Impulse Noise Cancellation based on the Common-Mode Signal

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***Abstract*—If there are only one or a few strong interferers in subscriber-line transmission, Common Mode (CM) and Differential Mode (DM) show significant correlations. We extend a cancellation method already known for RFI to impulse-noise disturbance elimination. The CM provides a perfect reference to cancel impulse noise in the DM. The training of an NLMS based canceler is restricted to the impulse duration. Impulse noise can easily be detected from the CM. Fortunately, the DM signal itself couples only weakly into the CM, ensuring that the canceler will not noticeably influence the received signal.**

***Index Terms*—impulse noise, cancellation, adaptive filter, Common Mode.**

I. Introduction

Transmission quality is often degraded by bursts of high amplitude referred to as impulse noise. High amounts of impulse noise can cause significant errors, possibly even requiring modems to restart. In video and audio, significant artefacts will become visible, such as pixel errors, block artefacts, or breaks. A modem restart will stop communication for around 10 seconds at least, possibly even for half a minute. A statistical model for impulse noise on subscriber loops is presented in [1]–[3]. Algebraic expressions for frequency distributions were derived from measurements for the duration, density of voltages, and interarrival times. Furthermore, spectral properties were quantified, even leading to representative impulses for one line. Impulse noise generation was studied, as well, finally leading to a procedure [3] allowing to realize all significant statistical and spectral properties.

Crosstalk can originate from a transmitter within the same cable or from a source outside that cable. In the first case, the crosstalk injected in the system is called *in-domain* crosstalk, while for the second case, the term *alien* crosstalk is used. [4] offers an overview of alien crosstalk cancellation for discrete multitone (DMT) systems.

The conventional approach of transmission over copper cables is carried out using Differential-Mode (DM) signals. Unlike DM signals, Common-Mode (CM) signals are more vulnerable to unwanted interference such as impulse noise and RFI. The reason behind this is that twisted-pair lines intercept coupled signals equally, so the incident signals appear only as Common-Mode signals. Exploiting the benefits of detection and estimation of interference from the CM signals was shown to achieve a channel capacity up to three times higher than in the case of DM processing only [5]. Both DM and CM signals are readily available on the receiver side. DM signals propagate through a pair of wires and appear as a voltage difference.

$$x_{DM}(t) = x_1(t) - x_2(t) \tag{1}$$

Technically, the CM signal is the arithmetic mean of the signals $x_1(t)$ and $x_2(t)$ which are measured with respect to ground.

$$x_{CM}(t) = \frac{x_1(t) + x_2(t)}{2} \tag{2}$$

The CM signal consists of three additive components: independent noise, noise correlated with the noise in DM and a component correlated with the desired signal from DM [5]. Crosstalk coupling from adjacent pairs is considered to be part of the correlated noise. In the case of strong interference, such as in the case of impulse noise, there is a strong correlation between DM and CM signals. While the dominant component in CM will be the impulse, this might not necessarily be the case for DM. There, impulse noise might be buried within the rest of the signal, making the detection less straightforward.

The benefits of joint DM-CM processing in xDSL have been previously investigated in [6]. [8] reveals a CM reference-based canceler for RFI mitigation which is split into an analog and a digital part. Section 2 of the current paper introduces the principle of impulse noise cancellation using CM signals. The coupling functions into DM and CM are introduced in Section 3. Section 4 presents impulse detection and cancellation, and Section 5 introduces simulation results. For the rest of this paper we pursue the following notations: bold capital letters denote matrices, bold lower case letters represent vectors, superscripts DM and CM refer to Differential-Mode and Common-Mode, and the subscript in $\mathbf{H}_{j,i}^{DM}$ refers to the path from the *i*th pair into the *j*th pair.

II. Common-Mode reference based canceler

The principle of impulse noise cancellation using the CM signal is illustrated in Fig. 1.

For convenience, the impulses were received and saved into non overlapping blocks of length N, before attempting cancellation.

In a multipair cable, crosstalk is modeled as originating from an arbitrary number of sources. We model our system as having *L* equal-length FEXT and *K* NEXT disturbers. We transmit signal **s** as a voltage difference at the transmitter side on pair *j*. At the receiver side, we measure two signals $\mathbf{y}_j^{DM}$

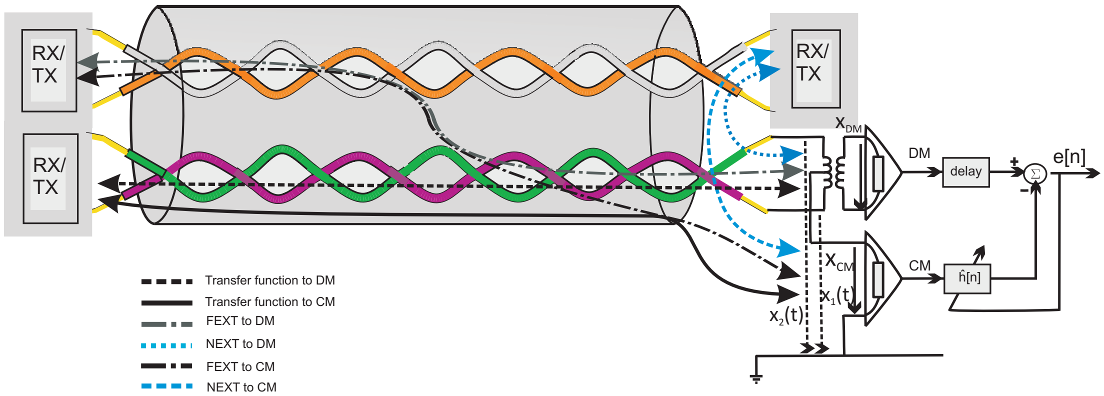

Fig. 1. Coupling functions and canceler structure

$$\begin{bmatrix}\mathbf{y}_j^{DM}\\ \mathbf{y}_j^{CM}\end{bmatrix} = \begin{bmatrix}\mathbf{H}_{j,j}^{DM}\\ \mathbf{H}_{j,j}^{CM}\end{bmatrix}\begin{bmatrix}\mathbf{s}_j\end{bmatrix} + \underbrace{\begin{bmatrix}\mathbf{H}_{j,1}^{DM}\cdots\mathbf{H}_{j,j-1}^{DM}\mathbf{H}_{j,j+1}^{DM}\cdots\mathbf{H}_{j,L}^{DM}\\ \mathbf{H}_{j,1}^{CM}\cdots\mathbf{H}_{j,j-1}^{CM}\mathbf{H}_{j,j+1}^{CM}\cdots\mathbf{H}_{j,L}^{CM}\end{bmatrix}}_{FEXT}\begin{bmatrix}\mathbf{s}_1\\ \vdots\\ \mathbf{s}_{j-1}\\ \mathbf{s}_{j+1}\\ \vdots\\ \mathbf{s}_L\end{bmatrix} + \underbrace{\begin{bmatrix}\mathbf{H}_{j,L+1}^{DM}\cdots\mathbf{H}_{j,L+K}^{DM}\\ \mathbf{H}_{j,L+1}^{CM}\cdots\mathbf{H}_{j,L+K}^{CM}\end{bmatrix}}_{NEXT}\begin{bmatrix}\mathbf{v}_1\\ \vdots\\ \mathbf{v}_K\end{bmatrix} + \underbrace{\begin{bmatrix}\mathbf{w}^{DM}\\ \mathbf{w}^{CM}\end{bmatrix}}_{AWGN} + \underbrace{\begin{bmatrix}\mathbf{i}^{DM}\\ \mathbf{i}^{CM}\end{bmatrix}}_{impulse\ noise} \quad (3)$$

and $\mathbf{y}_j^{CM}$ which can be expressed as given in (3), where $\mathbf{s}_j$ is the transmitted signal of size *N*x*1* on pair *j*, $\mathbf{H}_{j,j}^{DM}$ denotes the $N \times N$ convolution matrix describing the DM to DM path on the *j*th pair. $\mathbf{w}^{DM}$ denotes uncorrelated AWGN in DM referred to as background noise, and $\mathbf{i}^{DM}$ represents the DM coupled impulse noise signal. A similar notation stands for CM signals. The resulting CM signal consists mainly of ingress and is measured between the center tap of a balun and ground.

III. Coupling Functions and CM/DM impulse noise

Since wireline channels vary slowly with time, it is reasonable to consider them as being linear and time invariant during the transmission of our signal. It is also reasonable to assume that all the transmitted signals can be modeled as independent Gaussian random variables. Since neither statistical properties, nor coupling functions were previously defined for CM, our model relies on measurements. For the measurements in this section a Swiss 0.4 mm cable with 50 pairs of length 100 m was used. Measurements revealed a -50 dB attenuation of signal coupling into CM, for frequencies lower than 2 MHz. As the simulation section will demonstrate, for a -50 dB drop in magnitude, the risk of canceling the useful signal component becomes negligible.

Measurements of impulse noise have been taken at inhouse phone outlets, both in DM and CM. Figure 5 presents an impulse measured both in DM and CM.

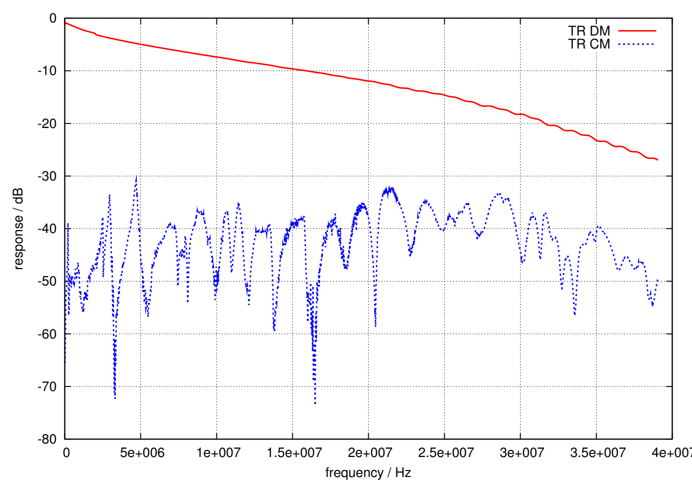

Fig. 2. Transfer functions for DM and CM obtained from measurements of a 0.4 mm Swiss cable of length 100 m

IV. Impulse noise detection and cancellation

A. Detection

The CM signal, besides providing a reference for most of the undesired interference in the system, comes with the advantage that its dominant component is impulse noise, which facilitates the detection of corrupted samples. Although many other detection methods for impulse noise have been successfully described in literature [11], the current paper presents two simple methods. For the first method (6), in order to obtain the envelope, the CM is split into non overlapping frames

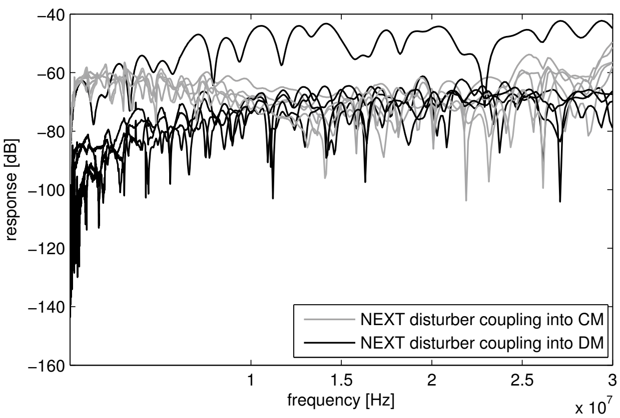

Fig. 3. NEXT coupling functions, obtained from measurements of different TPs in the bundle. The outlier is due to measuring the other TP in the same quad.

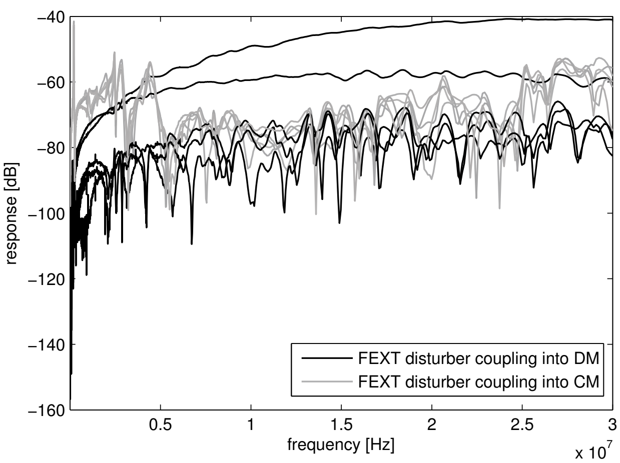

Fig. 4. FEXT coupling functions, obtained from measurements of different TPs in the bundle. The outliers are due to measuring adjacent TPs

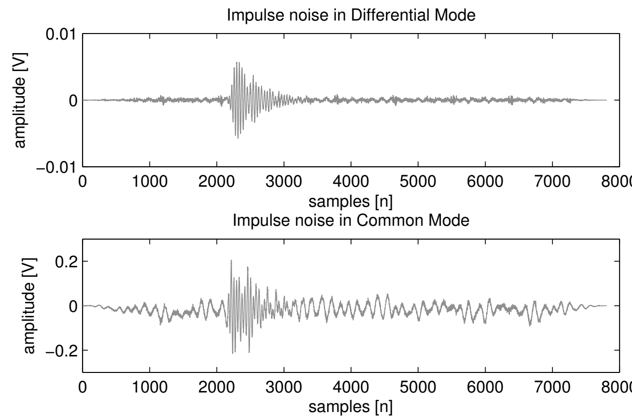

Fig. 5. Impulse noise generated from fluorescent light switching, both in DM and CM. Please note the different amplitudes of the waveforms.

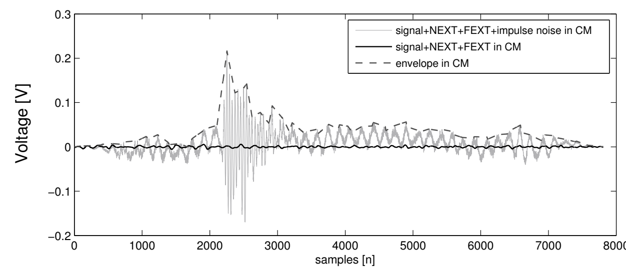

Fig. 6. Envelope of CM signal (dashed grey). The black line represents the CM coupling of the signal, along with 4 NEXT and 5 FEXT disturbers for a cable length of 3.5 km. Thin grey waveform represents the overall CM signal, including impulse noise. Impulse noise is the dominant signal in CM.

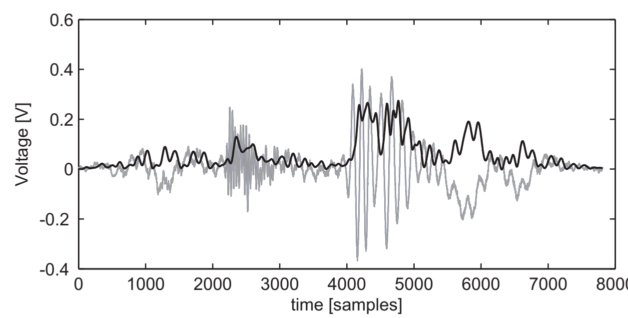

Fig. 7. Second method for CM envelope detection

of size M. Out of every frame, the maxim value is chosen and interpolation is performed among all local maxima. That is, after k distinct blocks of size M, $k-1$ values can be linearly interpolated, and from the corresponding $(k-1)M$ samples, the ones above a certain threshold τ can be flagged. Once flagged, the CM signal passes through the adaptive FIR filter which updates the coefficients only when a new flagged sample is detected. Under ideal assumptions, the resulting output would contain the DM signal, undistorted by impulse noise, and a term consisting of the minimum residual error. A second method which can be easily implemented in the analog domain uses a rectifier and a low pass filter to detect the envelope of the CM signal (see Fig. 7).

B. Cancellation

The concept of adaptive filtering has found a lot of applications over the past three decades, ranging from channel equalization and echo cancellation to mitigation of narrowband interference in wideband signals [9]. For our simulations, the Normalized Least Mean Squares algorithm (NLMS) was used. NLMS is typically used due to its reduced computational complexity and robustness [10]. [9] offers an extensive description of the algorithm, along with some discussions on convergence issues. As previously discussed, the noise present at CM can be split into a component correlated with the DM noise, a component correlated with the DM signal and one uncorrelated component. This leakage of DM signal into CM poses the risk of canceling the useful component, which is much more likely for a high DM to CM coupling and a high SNR. One way to circumvent this problem is to update the filter coefficients only when the far-end transmitter is inactive [7].

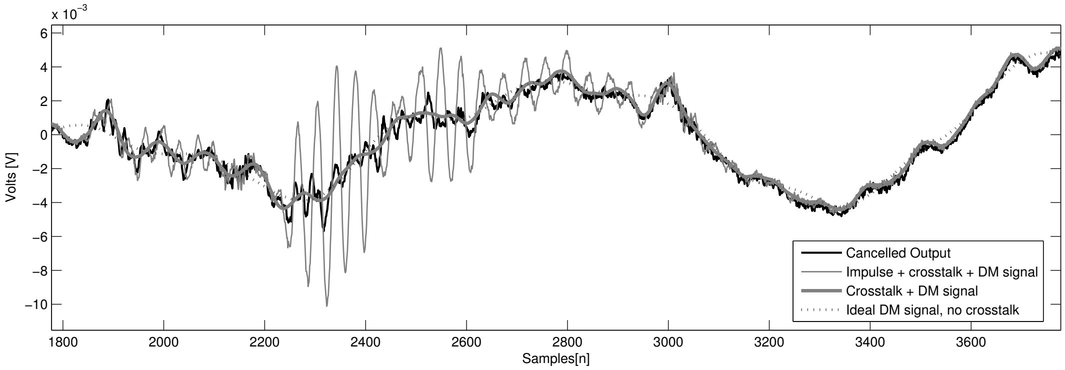

Fig. 8. The output of the NLMS canceler (black). The dotted grey line represents the ideal received signal, no crosstalk, no impulse noise and no background noise. Bold grey waveform denotes the sum of the ideal signal, 4 NEXT and 5 FEXT disturber signals, along with background noise. Grey thin line illustrates the DM signal including impulse noise before cancellation. For perfect impulse noise cancellation and no crosstalk cancellation, the black line should resemble the bold grey signal as close as possible.

Uncorrelated CM in-band noise induces the possibility that it will leak to the output of the adaptive filter, which will result in an SNR loss. This undesired effect can be minimized by updating the filter coefficients only when impulse noise is detected in CM, which is what we have done in our simulations. Crosstalk is not canceled along with impulse noise, since the total burst time is much smaller than the total transmission time, and the filter adaptation is performed sporadically. Although crosstalk cancellation was not pursued in this paper, the same concept can be extended to this situation, using a continuous adaptation of the filter, a reduced number of disturbers and a high ratio of correlated CM crosstalk power to uncorrelated CM noise power.

V. Simulation Results

Impulse noise cancellation was investigated in the context of ADSL transmission. Coupling and transfer functions were measured for both DM and CM for a cable length of 100 m. Length-scaling for ADSL-specific loop distances was employed using the method described in (4), where $H(f,L)$ and $H(f,L_m)$ represent the insertion loss given by the MAR model defined in [14], [15] and L_m designates the length of the loop (100 m) on which the measurements were performed.

$$H_{FEXT}(f,L) = H_{FEXT}(f,L_m)\sqrt{\frac{L}{L_m}}\frac{H(f,L)}{H(f,L_m)} \qquad (4)$$

Note that the same length-scaling method was used both for DM and CM, although this might not necessarily be accurate in the case of CM. If was used, nevertheless, since no other length-adaption method could be found in literature[1] for CM transfer functions. Transmit signals were modeled according to the PSD of ADSL as specified in [13]. For NEXT modeling, the AslMx (German abbreviation for subscriber loop multiplexer) spectral mask [12] was used. Far-end crosstalk was generated as established in [13]. Simulations used sets of measured impulses generated in industrial settings (caused by welding), as well as in household environments (caused by fluorescent light switching). ADSL transmission and reception was simulated, given the measured transfer and coupling functions, for different loop lengths and different number of NEXT and FEXT disturbers. Figure 8 depicts the canceler output (in black) for an ADSL simulation employing 5 FEXT and 4 NEXT disturbers. For illustration purposes, since the amplitude of the measured impulse noise vectors was relatively small, the length of the loop was extended beyond ADSL-specific loop lengths, in order to achieve a lower SINR ratio. The thin grey line in 8 depicts the overall received DM signal, which is corrupted by impulsive noise, while the bold grey waveform illustrates the same DM signal, impulse noise free. As expected, the canceler produces a good estimate of the uncorrupted DM signal but does not suppress crosstalk. The dashed grey line presents the ideal transmitted signal, with no interference, only attenuated by loop length. For perfect impulse noise cancellation and no crosstalk cancellation, the black line should resemble the bold grey waveform as close as possible, which is by the actual case.

[1]to the knowledge of the authors

VI. Summary and Conclusion

The conventional approach of transmission over copper cables, which uses only DM signals is extended to incorporate the CM signal, readily available at the receiver side. Since there is a high correlation between DM and CM, especially in the presence of one or a few strong external disturbers (ingress), the CM signal can be used to estimate the impulse noise present in DM. An adaptive CM reference-based impulse noise canceler was illustrated and simulation results proved its functionality. Detection of impulse noise was employed by thresholding the CM signal, and canceler training was performed only during impulse duration.

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