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BROADBAND COMMUNICATIONS IN THE INDOOR POWER LINE ENVIRONMENT: THE *pDSL* CONCEPT

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Abstract

The concept of *pDSL* networking, presented in this work, facilitates the realization of high speed broadband communications over power lines in the indoor environment. A *pDSL* network consists of a set of virtual high-speed links between a PLC Gateway and multiple *pDSL* devices. *pDSL* devices exploit a network response-estimation model and channel training procedures to allocate bandwidth to each virtual link. The paper describes the characteristics of *initial* and *inbound* training processes and presents the criteria for performing optimum bandwidth allocation to all active links on a *pDSL* network.

1. Introduction

In the era of Internet explosion and rapid spreading of the all-digital Smart Home/Office, the increasing demand for high speed data communications services has fostered the use of every available media, in order to realize the indoor local area network and connect this indoor environment to the backbone network by exploiting the 'last mile' connectivity. Since almost every device needs to be plugged into an electrical outlet for power supply, it seems that the transition of power lines from a pure mains network to a medium also delivering broadband services is called for. Relying on its ubiquitous node availability, even in areas with limited twisted-pair and coaxial cable installations and poor radio coverage, the power grid poses as a potentially convenient and inexpensive "no new wires" candidate for data transmission.

Broadband communications, delivering services such as fast Internet access, video conferencing, interactive multimedia and video-on-demand [1], are brought to the consumer premises' *doorstep* by a number of technologies including xDSL, wireless links and fiber optic techniques. Originating at this point, the indoor *pDSL* (powerline DSL) network proposes a novel technology, aiming to convert the existing indoor power distribution network into a '*virtual binder*' of high speed data transmission links. This paper presents the ideas that outline the conceptual design and the functional features of a *pDSL* network and investigates various communications topics that affect the realization of such an aspiring venture.

The concept of *pDSL* networking has sprung from the need to describe the general framework, under which the idea of utilizing the indoor power line infrastructure for high speed data transmission becomes feasible. The *pDSL* communications architecture defines the networking environment and facilitates the development of digital signal processing algorithms and transmission techniques that successfully mitigate the influence of the principal impairments on PLC channels: varying attenuation, multipath frequency-selective fading, multiple access interference, background and impulsive noise. The procedures involved in creating this optimized communications environment, which are discussed in this work, include channel training techniques and adaptation of bandwidth allocation to the underlying transmission conditions.

Section 2 presents an overview of the *pDSL* communications concept. A multipath propagation model, used for estimating the response of a point-to-point transmission link, is discussed briefly in Section 3. Section 4 outlines the channel training procedures, while Section 5 elaborates on the bandwidth re-allocation process. Finally, Section 6 demonstrates the application of the described *pDSL* procedures on an example network.

2. The *pDSL* Concept

A *pDSL* network consists of multiple high-speed communications devices and an internetworking device, called the *pDSL* Gateway, which functions as the central communication and coordination unit of the *pDSL* network and also as its interface to the external communications infrastructure. The *pDSL* Gateway is the counterpart to what is often

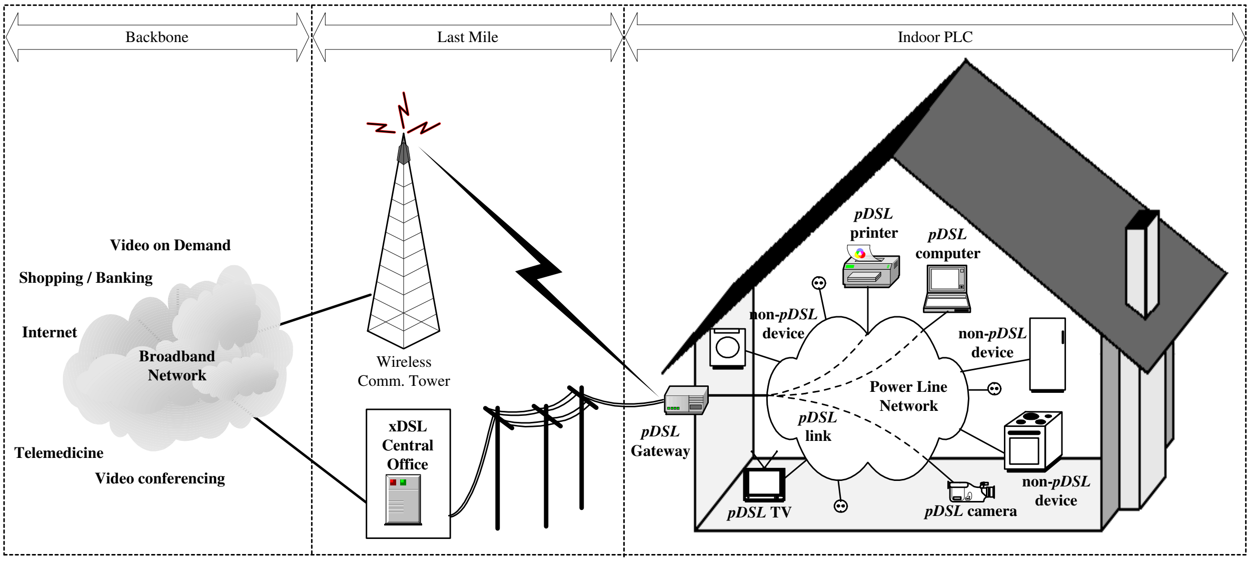

Figure 1: *pDSL* Service Structure.

referred to as the Residential Gateway.

Since the *pDSL* network exploits the existing indoor power grid, two categories of devices are connected to its termination points (the AC outlets), namely digital equipment that require high speed data transmission and appliances that have no use for such services, although they may have low-speed control-oriented power line communication capabilities. The devices that belong to the first category are referred to as *pDSL* devices and comprise the digital equipment and a *pDSL* modem that realizes its interface to the communications network. Consequently, the *pDSL* network forms a '*virtual binder*' of point-to-point communications links connecting the Gateway with each *pDSL* device, as shown in Figure 1. Transmission over these links is performed through a large number of propagation paths, as implied by the multipath nature of the power line environment. Each link is bidirectional with suitable upstream (from the *pDSL* device to the Gateway) and downstream (from the Gateway to the *pDSL* device) allocated bandwidth. Since, the network supports simultaneous communications on all active links, the available bandwidth is distributed to the corresponding communications channels using non-overlapping bandwidth allocation [2].

Improvement of a *pDSL* network's performance depends on its ability to adapt its transmission techniques to the medium's time varying characteristics. Therefore, the need for channel training procedures, performed during network activation and periodically during data transmission, becomes critical. Once the behavior of each link is identified, proper selection of transmission parameters such as bandwidth allocation and bit loading, may facilitate the optimization of communications on the medium. Adaptation of the utilized bandwidth allocation scenario may improve system performance even further, by excluding subchannels with high attenuation and low SNR levels from data transmission on each particular link.

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 communications 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 suitability of each subchannel for reliable communications. The process of determining the suitability of a certain subchannel can be performed by assessing the particular link's response over the requested frequency band, while considering the effect of disturbances on the SNR levels [3]. Therefore, in order to accomplish the task of bandwidth characterization and optimized allocation, a channel training process has to be developed that estimates every link's response in regular time intervals and properly elaborates these results to distribute the available bandwidth according to the suitability of each subchannel for the various communications links, aiming at the optimization of the achievable system data rate.

The first consideration in the development of a feasible channel training process is the effect of termination impedances on the network's behavior. Based on the aforementioned categorization of the connected devices, we observe that *pDSL* devices appear to have a dominant impedance related to the *pDSL* modem. This consideration is based on the condition that the digital equipment's supply unit, connected in parallel to the modem, imposes a negligible effect on the modem's input impedance. Therefore, it can be educed that *pDSL* devices appear as terminating loads of practically time-invariant impedances. We can also assume that since all *pDSL* devices present roughly the same termination impedance, the high speed communications links can be considered symmetrical, exhibiting identical behavior on both transmission directions [4].

On the contrary, non-*pDSL* devices present time-variant impedances, ranging from a few Ohms to a few kOhms, with diverse capacitive or inductive characteristics. Since these impedances appear at various network termination points and their location is often subject to change, they affect the network's response considerably and are responsible for its time varying behavior. Moreover, the impact of the effect related to a load impedance variation depends on each link's proximity to the load. Therefore, proper channel estimation procedures need to be implemented in order to assess the changes in each link's response and adapt transmission to the underlying conditions through subchannel reallocation.

It is useful to distinguish between *initial* and *inbound* channel training techniques, to account for the differences in the requirements set for these two stages of channel estimation. *Initial* channel training can be performed using sequences that cover the entire frequency band of interest on each link. It is performed only once, at the beginning of a requested communications session and therefore is not subject to strict timing limitations. *Inbound* channel training, on the other hand, has to be performed periodically during data transmission. Since the resulting overhead should be limited to the minimum, the process must comply with rigorous timing and bandwidth restrictions. Therefore, due to these restrictions, a capability of predicting each link's behavior must be incorporated in the *pDSL* devices, in order to aid the efficiency of the *inbound* training procedure. Such a prediction becomes feasible through the use of an analytical multipath propagation model of the power line network, based on the description of its topology, cables' characteristics and termination impedances.

Since the type of cables used for the wiring can be determined, their transmission characteristics (Z_0, γ) are either known in advance or can be measured and the network's topology can be described, the only missing element is an estimation of the impedances connected at its termination points. A convenient way of making this information available involves the connection of a small control device to each outlet or to each appliance, programmed to provide the impedance information of the load connected at that particular termination point, depending on its mode of operation. Such a device is necessary only for non-*pDSL* devices, since the *pDSL* devices exhibit a known impedance. Exchange of all necessary control information on the *pDSL* network, including impedance information, can be performed over a low speed *Control Channel*, located at a relatively low frequency band (in the kHz range). Therefore, the small smart-devices do not need to implement sophisticated transmission techniques. The transmission channel carrying user and training data is allocated in the MHz range and is referred to as the Communications Channel.

In the following sections, each of the communications issues mentioned above is elaborated and possible solutions are proposed.

3. The Analytical Multipath Propagation Power Line Model

In this section, we briefly describe the analytical process through which the indoor power line network is modelled as a multipath propagation environment, where delayed replicas of the transmitted signal reach the receiver with different amplitude and phase characteristics. These multipath signal components are caused by reflections on channel discontinuities, such as termination loads and line junctions. Analytical calculation of the multipath effect in the indoor power grid is feasible due to its loop-free topology and its bounded complexity. Thus, the multipath effect can be traced back to the channel's physical characteristics by calculating cable loss, reflection and transmission coefficients. Considering L different propagation paths between any two communicating devices, the channel impulse response can be calculated as the sum of the received signal components, according to:

$$h(\tau, t) = \sum_{i=1}^{L} \{ r_i . e^{j\theta_i} . e^{-\alpha l_i} . \delta\left(t - \tau_i\right) \} \quad (1)$$

where $re^{j\theta_i}$ is the complex reflection factor of path i, $e^{-\alpha l_i}$ is the propagation loss factor, which depends on the path's length l_i and the propagation constant $\gamma = \alpha + j\beta$, and $\tau = l_i/v$ is the path's delay, based on the group velocity of propagation $v = \omega/\beta$. The reflection factor is the product of all reflection/transmission coefficients of path i.

The indoor power grid can be described using the following parameters: termination impedances, line section types and lengths. For each type of cable, the characteristic impedance Z_0 and the propagation factor γ of the line can be measured [5] or calculated through transmission line theory equations. Network description matrices comprise information such as the number of termination points and nodes (where branches begin), their connectivity, line section lengths and cable characteristics (Z_0 and γ).

Consider a network with m termination points, T_i, and n nodes, C_j, which is described by the matrices $\mathbf{TC}$[mxn], $\mathbf{CC}$[nxn], $\mathbf{LT}$[mxn] and $\mathbf{LC}$[nxn]. The matrix $\mathbf{TC}$[mxn] describes the interconnections between termination points and nodes. Each line corresponds to a termination point T_i and each column to a node C_j. Element $TC(i,j)$ is equal to one when a connection between T_i and C_j exists, or zero otherwise. The matrix $\mathbf{CC}$[nxn] describes the interconnections between the internal network nodes. Each line and each column corresponds to a certain node C_i. Non-zero elements $CC(i,j)$ imply a connection between the corresponding nodes, whereas zero elements imply no direct connection. Since nodes cannot be connected to themselves and $C_iC_j = C_jC_i$, the matrix has zero diagonal and exhibits symmetry around it. The **LT**[mxn] matrix is generated by replacing the non-zero elements of $\mathbf{TC}$ matrix with the corresponding lengths $l_{T_iC_j}$. The $\mathbf{LC}$[nxn] matrix is generated by replacing the non-zero elements of $\mathbf{CC}$ matrix with the corresponding lengths $l_{C_iC_j}$. The $\mathbf{LC}$ matrix is also symmetric around its diagonal.

Using the above network description matrices and the cable's transmission properties, any indoor power line network can be described properly. The algorithm that analytically calculates the response of every point-to-point channel uses this description to realize the following fundamental processing steps:

1. Computation of the reflection and transmission coefficients at each network discontinuity, namely termination points and nodes.

2. Calculation of the network's input impedances as seen from every termination and node.

3. Estimation of the factors that comprise each of the multipath components received on the particular channel.

A detailed description of the calculation algorithms involved in this modelling process has been presented in [3].

4. Channel Training Procedures

The *pDSL* Gateway is a device of adequate processing power in order to perform network modelling and demanding signal processing algorithms for sophisticated channel training and bandwidth allocation. The Gateway uses the network's description matrices for determining the network topology and initiates a procedure, during which it gathers the necessary impedance information from each smart termination device through the *Control channel*. Therefore, we consider that the Gateway is capable of calculating each link's *expected* response. Each time a variation on any load impedance occurs, the Gateway is properly informed in order to recalculate the channels' *expected* response. In the following paragraphs, we describe the processing involved in *initial* and *inbound* channel training and explain how the channel response predictions can be utilized.

4.1. Initial Channel Training

The *initial* channel training procedure is initiated by the Gateway when the network is activated. During this procedure, the Gateway broadcasts a broadband training sequence towards all *pDSL* devices in the network. Each device uses the received sequence and a replica of the originally broadcasted sequence to produce an estimate of the coefficients that comprise the particular link's response in the entire frequency band of interest. Each device also produces an estimate of the SNR level of its specific link. These estimates are transferred back to the Gateway, through the Control channel. Therefore, due to the assumed 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 use in *xDSL* links.

Elaborating on the above, we assume a known training sequence, x_k, which is periodic with period N equal to or greater than the number of coefficients (p_k) of the particular channel's response. Assuming X_n and P_n as the corresponding variables in the frequency domain (n is the frequency index), the channel's output Y_n is given by:

$$Y_n = X_n \cdot P_n + U_n \tag{2}$$

where u_k is an additive noise signal assumed to be uncorrelated with x_k, and U_n is its frequency domain equivalent. The estimation process constructs an estimate of the channel's response, P_n, by minimizing the mean square of the error function E_n:

$$E_n = Y_n - X_n \cdot \widehat{P}_n \tag{3}$$

It is shown in [6] that by averaging over L channel output data blocks of length N, and dividing the result with the input data, we are capable of successfully identifying the channel's response by minimizing the estimation error $(\Delta_n = P_n - \widehat{P}_n)$ as L increases. Therefore, as presented in Fig.2, the coefficients' estimates are calculated according to:

$$P_n = \frac{1}{L}\sum_{i=1}^{L}\{\frac{Y_{i,n}}{X_{i,n}}\} \tag{4}$$

The training process also estimates the SNR level on the particular channel by calculating the following:

$$SNR_n = \frac{R_{xx,n}\,|\widehat{P}_n|^2}{\widehat{\sigma}_n^2} \tag{5}$$

where $R_{xx,n}$ is the Fourier transform of the autocorrelation function of the input, expressing its power spectrum, and $\widehat{\sigma}_n^2$ is the estimated variance of L samples of noise on the nth

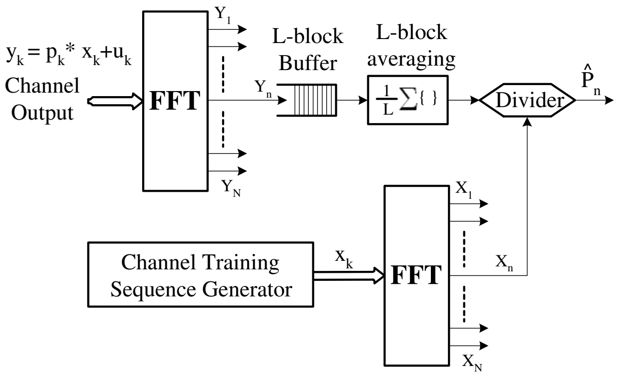

Figure 2: Functional diagram of the channel estimation process.

subchannel, according to:

$$\widehat{\sigma}_n^2 = \frac{1}{L}\sum_{i=1}^{L}\{|E_{i,n}|^2\} \tag{6}$$

Using the estimated coefficients for each link, the Gateway has to compare the *expected* and the *estimated* channel responses and to create an adjustment table that is used during the *inbound* channel training. The SNR estimates along with the calculated response coefficients are used to determine which subchannels are suitable for data transmission through a number of criteria that form the bandwidth allocation procedure.

4.2. Inbound Channel Training

Once each *pDSL* device is informed of its allocated bandwidth through the *Control channel* and various transmission parameters are set accordingly, the device may begin transmission on it *Communications channel*. In regular time intervals, the Gateway initiates a process of *inbound* training to assess possible changes in attenuation or SNR levels on the subchannels of each link. Since, the training sequences have to be injected among user data, only the allocated subchannels are available for training on each specific link. Using a possible implementation that employs a round-robin scheme, controlled by the Gateway, each device transmits band-limited training sequences (corresponding to a single subchannel) towards the Gateway, until every allocated subchannel is covered. Using the received sequences, the Gateway repeats the estimation process described in the previous subsection to estimate the current response coefficients of each link and its SNR in the particular allocated subchannels. Based on predefined criteria, the Gateway decides whether the changes in the estimated links' responses require bandwidth re-allocation. If such a case occurs, the Gateway appropriately modifies the *expected* response using the previously calculated adjustment tables and produces an estimate of the link's response on the entire frequency band of interest. This procedure is performed in order to fill in for the lack of information on the subchannels that were not estimated in the current training interval. These new estimates of each link's transmission characteristics are used by the bandwidth allocation procedure.

5. Bandwidth Allocation Procedure

Bandwidth allocation is based on a number of criteria that define which subchannels are considered suitable for data transmission on each link. Two fundamental parameters should be calculated, using the estimated links' responses, before the allocation process can be performed:

- The minimum subchannel bandwidth (BW_{min}) is defined by the requirements of the networking application with respect to the minimum bandwidth needed to employ the selected transmission techniques.

- The maximum subchannel bandwidth (BW_{max}) is defined so that the link's response exhibits constant characteristics inside the frequency range of each subchannel, based on a predefined deviation threshold.

Typical cases of the criteria used to allocate suitable subchannels to each communications link could include the following:

1. A subchannel is considered eligible for transmission on a certain link, if its frequency response does not deviate more than a predetermined value.

2. The allocation scenario should remain as invariant as possible, while variations in the network's loading occur.

3. Allocation of consecutive subchannels in the same link is preferred.

4. Bandwidth allocation should be performed with respect to the particular link's requirements for bandwidth and specific data transmission rates.

Therefore, we educe that if $(BW_{min}) > (BW_{max})$, subchannel bandwidth is set to (BW_{min}) and all subchannels that do not exhibit 'constant' behavior are excluded as unsuitable. In the opposite case, subchannel bandwidth can be set to as high as (BW_{max}). All the above are illustrated in the example presented in the next section.

6. Bandwidth allocation on an example network

In order to demonstrate the potential of the bandwidth allocation procedure, we present its application on the small scale power line example network, shown in Fig.3. The cable considered for the wiring consists of three stranded wires of $1.5mm^2$ cross section, whose transmission parameters were measured in [5]. We consider that the *pDSL* Gateway is connected to T_1 and three *pDSL* devices are located at points T_2, T_4 and T_6. All *pDSL* equipment exhibit impedances of 100 Ohms and the remaining termination impedances (at T_3, T_5 and T_7) vary according to three loading scenarios, described by the following $\mathbf{ZT}$ matrices:

$$\mathbf{ZT_{l.c.1}} = [\ 100 \quad 100 \quad 10^8 \quad 100 \quad 10^8 \quad 100 \quad 10^8\ ]$$

$$\mathbf{ZT_{l.c.2}} = [\ 100 \quad 100 \quad 100 \quad 100 \quad 100 \quad 100 \quad 100\ ]$$

$$\mathbf{ZT_{l.c.3}} = [\ 100 \quad 100 \quad 50 \quad 100 \quad 75 \quad 100 \quad 20\ ]$$

where open circuits are considered as 10^8 Ohms.

In Fig.4 the variations on the $T_1 - T_4$ link are demonstrated as the network's loading changes. The subchannel bandwidth is considered to be 78.125 kHz, which does not necessarily correspond to a practical application, but was selected for the clarity of the demonstrated results. The unsuitable subchannels on the $T_1 - T_4$ link, demonstrated in the sub-figure marked as (a), were assessed using the second criterion, which requires constant allocation, regardless of the loading variations. These subchannels display a variation in their response characteristics which exceeds a predefined threshold of 6 dBs. In the sub-figure marked as (b), we present the calculated unsuitable subchannels for the case of the first loading scenario, which exhibit a variation in the response of each subchannel exceeding a threshold of 0.5 dB and therefore fail to abide by the first criterion regarding subchannel response constancy. Using the above results and combining them with the respective results on other links, effective bandwidth allocation can be performed.

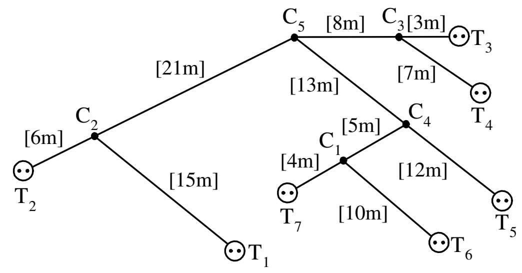

Figure 3: Example network's topology.

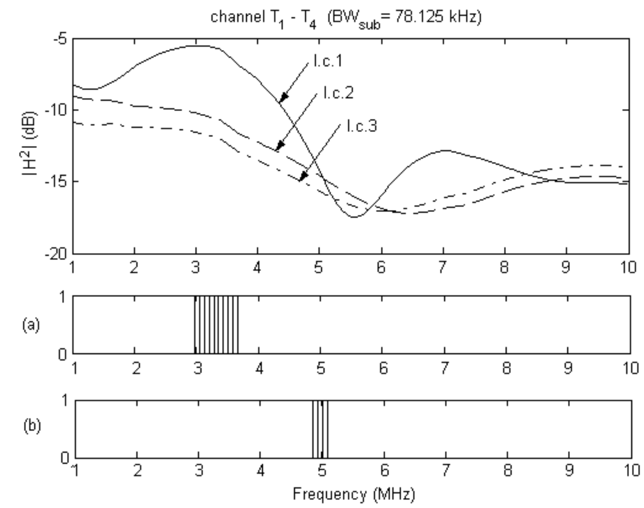

Figure 4: Unsuitable subchannels on the $T_1 - T_4$ link.

7. Conclusions

The *pDSL* networking concept aims at high speed broadband communications over power line networks, based on a centralized approach for establishing data transmission links between a Gateway and a number of *pDSL* devices. This paper proposed various procedures and techniques that facilitate proper bandwidth allocation to the *pDSL* links.

Acknowledgments

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