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CONTRIBUTION

TITLE: **Spatial Noise Cancellation using Extra Wire-pairs in the DSL Downstream**

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ABSTRACT

This document describes the use of extra wire-pairs in the DSL downstream, which are connected at the customer end but not necessarily at the service provider end. These extra lines can be used to cancel noises that are spatially correlated with the actual DSL line. This can lead to significant improvement in DSL line stability and in the downstream data rates, when alien noise (stationary or intermittent) is dominant. Examples of such noises include BPL, AM radio, intermittent noise from faulty devices, and impulse noise. Simulation results are provided which show significant improvement in performance of the DSL lines by employing the spatial noise cancellers with the aid of the extra wire-pairs. Level 3 DSM concepts can be further used to improve the data rates when strong self-FEXT is present on the extra wire-pair or when the service provider decides to use the second wire pair as well for data transmission. This contribution is provided for information only.

1 Introduction

The stability and data rates of a number of lines in current DSL systems are affected by alien noise. Such noise may be stationary or non-stationary. Examples of stationary alien noise include Broadband over Power Line (BPL) signals, signals from other DSL services, and AM noise. Intermittent noise from faulty devices (say within the customer premises) and impulse noise constitute examples of non-stationary noises. An effective solution to cancel these noises in DSL systems would greatly improve the stability of the so-called “trouble lines” and would also enable higher data rates. Level 3 DSM (of which vectoring is one option) helps in canceling the in-domain crosstalk within the vectored group of lines. Previous contributions and papers in literature have shown the use of level 3 DSM in the upstream to exploit the correlation in the noise between the different lines [1],[2] in order to cancel the alien noise as well. The interesting concept of canceling alien noise using the unused lines in the upstream was explored in [3]. A natural question to then ask is whether such cancellation is possible in the downstream. Interestingly enough, the answer is YES. In a typical customer premises, more than one pair of telephone wires is available, although only one pair may have been actually connected in order to provide DSL service. Any external noise source that is coupled to the actual DSL line would also couple with the extra wire-pair(s)[1] depending on the point of coupling of the noise. In this contribution, we discuss the use of one extra wire-pair in order to cancel the alien noise. The results presented here can be easily extended to noise cancellation using a multiple number of extra wire-pairs, if available. The rest of this contribution is organized as follows. Section 2 describes the factors influencing the coupling of external noise sources to the two twisted pairs and the effective transfer functions of the external noise between the two wire-pairs. Section 3 describes the training of the noise canceller and noise cancellation mechanism. Section 4 presents simulation results on the performance of the noise cancellers and the improvement in system performance. Section 5 briefly discusses the system architecture if both wire-pairs are used for DSL transmission. The summary of the contribution is provided in Section 6.

2 Spatial coupling of Alien Noise to Twisted Pairs and Noise Correlation

Alien noise may couple to the wire-pairs in the DSL network, either in the binder itself or more likely in the drop wire and inside the customer premises since the binder is usually shielded. The in-domain crosstalk inside the binder may be canceled by using vectoring (level 3 DSM). The other alien noise, which is the focus of this contribution, may include BPL, AM, intermittent noise, impulse noise, etc. Intermittent noise is caused when a certain device turns ON and disappears when the device turns OFF. These noise sources may couple to both the actual DSL wire-pair and the extra wire-pair in which case a spatial noise canceller can be used to sense the noise in the extra wire-pair and cancel it from the actual DSL line. The critical factor in order to achieve this cancellation is the estimation of the ratio of the noise coupling transfer functions of the two lines.

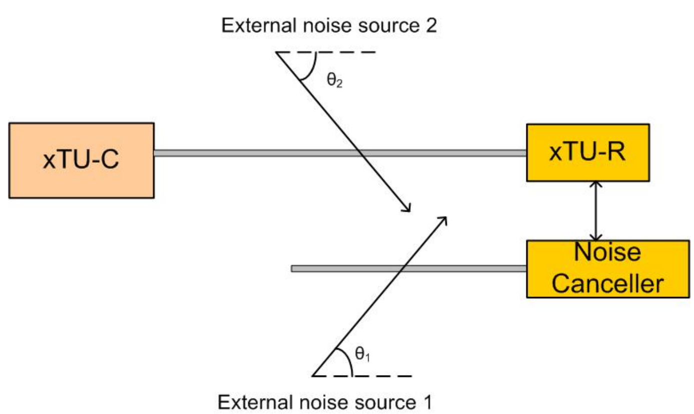


Figure 1: Mechanism of noise coupling to the wire-pairs.

Typically, the alien noise may get coupled to the wire-pairs from certain angles (depending on the location of the noise source) as illustrated in Figure 1. The angle of arrival of the noise source (θ_1 or θ_2) causes a phase difference between the external noise injected into the two wire-pairs. Let the distance between the

[1] By “wire-pair”, this contribution refers to both twisted pairs as well as quad cables.

two wire-pairs be denoted by *d*. Then the phase difference of the first noise source between the two wire-pairs is $\exp(j2\pi fd\sin\theta_1 / c)$ where *f* is the frequency, and *c* is the speed of the wave representing the noise source. Clearly, the phase difference of the noise between the two wire-pairs is a function of frequency. An additional factor is that the two wire-pairs will usually not be identical (slightly different twist characteristics or different quad geometries). The noise amplitude and phase will also differ between the two pairs due to this non-uniformity. Both these factors (angle of arrival of noise and non-uniformity among wire-pairs) together determine the ratio of the noise coupling transfer functions between the two wire-pairs. This transfer function ratio does not depend on the specific noise characteristics and is not time-varying although the noise source may be non-stationary. Therefore, once the transfer function ratio has been learned, the external noise on the DSL wire-pair can be cancelled by multiplying the noise on the extra wire-pair by this transfer function ratio and then subtracting it from the actual DSL wire-pair.

The performance of the noise canceller will depend on the correlation of the noise in the two wire-pairs. If there is only one noise source affecting both pairs, then the correlation coefficient between the noises will be 1. This is because the transfer function ratio of the noise coupling, which is simply the amplitude ratio and phase difference per tone, can be estimated. The noise on the DSL pair can then be perfectly cancelled by subtracting the noise of the extra wire-pair after adjusting its amplitude and phase. In practice, there will be other noise sources such as the receiver front end noise which are uncorrelated between the two wire-pairs. In this case, the noise correlation (often denoted by the symbol ρ) will not be exactly 1. However, if there is a single external noise source which is much larger than the uncorrelated noise, then again using the transfer function ratio for this noise, the noise on the actual DSL line can almost be cancelled except for the uncorrelated noise which will act as the noise floor. In this case, the correlation coefficient will be very close to 1 (~ 0.9 to 0.99). When there are more external noise sources each with different transfer function ratios, then in order to obtain near perfect cancellation, the number of extra wire-pairs must be greater than or equal to the number of external noise sources. Intuitively, one can think of using all the extra wire-pairs to first separate the different noise sources, estimate the transfer functions between these noises and the noises coupled to the actual DSL line and then cancel the external noises. This again implies that there is large noise correlation between the different lines. Smaller noise correlations can be observed when there are fewer extra wire-pairs than noise sources (with different transfer function ratios). This happens for example when there are two external noise sources coming from different angles and there is only one extra wire-pair as shown in Figure 1. As discussed in [3], in the upstream direction, many lines are available (either used or unused) and hence the noise will be highly correlated among the different lines which can be effectively used for noise cancellation.

3 System Description

This section elaborates on the noise canceller and discusses its training and canceling mechanisms.

3.1 Training of the Noise Canceller

For stationary noises such as BPL, AM, etc. the training of the canceller may be done at the time of initialization of the line. For non-stationary noises such as intermittent noise, impulse noise, etc. the training may need to be done during SHOWTIME as well depending on when the noise affects the system.

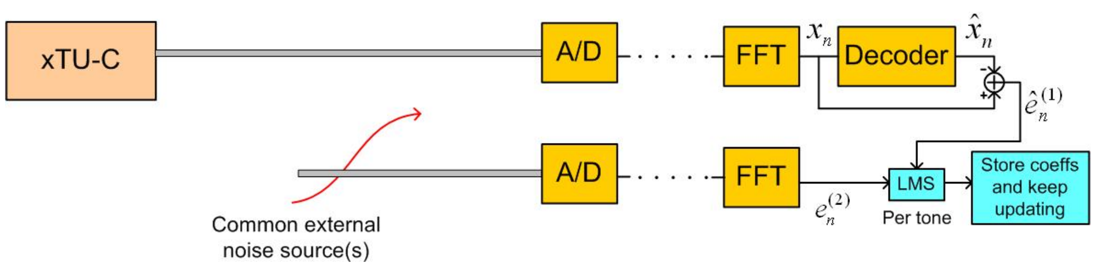


Figure 2: Block diagram describing training of the canceller.

Figure 2 shows the block diagram during the training of the noise canceller. The DSL line computes the estimate of the noise $\hat{e}_n^{(1)}$ (where n refers to the tone index) using knowledge of the transmit symbol (if training of the canceller is performed at the time of initialization) or using a decision directed scheme (setting noise = the difference between x_n and $\hat{x}_n$) if the canceller is trained during SHOWTIME. The noise on the second wire-pair is denoted by $e_n^{(2)}$. The LMS algorithm [4] is used in order to determine the transfer function per tone between these two noises (other estimation and tracking algorithms such as RLS can also be used). After training, the transfer function coefficients (consisting one amplitude and phase per tone) are stored. The stored coefficients will be used for canceling the external noise and these coefficients will be updated in order to track any changes in the noise coupling transfer functions.

When the external noise is not present at the time of training but appears during SHOWTIME, the DSL line typically experiences instability as the BER drops significantly. This often leads to re-trains and the system may train to a lower data rate. However, as far as training of the noise canceller is concerned, even a BER of 10^{-2} is not very high for the LMS algorithm. Therefore, when the external noise appears during SHOWTIME, the noise canceller will still train to the correct transfer function ratio. When the canceller turns ON, the external noise will be cancelled almost completely and the line will continue to operate at a high data rate. The training time required for the canceller can be as fast as only 100 DMT symbols i.e. 25 msecs (obtained from simulation results), depending on the step size of the LMS adaptation. The modem needs to ensure that it does not re-train for this duration. This is a one-time requirement. Once the canceller has been trained, the coefficients of the noise canceller will be stored and will be constantly tracked by the LMS algorithm. After the training of the canceller and the beginning of the noise canceling operation, the line will operate at a high data rate and will be very stable. Thus, the proposed canceller achieves stability of the DSL line without compromising on performance.

3.2 Operation of the Noise Canceller

The operation of the noise canceller is shown in Figure 3.

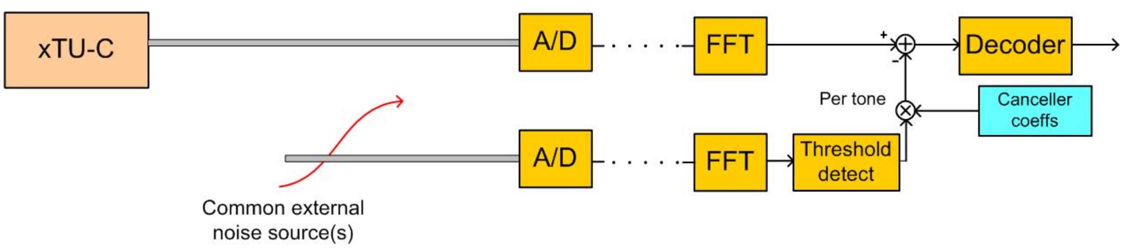


Figure 3: Block diagram describing operation of the canceller.

Using the stored transfer function ratio, then noise on the extra wire-pair is scaled and aligned in phase and then subtracted from the actual DSL line. Since, there will be uncorrelated noise and the external noise may not always be present (or may be small on some tones), the noise cancellation should to be avoided in some cases. This is achieved by using a threshold detector: If the noise is above a certain threshold, it will be cancelled, otherwise cancellation will not occur. The threshold detection is also a per-tone operation. This feature is also very useful for intermittent and impulse noise, as cancellation will only occur when the noise is present.

4 Performance of the Noise Canceller

4.1 Characteristics of Noises used in the simulations

Four different noise sources were used in the simulations.

1. **BPL:** A flat -100 dBm/Hz noise was assumed. The level of noise was obtained from [5].
2. **AM radio interference:** Tones from 530 KHz to 1.7 MHz were used. The interference power per tone was uniformly picked to be between -140 dBm/Hz and -110 dBm/Hz.
3. **Intermittent noise:** This noise source typically would originate from some device which does not strictly adhere to radiation requirements. The noise PSD used in the simulations corresponding to the device being ON is show in Figure 4.

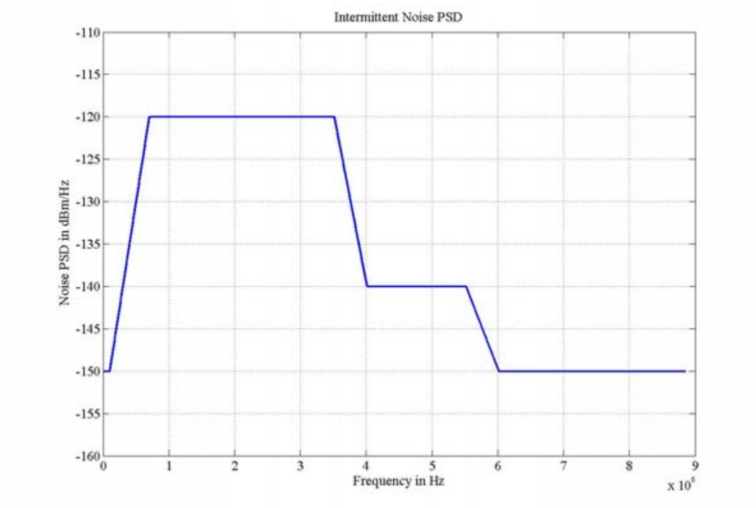


Figure 4: PSD of the Intermittent Noise

4. **Impulse Noise:** Impulse Noise Number 2 from G.996.1 [6] was chosen. The impulse waveform is shown in Figure 5. In order to obtain the impulse noise PSD, random shifts were assumed relative to the DMT symbol (which simulates what happens in reality).

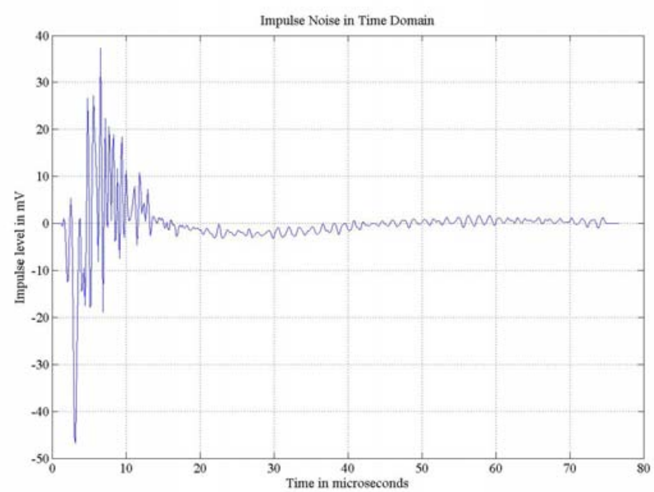


Figure 5: Impulse noise in the time domain

4.2 Simulation parameters:

Gap (at P_e=10^{-7}) = 9.8 dB

Margin = 6 dB

Coding gain = 4.2 dB

VDSL2 8.5 MHz band plan [7] and ADSL1 [8] are used for the simulations

4.3 Simulation Results:

4.3.1 Broadband over Power Line (BPL):

BPL noise is injected and uncorrelated white noise with a level of -140 dBm/Hz is also added to both the lines. A VDSL2 system is assumed. Figure 6 shows the PSDs of the noise affecting the DSL line before and after noise cancellation. The figure on the left corresponds to using 100 DMT symbols for training the noise canceller and the figure on the right corresponds to training the canceller with 500 DMT symbols. Training with more symbols improves performance; however once close to the uncorrelated noise floor, further training will lead to very small improvement. From the figures, it is very clear that the noise canceller significantly reduces the noise PSD and almost cancels all the BPL noise (figure on the right). Also, even with only 100 DMT symbols used for training the canceller, it is possible to obtain noise PSD reduction to the level shown in the figure on the right. This would be possible by using a larger step size in the LMS algorithm. However, in practice, the LMS step size used by the system may not be optimum and hence a longer training time may instead be a better solution. However, the figure on the left does indicate that the noise cancellation operation can be started even before the canceller is completely trained as significant noise reduction is already achieved with 100 DMT symbols of training.

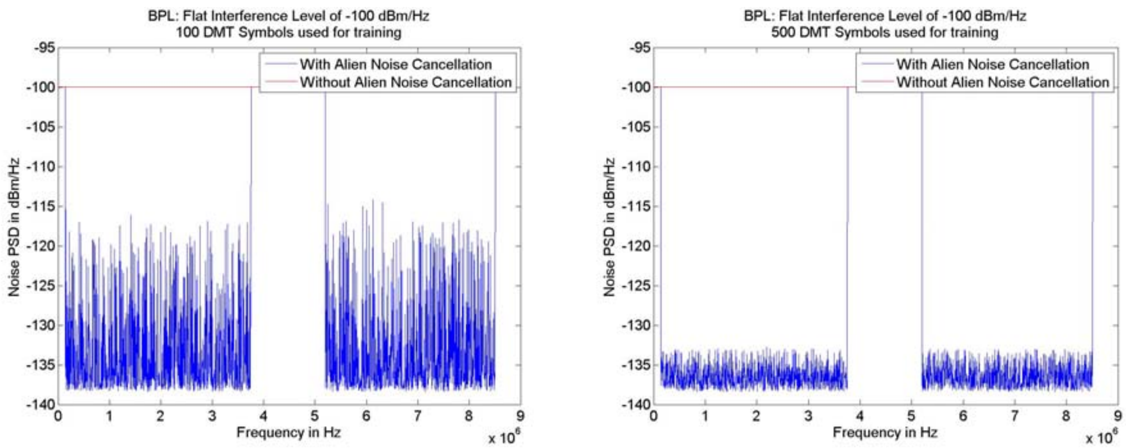


Figure 6: Noise PSDs with and without the use of the spatial noise canceller when BPL noise is present. Left: Uses 100 DMT symbols for training. Right: Uses 500 DMT symbols for training.

Figure 7 shows the data rate improvement using the noise canceller. Clearly, using the noise canceller leads to significant data rate improvement (more than 2 to 3 times) and is very close the performance of the DSL system which just -140 dBm/Hz noise!

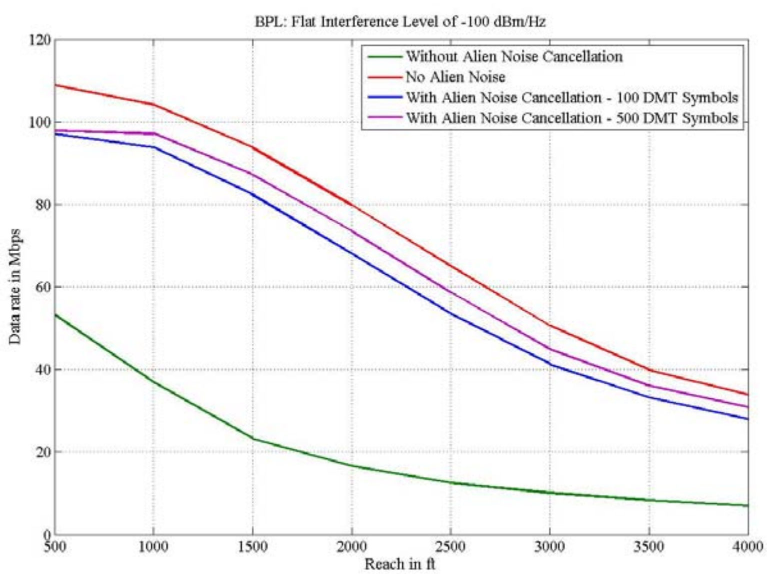


Figure 7: Data rate improvement using the spatial noise canceller.

4.3.2 AM Radio Interference:

Figure 8 shows the cancellation of AM radio interference in a ADSL1 system. The canceller aids in significantly reducing the noise on the tones where AM interference is present. Thus, the canceller solves one of the important interference problems in ADSL1 systems.

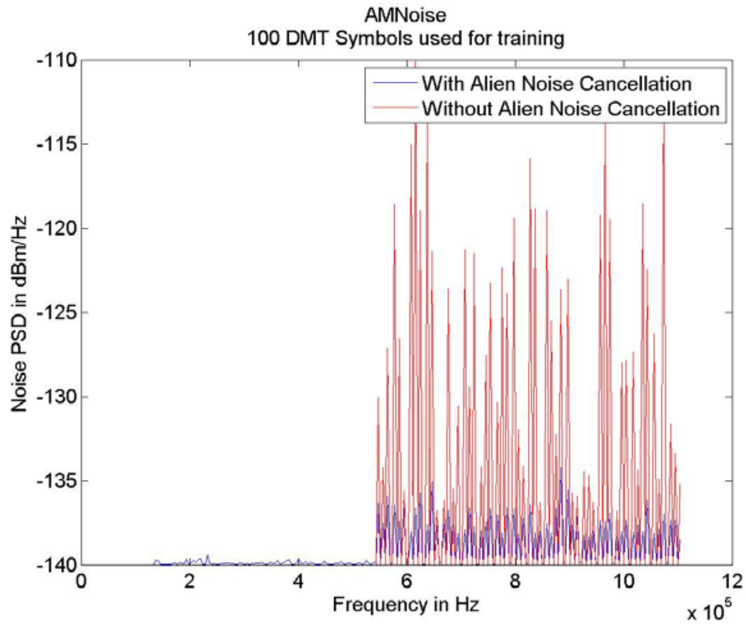


Figure 8: Reduction in AM radio interference using the spatial noise canceller.

4.3.3 Intermittent Noise:

Figure 9 shows the noise PSDs after canceling the intermittent noise in a VDSL2 system. The two figures correspond to training the canceller with 100 DMT symbols and 200 DMT symbols respectively. The noise is almost cancelled and it can also be seen that the residual noise is close to the -140 dBm/Hz background noise.

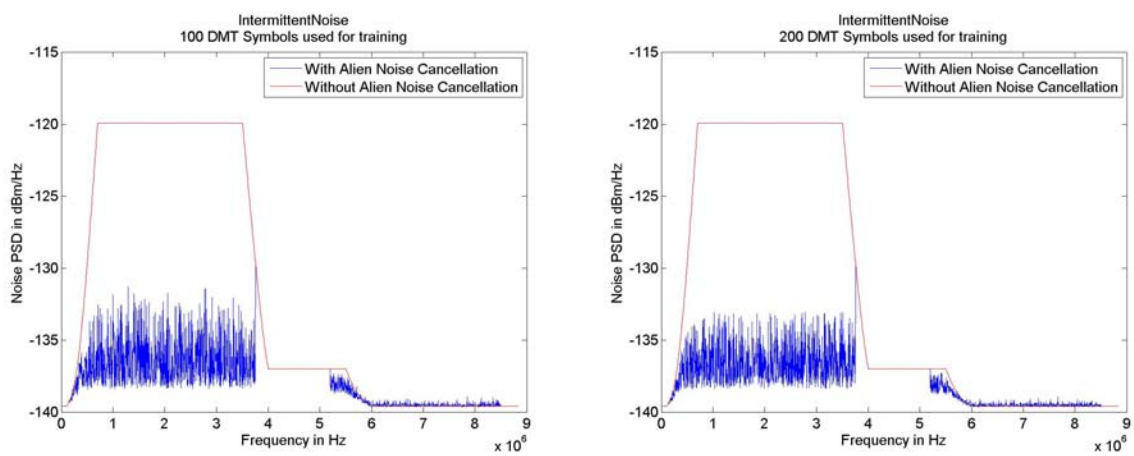


Figure 9: Noise PSDs with/without using the spatial noise canceller when quasi-stationary intermittent noise is present. Left: Uses 100 DMT symbols. Right: Uses 200 DMT symbols.

Figure 10 shows the corresponding improvement in the data rate when the intermittent noise is cancelled. The huge improvement in performance is achieved while also improving the stability of the DSL link.

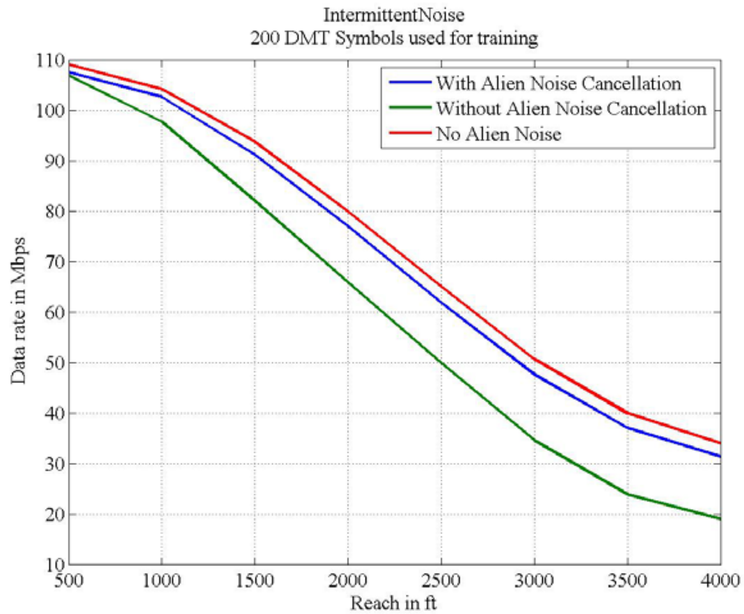
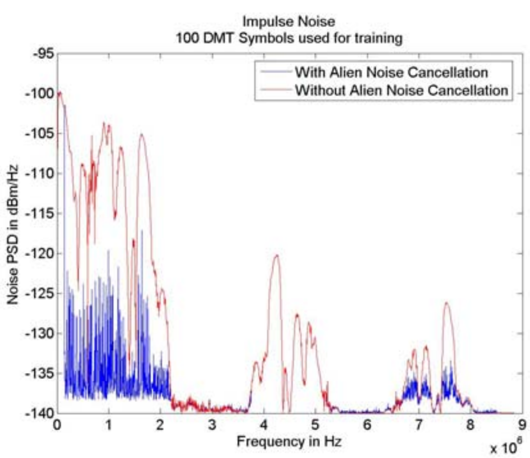


Figure 10: Improvement in data rate by canceling the intermittent noise. Line stability at the higher data rates is also improved.

4.3.4 Impulse Noise:

Figure 11 shows the ability of the noise canceller to eliminate impulse noise. The figures show the noise PSD corresponding to a particular occurrence of the impulse noise within a DMT symbol for the purpose of illustration. Clearly with 200 DMT symbols for training, the canceller nearly eliminates all the impulse noise. This will essentially solve a very important concern in current DSL systems.



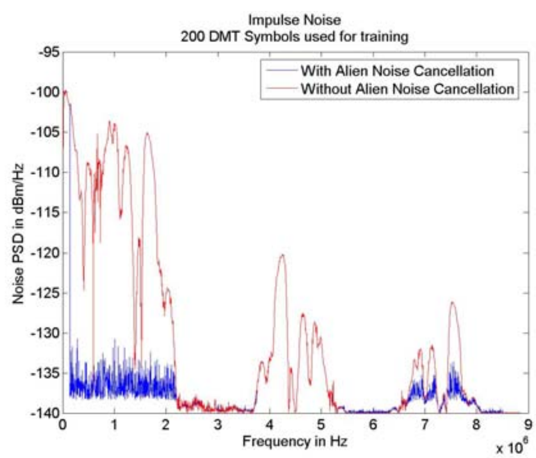


Figure 11: Cancellation of the non-stationary impulse noise.

4.4 Multiple Noise Sources:

As discussed earlier in Section 2, when there is only one extra wire-pair but more than one external noise source at a similar noise level, then the noise correlation between the two lines may reduce. The extent of the correlation will depend on the amplitude and phase with which the different noises couple to the two pairs. If one of the noise sources is dominant, then the results will be similar to those shown in Section 4.3. In this set of simulations intermittent noise and BPL (with a flat PSD of -120 dBm/Hz) was used. Figure 12 shows the noise PSDs when the correlation is not very high on some tones. The figure on the left shows that the noise correlation coefficient is smaller for the low frequency tones. Correspondingly, the figure on the right shows a greater reduction in the noise PSD in the high frequency tones and little reduction in the low frequency tones depending on the noise correlation.

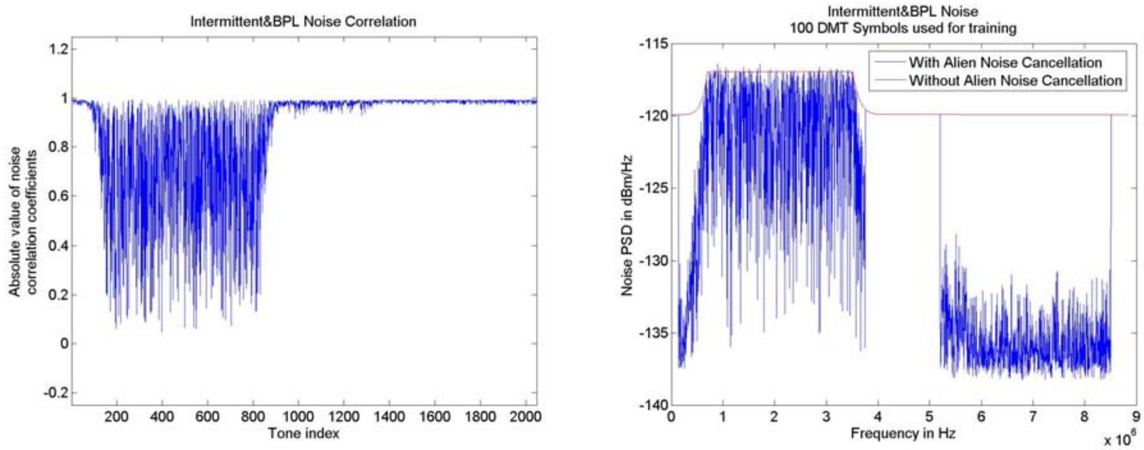


Figure 12: Two Noise Sources and Low Correlation Coefficient. Left: The Noise Correlation Coefficient between the two lines. Right: Reduction in Noise PSD with the canceller.

The greater reduction in the noise PSD obtained at higher frequencies is because the BPL noise is more dominant in that frequency range. Correspondingly, the noise correlation is close to 1 in those frequencies which explains the reason for the better noise cancellation.

5 Using more than one pair for data transmission

If the extra wire-pair contains not only the external noise but also some signal component, then a vectoring receiver (such as a GFDE [9][10]) can be used in order to exploit the extra signal power to improve the data rate. Moreover, if the service provider decides to transmit data over the second line as well to the same customer, then using the GDFE receiver, the data rate can be more than doubled since the noise correlation can be exploited to remove the large correlated interference. A block diagram of the system is shown in Figure 13.

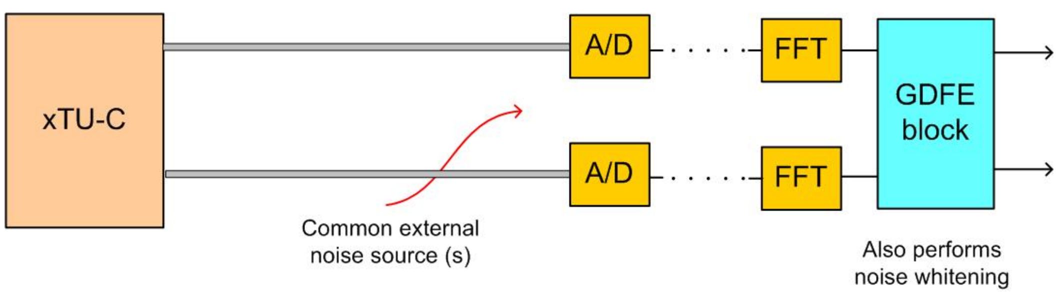


Figure 13: Using the extra wire-pair(s) for data transmission/reception.

6 Summary

Level 3 DSM concepts can be used in the DSL downstream to cancel spatially correlated noise with the aid of extra wire-pairs that may be connected at the customer-end. Using these wire-pairs, the line-stability and downstream data rate can be significantly improved. The cancellation of the spatially correlated noise enabled by these extra wire-pairs can occur for both stationary and non-stationary noise sources. The extra-wire pair can also use the self FEXT (if strong) to improve the data rate. Furthermore, if the second wire-pair is also connected at the service provider end, then even more significant gains can be expected. This contribution is informative.

7 References

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