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Jointly Optimizing the Virtual Noise Mask and the SNR Margin for improved Service in xDSL Systems

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***Abstract*—In Digital Subscriber Line (DSL) systems, the concept of Virtual Noise was introduced to improve the protection against fluctuating crosstalk and to increase link stability. This paper investigates the joint optimization of the Virtual Noise power spectral density and the initialization SNR margin. A new algorithm is developed for modems to estimate the optimum Virtual Noise power spectral density and the initialization SNR margin from crosstalk measurements. Using this algorithm leads to both a better stability in terms of outage probability and an improvement in the achieved data rates compared to the traditional SNR margin approach. Moreover, it makes the use of the Low Power mode in VDSL2 systems possible.**

I. Introduction

Over the last decade, Digital Subscriber Lines (DSLs) have emerged as a key technology for deploying services such as video and Voice-over-IP (VoIP) which pose high requirements on data rates, latency and line stability. With constantly growing bandwidth demands, the problem of far-end crosstalk (FEXT) between copper wires in telephone binders has become increasingly important and is in fact the dominant impairment in current DSL systems [3].

Crosstalk in DSL systems occurs due to electromagnetic coupling between copper wires in a multi-pair telephone cable [1]. The noise perceived by a DSL line is comprised of background noise and by the summation of crosstalk from all other active lines in the bundle. Hence, it fluctuates when DSL users turn on/off their modems or enter/exit the low power state. The Low Power (L2) state is an operational state in which the transmitted power can be scaled down by up to tens of dB if there is little or no need for transmission of information on the link from Transceiver Unit at the the Central Office to the Transceiver Unit at the remote site [5]. Furthermore, the received noise power is frequency-dependent and can be described by the noise power spectral density (PSD).

In asymmetric DSL (ADSL) and very high speed DSL (VDSL2) systems the transmission channel is divided to multi-tone subchannels using the discrete multi-tone modulation (DMT) [4]. For the bitloading of the used tones, the noise PSD needs to be known. Ideally, the bitloading is calculated every time the noise PSD changes. However, in DSL the noise PSD used for bitloading is measured during initialization and the resulting data rate remains usually constant during operation. In case the noise PSD increases during operation such that a transmission with the data rate and the error probability calculated during initialization is not possible, the connection is interrupted and the user is considered to be in outage.

The traditional way to protect against the fluctuating noise is to include a fixed tone-independent 6 dB SNR margin in the bitloading of the DMT modems at initialization. The SNR margin is the decrease in the SNR that can be withstood by the system at the same target data rate and error probability [2].

A major drawback of using a fixed SNR margin during initialization arises when modems are initialized during low noise times and the noise increases during operation such that the SNR margin assigned during initialization is not enough to sustain the connection. This problem occurs when disturber modems are switched on or exit the L2 state which leads to a sudden increase of the transmitted power by as much as tens of dB. This will result in a large and abrupt increase of the crosstalk and it is very likely that the modem will not be able to recover and the connection will therefore be interrupted [5]. For this reason, L2 mode is not widely used in ADSL2/ADSL2+ systems, although it has already been standardized. Furthermore, it was not yet standardized for VDSL2 [5].

The intuitive approach of assigning a higher SNR margin during initialization will lead to a tremendous loss in the overall data rate, since modems will use the same margin also when initialized during high noise times.

To improve the protection against fluctuating noise and increase link stability, the concept of Virtual Noise has been introduced [8]. The Virtual Noise is a tone-dependent noise PSD specified in the central office management information base and communicated to the transceivers during initialization [9]. The reference noise PSD, which is the maximum of the Virtual Noise PSD and the measured noise PSD, is used for calculating the bitloading on each tone during initialization and showtime [8]. An SNR margin much smaller than 6 dB is assigned during initialization to compensate any increase of the reference noise PSD during operation. Although the Virtual Noise concept has been standardized for VDSL2, there has been, to the best of the anthers' knowledge, no solutions published on how to determine the Virtual Noise PSD and the initialization SNR margin such that a target outage probability is achieved. In [8], [2] it was suggested that a worst-case noise PSD shall be used as a Virtual Noise PSD, but no approaches were shown neither on how to determine the worst-case noise PSD nor on how to determine the initialization SNR margin. For Virtual Noise to be implemented in todays DSL systems, approaches have to be found on how to determine the Virtual Noise PSD and the initialization SNR margin. The topic of estimating the Virtual Noise PSD and the initialization SNR margin from measurements is addressed in this paper and an algorithm that jointly optimizes the Virtual Noise PSD and the SNR margin for a given outage probability is presented. Furthermore, it is shown that by using the proposed algorithm, the L2 mode can be efficiently implemented in VDSL2 systems.

II. System model

An N-user DSL binder is considered. The N users employ DMT over tones $k = 1, \ldots, K$. Assuming perfect synchronization of the transmitters and a sufficiently long cyclic prefix, each tone can be modeled as an independent K-user Interference Channel. Let $h_k^{n,n}$ denote the direct channel coefficient of user n on tone k and $h_k^{n,m}$ $(n \neq m)$ denote the FEXT channel coefficient from disturber m to user n. Furthermore, we define $(\sigma_z^n)^2$ as the variance of the white Gaussian noise received by user n and s_k^n as the average transmit power of user n on tone k. Let VN_n^k denote the value of the Virtual Noise PSD at the receiver of user n on tone k. The Virtual Noise is communicated to the transceivers during initialization and remains constant during operation.

For the system explained above, the virtual-signal-to-noise-ratio (VSNR) seen at the receiver of user n and used for the bitloading of tone k is given by

$$VSNR_k^n = \frac{|h_k^{n,n}|^2 s_k^n}{\max\{VN_k^n, \sum_{m\neq n} |h_k^{n,m}|^2 s_k^m + (\sigma_z^n)^2\}} \quad (1)$$

Moreover, let Γ denote the SNR gap to the capacity of an uncoded QAM system. Γ is a function of the target bit error probability P_{e} and the coding gain. Let γ_k^n denote the virtual SNR margin on tone k of user n. The virtual SNR margin γ_k^n describes the decrease in the $VSNR_k^n$ that can be withstood at tone k such that the same bit-loading and SNR gap can still be used at that tone. Using the Shannon-gap approximation [1], [4], the bit-loading of user n on tone k results in

$$b_k^n = \log_2\left(1 + \frac{1}{\Gamma\gamma_k^n} VSNR_k^n\right). \quad (2)$$

The bit-loading is calculated at the receiver side and communicated to the transmitter. Given the bit-loading in (2) and with f_s being the symbol rate, the achievable total data rate R^n of user n is then found by

$$R^n = f_s \sum_k b_k^n. \quad (3)$$

III. Outage Probability

In DSL communication systems, the outage probability is an important metric for ensuring a certain Quality of Service (QoS) for the users. Techniques like the SNR margin and the Virtual Noise were developed to try to guarantee a certain QoS by taking into account future FEXT variations. Since the FEXT noise measured by a victim user at a tone k is comprised of single FEXT contributions from active DSL users who utilize tone k, the distribution of FEXT on DSL lines depends strongly on the DSL user activity. In [6] statistics measured from 20.000 DSL lines were presented and discussed. According to [6], the number of DSL active users is strongly daytime dependent. Consequently, the distribution of FEXT on DSL lines is daytime dependent and thus, not stationary. With this observation, and by assuming that the distribution of the number of active DSL users is cyclostationary with the period of one day, we define the outage probability as:

The outage probability $P_{\mathtt{out}}^n$ is the probability that the error probability exceeds the target error probability for a user n who is connected for 24 hours regardless of his initialization time and operating at the target data rate.

IV. Outage Probability as a function of Virtual Noise and SNR margin

This section shows how the outage probability can be expressed in terms of the Virtual Noise PSD and the SNR margin. We will first define an outage probability per tone and then derive an expression for the outage probability $P_{\mathtt{out}}^n$ defined in the previous section.

In DSL, the channel coefficients $h_k^{n,m}$ can be assumed to be static [1]. The average transmitted power s_k^n stays therefore constant for a fixed number of bits b_k^n being transmitted. Furthermore, let X_k^n be a random variable modeling the non-stationary noise $x_k^n = \sum_{m\neq n} |h_k^{n,m}|^2 s_k^m + (\sigma_z^n)^2$ experienced by user n on tone k. The variation in x_k^n results from disturbers changing their operational mode. Let $\gamma_{\mathtt{init}}^n$ be the SNR margin allocated to user n and $x_{\mathtt{init},k}^n$ the noise experienced by user n on tone k during initialization.

With these definitions, the random variable describing the variation in the virtual SNR margin $\gamma_k^{\mathtt{dB},n}$ over time is given in dB scale by:

$$\begin{aligned}\Upsilon_k^{\mathtt{dB},n} &= \gamma_{\mathtt{init}}^{\mathtt{dB},n} - \big(\max\{VN_k^{\mathtt{dB},n}, X_k^{\mathtt{dB},n}\} \\ &- \max\{VN_k^{\mathtt{dB},n}, x_{\mathtt{init},k}^{\mathtt{dB},n}\}\big). \end{aligned} \quad (4)$$

Knowing that the virtual SNR margin and not the actual SNR margin is considered in calculating the bitloading, we define the outage probability per tone $P_{\mathtt{out},k}^n$ as follows:

The probability $P_{\mathtt{out},k}^n$ is the probability that the virtual SNR margin $\Upsilon_k^{\mathtt{dB},n}$ becomes negative for a user n who is connected for 24 hours regardless of his initialization time.

The random variable $\Upsilon_k^{\mathtt{dB},n}$ is a function of $X_k^{\mathtt{dB},n}$ and is therefore also non-stationary. As a consequence, the probability $\mathtt{Pr}\{\Upsilon_k^{\mathtt{dB},n} < 0\}$ is a function of time and does not describe the per tone outage probability $P_{\mathtt{out},k}^{\mathtt{dB},n}$ defined above. To be able to express $P_{\mathtt{out},k}^n$ we need an expression for the per tone SNR margin that is stationary within 24 hours. We therefore define the random variables $Y_{\mathtt{max},k}^{\mathtt{dB},n}$ and $\Upsilon_{\mathtt{min},k}^{\mathtt{dB},n}$ modeling the maximum noise and the minimum virtual SNR margin that can be experienced by user n on tone k over 24 hours, respectively. The per tone outage probability $P_{\mathtt{out},k}^n$ can now be expressed by

$$P_{\mathtt{out},k}^n = \mathtt{Pr}\{\Upsilon_{\mathtt{min},k}^{\mathtt{dB},n} < 0\} \quad \text{with} \quad (5)$$

$$\begin{aligned}\Upsilon^{\mathrm{dB},n}_{\mathtt{min},k} &= \gamma^{\mathrm{dB},n}_{\mathtt{init}} - \Big(\max\{VN^{\mathrm{dB},n}_k, Y^{\mathrm{dB},n}_{\mathtt{max},k}\} \\ &- \max\{VN^{\mathrm{dB},n}_k, x^{\mathrm{dB},n}_{\mathtt{init},k}\}\Big). \end{aligned} \tag{6}$$

To express the over all outage probability $P^n_{\mathtt{out}}$ analogously to (5), an expression for the SNR margin over all used tones is needed. We therefore use the equivalent SNR margin defined in [2]. In [2], gain and bit-swapping procedures are assumed to be implemented. Gain and bit-swapping procedures equalize the SNR margin across tones by moving bits with higher energy cost to those with lower energy cost [10].

The equivalent SNR margin $\tilde{\gamma}^{\mathrm{dB},n}$ was defined in [2] to be: *The SNR margin that can be applied equally to all tones, while maintaining the data rate obtained using the unequal per tone SNR margins $\gamma^{\mathrm{dB},n}_k$ for a given channel, noise spectrum and transmit PSD.* The equivalent SNR margin $\tilde{\gamma}^{\mathrm{dB},n}$ is given by

$$\tilde{\gamma}^{\mathrm{dB},n} \approx \frac{1}{K}\sum_k \gamma^{\mathrm{dB},n}_k. \tag{7}$$

[2]. The approximation is accurate when the SNR is high, which is typical in DSL systems [2]. Applying (7) to the random variable $\Upsilon^{\mathrm{dB},n}_{\mathtt{min},k}$, the minimum possible equivalent virtual SNR margin over 24 hours is given by $\tilde{\Upsilon}^{\mathrm{dB},n}_{\mathtt{min}} \approx \frac{1}{K}\sum_k \Upsilon^{\mathrm{dB},n}_{\mathtt{min},k}$. The outage probability $P^n_{\mathtt{out}}$ can now be expressed by

$$P^n_{\mathtt{out}} = \mathtt{Pr}\{\tilde{\Upsilon}^{\mathrm{dB},n}_{\mathtt{min}} < 0\}. \tag{8}$$

Note that this definition takes into account that the virtual SNR is considered in the bitloading and not the actual SNR.

By inserting (6) in (8), the outage probability $P^n_{\mathtt{out}}$ is given by

$$\begin{aligned}P^n_{\mathtt{out}} &= \mathtt{Pr}\{\sum_k \max\{VN^{\mathrm{dB},n}_k, Y^{\mathrm{dB},n}_{\mathtt{max},k}\} \\ &- \max\{VN^{\mathrm{dB},n}_k, x^{\mathrm{dB},n}_{\mathtt{init},k}\} > K\gamma^{\mathrm{dB},n}_{\mathtt{init}})\}. \end{aligned} \tag{9}$$

Therefore, the cumulative distribution function (cdf) of the random variable

$$J^n = \sum_k \max\{VN^{\mathrm{dB},n}_k, Y^{\mathrm{dB},n}_{\mathtt{max},k}\} - \max\{VN^{\mathrm{dB},n}_k, x^{\mathrm{dB},n}_{\mathtt{init},k}\} \tag{10}$$

and the SNR margin $\gamma^{\mathrm{dB},n}_{\mathtt{init}}$ are required for the determination of the outage probability.

V. Jointly optimizing Virtual Noise and SNR margin

This section shows that the Virtual Noise PSD and the SNR margin can be jointly optimized to achieve a certain outage probability $P^n_{\mathtt{out}}$.

Here, we make the assumption that the K random variables $Y^{\mathrm{dB},n}_{\mathtt{max},k}$ come from a K-variate Gaussian distribution with the K marginal cdfs $F_{Y^{\mathrm{dB},n}_{\mathtt{max},k}}$, $k = 1,\cdots,K$.

The expression $\max\{VN^{\mathrm{dB},n}_k, Y^{\mathrm{dB},n}_{\mathtt{max},k}\}$ in (10) and the statistical correlation between the cdfs $F_{Y^{\mathrm{dB},n}_{\mathtt{max},k}}$, $k = 1,\cdots,K$ are what make the analytical derivation of the cdf of J^n complex. To be able to express the cdf of J^n, we denote the value of the Gaussian cdf at the 0,1% percentile as $P_{0,1}$ and set

$$VN^{\mathrm{dB},n}_k = \mathtt{min}\{Y^{\mathrm{dB},n}_{\mathtt{max},k}\} \approx F^{-1}_{Y^{\mathrm{dB},n}_{\mathtt{max},k}}(P_{0,1}), \tag{11}$$

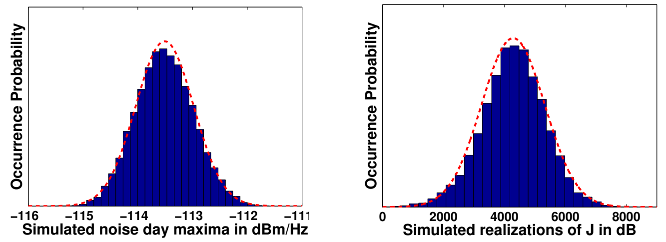

Fig. 1: Comparison of the occurrence probability of the simulated noise day maxima on tone 1800 and of simulated realizations of J^n with the probability density function of a Gaussian distribution.

Here, we approximated the minimum of $Y^{\mathrm{dB},n}_{\mathtt{max},k}$ by its 0,1% percentile. J^n becomes

$$J^n = \sum_k Y^{\mathrm{dB},n}_{\mathtt{max},k} - \sum_k \max\{F^{-1}_{Y^{\mathrm{dB},n}_{\mathtt{max},k}}(P_{0,1}), x^{\mathrm{dB},n}_{\mathtt{init},k}\}. \tag{12}$$

The first sum in (12) is a linear combination of the components of a K-variate Gaussian distribution and is therefore by definition Gaussian distributed. The second sum in (12) is a shift. Thus, the random variable J^n is Gaussian distributed. Furthermore, we denote the cdf of J^n by F_{J^n}. With this observation, the SNR margin $\gamma^{\mathrm{dB},n}_{\mathtt{init}}$ is given by

$$\gamma^{\mathrm{dB},n}_{\mathtt{init}} = \frac{F^{-1}_{J^n}(P^n_{\mathtt{out}})}{K}. \tag{13}$$

With the Virtual Noise PSD defined in (11) and with the SNR margin defined in (13) for a given initialization noise $x^{\mathrm{dB},n}_{\mathtt{init},k}$, the target outage probability $P^n_{\mathtt{out}}$ is achieved.

We justify the K-variate Gaussian assumption by simulating the maximum occurred noise over 24 hours. In the following, the maximum occurred noise over 24 hours will be referred to as noise day maxima. Figure 1 shows the occurrence probability of simulated noise day maxima for a single tone and of simulated realizations of J^n compared to the probability density function of a Gaussian distribution. In Figure 1, $x^{\mathrm{dB},n}_{\mathtt{init},k}$ is assumed to be smaller than $VN^{\mathrm{dB},n}_k$ for $k = 1,\cdots,K$. Obviously, both simulated distributions are similar to the Gaussian distribution.

VI. The hybrid Virtual Noise/SNR margin approach

This section presents an algorithm for the estimation of the Virtual noise PSD defined in (11) and the initialization SNR margin defined in (13). First, we will explain the estimation methods used in the algorithm and then, the general steps of the Hybrid Virtual Noise/SNR margin approach are presented. For simplicity of notation, the user index n is left out.

The estimate of an inverse of a Gaussian cdf F at a probability P calculated from a sample of size R is given by: $\hat{F}^{-1}(P) = \hat{\mu} + \Phi^{-1}(P)\frac{\hat{\sigma}}{c4(R)}$, where $\hat{\mu}$ and $\hat{\sigma}$ are the sample mean and the sample standard deviation, respectively. $\Phi^{-1}(\cdot)$ is the inverse function of a standard normal cdf and $c4(R)$ is a bias correction factor for a sample of size R [11]. In the following, estimating a distribution F from a sample, yielding $\hat{F}$, implies estimating its sample mean and its bias corrected sample standard deviation.

To be able to fulfill the outage probability even when the estimation is done from a small sample of measurements, a powerful tool for statistical inference known in literature as parametric Bootstrapping is used for the construction of the confidence interval [7]. For small sample sizes, the Bootstrap makes substantial corrections that significantly improve the inferential accuracy of the confidence interval estimate compared to standard methods [7].

In the following, the algorithm used by modems during initialization for the estimation of the Virtual noise PSD and the initialization SNR margin is presented. It is assumed that the noise day maxima $y^{\mathtt{dB}}_{\mathtt{max},k}(r)$, $r=1,\cdots,R$, $k=1,\cdots,K$ have been measured over R days and that a measurement of $x^{\mathtt{dB},n}_{\mathtt{init},k}$ is available during initialization.

Hybrid Virtual Noise/SNR margin approach

step 1 From $y^{\mathtt{dB}}_{\mathtt{max},k}(r)$, $r=1,\cdots,R$, $k=1,\cdots,K$ calculate estimates of the cdfs $F_{Y^{\mathtt{dB}}_{\mathtt{max},k}}$, $k=1,\cdots,K$, yielding $\hat{F}_{Y^{\mathtt{dB}}_{\mathtt{max},k}}$ and set $\widehat{V}N^{\mathtt{dB}}_k$ according to (11)

$$\widehat{V}N^{\mathtt{dB}}_k=\hat{F}^{-1}_{Y^{\mathtt{dB}}_{\mathtt{max},k}}(P_{0,1}),\quad k=1,\cdots,K$$

step 2 From $x^{\mathtt{dB},n}_{\mathtt{init},k}$, $y^{\mathtt{dB}}_{\mathtt{max},k}(r)$ and $\widehat{V}N^{\mathtt{dB}}_k$, $r=1,\cdots,R$, $k=1,\cdots,K$, calculate R estimate realizations of J according to (12), yielding $\hat{J}(r)$, $r=1,\cdots,R$.

step 3 From $\hat{J}(r)$, $r=1,\cdots,R$ calculate an estimate of the cdf F_J, yielding $\hat{F}_J$.

step 4 From $\hat{F}_J$ draw a random sample of size R. This is a resample.

step 5 From this resample calculate an estimate of the cdf F_J, yielding $\hat{F}^*_J$ and calculate the initialization SNR margin $\hat{\gamma}^{\mathtt{dB}*}_{\mathtt{init}}$ according to (13)

$$\hat{\gamma}^{\mathtt{dB}*}_{\mathtt{init}}=\frac{\hat{F}^{*\,-1}_J(P_{\mathrm{out}})}{K}.$$

step 6 Repeat steps 4-5 B times, where B is a large number.

step 7 Construct a 95% confidence interval, which is a common value for interval estimation, from the relative frequency histogram of the $B\times\hat{\gamma}^{\mathtt{dB}*}_{\mathtt{init}}$ values.

step 8 Set the initialization SNR margin $\hat{\gamma}^{\mathtt{dB}}_{\mathtt{init}}$ equal to the upper bound of the 95% confidence interval.

VII. User activity model

In this section, a stochastic model that describes the DSL user activity is introduced. The model is used in all the simulations shown in this paper.

We model the status of a DSL user by a three-state Markov chain. A user can be either connected, in showtime (L0 state) or L2 state, or off the Internet (L3 state). The model is shown in Figure 2. The probabilities $P_{L3L0}(t)$, P_{L0L3}, P_{L2L0}, P_{L2L3} and $P_{L0L2}(t)$ are the transition probabilities between the states L0, L2 and L3. Here, the L0 and L2 session durations are assumed to be daytime independent. The probabilities P_{L0L3}, P_{L2L0} and P_{L2L3} are therefore time invariant. $P_{L3L0}(t)$ and $P_{L0L2}(t)$ are time-variant to model the daytime-dependence of the user activity. For the determination of the transition probabilities, results from [6] were used. In [6], following statistics were presented:

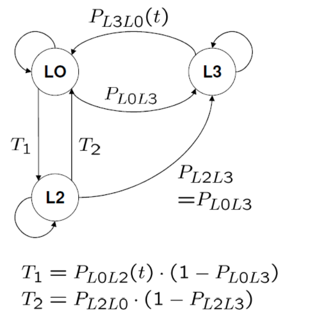

Fig. 2: Modeling user activity with a three-state Markov chain.

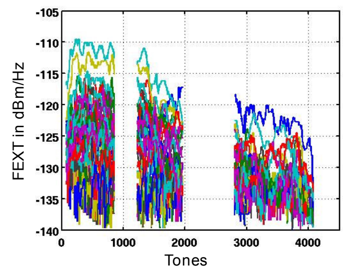

Fig. 3: FEXT noise experienced by the victim line when each disturber is active alone.

- Average relative number of active DSL lines over a 24h period.
- Probability density function of the online (L0+L2) session duration per DSL line.
- Fraction of active lines using at least 10% of their available bandwidth.

Furthermore, it was assumed that the fraction of active DSL users in L2 state over 24 h is given by the fraction of active lines using less than 10% of their available bandwidth. The transition probabilities were determined such that simulations of the previous statistics were consistent with the ones presented in [6].

VIII. Simulation results

This section presents simulation results to show the benefits of using the Hybrid Virtual Noise/SNR margin approach in both, DSL systems that implement L2 mode and DSL systems that do not implement L2.

For the simulations, a downstream scenario with a VDSL2 victim line and 39 VDSL2 disturber lines is assumed. The transmit PSD masks used are according to VDSL2 band plan 998ADE17M2xB [9]. The non-stationary noise used in the simulations is generated in two separate stages. In the first stage, we measure the background noise on a victim line and the noise resulting when each disturber is active alone at Nokia Siemens Network's DSL lab. Figure 3 shows the measured FEXT noise experienced by the victim line when each disturber is active alone. In the second stage, we generate non-stationary noise by using the user activity introduced in the previous section combined with the background noise and the FEXT contributions measured in the first stage. Since L2 mode was not included in the VDSL2 standard, we were not able to operate the modems in L2 mode and therefore we treated a modem in the L2 state as if it was turned off. For the data rate calculations we assume an SNR gap of 6.8 dB and a symbol rate of 4 kHz.

Figure 4 shows the outage probabilities when using the Hybrid

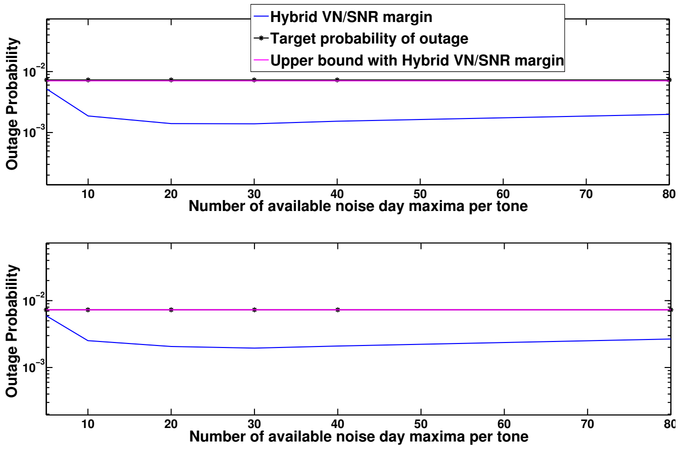

Fig. 4: Outage probabilities. In the upper Figure, L2 mode is implemented, in the lower Figure, L2 mode is not implemented.

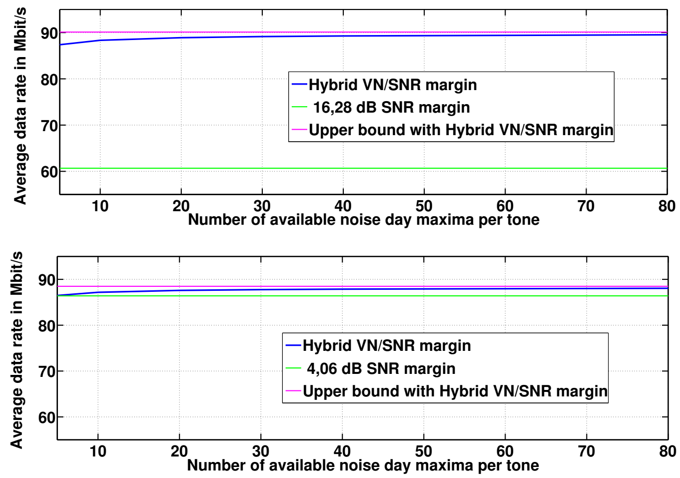

Fig. 5: Comparison of average data rates. In the upper Figure, L2 mode is implemented, in the lower Figure, L2 mode is not implemented

Virtual Noise/SNR margin approach for an increasing number of available noise day maxima. In the upper Figure, L2 mode is implemented and in the lower Figure, L2 mode is not implemented. The upper bounds of the outage probabilities, achieved with a large number of available noise day maxima are also shown. The outage probabilities are lower than the target outage probability even for a small number of available noise day maxima. As the number of available noise day maxima goes to infinity, the outage probabilities converge towards the target outage probability. Moreover, we have shown that by using the Hybrid Virtual Noise/SNR margin approach, the outage probability can be fulfilled in VDSL2 environments even when L2 is implemented.

In the following, we compare the average data rate achieved on the victim line when using the Hybrid VN/SNR margin approach and when using the traditional SNR margin approach. In order to have a fair comparison in terms of data rate, we need to compare both approaches for the same outage probability. For that purpose, we simulatively determine for the SNR margin approach the SNR margin that leads to the target outage and error probability for a user who connects at the lowest crosstalk times and operates at the target data rate for 24 hours. The resulting SNR margin was found to be 16,28 dB when L2 is implemented and 4,06 dB when L2 is not implemented. The comparison is shown in Figure 5. In the upper Figure, L2 mode is implemented and in the lower Figure, L2 mode is not implemented.

Although the SNR margin used by the traditional SNR margin approach was optimized to the used interference channel, which is not the case in real world applications, the Hybrid VN/SNR margin approach achieves higher data rates. The difference in the achieved average data rates is large when L2 is implemented. The SNR margin approach uses a huge SNR margin such that the outage probability is fulfilled even when the victim line is initialized at low crosstalk times. Moreover, this huge SNR margin is also used when the victim line is initialized at high crosstalk times, which leads to a strong decrease in the average data rate. The Hybrid VN/SNR margin approach does not consider any noise power lower than the Virtual Noise PSD in the determination of the SNR margin and is therefore not affected by the low noise levels which are typical when L2 mode is implemented.

IX. Conclusions

An algorithm that jointly optimizes the Virtual Noise PSD and the initialization SNR margin has been presented. The algorithm can be used by modems to ensure line stability while maintaining a good data rate performance. The outage probability achieved by the algorithm is always below the target outage probability and converges toward it with an increasing number of measured noise day maxima. The data rate achieved by the algorithm is higher than the data rate achieved by the traditional SNR margin approach, especially when Low power mode is implemented. Moreover, it has been shown that by using this algorithm Low power mode can be beneficial when implemented in VDSL2 systems.

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