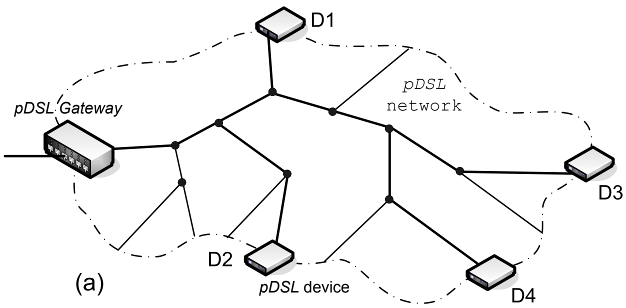
In this work we present a new algorithm that can be used on the *pDSL* gateway for bandwidth allocation (in the form of subchannels) to all active links on a *pDSL* network. The algorithm exploits the measurements performed on every *pDSL* link at regular time intervals and the assumption that the high speed communications links can be considered symmetrical, exhibiting identical behavior on both transmission directions [4]. Using training procedures, the frequency response of each link is calculated initially and is updated periodically, based on measurements performed during the normal network operation. In order to achieve reliable system operation and improved performance, a time-varying bit-loading mechanism is used in each active link [5]. The *pDSL* gateway may also exploit a network response-estimation model [6] along with the channel training procedures to allocate bandwidth to each virtual link, but the estimation procedure is not discussed in this work.

Section II presents in details the bandwidth allocation problem that has to be solved in a *pDSL* network, while Section III explains the algorithms developed for addressing this problem. Section IV presents simulation results that explain the application of the proposed algorithms to a *pDSL* network using an illustrative example.

II. The Bandwidth Allocation Problem

A *pDSL* network that consists of a *pDSL* gateway and k *pDSL* devices forms k bidirectional *pDSL* links, resulting to $2k$ virtual links, k upload and k download links (see Fig. 1). Each link may support different data rates at each direction of transmission and the virtual links at each direction may support different data rates. The following analysis considers only one direction of transmission (i.e. the downlink) and the same data rate on all links.

The bandwidth allocation process is based on a number of criteria that define which subchannels are considered appropriate for data transmission on each virtual link. Assuming fixed subchannel bandwidth, we list some quantitative criteria



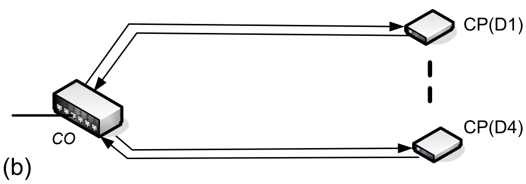


Fig. 1. A *pDSL* network and the equivalent DSL topology.

that can be associated with a cost function and can be used to allocate a subchannel to a specific virtual link:

1) A subchannel is allocated to the virtual link in which it has the highest measured/estimated SNR value.
2) The allocation scenario should remain as invariant as possible, when new loading conditions occur.
3) Subchannel allocation should be analogous to the required data transmission rates and to the quality of the respective virtual links.

In all cases, the subchannels' bandwidth is selected so that the frequency response of each subchannel practically remains invariant and all subchannels have the same bandwidth. Note that during network activation, the quality of all subchannels is measured explicitly, but during the normal network operation only the subchannels allocated to each link are measured and the rest SNR values are estimated by exploiting the analytic network response-estimation model presented in [6].

III. The Subchannel Allocation Algorithm

The subchannel allocation problem has to be considered in two discrete phases, during the '*initial subchannel allocation*' phase and during the '*periodic subchannel allocation*' phase. The '*initial subchannel allocation*' phase is executed when the *pDSL* network is activated and before starting the actual data transmission ('show-time'), while the '*periodic subchannel allocation*' phase is executed periodically during 'show-time' and is based on the existing subchannel allocation and the estimation of the new channel conditions.

A. The initial subchannel allocation algorithm

As it was described in [1], the *pDSL* gateway starts the *initial* channel training procedure when the network is activated. During this phase, the gateway broadcasts a broadband training sequence towards all *pDSL* devices in the network and each device estimates the particular link's response in the entire frequency band of interest and the noise level of each subchannel. These estimates are uploaded to the gateway in the form of CNR values, through a low-speed control channel. Therefore, due to the channel symmetry, the link is characterized in both transmission directions, although channel training can also be performed in the reverse direction. The technique used to produce these estimates is a training technique similar to the one used in xDSL links.

Let N be the number of all available subchannels, and $2K$ be the number of all virtual links in the network. $CNR_{i,j}(t)$ is the measured/estimated CNR of subchannel i on virtual link j during the previous loading conditions and $CNR_{i,j}(t+T)$ is its current CNR value.

At the end of the *initial* channel training procedure, the *pDSL* gateway creates the $\mathbf{CNR}(t_0)_{[K\times N]}$ matrix and computes the matrices $\mathbf{B}(t_0)_{[K\times N]}$ and $\mathbf{P}(t_0)_{[K\times N]}$, which determine the number of bits and the power allocated to each subchannel at each link, respectively. The subchannel allocation matrix, $\mathbf{AT}(t_0)_{[K\times N]}$, is also generated and specifies which subchannels have been allocated to each link. Each row of these tables is associated to a virtual link and if a subchannel has been allocated to a link, the same subchannel is not used by all other links, therefore:

$$\text{if } AT_{m,j}=1 \text{ then } AT_{i,j}=0 \quad \forall i\neq m, \forall j \tag{1}$$

Before starting the bandwidth allocation process, the gateway determines the subchannels which are unsuitable for data transmission, even if the maximum allowable power is used. Let Γ be the minimum SNR gap, P_{max} be the maximum power that can be allocated to a single subchannel, $CNR_{i,j} = |H_{i,j}|^2/N_{i,j}$ be the gain-to-noise ratio of subchannel i of link j, and $b_{i,j}$ the number of bits at this subchannel, then according to [7]:

$$b_{i,j} = \log_2\left(1+\frac{P_{i,j}\cdot CNR_{i,j}}{\Gamma}\right) \tag{2}$$

If $CNR_{i,j} < \Gamma/P_{max}$, the subchannel i will not participate in the bandwidth allocation process of link j. The minimum SNR gap, Γ, takes a value much greater than the one used in xDSL systems, due to the varying channel conditions. Equation (2) also determines the minimum power required for loading $b_{i,j}$ bits in a specific subchannel and is related to the desired target-rate. The difference between the power $P_{i,j}$ and P_{max} may be exploited for increasing the margin of each subchannel. The PLC network is a time-varying channel where strong SNR variation may be experienced and therefore large values of margin are required.

Since the different virtual links exhibit different transmission characteristics and may have different target-rates, R_j, we define as the *network's quality factor* the metric:

$$Q(t_0) = \frac{1}{K}\cdot\sum_{j=1}^{K} Q_j(t_0) \tag{3}$$

where $Q_j(t_0) = \frac{1}{N} \cdot \sum_{i=1}^{N} CNR_{i,j}(t_0)$ and the *channel quality factor* of each individual virtual link is given by:

$$Q_j = \left| \frac{Q_j(t_0)}{Q(t_0)} \right| \tag{4}$$

The higher the value of Q_j, the poorer the quality of the virtual link. If $R = \sum_{j=1}^{K} R_j$ is the total data rate that have to be supported by the *pDSL* network, then the '*initial subchannel allocation*' algorithm has to allocate N_j subchannels to the virtual link j using the following equation:

$$N_j = \left\lfloor N \cdot \frac{R_j \cdot Q_j^{1/r}}{\sum_{j=1}^{K} R_j \cdot Q_j^{1/r}} \right\rfloor \tag{5}$$

where the parameter r depends on the modulation used for user data transmission, the higher-order statistics of the virtual links' CNRs and on the ratio of the target to the maximum data rate. The algorithm used for computing the matrices **AT**, **B** and **P** according to the previous analysis, is the following:

- Initialize an array, $\mathbf{I}_{[\mathbf{K}\times\mathbf{1}]} = \mathbf{1}$, that contains the links that participate in the subchannel allocation procedure. The N_j values determined using (5) are used to create the $\mathbf{N}_{[\mathbf{K}\times\mathbf{1}]}$ array.
- Determine the subchannel with the maximum CNR value. The subchannel must belong to one of the links participating in the **I** array.
- Set to 1 the respective position in the **AT** matrix (set to 0 all other positions of the same column). Exclude the respective link from the next subchannel allocation round (delete it from the links' array, **I**) and decrease by one the respective position in array **N**.
- Set to 0 the respective column in the **CNR** matrix.
- Start a new subchannel allocation round if there are more subchannels to be allocated. If $\mathbf{I} = \mathbf{0}$, re-initialize **I** for all links in which more subchannels have to be allocated (their respective value in **N** is greater than 0).
- If $\sum N_j < N$, the subchannels not allocated using the above procedure are allocated to the virtual links having subchannels with the maximum CNR values. It is obvious that $0 \leq N - \sum N_j \leq K$.
- Using the discrete bit-loading algorithm of [8] on each row of the **CNR** matrix, the respective rows of matrices **B** and **P** are computed. If the maximum possible margin is required for a specific target rate, then $P_{i,j} = P_{max}\ \forall i, j$
- If there are links that achieved less data rate than they initially requested, a final adjustment step has to be executed that transfers subchannels from links with higher data rates to links with lower data rates.
- Using the final subchannel allocation matrix, **AT**, the **N** array is re-calculated and is used in all *periodic subchannel allocation* rounds. The number of subchannels allocated to each virtual link remains constant until the network is re-activated.

Although the above described algorithm was developed for supporting links in one direction, it can be easily modified to support links in both directions.

B. The periodic subchannel allocation algorithm

When the network becomes operational and user data are exchanged, the *pDSL* devices perform *inbound* training to assess possible changes in attenuation or SNR levels on the subchannels of each link [1]. Since, the training sequences have to be injected among user data, only the allocated subchannels are available for training on each specific link. Each device transmits, in the uplink direction, band-limited training sequences on each subchannel using a round-robin scheme, until all allocated subchannels of its virtual link are trained. The *pDSL* gateway uses this information, the network topology and the network's model [6], to generate the new **CNR** matrix. The gateway produces an estimate of the links' responses on the entire frequency band of interest. This procedure has to be performed due to the lack of information on the subchannels that were not measured in the current training interval. Based on the set of criteria defined in the previous section, the gateway decides whether bandwidth reallocation has to be performed.

The subchannels that do not present significant variation to their CNRs, will be allocated to the same link as in the previous stage. Using (2) and knowing that, based on the previous bandwidth allocation procedure, $b_{i,j}$ bits were allocated to subchannel i of link j:

if the new $CNR_{i,j}$ satisfies the inequality:

$$\frac{1}{\Gamma_{i,j}(t_k)} \leq \frac{CNR_{i,j}(t_k+T)}{CNR_{i,j}(t_k)} \leq \frac{2^{b_{i,j}(t_k)+1}-1}{2^{b_{i,j}(t_k)}-1} \tag{6}$$

the corresponding bit allocation $b_{i,j}$ is still supported.

The above inequality determines the bounds in order to consider the CNR invariant at time $t_k + T$. In particular, the lower bound depends on the subchannel margin $\Gamma_{i,j}$ used for gain-to-noise ratio degradation immunity, while the upper bound describes the situation of gain-to-noise ratio improvement that enables one additional bit to be assigned.

If subchannel i remains to the link j, the new **AT** matrix is initialized accordingly. The algorithm used for re-allocating the rest subchannels is the following:

- Decrease the initial N_j values by the number of subchannels considered invariant in each virtual link and initialize the array **I** correspondingly.
- Determine the subchannel with the maximum CNR value. The subchannel must belong to one of the links participating in the **I** array.
- Update the **AT** and **CNR** matrices. Exclude the respective link from the next subchannel allocation round (delete it from the links' array, **I**) and decrease by one the respective position in array **N**.
- Start a new subchannel allocation round if there are more subchannels to be allocated.

IV. Simulation Results

For the simulation results presented in this section, we consider the network example of [1] and we assume that the *pDSL* gateway is connected to the termination point T_1, while there

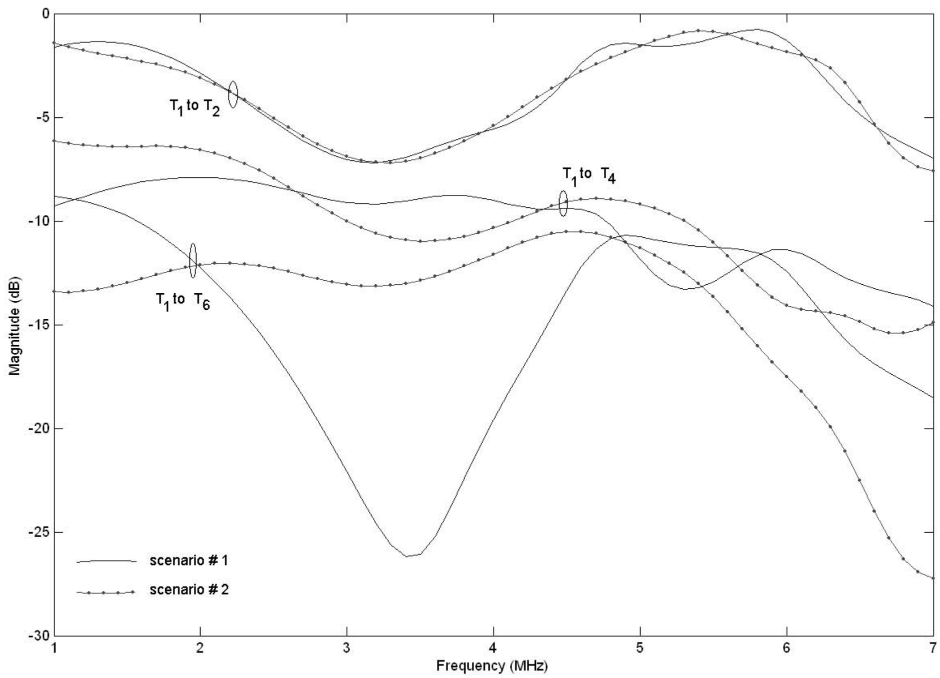


Fig. 2. The CNR values of the three links under different loading conditions.

are three *pDSL* devices which are connected to T_2, T_4 and T_6. We also consider that there are 64 available subchannels and we demonstrate results of two loading scenarios. Scenario $\sharp 1$ is used to describe the loading conditions when the network is activated, while scenario $\sharp 2$ represents the loading conditions the first time the periodic subchannel allocation algorithm is executed. All *pDSL* equipment exhibit impedances of 100 Ohms, and the remaining termination impedances vary according to the loading scenario. In scenario $\sharp 1$ all remaining terminations are open circuit, while in scenario $\sharp 2$ a $10\angle -90^o$ Ohms impedance is connected at T_5.

Figure 2 shows the CNR values of all links in both cases. The transfer function of all virtual links changes, even when a single termination impedance changes, and the different virtual links demonstrate different *initial channel qualities*. Using equations (3)-(5), the values presented in Table I have been used in the *initial subchannel allocation* algorithm, for the same data rate in all channels. Figure 3 shows the subchannel allocation of the three virtual links during the '*initial subchannel allocation*' and the '*periodic subchannel allocation*' phase. Using the discrete bit-loading algorithm of [8], the achieved date rates of both subchannel allocation phases have been calculated and presented in Tables I and II.

TABLE I
PARAMETERS OF THE INITIAL SUBCHANNEL ALLOCATION ALGORITHM

Link	T_1 to T_2	T_1 to T_4	T_1 to T_6
Q_j	0.132	0.348	0.519
N_j	19	21	22
Subchannels	21	21	22
Data Rate	$0.328 \cdot R$	$0.328 \cdot R$	$0.344 \cdot R$

TABLE II
PARAMETERS OF THE PERIODIC SUBCHANNEL ALLOCATION ALGORITHM

Link	T_1 to T_2	T_1 to T_4	T_1 to T_6
Invariant subchannels	21	8	3
Subchannels	21	21	22
Data Rate	$0.328 \cdot R$	$0.328 \cdot R$	$0.344 \cdot R$

V. CONCLUSIONS

In this work we presented a dynamic subchannel allocation algorithm for the *pDSL* networking environment. The subchannel allocation algorithm is executed at the *pDSL* gateway during network activation and periodically as user data are exchanged. The algorithm is based on measured and estimated transmission conditions of all virtual links, and on the target data rate of each link. In both cases, the bandwidth is allocated to the different *pDSL* links so that the total data rate is distributed to all of them according to their target rates.

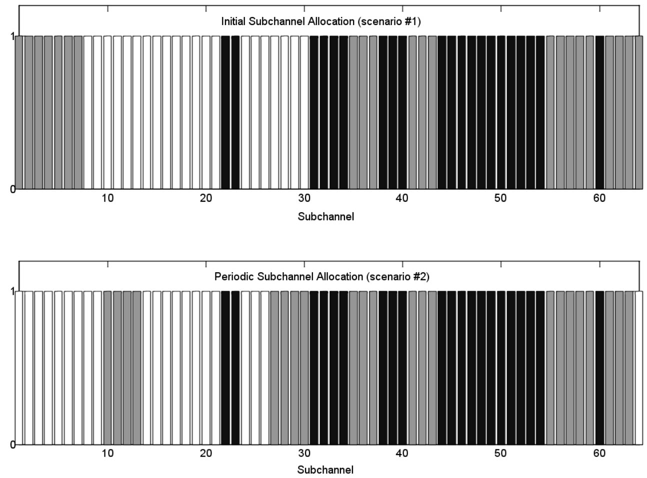


Fig. 3. Subchannel allocation of the three virtual links. Each shading represents a different virtual link.

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