Waterfilled VDSL Echo Limitation for Rate-Reach Performance Improvement

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ABSTRACT

Digital Subscriber Line (DSL) deployment is evolving to ever higher bit rates resulting in the use of broader spectra. The DSL flavor using the broadest spectrum today is known as VDSL.

The reach performance of VDSL is upstream limited as the upstream bands use the highest frequencies. These high frequencies experience more channel attenuation, resulting in smaller SNR values. In this contribution, a way of increasing the upstream reach performance is described.

After investigating the VDSL transceiver, the reach performance of a VDSL modem is identified to be dominated by the echo power. Therefore, limiting the downstream echo yields a better upstream receive signal. This results in trading off downstream bit rate for more upstream bit rate. The way to optimally limit the echo is derived and high performance gains can be achieved. Finally, the optimal solution is approximated with a near-optimal solution with considerably less complexity. The near-optimal solution performs very well compared to the optimal solution.

KEYWORDS

Digital Subscriber Line (DSL), VDSL, waterfilling, echo limitation, spectrum management.

1. INTRODUCTION

The new xDSL flavors are the answer to an increasing demand for higher bit rates. Such high bit rates can be achieved by, on the one hand, increasing the quality of the signal at the receiver and, on the other hand, by using broadband spectra. This resulted in the use of frequencies as high as 12 MHz as defined in the VDSL standards [1], [2]. With VDSL, data rates as high as 52 Mbps can be achieved enabling a broad range of applications such as video-conferencing, on line education and video on demand.

VDSL systems are designed as Frequency Division Duplex (FDD) systems. Downstream and upstream have separated frequency bands. The standards have adopted 4 different frequency bands with the higher bands allocated for upstream. This means that for relatively long loops, the upstream will suffer more from the loop attenuation. The VDSL reach performance is thus upstream limited.

Looking to VDSL transceivers, the design is focused on flexibility for the frequency band allocation. The VDSL transceivers are desired to support various band plans within one system. The result is that no analog filtering occurs in the frequency range starting from 138 kHz up to 12 MHz, which means that no analog filters separate upstream from downstream. The drawback of this flexible implementation is the echo sensitive behavior of VDSL. Indeed, the echo PSD is attenuated by the hybrid only, resulting in an attenuation of the echo with only 12 to 20 dB. The incoming echo power is therefore the dominant input power at the receiver.

The sensitive behavior towards echo can be explained by the fact that VDSL signals have a large Peak-to-Average Ratio (PAR). The Analog-to-Digital Converter (ADC) has a limited voltage range and a limited bit precision, which results in a Crest factor, the ratio between

$V_{\max}$ of the ADC and V_{rms} of the incoming signal. Therefore, an LNA is implemented to amplify the incoming signal to match the desired input power at the ADC. As a result, the higher the echo power, the lower the gain of the LNA which results in a low far-end signal amplification.

In this document, the behavior of the SNR is studied in function of the echo power and a simple equation is derived to optimize the overall downstream and upstream bit rate. The aim is to increase the reach of VDSL deployment by increasing the upstream bit rate.

The optimal transmit PSD allocation is derived for increasing reach performance. When applying this scheme for long loops, it results in an optimal power back-off equation for downstream transmit PSD. Simulations show a high increase in bit rates for the upstream direction, resulting in a much better reach performance.

Finally, the optimal power back-off scheme is approximated with a near-optimal solution. The near-optimal solution has the advantage to be less complex and furthermore, simulations show a small performance loss compared to the optimal scheme.

2. THE VDSL CHANNEL

A. Analog front-end architecture

A simplified architecture of the analog front end is depicted in Fig. 1. In the transmitter, the digital signal coming from the FFT is converted in the Digital-to-Analog Converter (DAC). Once converted, the signal is amplified by the Programmable Gain Amplifier (PGA) to match the wanted PSD on the line. The hybrid is designed to separate the transmit signal going to the line from the receive signal coming from the line. Unfortunately, the hybrid has no perfect echo rejection such that a certain amount of echo mixes with the far-end signal. This signal is mixed in time domain, but frequency multiplexed. The far-end signal together with the echo is amplified by the Low Noise Amplifier (LNA) to match the V_{rms} the ADC is designed for. The output of the ADC is feeding the FFT of the receiver.

B. The receiver path

The V_{rms} of the signal at the ADC has to be as close as possible to the design input voltage of the ADC. The value of V_{rms} can be calculated in the frequency domain and is given by (1).

$$V_{rms}^2 = Z \cdot \sum_{k=0}^{2K-1} PSD(k) \qquad (1)$$

with Z being the real part of the input impedance of the ADC and k, the tone index. The Nyquist frequency is given by tone index K.

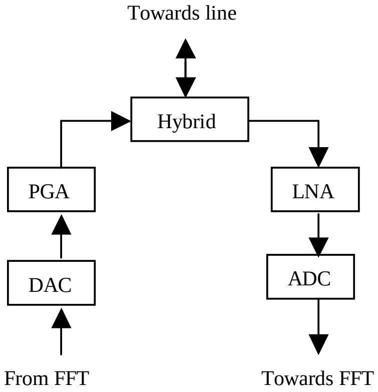

Fig. 1 Simplified VDSL analog front-end

As Z is fixed with the design, V_{rms}^2 is proportional to the sum over the frequencies of the input PSD at the ADC. The input PSD is made out of signal, noise and echo. From (1) one knows that the larger the echo, the lower the LNA may boost the incoming signal. The Analog Front-End (AFE) is designed to introduce low noise compared to the quantisation noise of the ADC, increasing the gain of the LNA increases thus the Signal-to-Noise Ratio (SNR). This results in a higher bit rate. The solution is then to apply power back-off at the near-end to lower the echo enabling an LNA boost.

C. VDSL band plan

The standard VDSL band plans [1] are designed with the first band corresponding to a downstream band. From Fig. 2 one can see that VDSL is upstream limited as the line attenuation increases with frequency. A solution for increasing the reach is to boost the upstream PSD and to apply downstream power back-off. This study only focuses on downstream power back-off.

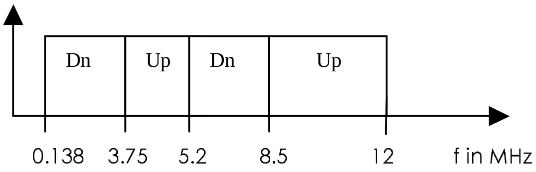

Fig. 2 ANSI VDSL band plan 998

3. DOWNSTREAM POWER BACK-OFF

Consider one line and call the CO as modem 1 and the CPE as modem 2, define the downstream rate as R_1, with transmit PSD S_1 at the CO, and the upstream rate as R_2, with transmit PSD S_2 at the CPE. The purpose is to maximize the upstream rate while keeping the downstream rate above a particular target rate. This resumes to optimizing a weighted rate sum as shown in [5]. The sum of the weighted rates, using the Shannon formula, is given by (2) .

$$\begin{aligned} R &= \alpha \cdot R_1 + (1-\alpha)\cdot R_2 \\ &= \alpha \cdot \sum_{k=0}^{K-1} \log_2\left(1+\frac{S_1(k)h_{21}^2(k)h_{LNA_2}^2}{\Gamma\left(N_2(k)h_{LNA_2}^2+Q_2\right)}\right) \\ &+ \\ &(1-\alpha)\cdot \sum_{k=0}^{K-1} \log_2\left(1+\frac{S_2(k)h_{12}^2(k)h_{LNA_1}^2}{\Gamma\left(N_1(k)h_{LNA_1}^2+Q_1\right)}\right) \end{aligned} \quad (2)$$

with $S_i(k)$ the transmit PSD on tone k of modem *i*, $N_i(k)$ the noise PSD on tone k at modem *i* and $h_{ij}(k)$ the channel transfer function from the DAC of modem *j* to the input of the LNA of modem *i*. The PGA is included in the channel transfer function as shown in Fig. 3. The gain of the LNA of modem *i* is represented by h_{LNA_i} and Q_i represents the quantisation noise introduced by the ADC of modem *i*.

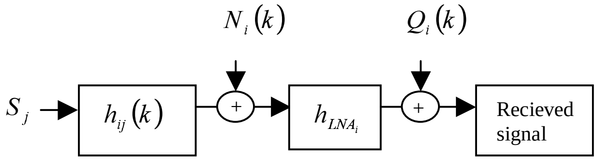

Fig. 3 Transfer functions and additive noises

Equation (2) shows that as long as $N_i(k)\cdot h_{LNA_i}^2$ is smaller than Q_i, the gain of the LNA can be increased to increase the SNR. The AWGN on the line is much lower than the quantisation noise as, for ambient temperature, AWGN is theoretically equal to –173 dBm/Hz compared to the typical ADC noise floor of –140 dBm/Hz. In practice, the measured level of AWGN varies between –160 and –155 dBm/Hz [4]. In case FEXT has to be taken into account, FEXT is in general at least 20 dB lower than the far-end signal. This means that for the tones with the received signal PSD more or less 12 dB higher than the quantisation noise, resulting in a 1 bit loading, the FEXT noise is at least 8 dB below the quantisation noise. This means the LNA can boost the signal without increasing the noise substantially, which results in a better SNR.

The gain of the LNA can be found by applying the power restrictions at the input of the ADC given by (3)

$$\begin{aligned} P_{ADC_i} &= h_{LNA_i}^2 \cdot \sum_k \left[S_i(k)h_{ii}^2(k)+S_j(k)h_{ij}^2(k)+N_i\right] \\ &= \frac{V_{i_{rms}}^2}{Z_i} \end{aligned} \quad (3)$$

with $h_{ii}(k)$ corresponding to the echo transfer function at modem *i*, from the DAC up to the input of the LNA, on tone k. P_{ADC_i} represents the maximum input power of the ADC of modem *i*. Looking at (3), the LNA gain is closely related to the transmit power of both modems. For long lines the echo mostly dominates the input power at the CO. If the echo power changes, the LNA gain will have to scale to achieve the optimal input power at the ADC.

A. Bit rate optimization

Equation (3) can be approximated by (4) as for long lines, the attenuation of the far-end signal is much higher than the attenuation of the echo. The echo power is thus much larger than the far-end power and the noise on the line.

$$h_{LNA_i}^2 \cdot \sum_k \left[S_i(k)h_{ii}^2(k)\right] \approx P_{ADC_i} \quad (4)$$

Using the Lagrange multipliers to take the ADC power restriction into account gives us the cost function (5).

$$\begin{aligned} J = R &+ \lambda_1 \cdot \left(P_{ADC_1} - h_{LNA_1}^2 * \sum_k \left[S_1(k)h_{11}^2(k)\right]\right) \\ &+ \lambda_2 \cdot \left(P_{ADC_2} - h_{LNA_2}^2 * \sum_k \left[S_2(k)h_{22}^2(k)\right]\right) \end{aligned} \quad (5)$$

The goal is to maximize this cost function. The derivative of this cost function should then be equal to zero. The derivative to $S_1(k)$ equals

$$\frac{\partial J}{\partial S_1(k)} = \frac{\partial R}{\partial S_1(k)} - \lambda_1\, h_{LNA_1}^2\, h_{11}^2(k) = 0 \quad (6)$$

with

$$\frac{\partial R}{\partial S_1(k)} = \frac{h_{21}^2(k)}{\Gamma\left(N_2(k)+\frac{Q_2}{h_{LNA_2}^2}\right)+h_{21}^2(k)S_1(k)}\cdot\frac{\alpha}{\ln(2)} \tag{7}$$

which finally yields

$$\begin{aligned} S_1(k) &= \left(\frac{1}{\lambda_1\, h_{LNA_1}^2\, h_{11}^2(k)}\,\frac{\alpha}{\ln(2)}\right) - \Gamma\,\frac{\left(N_2(k)+\frac{Q_2}{h_{LNA_2}^2}\right)}{h_{21}^2(k)} \\ &= \beta(k) - \Gamma\,\frac{\left(N_2(k)+\frac{Q_2}{h_{LNA_2}^2}\right)}{h_{21}^2(k)} \end{aligned} \tag{8}$$

The optimal downstream power back-off resumes to a *weighted waterfilling* solution as can be seen from (8). A similar formula can be found for $S_2(k)$.

As for VDSL the reach performance is upstream limited, our goal is to transmit at maximum PSD for the upstream and to shape the downstream PSD in order to achieve better reach performance. The shape of the downstream transmit PSD is given by (8).

B. Simulation results

Fig. 4 shows the simulation results for the rate-reach performance when the downstream transmit PSD is reduced by applying weighted waterfilling. The two upper curves represent the downstream rate-reach performances. The most upper curve shows the downstream rate when no power back-off is applied and the second most upper curve shows the downstream bit rate when power back-off is applied. The latter results in an upstream rate increase as shown by the two lowest curves. As can be seen from the figure, even for relatively short loops a large increase in bit rate can be achieved for upstream, as long as the target bit rate for downstream is achieved. This scheme offers the possibility to increase the reach for particular services. The simulation results show that for very short loops the approximation of (4) does not hold. Indeed, for very short loops, the echo power is not the dominant power at the input of the ADC. Reducing the echo will therefore not induce any significant performance gain.

4. NEAR-OPTIMAL DOWNSTREAM POWER BACK-OFF

Equation (8) shows the frequency dependency of β(k), the weighted waterfilling level. This weighted waterfilling level is inversely proportional to the squared echo transfer function as given in (9).

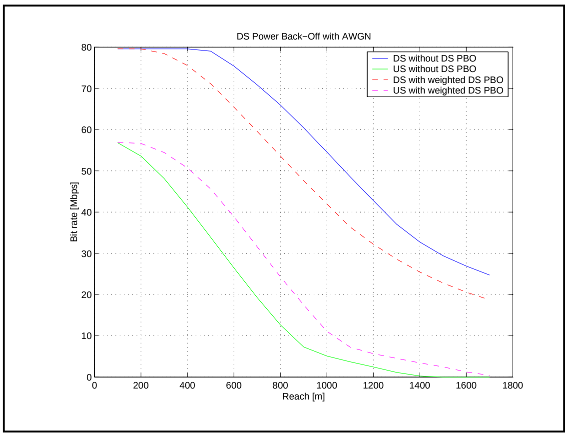

Fig. 4 Reach performance increase with the optimal DS transmit PSD reduction

$$\beta(k) \sim \frac{1}{h_{11}^2(k)} \tag{9}$$

Downstream power back-off depends therefore on the frequency behavior of the echo transfer function. On frequencies with larger echo attenuation, less power back-off has to be applied. This frequency dependency increases the complexity, as for each frequency a different power back-off value has to be computed. A simplified solution is introduced here and the reach performance is compared with the optimal solution for downstream power back-off.

The frequency dependency of β(k) is only due to the frequency dependency of the echo transfer function. As the echo transfer function varies only between more or less 12 and 20 dB, a good approximation is to take only into account the average of the echo transfer function. It gives a constant waterfilling level β_c over the entire bandwidth equal to

$$\beta_c = \frac{1}{\lambda_1\, h_{LNA_1}^2\, h_{11\_AVG}^2}\,\frac{\alpha}{\ln(2)} \tag{10}$$

where h_{11_AVG} represents the average echo transfer function

Applying downstream power back-off by implementing waterfilling is nearly optimal in DSL channels. This solution makes it possible to implement downstream power back-off with a simple transceiver algorithm.

Simulation results are shown in Fig. 5. The figure shows also the performance of the optimal scheme. From the figure one can see that the difference in reach performance is negligible.

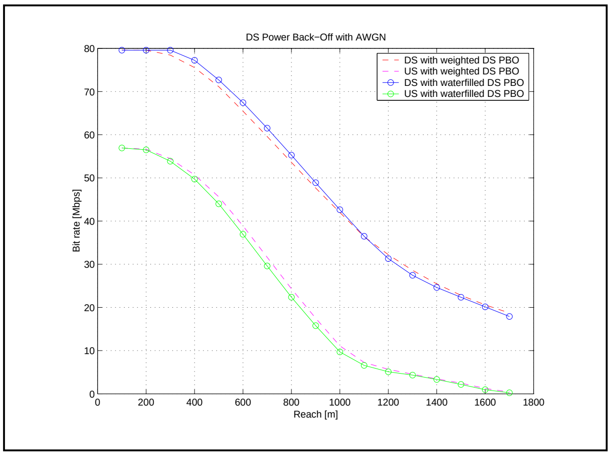

Fig. 5 Comparison between the optimal and the near optimal power back-off

5. CONCLUSION

This study focuses on the optimal power allocation for improved rate-reach VDSL performance. Upstream and downstream channels are impacting each other due to the echo leakage at both CO and CPE. The study starts from a simplified analog front-end and a general bit rate optimization is derived. As the VDSL reach performance is upstream limited, the results of optimal power allocation can be used to improve reach performance by improving the upstream bit rate. This is achieved by trading some downstream bit rate for upstream bit rate. Looking at the optimal power allocation for downstream, it turns out to be a weighted waterfilling with frequency dependency.

Furthermore, a simplified, near-optimal solution is presented with much less complexity. The frequency dependency of the weighted waterfilling is averaged out over the frequencies such that the near-optimal solution becomes traditional waterfilling. The reach performance of the near-optimal solution is comparable to the optimal solution.

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