DSM PERFORMANCE ON PRACTICAL DSL SYSTEMS BASED ON ESTIMATED CROSSTALK CHANNEL INFORMATION

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ABSTRACT

This paper investigates practical aspects associated to the adoption of dynamic spectrum management (DSM) in existing digital subscriber lines (DSL) access networks. A standard-compliant crosstalk estimation method is utilized in order to retrieve the crosstalk channel information needed by, *e.g.*, a DSM level 2 system. A DSM application framework was developed to help testing DSM in practice and investigate the foreseen gap between the DSM results obtained with simulations and practical achievable data rates. This framework is based on "off-the-shelf" DSL equipments and is responsible for coordinating and monitoring the test procedures via DSL standardized protocols. The work also discusses the discrepancies identified in laboratory experiments, associated to different sources of mismatch between simulations and practice.

1. INTRODUCTION

The performance of broadband communication on digital subscriber lines (DSL) is severely limited by crosstalk interference from adjacent copper twisted-pair lines in the access network. The crosstalk between neighboring lines is therefore considered as one of the most dominant performance impairment [1, 2]. For this reason, dynamic spectrum management (DSM) has been proposed as a multi-user resource management approach for crosstalk mitigation. The DSM solutions optimize the transmission by coordinating the transmit spectra to the slowly time-varying crosstalk channel conditions [3–5].

The DSM rate maximization was explored in *e.g.* [6–11], whereas the usage of DSM to minimize the power consumption recently regained attention in *e.g.* [12–14]. Most of the proposed DSM algorithms assume that the crosstalk channel information is available (an exception is *Iterative Waterfilling* [6]). In a laboratory, where both ends of a line (cable) are accessible at the same location, the crosstalk channel information can be measured using, for example, a network analyzer. However, in a DSL access network, the ends of a line can be kilometers away. Thus, it is impractical and costly for a DSL operator to dispatch personnel to conduct these measurements for all the crosstalk channels in the network.

The application of DSM in practice has been considered in *e.g.* [15–17]. One practical and standard-compliant crosstalk channel estimator is presented in [18]. Moreover, the impact of this estimator on the DSM performance is evaluated in [19]. However, only simulations of the DSM algorithms were performed in [19].

In this paper, the DSM performance evaluation is taken one step further when compared to [19], by also considering the practical limitations of the optimized transmission spectra. By means of a developed DSM application framework, the practical DSM performance achieved with commercially available DSL modems on a cable binder is evaluated.

The paper is organized as follows. Section 2 introduces the system model considered, defines notation and briefly describes the general bit loading formulation of a general DSM algorithm. The crosstalk channel estimation method applied during the laboratory experiments is briefly described in Section 3. The Section 4 is devoted to the description of the DSM application framework, which is implemented in order to obtain and evaluate the DSM performance for the chosen study case. Dedicated to present the practical results, Section 5 provides a comparison of the practical DSM performance, applying measured and estimated crosstalk channel information in the proposed DSM application framework. Finally, a summary and conclusions are provided in Section 6.

2. SYSTEM MODEL

The DSM optimization considered in this work can be modeled as a copper access binder consisting of N users (*i.e.* N lines) equipped with DSL transceivers. Each transceiver employs discrete multi-tone modulation (DMT) and operates over a twisted-pair line with K parallel subchannels (tones), which are free of intersymbol interference [1]. By assuming only frequency division duplex (FDD) DMT transmission, where upstream and downstream frequency bands are non-overlapping, only the far-end crosstalk (FEXT) is considered. The weak near-end crosstalk (NEXT) influence is neglected [1] during experiments.

The problem of bit-allocation, also known as bit loading, can be expressed as follows for tone k and for user n

$$b_n^k = \log_2\left[1+\frac{s_n^k\left|h_{n,n}^k\right|^2}{\Gamma\left(\sigma_n^k+\sum_{m\neq n}s_m^k\left|h_{n,m}^k\right|^2\right)}\right], \quad (1)$$

where

- b_n^k is the number of allocated bits on tone k for user n.
- s_n^k denotes the power allocated for user n at tone k;
- σ_n^k represents the background noise power on tone k at the receiver of user n.
- Γ denotes the signal-to-noise ratio *gap*, which is a function of the desired bit error rate (BER), typically 10^{-7}. The *gap* is an indicator of how closely the bit rate comes to the theoretical channel capacity [1].
- $|h_{n,n}^k|^2$ denotes the square-magnitude of the direct channel gain for user n at tone k.
- $|h_{n,m}^k|^2$ denotes the square-magnitude of the far-end crosstalk channel[1] from transmitter m to receiver n at tone k.

[1] In this work, the crosstalk channels are both measured with a network analyzer and estimated via *Loop Diagnostic*. For more information about the latter and its application to DSM see [18, 19].

3. CROSSTALK CHANNEL ESTIMATION

The crosstalk channel estimation method used during the laboratory tests is briefly described in this section. More detailed information about this method can be found in [18]. The estimator is based on sequential power spectrum density (PSD) measurements at the far-end side of the lines with only one near-end transmitter active per measurement sequence. By utilizing the two-port measurement procedure referred to as *Loop Diagnostic* [20], the measurements can be executed and coordinated from a network management system. Making use of a matrix notation, we can formalize the sequential estimation method as a single-input multiple-output (SIMO) system expressing the m-th sequence as follows, where only the m-th transmitter is active at a time,

$$\mathbf{y}(m) = \mathbf{x}(m)\mathbf{H}(m) + \mathbf{z}(m). \tag{2}$$

Here $\mathbf{y}(m) = [\bar{y}_1(m)\,\bar{y}_2(m)\ldots\bar{y}_N(m)]$ is the $K \times N$ matrix containing the received signals in all K subchannels and for all N receivers, and $\mathbf{H}(m) = [\bar{h}_{1,m}\,\bar{h}_{2,m}\ldots\bar{h}_{N,m}]$ denotes the $K \times N$ SIMO matrix. The known transmitted $K \times K$ signal matrix from transmitter m yields

$$\mathbf{x}(m) = \begin{pmatrix} x_m^1 & 0 & 0 & 0 \\ 0 & x_m^2 & \ddots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \cdots & \cdots & x_m^K \end{pmatrix}.$$

In (2) the added (complex) noise is denoted by the $K \times N$ matrix $\mathbf{z}(m) = [\bar{z}_1(m)\,\bar{z}_2(m)\ldots\bar{z}_N(m)]$.

The PSD-based estimate of the FEXT attenuation matrix for sequence $m = 1, 2, \ldots, N$ can be formulated as, [18],

$$\widetilde{|\mathbf{H}|^{\mathbf{2}}}(m) \quad = \quad \mathbf{P}_x(m)^{-1}\Big(\mathbf{P}_y(m) - \mathbf{P}_z(m_0)\Big), \tag{3}$$

where $\mathbf{P}_y(m)$, $\mathbf{P}_x(m)$, and $\mathbf{P}_z(m)$ are the corresponding PSD matrices obtained by taking the absolute-squared value of the elements of $\mathbf{y}(m)$, $\mathbf{x}(m)$, and $\mathbf{z}(m)$, respectively. In (3), $\mathbf{P}_z(m_0)$ denotes the background noise measured with no active transmitters prior to the start of sequence m. From (2)–(3) it follows that the estimate $\widetilde{|\mathbf{H}|^{\mathbf{2}}}(m)$ becomes unbiased if $\mathbf{P}_z(m) \approx \mathbf{P}_z(m_0)$. This assumption of (temporary) stationarity is reasonable from at least two aspects: in the SIMO case no other active disturber is present, and the twisted-pair channel is non time-varying. A more detailed description of the estimator and its performance is available in [18]. It should be emphasized that since the FEXT channels do not significantly change over time, the (intrusive) FEXT channel estimation is only seldom conducted in practice.

4. DSM APPLICATION FRAMEWORK

This section is devoted to the description of a DSM application framework, which is implemented in order to obtain and evaluate the DSM performance results. The framework employs unmodified commercial equipment where the crosstalk channel information is estimated according to the method described in previous section.

Most DSM algorithms do not cope with the physical layer implementation, or practical limitations imposed by existing hardware. For example, commercially available DSL modems cannot arbitrarily change their PSDs during showtime state.

Although the PSDs cannot be altered in showtime state, there is a standardized set of parameters called *transmitter spectrum shaping* (tss_i), that allow PSD shaping to be performed on ADSL2 and ADSL2+ [20, 21]. Using these parameters, it is possible to define a limiting PSD mask, which the modems cannot exceed while transmitting. Unfortunately, the limiting PSD masks can only be updated when the line of interest is disabled (C-IDLE state [20]).

A flowchart of the developed DSM framework is illustrated in Fig. 1. The framework execution is as follows:

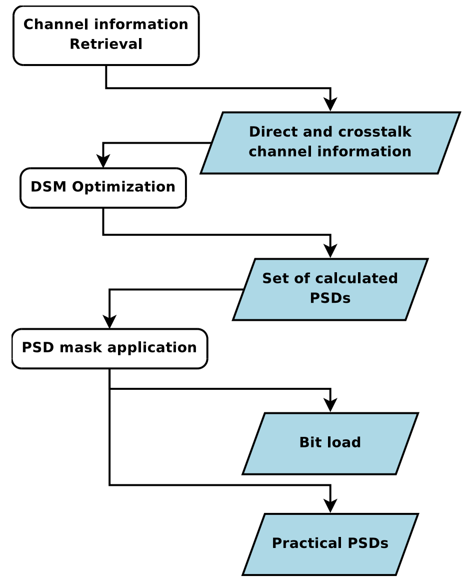

Figure 1: Optimization flowchart: main steps for spectrum optimization and their respective intermediate outcomes (in shaded boxes).

- First, the direct and crosstalk channel information is estimated and retrieved with the method described in the previous section. Alternatively the crosstalk transfer function measurements may be performed using a network analyzer.
- A DSM algorithm is used to calculate a set of optimized PSDs based on the obtained quantities in the first step.
- The PSDs resulting from DSM optimization are modified [22] to generate a set of valid control parameters (tss_i values) to be applied at the Central Office (CO) modem, *i.e.* at the DSL access multiplexer (DSLAM).
- Finally, after PSD mask application, the framework polls for feedback from the network (bit rates, bit load, output power, among others), in order to assess the performance.

There are two major sources of discrepancies in the procedure. First, the estimated crosstalk channel data is affected by the estimation method and hardware used, *i.e.*, the implementation of the Loop Diagnostic protocol may vary depending on the hardware vendor. Secondly, there may be an error in the mapping between the calculated PSDs and the ones that can be reproduced in hardware, since the transmit PSDs are only required not to exceed the imposed limiting mask (effectively, the transmit PSD levels can be lower than the mask).

The next section details how this framework is used to evaluate the performance of DSM, based on both measured and estimated crosstalk channel information.

5. EVALUATION AND RESULTS

This section presents a comparison of the practical DSM performance, applying measured estimated crosstalk channel information in the DSM application framework. It is important to notice that the estimated crosstalk channels are obtained using the estimation method described in Section 3.

The main objective here is to investigate whether the estimated channel information usage degrades the performance of DSM on a practical DSL deployment, when compared to measurement-based channel information. As mentioned, accurate channel information provided by specialized measurement equipments such as a network analyzer will not be available in practice.

The comparison is carried out by the evaluation of different *rate* *regions*[2] achieved by the same DSM algorithm, taking as input the two forementioned channel information sources.

The experimental results are obtained using the DSM application framework described in previous section with the following setup:

- The measured channel information is provided by an Agilent 4395*A* network analyzer.
- Standard telephone cables as used in field deployment (24 AWG).
- Unmodified Ericsson DSLAMs and commercial CPEs (costumer premises equipment) from different vendors are used.
- Iterative spectrum balancing (ISB) [7,23] is the DSM algorithm in the optimization.

For the sake of illustration, the scenario of Fig. 2 with two DSL lines is used. The extension for more lines is straightforward and the essence of the conclusions are comparable to the presented two-users case.

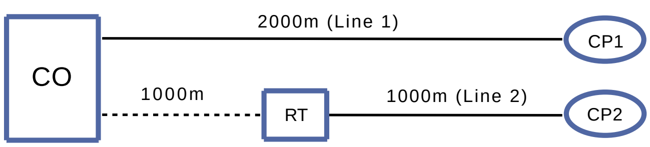

Figure 2: Near-far topology with one remote terminal (RT).

The results are obtained based on the procedure described in Fig. 1. The outcomes of the process, shown in the blue shaded boxes will be the subject of the present analysis.

5.1 Direct and crosstalk transfer functions

The first step in order to perform DSM optimization using the framework is to obtain the channel information. A set of measurements, for both direct and crosstalk transfer functions are carried out. These data, provided by a network analyzer, are considered and used in this work as the basis for the DSM performance comparison.

Next, the estimation process is executed, to retrieve estimated crosstalk channel information. This procedure is performed via software, without human intervention. The direct transfer functions from the estimated case are provided by the Loop Diagnostic protocol.

Fig. 3 depicts a comparison of the resulting crosstalk transfer functions provided by both sources: network analyzer and estimation. Note that the raw estimation (green curve in the figure) results in a rather noisy transfer function. For this reason, it was decided to smooth the signal using a moving average filter with a window size of 21 samples. This smoothed transfer function, referred as “treated” on the figure legend (red curve), is used as input for the DSM optimization.

The mean deviation between the estimation (treated) and the reference measurement is approximately 3 dB, a value that resembles the results presented in [18].

5.2 Practical rate region

The DSM optimization is carried out with ISB for both sets of transfer functions, using different priority settings, in order to generate two rate regions.

Next, the PSDs calculated by ISB for each point in the rate region are translated into tss_i values and configured in the DSLAM. After both CPEs are in showtime state, the attainable net data rate, (*ATTNDR*) [20] is retrieved for each modem. The collected data is used to plot a named “practical” rate region. Typically, the rate

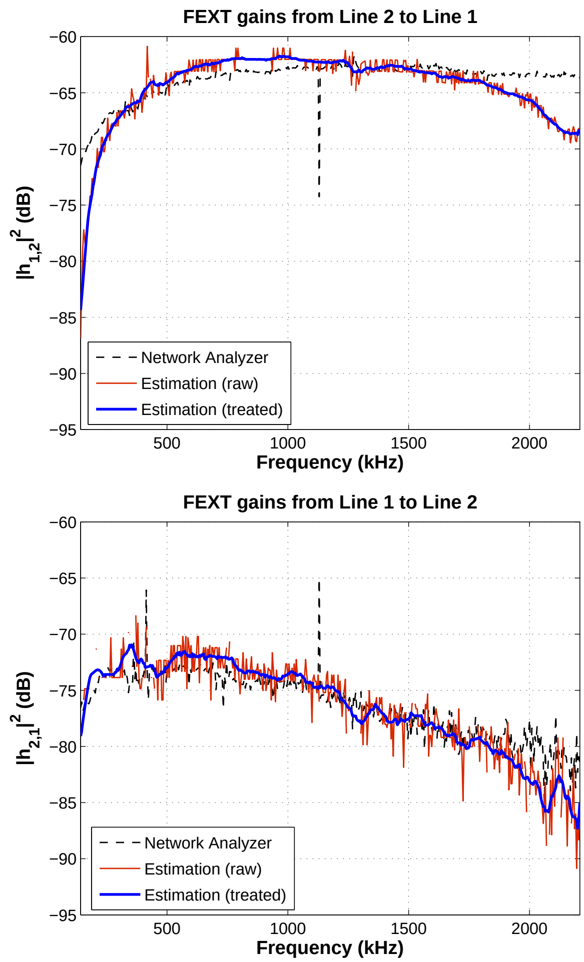

Figure 3: Comparison between measured and estimated transfer function. The mean error value is approximately 3 dB. The error tends to be higher on lower and higher frequencies, because the estimator includes extra attenuation caused by the low-pass and high-pass filters present in the DSL transceivers.

regions presented in the literature are obtained by simulations. In contrast, this work presents regions constructed with data acquired from DSL hardware.

Fig. 4 depicts the points[3] of the practical rate region that express the DSM performance based on measured (accurate) and estimated channel information. The relatively small distances between both rate regions indicate that the impact of using crosstalk channel information provided by the estimator described in Section 3 is not significant.

5.3 PSDs and bit load

So far, the rate regions in Fig. 4 have shown that the performance of DSM is not affected by the adoption of estimated channel information. Now, in order to give a better (fine grained) picture of their differences, bit load and PSD levels are compared as follows. To make the comparison fair, the point with largest aggregated rate $R_{Line1}+R_{Line2}$ is selected from each region.

[2]The rate region is the set of bit rates that can be achieved in a DSL network. In the practical context of this paper, the rate region represents the combination of bit rates obtained from hardware using PSD masks calculated by DSM methods.

[3]Note that each point in the rate region corresponds to a set of different PSDs.

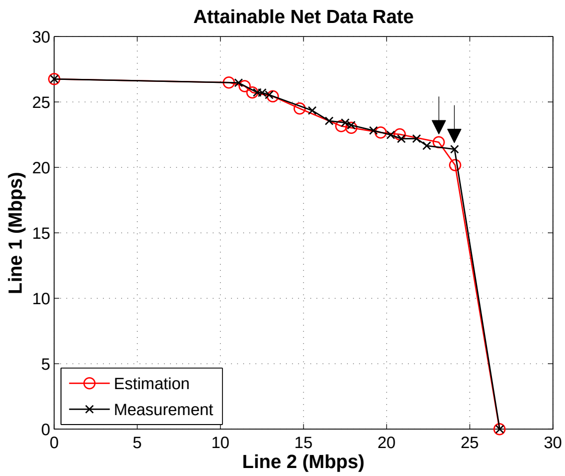

Figure 4: Practical DSM level 2 performance when using measured (accurate) and estimated channel information. The minimal distance between the rate regions indicates a small impact of the error introduced by the estimated channels in the system. The arrows indicate the points with largest aggregated rate in each region.

Fig. 5 shows the calculated PSD masks imposed to the DSLAM by the DSM framework. The upper plot contains the resulting PSDs for *Line 1*, the longer line. Both PSDs were quite similar. The lower plot contains the PSDs for the shorter line (*Line 2*). Here it is possible to visualize the more accentuated difference on lower frequencies.

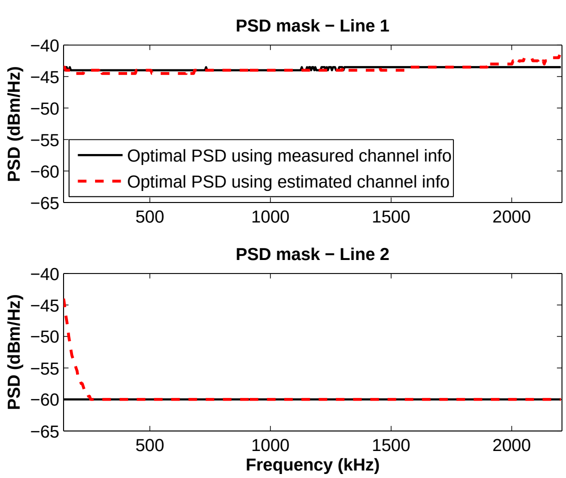

Figure 5: Calculated PSD mask comparison. Except for the lower frequencies on *Line 2*, both PSDs are quite similar.

Fig. 6 depicts measurements of the real PSDs transmitted by the DSL transceivers while in showtime. Even though a difference is observed in the calculated PSDs for *Line 2*, the PSD measurement results were quite similar. As stated before, whenever a limiting mask is imposed, it is not guaranteed that it will be reproduced exactly on all tones.

Fig. 7 and Fig. 8 compare the bit load on each line, based on information retrieved from the DSLAM. The mean absolute error for both lines is close to zero.

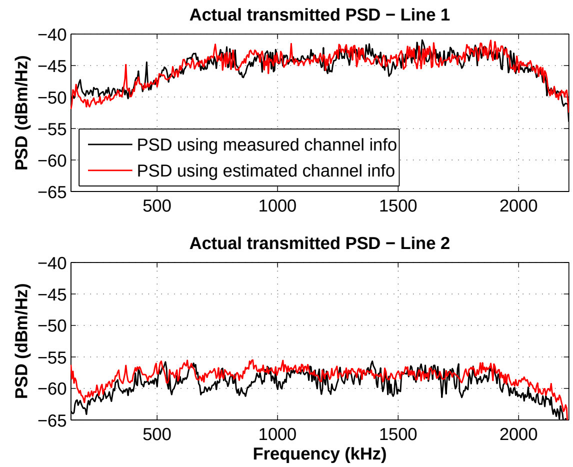

Figure 6: Measured PSD comparison, for DSM solutions based on measured and estimated channel information.

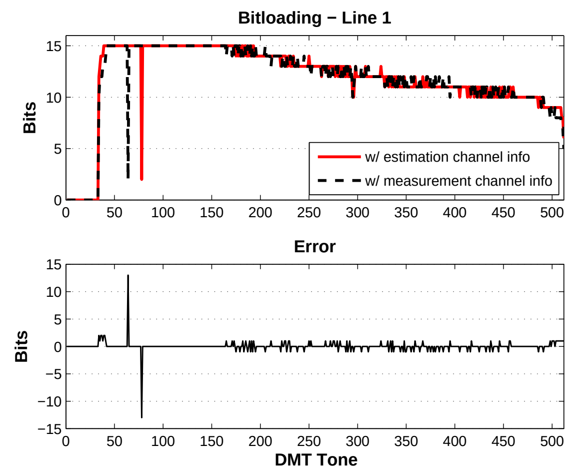

Figure 7: Bit load comparison for *Line 1*. The average error is 0.0293. The large error values around tone 70 are due to the *downstream pilot tone* [20].

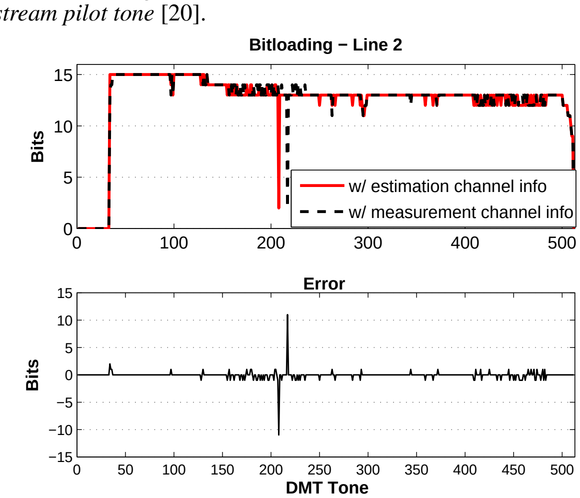

Figure 8: Bit load comparison for *Line 2*. The average error is −0.0430. The large error values around tone 210 are due to *downstream pilot tone* [20].

6. SUMMARY AND CONCLUSIONS

The results presented here suggest that the usage of the estimated crosstalk channel information poses a small impact to the performance of DSM, when considering its application on unmodified commercial DSL modems. Although there is a noticeable difference in the achieved bit rates, this error is in the order of tens of Kbps, which on practice should not matter from a DSL operator point of view.

A successful DSM application framework was developed, and its integration with the crosstalk channel estimator described here makes it independent from human intervention.

The claims made in [18] about the accuracy of the estimator were verified by experimental results presented in this work. In addition to that, the comparison between measured versus estimated channel information for DSM, proposed in [19], was extended with practical results provided by unmodified commercial DSL hardware.

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