CROSSTALK CANCELLATION IN VDSL SYSTEMS

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ABSTRACT

The existing copper line telephone network is used successfully for very high speed digital subscriber line (VDSL) transmission systems. There is a major limitation in the resulting data rate by far-end crosstalk (FEXT), which can be mitigated by zero-forcing crosstalk cancellation procedures in upstream and precoding procedures in downstream. In order to obtain the channel state information (CSI) which crosstalk cancellation and precoding rely on, this paper presents a pilot-based channel estimation technique. Additionally a channel adaptation procedure is proposed, applying orthogonal pilot sequences. To avoid any pilot overhead, the pilots are continuously transmitted during the sync frames. In downstream, the precoder coefficient update is based on the feedback of the normalized error sample. The presented techniques lead to a higher efficiency and increased performance of VDSL systems. Simulations show that 95% of the data rate obtained with perfect CSI can be achieved in upstream and downstream.

1. INTRODUCTION

Modern DSL communication systems such as VDSL2 use the frequency band up to 30 MHz on each copper cable to offer high data rates and to provide high-speed internet access to all users. Additionally the telephone copper line network infrastructure has been changed in the last years to provide shorter line lengths to the VDSL2 customer. However, the major performance limitation in these systems is still given by crosstalk interferences between adjacent cables inside a cable binder. The typical crosstalk level can be up to 20 dB larger than the background noise. Because of that it is very reasonable and highly effective to eliminate the crosstalk interferences as proposed in [1, 2, 3].

The increased system performance achieved by crosstalk cancellation techniques can only be achieved with full CSI knowledge and strongly depends on the CSI accuracy for both upstream and downstream. Therefore the channel needs to be measured initially with adequate precision and accuracy before any transmission including crosstalk cancellation can be done.

The DSL channel is generally stable, nevertheless it can vary slowly, for example due to temperature or humidity changes. Although these changes are relatively small and smooth, without any adaptation of the coefficients they will lead to an additional inaccuracy in the CSI knowledge and performance degradation. Accordingly, updating the canceller coefficients is needed to deploy the full potential of the DSL system.

A straightforward way to estimate and update the CSI is to periodically transmit a set of pilots as shown in [4]. These classical pilot-based estimation techniques provide good performance but have the disadvantage of utilizing parts of the useful bandwidth for pilot transmission. In addition there is a large signaling overhead in downstream estimation and adaptation given by the estimates which need to be sent back to the Central Office (CO). In [5, 6], LMS-based channel estimation and adaptation algorithms are applied in order to decrease computational complexity of the adaptive precoder and canceller as well as to reduce overhead in downstream by feeding back the error samples. Further overhead reduction in downstream is considered in [7, 8] where only the sign of the error samples is fed back.

This contribution introduces channel estimation and adaptation procedures which combine the good performance of the pilot-based estimation techniques with low pilot and signaling overhead. An estimation algorithm for channel state information is proposed which is based on orthogonal pilot sequences (see chapter 4.1). For channel adaptation it is further suggested that pilot signals are additionally transmitted during the sync frame which avoids any overhead in the DSL system. In the upstream, a receiver-based procedure is presented. In the downstream, CSI is lacking on the transmitter side and therefore a transmitter-based procedure with error feedback is applied (see chapter 4.2).

2. SYSTEM OUTLINE

Like for most DSL systems, a VDSL2 transmission typically exists between a CO or Digital Access Multiplexer (DSLAM) and different Customer Premises Equipment (CPE). The copper cables of the different users are all bundled in a cable binder. Since the different cables are not ideally isolated strong crosstalk interferences will occur. This kind of transmission scenario is shown schematically in Figure 1 and is also considered here.

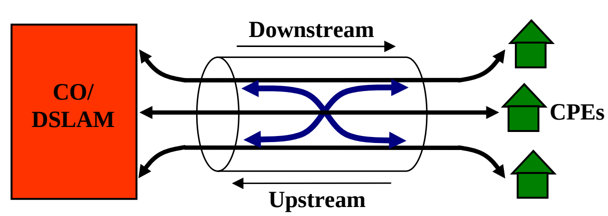

Figure 1: Considered transmission scenario

In the VDSL2 system the DMT Technique is applied to a frequency selective channel. By partitioning the total bandwidth into a large number of subchannels, narrowband transmission is enabled on each so called tone. Each tone is modulated individually and independently and all subchannel signals are transmitted in a superimposed form. When the symbol duration is extended additionally by a cyclic prefix of sufficient length, Intersymbol Interferences (ISI) can be completely avoided. Inter Carrier Interferences do not occur due to synchronous transmission. Adequate symbol length and perfect synchronization are assumed here.

Hence, for a single tone and M users (i.e. M cables) in a cable binder the received signal vector $\mathbf{y}$ is given by

$$\mathbf{y} = \mathbf{H} \cdot \mathbf{x} + \mathbf{n}$$

where $\mathbf{x}$ is the transmit vector and $\mathbf{n}$ is the noise contribution on the different lines, which is assumed to be white. All vectors are of length M. Matrix

$$\mathbf{H} = \begin{pmatrix} H_{11} & H_{12} & \cdots & H_{1M} \\ H_{21} & H_{22} & \cdots & H_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ H_{M1} & H_{M2} & \cdots & H_{MM} \end{pmatrix}$$

contains the direct channel and the crosstalk coefficients and therefore is of size $M \times M$. The diagonal elements of matrix $\mathbf{H}$ correspond to the direct channel coefficients of the different CPEs. The off-diagonal elements correspond to the crosstalk interference contributions and are called crosstalk coefficients.

3. CROSSTALK CANCELLATION TECHNIQUES

In order to reduce the severe crosstalk interferences coming from all adjacent lines, several crosstalk cancellation techniques have been invented. For both upstream and downstream there are various ways to decrease the crosstalk interference power. In this paper we focus on zero-forcing crosstalk cancellation in upstream and decomposition-based zero-forcing precoding in downstream.

3.1 Upstream

In the upstream case, data is transmitted from the different users to the CO, inducing collocation of the receivers. Therefore zero-forcing crosstalk cancellation can be performed on the receiver side. The transmission block diagram including cancellation is shown in Figure 2.

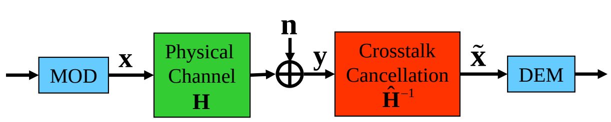

Figure 2: Upstream transmission block diagram

As already mentioned, there are various ways to remove the interferences produced by cable coupling. In zero-forcing crosstalk cancellation the received signal is simply equalized with the inverse of the estimated channel matrix $\hat{\mathbf{H}}$, thus producing an estimated received signal $\tilde{\mathbf{x}}$. It is given by

$$\begin{aligned} \tilde{\mathbf{x}} &= \hat{\mathbf{H}}^{-1} \cdot \mathbf{y} \\ &= \hat{\mathbf{H}}^{-1} \cdot \mathbf{H} \cdot \mathbf{x} + \tilde{\mathbf{n}} \end{aligned} \qquad (1)$$

From equation 1 it can be seen that the correctness of $\tilde{\mathbf{x}}$ strongly depends on the accuracy of the CSI.

3.2 Downstream

In downstream transmission, the different receivers have various locations and receiver coordination is not possible. On the contrary, the transmitters are collocated in the CO and for that reason decomposition-based zero-forcing precoding is applied. The transmission block diagram is shown in Figure 3.

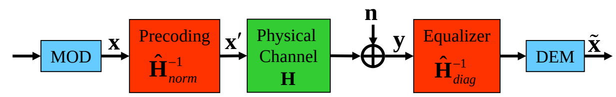

Figure 3: Downstream transmission block diagram with precoding

In order to remove the crosstalk influence of all surrounding cables, the transmit signals are pre-equalized by the inverse of the normalized estimated channel matrix $\hat{\mathbf{H}}_{\mathbf{norm}}$. It is given by

$$\hat{\mathbf{H}}_{\mathbf{norm}} = \hat{\mathbf{H}}_{\mathbf{diag}}^{-1} \cdot \hat{\mathbf{H}}$$

where $\hat{\mathbf{H}}_{\mathbf{diag}} = diag\{H_{11}, H_{22}, \cdots, H_{MM}\}$ represents a diagonal matrix containing the direct channel transfer factors. On the receiver side only direct channel equalization is done in the individual receivers producing an estimated received signal $\tilde{\mathbf{x}}$ described by

$$\begin{aligned} \tilde{\mathbf{x}} &= \hat{\mathbf{H}}_{\mathbf{diag}}^{-1} \cdot \mathbf{y} \\ &= \hat{\mathbf{H}}_{\mathbf{diag}}^{-1} \cdot \mathbf{H} \cdot \hat{\mathbf{H}}_{\mathbf{norm}}^{-1} \cdot \mathbf{x} + \tilde{\mathbf{n}} \end{aligned}$$

4. CHANNEL ESTIMATION AND ADAPTATION

Crosstalk cancellation techniques rely on CSI and on the CSI accuracy wherefore the channel has to be measured with adequate precision. In order to apply zero-forcing cancellation and precoding, the direct channel as well as all crosstalk channels have to be measured. Due to the fact that the DSL channel can vary slowly, for example due to temperature changes, the CSI knowledge in canceller and precoder also needs to be adapted to these changes.

4.1 Channel and crosstalk measurement

Pilot-based channel estimation methods offer high measurement accuracy and avoid any error propagation. There a various ways to measure the direct and the crosstalk channels of a copper cable binder. For the purpose of measurement accuracy improvement and reduction of needed time for estimation an orthogonal pilot-based estimation technique is used.

Like shown in Figure 4 a set of M orthogonal pilot sequences of length L is transmitted on the appropriate lines over time. Transmitting more than one pilot for estimation, the estimation error is reduced. Simultaneously the needed time for estimation is kept as short as possible as all lines transmit at the same time.

After reception of the complete sequence the direct and crosstalk coefficients can be calculated via correlation. In upstream and downstream each direct and crosstalk coefficient is then given by

$$\hat{H}_{ij} = \frac{\sum_{l=1}^{L} \tilde{P}_{i,l} \cdot P_{j,l}^{*}}{\sum_{l=1}^{L} \left| P_{j,l} \right|^2} \qquad (2)$$

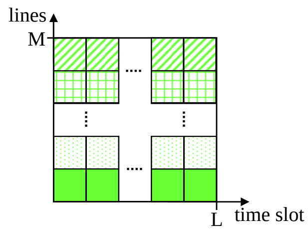

Figure 4: Transmission pattern for the initial channel estimation

where $\mathbf{P}$ is an $M \times L$ matrix given by

$$\mathbf{P} = \begin{pmatrix} P_{1,1} & \cdots & P_{1,L} \\ \vdots & \ddots & \vdots \\ P_{M,1} & \cdots & P_{M,L} \end{pmatrix}$$

containing the transmitted pilots for all M users and the sequence length L. $\tilde{\mathbf{P}}$ is a matrix containing the respective received pilots.

4.2 Channel adaptation

In order to guarantee good crosstalk cancellation performance, the DSL channel does not only need to be measured once. Although DSL channels are generally stable, they can still vary slowly, e. g. due to temperature changes. This requires a continuous estimation of all channel parameters, as crosstalk cancellation techniques for upstream and downstream are especially sensitive to inaccurate CSI knowledge.

Canceller coefficient adaptation is done continuously. Therefore when using a pilot-based technique, transmitting pilots instead of data symbols is to be avoided. During DSL transmission every 257th transmitted symbol is a sync symbol (see Figure 5). It is normally used for synchronization purposes but can be used alternatively to transmit pilot signals. To achieve a channel measurement with sufficient accuracy, pilot sequences are transmitted, where one pilot is transmitted every superframe, i. e. every $T_{Superframe} = 64.25ms$ (see Figure 5). To enable parallel transmission on all lines, orthogonal pilot sequences are again used. After reception of a complete sequence, channel coefficient estimation is done via correlation.

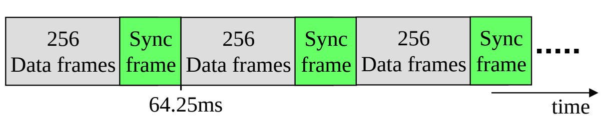

Figure 5: Pilot signal sequence

In upstream, receivers are collocated and therefore all CSI is available after estimation. Thus, canceller adaptation is done computing $\hat{\mathbf{H}}^{-1}$. Receiver collocation does not exist in downstream wherefore transmitter-sided precoding is done. Full channel state information is required on the transmitter side, implying that some information has to be fed back from the receiver to the transmitter. Due to standardization purposes, the normalized complex error is fed back given by [9]

$$E_i(t) = \tilde{P}_i(t) - P_i(t)$$

Parameter	Value
Bandwidth	17.664MHz
Number of subcarriers K	4096
Subcarrier spacing Δf	4.3125kHz
Symbol duration	0.232ms
Transmitter PSD	-60dBm/Hz
Background noise	-140dBm/Hz
Cable type	0.5mm
Number of cables	10
Cable length	500,700,900,1100m

Table 1: Simulation Parameters

It is normalized to the direct channel coefficients and given by the complex-valued deviation of the received pilot to the transmitted pilot. On the transmitter side, the updated channel matrix is given by

$$\hat{\mathbf{H}} = \hat{\mathbf{H}}_{\mathbf{diag}}^{-1} \cdot \hat{\mathbf{B}}$$

where matrix $\hat{\mathbf{B}}$ is calculated by equation 2. Using matrix decomposition and inversion the precoder is updated with

$$\hat{\mathbf{H}}_{\mathbf{norm}}^{-1} = \left(\hat{\mathbf{H}}_{\mathbf{diag}}^{-1} \cdot \hat{\mathbf{H}}_{\mathbf{diag}}^{-1} \cdot \hat{\mathbf{B}}\right)^{-1}$$

5. QUANTITATIVE ANALYSIS

For the quantitative performance analysis based on simulations, several system and channel parameters need to be defined. In this paper a cable binder with 10 cables of equal length is considered. The cable diameter is given by 0.5mm [10].The achievable data rate is calculated by the SNR-gap capacity approximation [11]. No coding gain is considered, the target symbol error rate is given by 10^{-7} and the noise margin is 6dB. All other system parameters are given in Table 1. The orthogonal sequences are realized using Walsh-Hadamard codes of length 16, 32 and 64. Considering the time-variance of the channel, a slow linear change of amplitude and phase of the crosstalk coefficients is assumed given by

$$\begin{aligned} \Delta|H_{ij}| &= 20 \cdot log\left(\frac{H_{ij}(t)}{H_{ij}(0)}\right) = 1\frac{dB}{min} \cdot t, i \neq j \\ \Delta\phi_{H_{ij}} &= \phi_{H_{ij}}(t) - \phi_{H_{ij}}(0) = 0.1\frac{rad}{min} \cdot t, i \neq j \end{aligned}$$

The direct channel coefficients remain constant. This is reasonable as inaccurate off-diagonal coefficient knowledge decreases the cancellation performance much more.

For data rate evaluation of the initial channel estimation procedure, cable lengths of $500, 700, 900$ and $1100m$ are considered. Pilot sequence lengths of $L = 16, 32$ and 64 are simulated. As obvious from Figures 6 and 8 increasing the length of the pilot sequence decreases the measurement error and increses the data rate. For both upstream and downstream using a pilot sequence of length $L = 32$ results in data rates larger than 95% of the data rate achievable with perfect CSI. Figure 7 and Figure 9 show data rate results for adapted CSI in upstream and downstream respectively. Results are presented for a cable length of $500m$ and a pilot sequence length of 32. The data rate over time with adapted CSI is compared

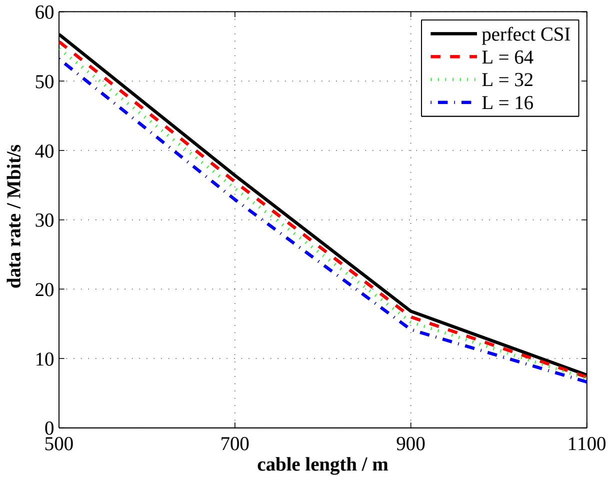

Figure 6: Upstream performance for different L

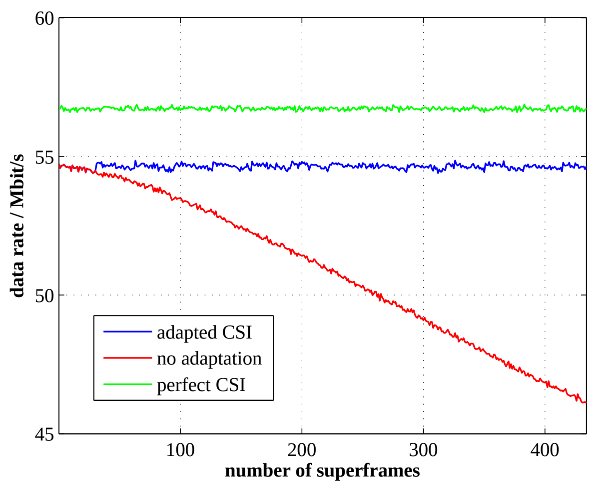

Figure 7: Data rate comparison in upstream

to the case, where perfect channel knowledge is assumed and to the no adaptation case. If canceller and precoder are not adapted, the initial channel estimation is necessary anyhow. As obvious from both figures, adapting the CSI avoids any data rate losses due to the channel changes. Whereas the performance drops drastically within the simulation time if no adaptation is performed, CSI adaptation leads to a stable data rate of at least 95% of the data rate achievable with perfect CSI. Therefore the performance is only affected by the inaccuracy of the pilot-based estimation.

6. CONCLUSION

In this paper, channel estimation and adaptation procedures are presented to measure the DSL channel with sufficient accuracy and to overcome data rate losses due to channel changes. The presented methods use orthogonal pilot sequences which are transmitted in an initial channel estimation as well as continuously during the sync frames. Due to transmission during the sync frames, any pilot overhead is

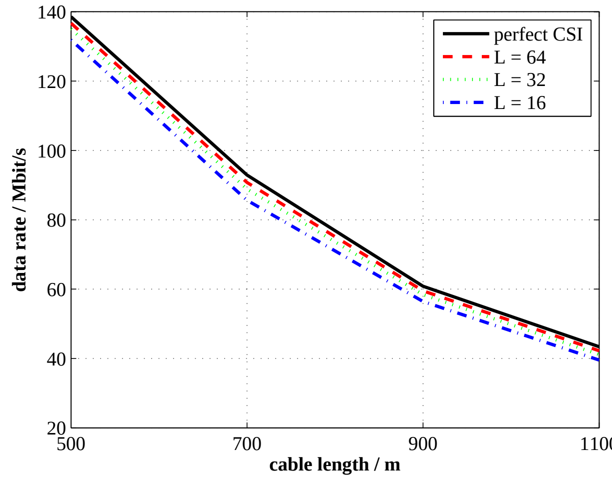

Figure 8: Downstream performance for different L

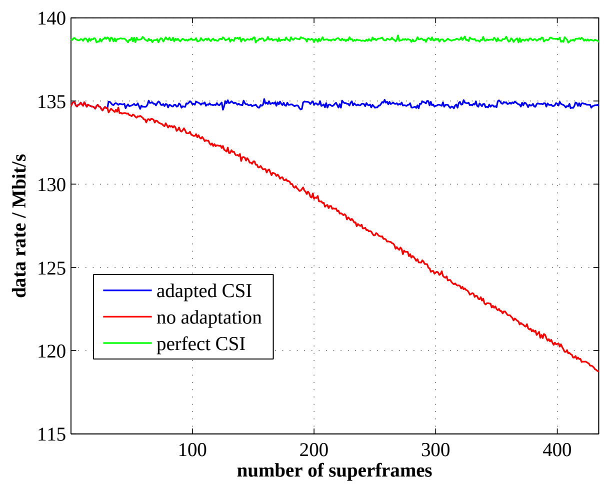

Figure 9: Data rate comparison in downstream

avoided. For the channel adaptation in upstream, correlation is applied in the receiver. In downstream, feedback of the normalized error sample is required and therefore the coefficient update is calculated on the transmitter side using correlation. It is shown that both procedures achieve high data rate increases.

In summary, the designed channel estimation and estimation adaptation procedures lead to a higher efficiency and increased performance figures in a VDSL2 system.

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