EXPLOITING THE COMMON-MODE SIGNAL IN xDSL

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ABSTRACT

Communication over the copper twisted-pair channel is performed by transmitting and receiving differential-mode (DM) signals. In this paper, we extend the conventional DM receive scheme by incorporating the common-mode (CM) signal, which can be extracted at the end of every wire pair. We assess the potential of this idea for digital subscriber line systems (xDSL) in terms of channel capacity using channel measurement data.

We show that especially those scenarios that suffer strong interference benefit most from joint DM-CM processing, since the interference at the DM port is strongly correlated with the interference at the CM port in these cases. Numerical evaluation of VDSL example scenarios shows that the capacity of the twisted-pair channel when using also the CM signal can exceed the capacity of the conventional DM channel by a factor of up to three.

1. INTRODUCTION

Communication over the copper twisted-pair (TP) cable is one of the major access technologies. Several types, characterised by different transmission rates and different loop lengths, are standardised and widely deployed as digital subscriber line (xDSL) technologies [1]. In all these schemes, transmission is carried out by sending and receiving differential-mode (DM) signals, as depicted in Fig. 1. At physical layer level, DM signals appear as a voltage difference

$$d(t) = c_1(t) - c_2(t)$$

measured between the two wires, as shown in Fig. 1. The common-mode (CM) signal, in contrast, is the arithmetic mean of the voltages $c_1(t)$ and $c_2(t)$, which are measured between each wire and earth:

$$c(t) = \frac{c_1(t) + c_2(t)}{2}.$$

The CM signal, freely available at the end of every TP, is easily extracted by a symmetric impedance network, *e.g.*, from the center tap of a transformer (cf. Fig. 1). In this paper, we treat the CM signal as an additional receive signal. This idea, also described in [2-4], is motivated by an interference mitigation technique that employs the CM signal as a reference in order to detect and cancel narrowband disturbance [5, 6].

Due to electromagnetic coupling, the CM signal consists of a component correlated with the useful signal we would like to receive and two different noise components: noise that is correlated with the noise that appears at the DM input and independent noise. We assume that these correlations are known at the receiver and investigate the capacity gain that can be achieved by joint DM-CM reception compared to the conventional DM-scheme (cf. Fig. 1). Note that we incorporate the CM signal only in the receiver. We do not transmit CM signals since this would lead to radio frequency emission and cause severe interoperability problems with existing wireless services. Compared to other interference mitigation techniques [7, 8] or multiuser schemes [9, 10], this approach has the advantage that no access to transmitted or received data of transceivers operating on adjacent lines is required.

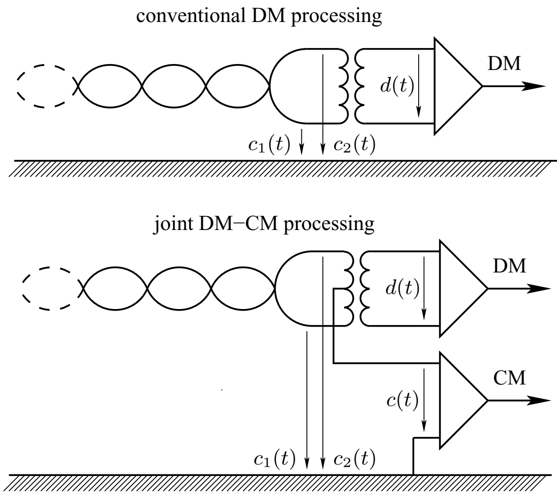

Figure 1: Conventional DM processing and joint DM-CM processing.

In Section 2, a suitable channel model based on supporting cable measurements, as well as the channel capacity calculation are introduced. Capacity gain results for VDSL transmission are presented in Section 3 followed by concluding remarks in Section 4.

2. CHANNEL MODEL AND CAPACITY

2.1 Channel Model

We consider the channel to be time-invariant during the transmission of our signal segment of interest. This is a reasonable assumption for wireline channels, which change their transmission properties only due to slowly varying parameters, *e.g.*, temperature.

The TP can be modelled as a Gaussian channel with intersymbol interference (ISI). The time-domain output of the k-th TP in a K-pair cable is given by (1), where the used symbols are summarised in Table 1. The transmit signals $\mathbf{x}_m, m \neq k$ of neighbouring pairs cause mutually correlated noise components on the CM port and the DM port due to far-end crosstalk (FEXT). Near-end crosstalk (NEXT) and echo may be caused by transmitters located at the same side as our receiver. These disturbers as well as other impairments leading to correlated noise are taken into account by the M vectors $\mathbf{v}_m$. An example for such a noise source that has its origin outside the cable is radio frequency interference (RFI) [6]. Apart from these dependent noise components there are two independent noise components, one at the DM port and one at the CM port of the TP modelled by $\mathbf{v}_k^{(d)}$ and $\mathbf{v}_k^{(c)}$, respectively. Independent noise models thermal background noise and noise generated by the analog front-end. The time-domain model (1) does not assume any particular modulation type or synchronised transmission of all the

$$\underbrace{\begin{bmatrix} \mathbf{d}_k \\ \mathbf{c}_k \end{bmatrix}}_{\mathbf{y}} = \underbrace{\begin{bmatrix} \mathbf{H}^{(d)}_{k,k} \\ \mathbf{H}^{(c)}_{k,k} \end{bmatrix}}_{\mathbf{H}_x} \underbrace{\begin{bmatrix} \mathbf{x}_k \end{bmatrix}}_{\mathbf{x}} + \underbrace{\begin{bmatrix} \mathbf{H}^{(d)}_{k,1} & \cdots & \mathbf{H}^{(d)}_{k,(k-1)} & \mathbf{H}^{(d)}_{k,(k+1)} & \cdots & \mathbf{H}^{(d)}_{k,K} & \mathbf{H}^{(d)}_{k,K+1} & \cdots & \mathbf{H}^{(d)}_{k,K+M} & \mathbf{I} & \mathbf{0} \\ \mathbf{H}^{(c)}_{k,1} & \cdots & \mathbf{H}^{(c)}_{k,(k-1)} & \mathbf{H}^{(c)}_{k,(k+1)} & \cdots & \mathbf{H}^{(c)}_{k,K} & \mathbf{H}^{(c)}_{k,K+1} & \cdots & \mathbf{H}^{(c)}_{k,K+M} & \mathbf{0} & \mathbf{I} \end{bmatrix}}_{\mathbf{H}_v} \underbrace{\begin{bmatrix} \mathbf{x}_1 \\ \vdots \\ \mathbf{x}_{k-1} \\ \mathbf{x}_{k+1} \\ \vdots \\ \mathbf{x}_K \\ \mathbf{v}_1 \\ \vdots \\ \mathbf{v}_M \\ \mathbf{v}^{(d)}_k \\ \mathbf{v}^{(c)}_k \end{bmatrix}}_{\mathbf{v}} \quad (1)$$

users. It is reasonable to assume that background noise, the transmitted signals, at least for discrete multitone (DMT) systems, and thus also crosstalk are Gaussian. Hence, the entries of both $\mathbf{x}$ and $\mathbf{v}$ are independent Gaussian random variables. Correlation among the samples, or equivalently, spectral shaping, is introduced by the convolution matrices contained in $\mathbf{H}_x$ and $\mathbf{H}_v$. The entries of all convolution matrices and all vectors are real valued.

Since there are no established crosstalk models for the CM path, as it is the case for the DM path [11], our model is based on measurement results described in the following subsection.

2.2 Channel Measurements

For evaluation of the channel capacity it is essential to apply real data for the convolution matrices in (1). We measure the frequency-domain transfer functions (both magnitude and phase) with a resolution of 8192 points in the range from 0 to 30 MHz, as described in [12]. The impulse responses and convolution matrices are obtained from the transfer functions using the inverse discrete Fourier transform (IDFT). For the capacity results presented in the next section we use the measurement data of a 0.6 mm cable with 6 pairs (vendor identification: F02YHJ2Y, PMD6x2x0.6) of length 100 m.

time-domain vectors	
$\mathbf{x}_k$	transmit signal on k-th TP
$\mathbf{d}_k$	DM receive signal on k-th TP
$\mathbf{c}_k$	CM receive signal on k-th TP
$\mathbf{v}_m$	near-end transmit signal on m-th TP, or other disturber
$\mathbf{v}^{(d)}_k$	independent noise on DM of k-th TP
$\mathbf{v}^{(c)}_k$	independent noise on CM of k-th TP
convolution matrices	
$\mathbf{H}^{(d)}_{k,k}$	DM to DM path of k-th TP
$\mathbf{H}^{(d)}_{k,j}, 1 \le j \le K$	FEXT path from j-th TP to k-th TP
$\mathbf{H}^{(d)}_{k,K+j}$	NEXT path from j-th TP to k-th TP, DM echo path of k-th TP, or coupling path of other disturber to DM port
$\mathbf{H}^{(c)}_{k,k}$	DM to CM path of k-th TP
$\mathbf{H}^{(c)}_{k,j}, 1 \le j \le K$	DM to CM FEXT path from j-th TP to k-th TP
$\mathbf{H}^{(c)}_{k,K+j}$	CM NEXT path from j-th TP to k-th TP, CM echo path of k-th TP, or coupling path of other disturber to CM port

Table 1: Definition of the symbols used in the model (1).

2.3 Channel Capacity

The channel capacity is defined as the maximum mutual information of the two random vectors $\mathbf{y}$ and $\mathbf{x}$ [13]:

$$C = \max_{\mathrm{pdf}(\mathbf{x}),\ \sigma_x^2 = \mathrm{const.}} \mathrm{I}(\mathbf{y};\mathbf{x}). \quad (2)$$

Maximisation is performed over all probability density functions $\mathrm{pdf}(\mathbf{x})$ of the input vector $\mathbf{x}$ with a given finite per-sample variance σ_x^2. As discussed above, we assume that the elements of both the transmit signal vector $\mathbf{x}$ and the noise vector $\mathbf{v}$ are independent zero-mean Gaussian distributed random variables. The channel is deterministic and known at the receiver. Thus the channel capacity C corresponds to the mutual information since Gaussian distribution of the input signal maximises (2). The numerical results presented in the next section have been obtained using the capacity result of [14] for our Gaussian channel model (1).

Note that the numerical results presented in this paper are obtained using measurement results for the CM transfer functions, since there exist no models, neither of deterministic nor statistical nature, that describe the CM behaviour of cables. Consequently, the actual capacity results may vary largely from cable to cable. The main point of this work is to illustrate the potential of joint DM-CM processing for xDSL.

3. ASSESSMENT OF CHANNEL CAPACITY GAIN

In the following we investigate a VDSL scenario with particularly severe noise conditions. We assess the benefit of joint DM-CM processing in terms of relative capacity gain

$$\Delta C = \frac{C_{\text{DM-CM}} - C_{\text{DM}}}{C_{\text{DM}}},$$

where $C_{\text{DM-CM}} = \mathrm{I}(\mathbf{y};\mathbf{x})$ and $C_{\text{DM}} = \mathrm{I}(\mathbf{d}_k;\mathbf{x})$ are the capacities[1] achieved by joint DM-CM reception and conventional DM reception, respectively.

Very high datarate DSL (VDSL) transmission exploits the frequency range up to 12 MHz according to the current status of standardisation [15, 16]. Since frequency division duplexing is employed, the performance of this scheme is potentially FEXT-limited. Fig. 2 depicts the scenario under consideration. A long-reach transmission over a loop of length $L_{\text{loop}} = 1000\,\text{m}$ is disturbed by crosstalk from N_{FEXT} VDSL modems that are located $L_{\text{xt}} = 100\,\text{m}$ away from our receiver. This unequal-length FEXT scenario would necessitate a power backoff scheme in order to ensure reasonably low crosstalk levels on our loop [17, 18]. However, in case power

[1] The capacity corresponds to the mutual information since the channel is assumed to be known only at the receiver and the input signals are Gaussian.

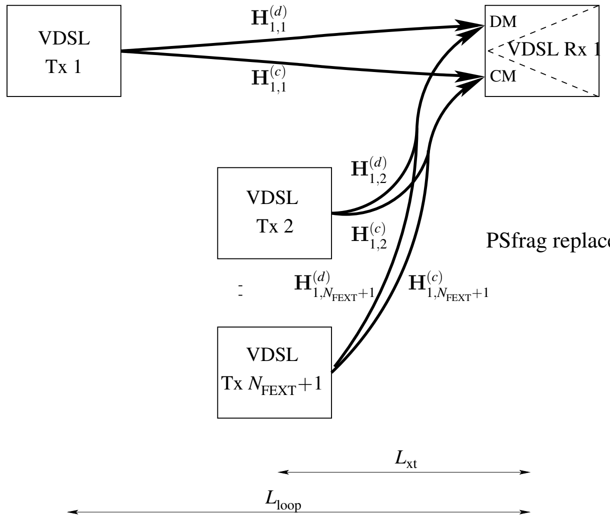

Figure 2: Simulation setup: VDSL transmission over a pair of length L_{loop} with N_{FEXT} self-FEXT disturbers located at a distance $L_{xt} = 100$ m from the receiver. The convolution matrices correspond to the model (1) with $k = 1$.

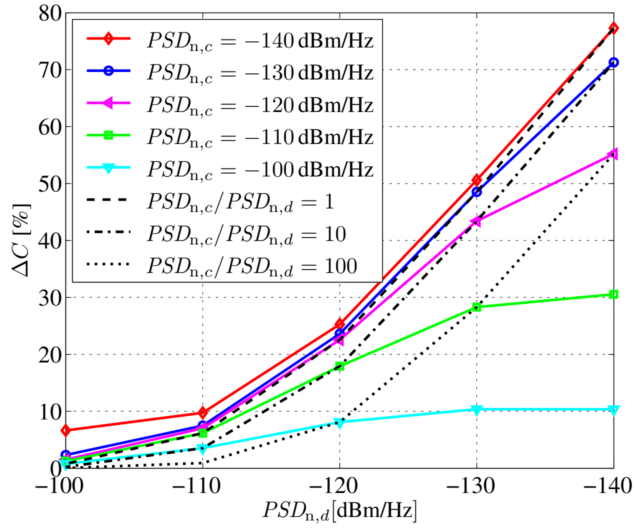

Figure 4: Capacity gain ΔC as a function of the background noise PSD levels $PSD_{n,d}$ at the DM port and $PSD_{n,c}$ at the CM port in *downstream direction* for a 0.6 mm loop of length $L_{loop} = 1000$ m with a single equal-power FEXT disturber ($N_{FEXT} = 1$) located at a distance $L_{xt} = 100$ m. The non-solid lines show the capacity gains for constant ratios $PSD_{n,c}/PSD_{n,d}$.

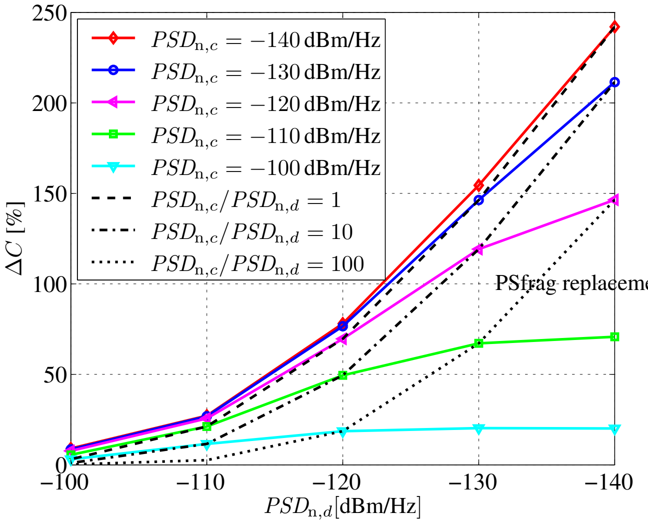

Figure 3: Capacity gain ΔC as a function of the background noise PSD levels $PSD_{n,d}$ at the DM port and $PSD_{n,c}$ at the CM port in *upstream direction* for a 0.6 mm loop of length $L_{loop} = 1000$ m with a single equal-power FEXT disturber ($N_{FEXT} = 1$) located at a distance $L_{xt} = 100$ m. The non-solid lines show the capacity gains for constant ratios $PSD_{n,c}/PSD_{n,d}$.

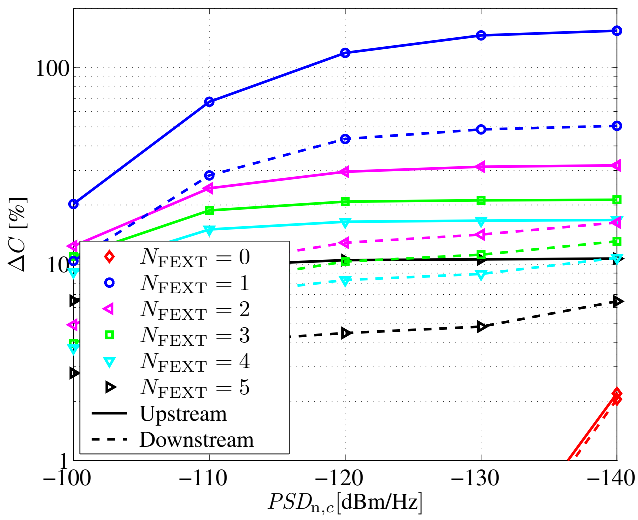

Figure 5: Capacity gain ΔC versus CM background noise PSD level $PSD_{n,c}$ for *different numbers* N_{FEXT} *of FEXT disturbers* in upstream (solid lines) and downstream (dashed lines) direction ($PSD_{n,d} = -130$ dBm/Hz, $L_{loop} = 1000$ m, $L_{xt} = 100$ m).

backoff is employed, the crosstalking transmitter has to reduce its transmit power, thus limiting its own datarate or reach, respectively. We use a standardised 4-band plan referred to as "997"-plan [16].

The relative capacity gain results for upstream and downstream transmission with a single FEXT disturber ($N_{FEXT} = 1$) are shown in Fig. 3 and Fig. 4, respectively. Let us first consider the solid lines, which denote constant CM noise power spectral density (PSD) levels. With decreasing DM background noise PSD level $PSD_{n,d}$ the capacity gain rises for low CM noise PSD values $PSD_{n,c}$ since the two clear views on the interference allow cancellation. The flattening of the curves for high CM background noise PSD levels, *e.g.*, $PSD_{n,c} = -100$ dBm, and for low DM background noise PSD levels $PSD_{n,d}$ indicates that the influence of the CM background noise becomes more severe. The non-solid lines show the capacity gain for constant ratios $PSD_{n,c}/PSD_{n,d}$ of the background noise PSD levels. The lower this ratio, the clearer the view on the interference at the CM port, the higher the capacity gain. The results for the two directions differ due to the different band allocation. For upstream transmission the benefit is larger compared to the downstream case since the bands used for upstream are located at higher frequencies and therefore suffer more attenuation.

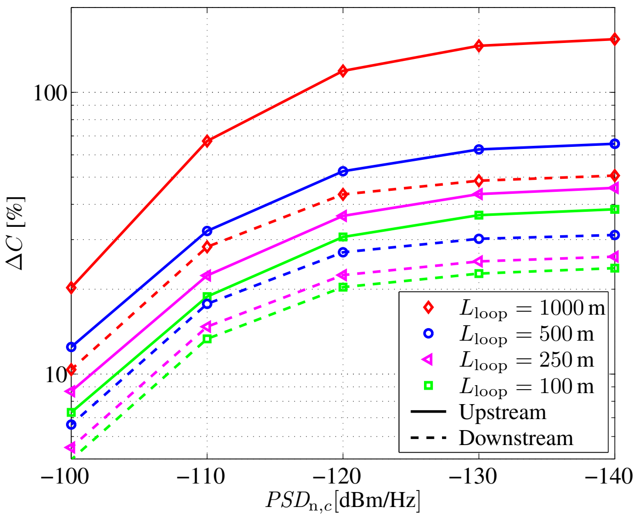

Figure 6: Capacity gain ΔC versus CM background noise PSD level $PSD_{n,c}$ for *different loop lengths* L_{loop} and a single FEXT disturber in upstream (solid lines) and downstream (dashed lines) direction ($N_{FEXT} = 1$, $PSD_{n,d} = -130$ dBm/Hz, $L_{xt} = 100$ m).

Fig. 5 shows ΔC as a function of the CM background noise PSD level $PSD_{n,c}$ for different numbers of FEXT disturbers N_{FEXT} and for a constant DM background noise PSD level $PSD_{n,d} = -130$ dBm/Hz. In case only background noise is present ($N_{FEXT} = 0$), there is virtually no benefit of joint DM-CM processing, since the additional signal power gained from the CM port is very low. The case with a single FEXT disturber ($N_{FEXT} = 1$) yields the largest benefit since the FEXT can, at least in theory, be completely cancelled—the capacity gain is limited by the background noise on both the CM port and the DM port. The values of ΔC drop drastically as the number of disturbers increases ($N_{FEXT} > 1$).

Fig. 6 shows ΔC as a function of $PSD_{n,c}$ for different loop length L_{loop} and a single FEXT disturber ($N_{FEXT} = 1$). The capacity gain increases with the loop length since the receive signal becomes weaker while the crosstalk level stays constant. Viewing the situation from an interference cancellation perspective reveals that a reduction of the crosstalk level by a certain amount results in a larger relative signal-to-noise ratio (and thus also capacity) gain for a weaker signal.

4. SUMMARY AND CONCLUSION

Conventional communication over copper twisted-pair channels is performed by transmitting and receiving differential-mode (DM) signals. In this paper, we extend this approach by incorporating the common-mode (CM) signal, a freely available signal at the output of every channel, at the receiver. We evaluate this approach in terms of relative channel capacity gain using channel measurement data.

For the VDSL example scenario, the relative capacity gain amounts to a factor of up to three when a single strong FEXT disturber is present. The capacity gain drops significantly with the number of FEXT disturbers. As expected, there is virtually no benefit of joint DM-CM processing in case only background noise is present.

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