Impulse Noise Cancellation Utilizing the Common-Mode Signal to Improve the Bit-error Ratio in DSL Systems

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***Abstract*— In subscriber-line transmission, when only one or a few strong interferers are present, Common Mode (CM) and Differential Mode (DM) signals show significant correlations. A cancellation method already known for RFI is extended to impulse-noise elimination in DSL systems, by using the CM as a reference. Fortunately, the DM signal itself couples only weakly into the CM, ensuring that the canceler will not noticeably influence the received signal. Bit-error curves, before and after Reed-Solomon decoding, are provided in support of the cancellation algorithm.**

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

I. Introduction

IMPULSE noise, characterized by high amplitudes and random inter-arrival times, is known to be one of the major impairments of DSL transmission. 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. Reed-Solomon codes, used in conjunction with interleaving, were chosen with the aim of neutralizing the effect of bursty disruptances in DSL systems. 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 inter-arrival 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, alongside impulse noise, is another significant impairment in a multi-pair cable DSL system. Crosstalk originating from transmitters within the same cable is referred to as *in-domain*, while we use the term *alien* for crosstalk injected in the system by an external source, outside the cable. An alien crosstalk cancellation method for discrete multitone (DMT) systems is detailed in [4].

Differential-Mode (DM) signaling, due to the high immunity against interference exhibited, was chosen as the conventional approach of transmission over copper cables. On the receiver side, the voltage difference between the two wires is measured. A Common-Mode (CM) signal, also freely available on the receiver side, is defined as the arithmetic mean of the two signals measured with respect to ground. Since twisted pairs intercept signals equally, any incident signals appear as CM signals, thus making CM very susceptible to undesired interference such as RFI and impulse noise. When a reduced number of interferers is present in the system, DM and CM signals exhibit a strong correlation [6]. The benefits of joint CM-DM processing have been investigated in [6], where results show a channel capacity increase up to a factor of three when compared to the case of conventional DM processing. A CM reference-based canceler for RFI mitigation, split into an analog and digital part, has been proposed in [8].

Section 2 of the current paper introduces the energy density spectra and the average correlation factor between DM and CM impulses. The transfer functions are introduced in Section 3, along with coupling functions into DM and CM for NEXT and FEXT. Section 4 proposes a CM reference-based canceler, and Section 5 introduces simulation results. A summary concludes the paper in Section 6.

II. Correlation and energy spectra

Measurements of impulse noise have been taken at inhouse phone outlets, both in DM and CM. Figure 1 presents an impulse measured both in DM and CM. Additionally, energy density spectra are plotted. The relation between DM and CM signals is obvious with a significantly higher amplitude in CM. The corresponding spectra show a concentration at lower frequencies as is well-known from earlier publications [1]–[3]. In Fig. 2, the average correlation factor

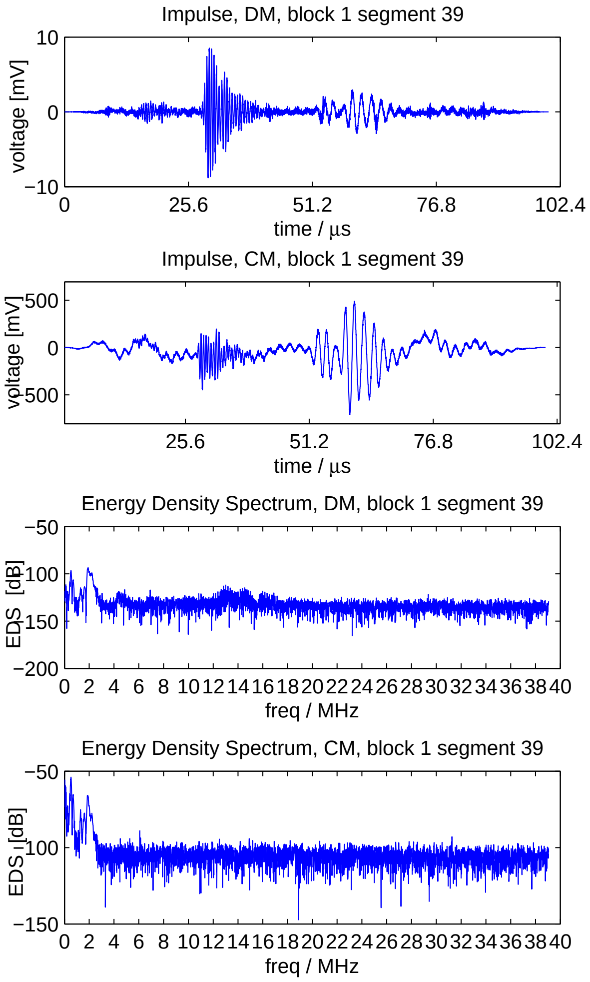

Fig. 1. Impulse noise measured at a customer premises phone outlet, both in DM and CM.

is shown for a measurement consisting of more than 14000 impulses. Strong correlations become visible where significant spectral components are present. The CM signal can be modeled as a summation of several components: independent noise, a component correlated with the noise and crosstalk in DM, and a component correlated with the desired signal from DM. Detection and estimation of the impulse noise in DM is difficult and unreliable since the

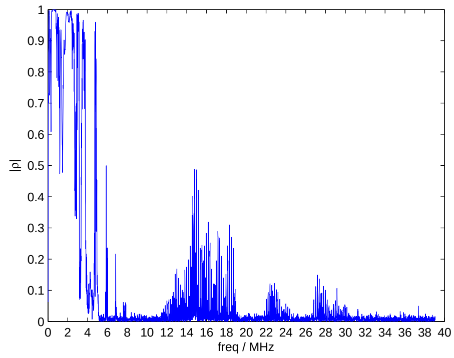

Fig. 2. Frequency dependent correlation coefficient between CM and DM

impulses are buried within the rest of the signal, and mitigation techniques such as blanking and clipping might prove to be inefficient. CM, on the other hand, presents a perfect reference signal, since its dominant component is impulse noise (and RFI).

III. Coupling Functions

Since neither statistical properties, nor coupling functions were previously defined for CM, our model relies on measurements. Figure 3 presents DM and CM transfer functions measured on a 0.4 mm Swiss cable of length 100 m. For frequencies below 2 MHz, a CM attenuation of approximately -50 dB was observed. As the simulation section will demonstrate, for a -50 dB drop in magnitude, the risk of canceling the useful signal component becomes negligible. Since no length-dependency studies for CM attenuation have been found in literature[1], both DM an CM transfer and coupling functions have been extended to ADSL-specific distances by employing the length-scaling method defined in (1), 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.

$$H_{FEXT}(f, L) = H_{FEXT}(f, L_m)\sqrt{\frac{L}{L_m}}\frac{H(f, L)}{H(f, L_m)} \tag{1}$$

This model is not completely correct for signals coupled into CM, however, currently, there is no other model available. Figures 4 and 5 show NEXT and FEXT coupling functions for DM and CM for different twisted pairs in a bundle.

[1] to the knowledge of the authors

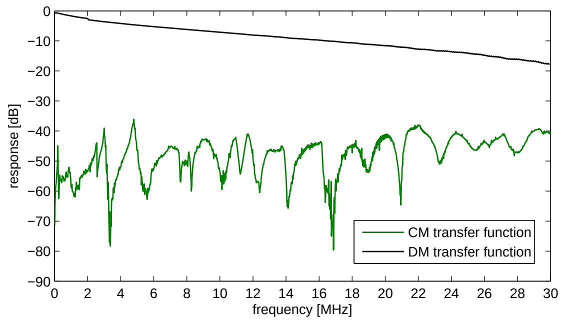

Fig. 3. DM and CM transfer functions measured on a 0.4 mm Swiss cable of length 100 m

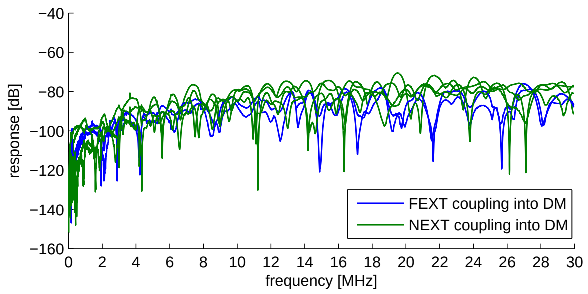

Fig. 4. NEXT and FEXT coupling functions into DM, obtained from measurements of a 0.4 mm Swiss cable of length 100 m.

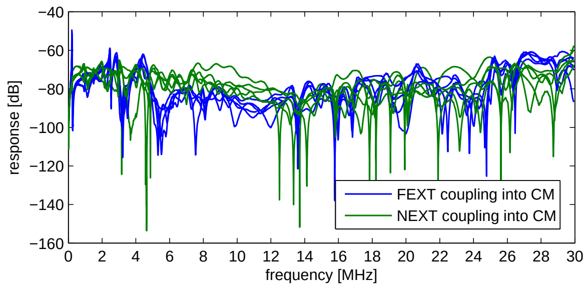

Fig. 5. NEXT and FEXT coupling functions into CM, obtained from measurements of a 0.4 mm Swiss cable of length 100 m.

IV. Common-Mode reference based canceler

The system model is summarized in (2), where the following notations are pursued: 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 ith pair into the jth pair. Figure 6 illustrates the impulse noise cancellation principle. We transmit signal $\mathbf{s}$ as a voltage difference at the transmitter side on pair j. Crosstalk is introduced in the system by originating from Q equal-length FEXT and K NEXT disturbers. At the receiver side, we measure two signals $\mathbf{y}_j^{DM}$ and $\mathbf{y}_j^{CM}$, where $\mathbf{s}_j$ is the transmitted signal of size Nx1 on pair j, $\mathbf{H}_{j,j}^{DM}$ denotes the $N \times N$ convolution matrix describing the DM to DM path on the jth 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.

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. A small leakage of the DM useful signal is to be expected into CM, especially for a strong DM into CM coupling and high SNRs. Since the proposed canceler uses the CM signal as reference, this introduces the risk of canceling the desired signal. In order to circumvent both problems, the filter coefficients adaptation could be performed only when an impulse is detected in CM and the far-end transmitter is inactive. 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, given 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, given the measured transfer and coupling functions, for different loop lengths. 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). Both constant and random inter-arrival times were considered. For the inter-arrival times, the distribution detailed in [1] was used, and for the constant inter-arrival time, the parameters in [16] were considered. The inter-arrival time there was chosen as 1.4 ms, which is extremely short. For robustness and computational complexity considerations, an adaptive Normalized Least Mean Squares (NLMS) filter was implemented. Figures 7 and 8 present BER values versus loop lengths for

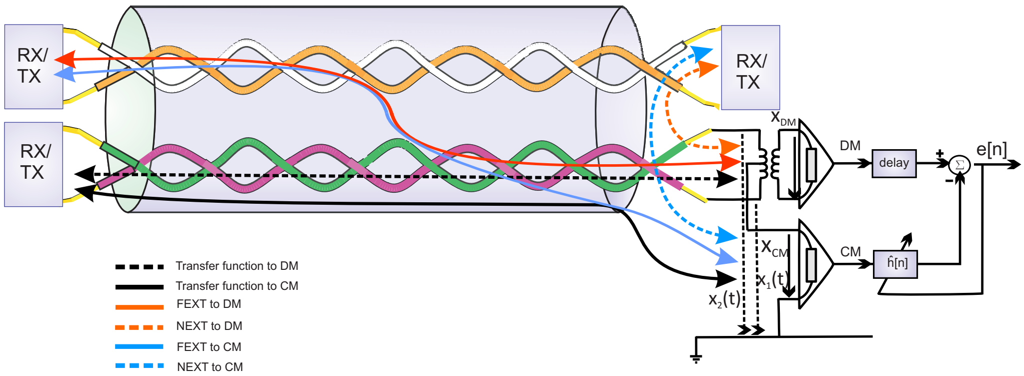

Fig. 6. Canceler structure

$$\begin{bmatrix} \mathbf{y}_j^{DM} \\ \mathbf{y}_j^{CM} \end{bmatrix} = \begin{bmatrix} \mathbf{H}_{j,j}^{DM} \\ \mathbf{H}_{j,j}^{CM} \end{bmatrix} [\mathbf{s}_j] + \underbrace{\begin{bmatrix} \mathbf{H}_{j,1}^{DM} \cdots \mathbf{H}_{j,j-1}^{DM} \mathbf{H}_{j,j+1}^{DM} \cdots \mathbf{H}_{j,Q}^{DM} \\ \mathbf{H}_{j,1}^{CM} \cdots \mathbf{H}_{j,j-1}^{CM} \mathbf{H}_{j,j+1}^{CM} \cdots \mathbf{H}_{j,Q}^{CM} \end{bmatrix}}_{FEXT} \begin{bmatrix} \mathbf{s}_1 \\ \vdots \\ \mathbf{s}_{j-1} \\ \mathbf{s}_{j+1} \\ \vdots \\ \mathbf{s}_Q \end{bmatrix} + \underbrace{\begin{bmatrix} \mathbf{H}_{j,Q+1}^{DM} \cdots \mathbf{H}_{j,Q+K}^{DM} \\ \mathbf{H}_{j,Q+1}^{CM} \cdots \mathbf{H}_{j,Q+K}^{CM} \end{bmatrix}}_{NEXT} \begin{bmatrix} \mathbf{v}_1 \\ \vdots \\ \mathbf{v}_K \end{bmatrix} + \underbrace{\begin{bmatrix} \mathbf{w}^{DM} \\ \mathbf{w}^{CM} \end{bmatrix}}_{AWGN} + \underbrace{\begin{bmatrix} \mathbf{i}^{DM} \\ \mathbf{i}^{CM} \end{bmatrix}}_{impulse\ noise} \quad (2)$$

constant impulse free durations. Results revealed an improvement by a factor of 10 before Reed-Solomon (RS), and down to a BER of 10^{-4} after RS decoding for cable loops of 2.4 km. For random inter-arrival times, results showed improvements in BER of down to 10^{-4} before RS decoding (9) and down to 10^{-8} after RS decoding (10).

VI. Summary and Conclusion

The conventional approach of transmitting over copper cables, which uses only DM signals was 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. BER curves, before and after Reed-Solomon decoding were provided, both for constant and random inter-arrival time. Detection of impulse noise was employed by thresholding the CM signal, and canceler training was performed only during impulse duration.

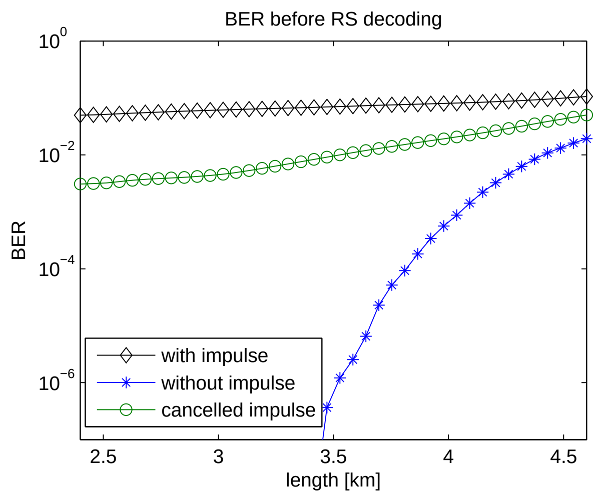

Fig. 7. BER before RS decoding, for different cable lengths, NEXT from four subscriber line multiplexers (AslMx), -120 dBm background noise level, constant inter-arrival time.

Acknowledgments

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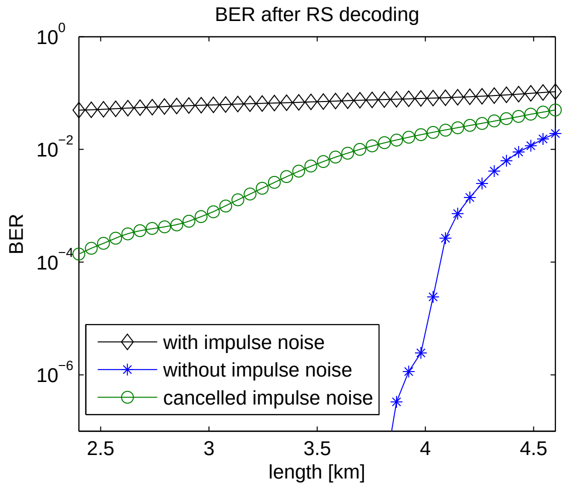

Fig. 8. BER after RS decoding, for different cable lengths, NEXT from four subscriber line multiplexers (AslMx), -120 dBm background noise level, constant inter-arrival time.

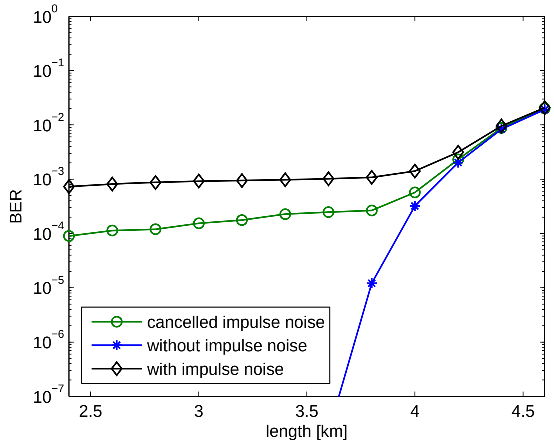

Fig. 9. BER before RS decoding, for different cable lengths, NEXT from four subscriber line multiplexers (AslMx), -120 dBm background noise level, random inter-arrival times.

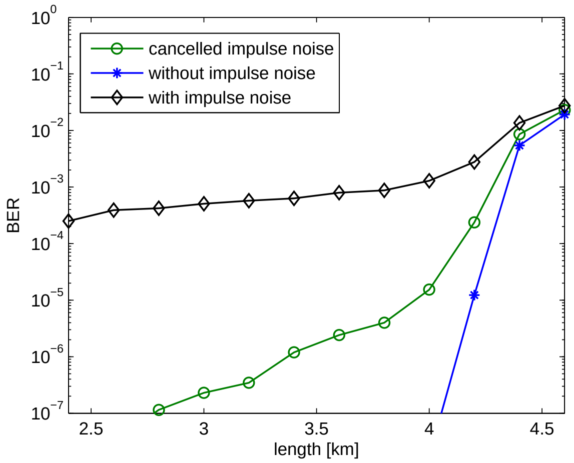

Fig. 10. BER after RS decoding, for different cable lengths, NEXT from four subscriber line multiplexers (AslMx), -120 dBm background noise level, random inter-arrival times.

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