Downstream Power Backoff in CO/RT-Deployed xDSL Networks

Jan Vangorp, Marc Moonen, Mamoun Guenach, and Michael Peeters

***Abstract*—To gradually expand their networks, operators deploy new xDSL technologies from remote terminals (RT's) closer to the customer. However, since xDSL lines deployed from an RT can share a binder with lines deployed from the central office (CO), a near-far problem is introduced and crosstalk may cause a severe performance degradation for the CO-deployed lines. RT lines have to be careful about how to allocate transmit power to the transmission frequencies, such that the impact on the CO lines is acceptable. Noise Impact (NI) methods have been proposed based on a target noise shape generated by the disturbers (RT lines). In this paper new methods based on the actual impact on the bit rate of the victims (CO lines) are proposed. These Bit Impact (BI) methods closely approximate the optimal power allocation.**

***Index Terms*—Digital Subscriber Line, power backoff, near-far scenario.**

I. Introduction

TO remain competitive with other emerging broadband access technologies such as cable and wireless networks, xDSL operators must continue to improve their technologies for data transmission over the existing telephone network. To maximize the capacity of the twisted pair lines, these should be kept as short as possible so as to minimize the effect of attenuation. Therefore, new xDSL technologies such as VDSL2 are deployed from remote terminals (RT's) close to the end-users.

To allow for a gradual upgrade of the xDSL networks, lines deployed from an RT can share the same binder with lines deployed from the central office (CO) that are still supporting older technologies such as ADSL or technologies with a higher reach such as ADSL2+. This, however, creates a so-called near-far problem. At the point where the RT deployed lines enter the binder, the signals on the CO deployed lines have already traveled some distance and are attenuated. Strong transmit signals on the RT lines cause crosstalk interference on the CO lines that can sometimes completely overpower the desired signal. This far-end crosstalk (FEXT) is then the dominant source of performance degradation for the CO lines.

This near-far problem can be mitigated by using spectrum management techniques. Instead of using static transmit spectra as defined in xDSL standards [1] [2], the transmit spectrum of the RT lines is then adapted to the network topology at hand, such that the performance degradation of the CO lines due to crosstalk interference is acceptable. Dynamic Spectrum Management (DSM) techniques [3] try to optimize the transmit spectra of all the users such that the overall data rate is maximized. However, to do so, they need complete knowledge of the network topology (crosstalk channels) and a lot of computational power.

To overcome these practical problems, a spectrum management technique referred to as Power Backoff (PBO) can be used. PBO only relies on limited knowledge of the topology, in the case of near-far scenarios the distance between the CO and the RT. Noise Impact (NI) methods [4] have been proposed, the principle upon which the current standard is based [5]. These methods assume that the transmit spectra for the CO lines are fixed and cannot be optimized. This is typically the case in practical scenarios, where lines deployed from the CO transmit at their spectral mask. The RT lines then determine a modified spectral mask based on the crosstalk noise they generate into the CO lines, thereby trying to protect these CO lines.

NI methods only indirectly estimate the performance degradation of the CO lines through the noise that is generated by the RT lines. In this paper, alternative methods are proposed that directly take into account the performance degradation of the CO lines in terms of bit rate when determining the modified spectral mask for the RT lines. These are then referred to as Bit Impact (BI) methods.

In section II, NI methods are reviewed. The new BI methods are presented in section III. In section IV, simulation results compare the various methods. Section V concludes this paper.

II. Noise Impact Methods

In order to protect the CO lines, the RT lines have to implement some form of power backoff on their transmit spectra. Noise Impact (NI) methods define this power backoff by specifying a target noise shape at the victim receivers, i.e. the receivers on the CO lines. The power backoff for the RT lines must be such that the effective noise at the victim receivers is bounded by the target noise shape.

The Equal Noise Impact (ENI) method defines the target noise shape at the victim receiver as the noise shape that would be generated by a number of co-located virtual lines identical to the victim line [4]. This is shown in Fig. 1. This results in the following closed form formula for the transmit PSD for the RT lines:

$$S_{RT}(f) = \frac{L_{CO}}{L_{coupling}} \left(\frac{n_{CO}}{n_{RT}}\right)^{0.6} |H(f, L_{CO-RT})|^2 S_{CO}(f) + \frac{\sigma_{CO}(f)}{k_{FEXT} L_{coupling} |H(f, L_{CO} - L_{CO-RT})|^2 n_{RT}^{0.6}}. \quad (1)$$

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J. Vangorp and M. Moonen are with the Department of Electrical Engineering, Katholieke Universiteit Leuven, Belgium (e-mail: {Jan.Vangorp, Marc.Moonen}@esat.kuleuven.be).

M. Guenach and M. Peeters are with Alcatel-Lucent Bell Labs, Belgium (e-mail: {guenach, michael.peeters}@ieee.org).

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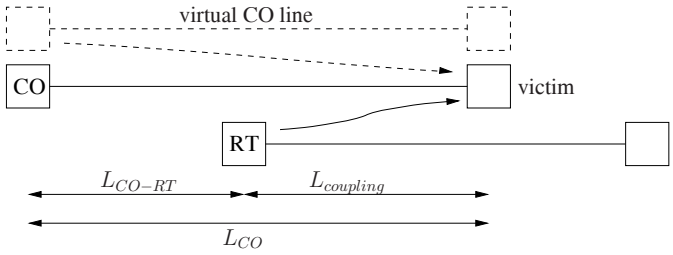


Fig. 1. Principle of equal noise impact.

Only the distance between the CO and the RT (L_{CO-RT}), the coupling length between the CO line and RT lines ($L_{coupling}$) and the length of the CO line (L_{CO}) are required at the RT. n_{RT} is the number of RT lines, $H(f,x)$ the insertion gain of a loop section with length x, S_{CO} the transmit PSD of the CO lines, $\sigma_{CO}(f)$ the background noise on the CO line and $k_{FEXT} = 31 \times 10^{-18}$ the crosstalk coupling coefficient. By varying the number of virtual CO lines n_{CO}, the amount of power backoff on the RT can be controlled, setting the trade-off between the bit rate of the CO line and the RT lines.

When the transmit spectra are defined with the ENI method, the fact that RT lines are restricted to only cause crosstalk equivalent to a CO line, however, results in an unwanted side effect. The reference noise shape defined by the crosstalk from the virtual CO lines is small and decreases with increasing frequency. Indeed, a long distance between the transmitter and the receiver also causes the crosstalk to be attenuated. A small reference noise shape means that the RT lines will have to apply a strong power backoff, especially on the high frequency tones. However, typically long CO lines do not use the higher frequencies and thus do not need to be protected there. Strong power backoff on the RT lines then results in a strong impact on their achievable bit rate without giving any benefit on the CO line.

A problem arises when there is more than one CO line and when these CO lines have different lengths. Because of the multiple coupling lengths, the CO lines have to be reduced to one reference CO line such that if the reference CO line is protected, all the other CO lines are also protected. To avoid the necessity for a reference CO line altogether, simplified-ENI is an NI method that determines the power backoff based only on the distance between the CO and the RT. Simplified-ENI defines the transmit spectrum for the RT lines as a scaled version of the attenuated PSD of the CO lines at the RT:

$$S_{RT}(f) = \left(\frac{n_{CO}}{n_{RT}}\right)^{0.6} |H(f, L_{CO-RT})|^2 S_{CO}(f). \quad (2)$$

Comparing this transmit spectrum to the ENI method (1), one can see that more backoff is applied to the RT lines: the second term of (1), which is positive, is omitted and removing $\frac{L_{CO}}{L_{coupling}}$ also reduces $S_{RT}(f)$ since this factor is larger than 1. Therefore, simplified-ENI provides more protection to the CO lines than the ENI method, but results in a lower bit rate for the RT lines.

The simplified-ENI method introduces a Maximum Usable Frequency (MUF) above which RT lines do not have to provide power backoff. This avoids power backoff on tones where the CO cannot load bits anyway. A safe estimate of the MUF which does not depend on the length of the CO lines or a reference line is to use the MUF of a line of length L_{CO-RT}. Since this line will never be longer than the CO lines or the reference line, the estimate of the MUF will be an upper bound for the real MUF and so the transmit spectrum at the RT is guaranteed to protect all the tones that are usable for the CO lines.

III. Bit Impact Methods

Since actual performance is measured in terms of bit rate, it is not clear how the performance of the CO lines is impacted by limiting the crosstalk to a predefined target noise shape. Bit Impact (BI) methods address this problem by defining the transmit spectrum for the RT lines such that the crosstalk originating from the RT lines causes the bit rate of the CO lines to reduce by a tone dependent number of impact bits $I(f)$, compared to the case where the CO lines do not experience any crosstalk.

The Equal Bit Impact (EBI) method defines the impact to be I bits and equal on each tone. The resulting expression for the transmit spectrum is then:

$$S_{RT}(f) = \frac{\left(\frac{2^I |H(f,L_{CO})|^2 S_{CO}(f)}{\Gamma\left[1+\frac{|H(f,L_{CO})|^2 S_{CO}(f)}{\Gamma\sigma_{CO}(f)}-2^I\right]^+} - \sigma_{CO}(f)\right)}{k_{FEXT} L_{coupling} f^2 |H(f, L_{CO} - L_{CO-RT})|^2 n_{RT}^{0.6}} \quad (3)$$

with $[x]^+ = max(0,x)$ and depends on the same limited information on the network topology as used in the ENI method.

By varying the number of impact bits I, a rate region can be traversed: increasing I leads to more impact and thus the importance of the RT lines is increased. In contrast to adapting the number of virtual lines n_{CO} in NI methods, the trade-off is directly related to the decrease of the bit rate of the CO line. Indeed, with an impact of I bits per tone there is an upper bound on the performance impact on the CO line of $f_s K I$ bps, with f_s the symbol rate and K the number of tones. This greatly reduces the need for a tuning procedure to find the right trade-off between the CO line and the RT line.

When the impact I is larger than the data rate of the CO line on a certain tone when the RT lines are off, this means that this tone will no longer be used by the CO line. The RT line is allowed to transmit an infinite amount of power (division by zero) on this tone, which will then be clipped at the spectral mask. Compared to the ENI method, the EBI method inherently detects when the CO line does not need to be protected and the definition of useful tones is adapted according to the relative importance between the CO and the RT line.

The base rate of the CO line can be taken even more explicitly into account by making the number of impact bits inverse proportional to this base rate: tones that are important (large base rate) will experience less impact than tones that are not important (small base rate). This results in a transmit spectrum that gives more protection on those tones where the CO line achieves most of its bit rate, with the same expression (3) as EBI, but with I replaced by

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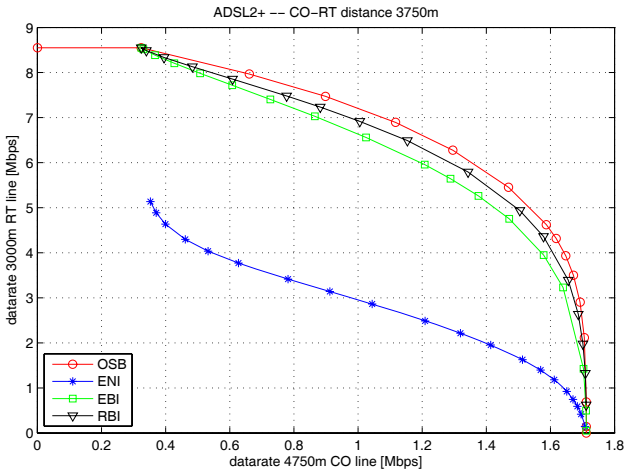


Fig. 2. Rate region for the 2-user scenario.

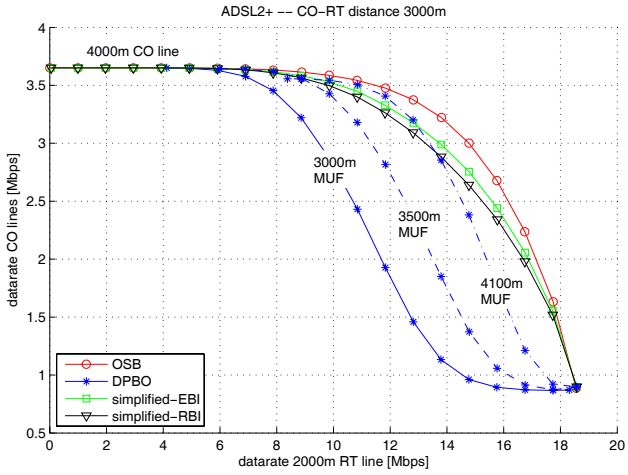


Fig. 3. Rate region for the 4-user scenario. Similar relative performance differences hold for the rate regions of the 5000m and 6000m CO lines.

$\tilde{I}(f) = \frac{I}{\log_2\left(1+\frac{|H(f,L_{CO})|^2 S_{CO}(f)}{\Gamma\sigma_{CO}(f)}\right)}$. This will be referred to as Relative Bit Impact (RBI) based power backoff, which still depends on the same topology information as EBI and ENI.

To further reduce the complexity of the BI methods, the expressions for their transmit PSD can be adapted such that they only depend on the distance between the CO and the RT. This removes the necessity for a reference CO line in case there is more than one CO line with different lengths. The resulting expression for the simplified-EBI transmit PSD is then

$$S_{RT}(f) = \frac{2^I |H(f,L_{CO-RT})|^2 S_{CO}(f)}{\Gamma\left[1+\frac{|H(f,L_{CO-RT})|^2 S_{CO}(f)}{\Gamma\sigma_{CO}(f)} - 2^I\right]^+ k_{FEXT} L_{RT} f^2 n_{RT}^{0.6}} \quad (4)$$

For the simplified-RBI method, I has to be replaced with the relative impact $\tilde{I}(f)$.

So far, the NI and BI methods have not taken into account the maximum total transmit power that is available. To make sure the transmit PSD of the RT line does not exceed the available power budget, the computed transmit spectra are used as a spectral mask against which a waterfilling procedure can be applied [6]. Finally, since NI and EBI methods are independent of the length of the RT line, all RT lines have the same modified spectral mask. In the case of simplified-BI, the modified spectral masks are equal up to a scaling determined by the length of the RT line, which can be easily determined. The RT lines will still cause interference amongst themselves and they can use any spectrum management technique within the modified spectral mask to make a performance trade-off between each other, e.g. Iterative Waterfilling [7] which has indeed shown good performance in scenarios with co-located lines.

IV. Simulation Results

For the simulations, ADSL2+ is used with a line diameter of 0.5 mm (24 AWG). The maximum total transmit power is 20.4 dBm. The SNR gap Γ is set to 12.95 dB, corresponding to a target bit error probability of 10^{-7}, coding gain of 3 dB and a noise margin of 6 dB. The tone spacing $\Delta_f = 4.3125$ kHz and the DMT symbol rate $f_s = 4$ kHz [8].

Fig. 2 shows rate regions (trade off between the bit rate of the CO line versus the RT line) for the ENI, EBI and RBI methods discussed in sections II and III. The OSB region [3] gives the optimal performance that can be achieved given the empirical channel model, a fixed transmit spectrum at the CO and the extra assumption that the exact line lengths are known. A scenario with a 4750m CO line and a 3000m RT line located at 3750m from the CO is considered. Note that the ENI method can cause a significant performance degradation for the RT line due to the fact that it cannot determine on which tones the CO line has to be protected. This is the advantage of the EBI/RBI methods, that detect when the CO line needs to be protected. The EBI and RBI methods are found to outperform ENI over a wide selection of scenarios and the performance of RBI is near optimal for the available channel information.

Fig. 3 shows the result for a 4-user scenario: 3 CO lines (4000m, 5000m and 6000m) and an RT line (2000m) at 3000m from the CO. Only the rate region for the 4000m CO line is shown, for the other CO lines, the different methods give a similar relative performance difference. This shows that even in the case of multiple CO lines, the simplified-EBI method performs close to OSB. Fig. 3 also shows the influence of the Maximum Usable Frequency corresponding to a reference line of 3000m, 3500m and 4100m. The performance is typically best if the MUF is based on a reference line with the same length as the shortest CO line. For shorter reference lines, the MUF is too optimistic about the data rate that can be achieved by the CO lines resulting in lower rates at the RT, for longer reference lines there is a risk that short CO lines are not sufficiently protected. In this scenario, a reference line longer than 4100m leaves the CO lines completely unprotected. In practice there is however no information available at the RT about the shortest CO line. Therefore, the best an RT can do is to use the distance between the CO and the RT for the reference line, 3000m in this case. By comparison, the simplified-EBI method does not depend on a reference line (or

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equivalently a MUF) and can still provide good performance for both the CO and the RT lines.

V. Conclusion

In this paper, new methods have been introduced to deal with the near-far problem in CO/RT-deployed xDSL networks. These Bit Impact (BI) methods redefine the spectral mask for the RT lines taking into account the actual impact on the bit rate of the victim CO lines, thereby looking at the true performance degradation of the CO lines. The performance of these methods was found to be close to the optimal obtainable data rate over a wide selection of scenarios. Compared to the currently available Noise Impact (NI) methods that define a target noise shape to protect the victim CO lines, the simplified-BI methods do not rely on a reference line or Maximum Usable Frequency. Since this information is not available at the RT, NI methods are forced to use a conservative setting for these parameters. This gives the simplified-BI methods a performance advantage over the NI methods.

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