ENSURING THE ROBUSTNESS AGAINST NON-STATIONALY NOISE OF ADSL TRANSCEIVERS WHEN APPLYING DSM

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ABSTRACT

Dynamic spectrum management (DSM) comprises a new set of techniques for multi-user power allocation in digital subscriber line (DSL) networks. One particular DSM algorithm is known as iterative water-filling, on which this study focuses. Iterative water-filling minimizes the transmit power while achieving the target bit rate. This is equivalent to decreasing the noise margin, hence lowering the robustness against non-stationary noise, as compared to today’s DSL margin-adaptive (MA) operation. The noise robustness of DSL modems translates into the stability of the DSL link.

This paper describes measurement results of non-stationary-noise robustness of DSM-enabled ADSL modems and compares it with the standard, margin-adaptive ADSL operation. Additionally, the causes for the bad noise resilience are detailed and a new bit swap procedure is introduced showing better noise robustness.

KEYWORDS

Dynamic Spectrum Management, ADSL and noise robustness.

1 Introduction

ADSL deployment is evolving to, on the one hand, ever higher bit rates enabling video services over DSL and, on the other hand, increased reach to enlarge the customer base. Both higher bit rates and increased reach can either be obtained by deploying remote terminals (RTs) or by applying dynamic spectrum management (DSM) techniques [1] [2]. DSM can provide rate/reach improvements on the shorter term, because it only requires software adaptations, whilst RT deployment involves heavy investments and hence is rather suited for the longer term.

One particular DSM technique called iterative water-filling has been implemented on ADSL modems resulting in substantial gains, especially in the case of mixed CO/RT deployment [3]. However several open questions have remained, especially with respect to spectral compatibility and stability. The spectral compatibility of ADSL modems implementing iterative water-filling, is studied in [4], while this paper focuses on the stability aspect. Indeed, robustness of a DSL modem against non-stationary noise translates to stability on the level of DSL link. Remark that throughout this paper the term DSM refers to iterative water-filling. In this paper we first study the DSL channel and the occurrence of non-stationary noise. The noise robustness of DSM-enabled ADSL modems and legacy ADSL modems operating in margin-adaptive mode are compared with one another in section 3. Additionally, a new bit swap procedure is proposed, which increases the noise robustness. In section 4 the limitation of the noise measurement of the modem is elaborated, which explains the results of section 3. Finally, some conclusions about the noise robustness and stability of ADSL modems applying DSM are drawn.
2 DSL channels and non-stationary noise

ADSL modems use discrete multi-tone (DMT) modulation as adopted in the ADSL standard [5]. The maximum bit loading is calculated on a per-tone basis, as given by equation (1), and depends on the signal-to-noise ratio (SNR) at the receiver. $k$ represents the tone index, $N_i(k)$ denotes all the noise sources different from self-FEXT (far-end crosstalk), and $\Gamma_i = 12 \text{ dB}$ is equal to the SNR gap of 9.75 dB for uncoded quadrature amplitude modulation (QAM) transmission (guaranteeing a bit-error rate (BER) of $10^{-7}$), minus the coding gain of 3.75 dB, plus the noise margin of 6 dB. $b_i^t$ denotes the number of bits that can be allocated to tone $k$ of the transmitter of user $i$. $H_x(k)$ represents the direct channel transfer function for user $i$, $H_x(k)$ the crosstalk transfer function from user $j$ to user $i$, and $S_i(k)$ the transmit power spectral density (PSD) of user $i$. An example of measured channel transfer functions for a 1400-m section of a 0.4 mm 4-quadr France Telecom cable is shown in Fig. 1.

$$b_i^t = \log_2 \left( 1 + \frac{\text{SNR} (k)}{\Gamma_i} \right)$$
$$= \log_2 \left( 1 + \frac{\left| H_x(k) \right|^2 S_i(k)}{\Gamma_i \left( \sum_{j=1}^{N_\text{t}} \left| H_{xy}(k) \right|^2 S_j(k) + N_i(k) \right)} \right) \quad (1)$$

In the following the assumption is made that the background noise of an ADSL receiver is at a PSD level of $-140 \text{ dBm/Hz}$. As can be derived from Fig. 1, the self-FEXT interference from an ADSL line operating in this cable will, on the average, approximately be at a PSD level of $-120 \text{ dBm/Hz}$, taking into account that ADSL modems transmit at $-40 \text{ dBm/Hz}$. Even worse FEXT transfer functions can be encountered in a twisted-pairs network with gains as high as $-60 \text{ dB}$. A modem initialising without crosstalkers active, will experience a drastic noise margin reduction, when a disturber comes up. The noise margin might become negative, resulting in a BER above $10^{-7}$ and possibly leading to a resynchronisation. Therefore, to avoid frequent resynchronisations, operators do not deploy ADSL at the maximum attainable bit rate, but rather at a fixed target bit rate. The remaining SNR is turned into additional noise margin, which can be quite large, especially on short loops.

A large noise margin has the advantage of high robustness against non-stationary noise sources, but it means also transmitting at high power, which, in turn, results in high crosstalk interference towards the DSL lines in the same binder. DSM proposes to optimise the overall binder capacity by decreasing transmit power (power back-off) on the lines with a high noise margin [1] [3].

Decreasing the noise margin has the disadvantage that modems become more vulnerable to fast-changing noise or channel conditions. In the next section, the DSL noise robustness is investigated, comparing traditional margin-adaptive operation and DSM.

![Fig. 1. Direct and FEXT channel transfer functions of a 1400 m section of a 4-quadr 0.4 mm France Telecom cable.](image1)

3 Non-stationary noise robustness

3.1 Noise injection set-up

Non-stationary-noise robustness is investigated by injecting time-varying noise on the line. To show DSM gains one typically needs multiple active DSL lines in a binder, but for the sake of simplicity only one DSL line is here taken into account and the non-stationary noise is emulated. As DSM is only applied to downstream transmission in the case of ADSL, the noise injection happens only at the customer premises equipment (CPE) side. Many parameters play a role in the noise-robustness measurement: loop length, bit rate, noise margin, injected noise level, noise level change, etc., but, as can be seen in the next section, the results show that the key parameters are noise margin, power back-off, changing noise level and number of active tones. Indeed, the non-stationary noise robustness is by definition the robustness versus the changing noise level. However, the study will show that the level of power back-off influences the results.

In this study, the spectral shape of the noise has been kept flat over the entire bandwidth.

![Fig. 2. Measurement set-up.](image2)
3.2 Noise robustness measurements

DSM is achieved by provisioning the modems with a target bit rate and a maximum additional noise margin set to zero. The target noise margin is set to 6 dB and the only noise robustness the modems have left beside the noise margin is the bit swap procedure. Unfortunately, the bit swap protocol is limited to maximum 6 swaps per message [5]. Furthermore, the bit swap is done over the ADSL overhead channel (AOC) with at least 800 ms between every bit swap message. Both restrictions limit the achievable noise-increase recovery. The measurement results for DSM, when all tones are loaded with bits, are shown in Fig. 3 and labeled as ‘DSM without QB’. The label ‘DSM with QB’ is explained further. The modems are DSM-enabled prototypes and can apply power back-off up to 20 dB, in comparison with standard ADSL1 modems, which are limited to 12 dB of power back-off. The figure shows the maximum noise increase an ADSL transceiver can handle without re-synchronisation versus the power back-off level.

![Fig. 3. Noise-robustness measurements.](image)

Fig. 3 shows us that conventional ADSL1 modems operating at fixed margin (DSM without QB) can only recover from a maximum noise increase of 7.5 dB. Indeed, the maximum power back-off of a standard ADSL modem is limited to 12 dB, for which the figure shows that the maximum noise increase is equal to 7.5 dB. In case of an upcoming first disturber, this is certainly not enough. Concerning the enhanced power back-off of a standard ADSL modem, one remarks that a larger power back-off results in a better noise robustness. The explanation can be found in the difference between initialisation and showtime. During initialisation, the modem is training and transmits at –40 dBm/Hz (somewhat lower if politeness is applied). During the training period, a noise measurement is performed on which the modem will compute the power back-off value assuming the noise level will remain constant. The noise measurement comprises the background noise and crosstalk noise, but also signal-related noises such as inter-symbol interference (ISI), inter-carrier interference (ICI) and noise inherent to the modem. This means that, if a modem performs a large power back-off, the total noise will decrease also. This is why the noise margin, when entering showtime, is slightly larger than 6 dB, which results in a slightly better noise robustness.

The figure shows also the comparison with margin-adaptive operation, which is equivalent to no DSM. In that case, the x-axis has to be seen as additional noise margin instead of power back-off. Indeed, the noise margin is not decreased and no power back-off is applied. As expected, the robustness against a sudden noise increase grows linearly with the noise margin.

In case only a few tones are loaded with bits, the modems operating in DSM mode perform better against non-stationary noise. Indeed, for a few active tones the bitswap can increase the transmit PSD faster than when many tones are active. The results when 40 tones are active are shown in Fig. 4. However, this study focuses on high bit rates with modems applying power back-off and its impact on non-stationary noise robustness. Modems with only a few active tones are most of the time operated at the line’s maximum bit rate, be it a low bit rate, hence no power back-off can be applied.

![Fig. 4. Noise-robustness measurement on long loop](image)

3.3 Improved noise robustness

Applying DSM with a slow bit swap algorithm makes it impossible for the modem to adapt to quick noise or channel changes. Therefore, we have introduced a quick g, boost message, i.e. a very short message that asks the far-end to boost all carriers with a certain gain included in the message. The noise robustness increases thanks to two factors. First, the message is very short. This lowers considerably to probability of corrupt message reception [6]. Second, the transmit PSD of all carriers is increased at once. In our emulation, the noise increase is flat, for which
a flat quick g, boost gives great benefit, but even for shaped noise increases, a quick g, boost makes it possible to recover very fast from a negative noise margin. The fine-tuning to restore the noise margin to the same level for all carriers happens then with the traditional bit swap mechanism.

In Fig. 3, the possible noise increases versus power back-off is denoted as ‘DSM with QB’. As can be seen from the figure, the noise robustness is better by up to three dB compared to DSM without quick g, boost. DSM with quick g, boost can be said to be as stable as fixed power operation up to 4 dB power back-off. Once more power back-off is applied, the noise robustness decreases.

There are 2 reasons for this relatively small robustness improvement. First, the noise measurement within the modem is not accurate when large noise increases occur. The modem measures a noise increase smaller than it is in reality and therefore makes a request for a quick g, boost that is too low compared to the noise. Second, the AOC protocol carrying the bit swap is slow such that no more than two consecutive quick g, boost messages can be carried out before the modem goes out of showtime.

How the noise measurement within a modem happens and its limitations are detailed in next section. Concerning the AOC protocol and its impact on noise robustness, we refer to [6]. It has to be noted that AOC and bit swap are improved in ADSL2, but still no quick g, boost message is implemented.

No investigation has been done on mutual interference and stability of several modems applying quick g, boosts. Although the convergence of iterative water-filling has been theoretically proven in [1], the stability of many modems applying DSM together with quick g, boosts is still an open issue. Indeed, a quick g, boost changes suddenly the transmit PSD on one line, but this results in a sudden change of the crosstalk seen by neighbouring lines, hence triggering a quick g, boost on the neighbouring lines.

4 Modem noise measurement limitations

DMT is based on quadrature amplitude modulation (QAM) on many tones. Looking to one tone, QAM modulation bit loading is given by equation (1) where the implicit accepted BER is equal to $10^{-3}$. The BER is derived from the symbol error probability, i.e. the probability that a wrong decision is made at the receiver. QAM demodulation at the receiver is based on hard decisions and the process of corrupt symbol detection is shown in Fig. 5. After the decision is made, right or wrong, the difference between the demodulated symbol and the received signal is measured as noise. This means that the measured noise will never exceed the maximum distance from demodulated to received symbol within one decision region, which is $\sqrt{2} \cdot d$.

During normal operation, noise measurement is quite accurate as symbol-error occurrence is relatively small, but as soon as the noise increases substantially, more symbol errors are introduced and the accuracy of the noise measurement degrades. From a quantitative point of view, an increase of the noise implies an increase of the variance of the gaussian noise probability density function. In extreme noise-increase cases where the noise blows away the signal, the noise can be seen as equally distributed over the decision region. The measured noise is then given by equation (2), the variance of the decision region.

Comparing this noise variance with the noise variance during normal operation yields a ratio close to $\Gamma_i$ defined in equation (1). Indeed, from equation (1), one knows that the stationary noise $N = \frac{S_y}{(2^b - 1)\Gamma_i}$, with $S_y$ the power of the received signal. As an example, for 16 QAM shown in Fig. 5, $S_y = \frac{10}{4} d^2$ for which then $N = \frac{d^2}{6\Gamma_i}$. The noise increase is then given by equation (3).

$$\sigma^2 = \frac{1}{d^2} \iiint (x^2 + y^2) dx\ dy = \frac{1}{6} d^2$$

$$\frac{\sigma^2}{N} = \Gamma_i$$

For huge noise increases, the noise increase measurement is thus approximately limited to $\Gamma_i$. As a consequence, in case of a large noise increase, the modem will sense a smaller noise increase than it is in reality. The modem will therefore send a request for a quick g, boost of a lower value than really needed resulting in the necessity for several quick g, boosts. The time needed for recovery from a noise increase is then too long and the modem resynchronises.
5 Conclusion

In this paper the non-stationary-noise robustness of ADSL modems applying iterative water-filling, also known as autonomous DSM, is investigated. DSM is known to trade off the excess noise margin of traditionally operated ADSL for performance increase. To quantify the noise robustness, DSM-enabled ADSL modem prototypes are compared to traditionally operated margin-adaptive ADSL modems.

The results show that the non-stationary robustness of DSM-enabled lines can be increased with about 3 dB, by introducing a quick $g_i$ boost procedure. There are 2 opportunities to improve the noise robustness even further.

The first opportunity is inherent to QAM modulation: the modem measures a noise increase smaller than it is in reality. Second, the AOC protocol carrying the bit swap is too slow to be able to track fast time-varying noises, the modem runs too fast out of margin triggering a re-initialisation.

Finally, the mutual interference and stability of several modems applying DSM and $g_i$ boost is still an open issue to be further investigated.

References:


