INSURING SPECTRAL COMPATIBILITY OF ITERATIVE WATER-FILLING

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ABSTRACT

DSM (Dynamic Spectrum Management) consists of a set of techniques that basically allow a DSL modem to adapt its transmit spectra according to the noise on the line, instead of using a fixed mask. There are several algorithms that perform DSM, and this contribution will refer to the well-known "Iterative Water-Filling" (IWF) [1].
The T1E1.4 group (ANSI) specifies several methods to ensure spectral compatibility [2]: Method A (fixed mask) and Method B (a set of tests that the new service's transmit power spectral density (PSD) must pass. Since simulations have shown that Method A is too restrictive for Iterative Water-Filling, a new set of masks is proposed in the present contribution (satisfying Method B). Simulation results are presented as well, showing the gains of Iterative Water-filling under these conditions.

1. INTRODUCTION

DSL is now the most popular broadband technology. It gained 10.7 million subscribers during the first half of 2003, and a further 15 million subscribers are expected to have signed up during the second half. Among these, ADSL is the most widely deployed DSL technology, and can achieve maximum rates of 8 Mbit/s downstream and 800 kbit/s upstream. The user's demands have increased as well in the last years, from simple browsing on the Internet and e-mail, to peer-to-peer applications and video-on-demand. The "triple play"(delivering data, voice, and video over DSL) is expected to generate greater revenues for operators, but it demands significantly greater bandwidths (over 4 Mbit/s) for downstream transmission.
There are various solutions to this increasing demand for more bandwidth: on one side the installation of newer DSL flavours (such as VDSL), with the deployment of the fibre closer to the customer, or the improvement of existing technologies by means of innovative signal processing techniques such as DSM. The latter seems attractive for the telecom operators, since it provides a simple, efficient and cheap solution (software upgrades only). The issue at hand is the spectral compatibility of IWF. A solution is presented in this contribution.

2. ITERATIVE WATER-FILLING

Dynamic spectrum management (DSM) is a new technique for multi-user power allocation in digital subscriber line (DSL) networks. In DSM transmit spectra are adapted based on the direct and crosstalk channels seen by the modems within a network. This allows binder bit rate performance maximisation.
There are several algorithms for implementing DSM, and the most famous is "Iterative Water-filling".
ADSL modems use discrete multi-tone (DMT) modulation as adopted in the ADSL standard. The bit loading is calculated on a per tone basis, as given by equation (1) (for a 2-user scenario), and depends on the signal-to-noise ratio (SNR) at the receiver.

$$b_k^1 = \log_2\left(1+\frac{SNR_1(k)}{\Gamma_1}\right) = \log_2\left(1+\frac{h_{11}^2(k)S_1(k)}{\Gamma_1\left(N_1(k)+h_{12}^2(k)S_2(k)\right)}\right) \tag{1}$$

In equation (1) k represents the tone index, $N_1(k)$ denotes all the noises different from self-crosstalk, and $\Gamma_1 \approx 12\,dB$ is equal to the Shannon gap including noise margin and coding gain. h_{11} represents the channel transfer function, and h_{12} the crosstalk transfer function. The Shannon gap to achieve a bit error rate (BER) of 10^{-7} is approximately equal to 9.75 dB. Adding to this a noise margin of 6 dB minus a coding gain of 3.75 dB, one gets an overall value of 12 dB for Γ_1. This bit loading allows the modem to adapt to the changing line conditions by dynamically varying the constellation used on each tone. Equation (1) tells us that the bit loading for user 1 depends on the crosstalk coming from user 2. If the crosstalk increases on a particular carrier, fewer bits can be put on the carrier. The same is true for user 2, the crosstalk coming from user 1 interferes with the signal of user 2.
The goal is to optimise the overall bit rate by means of a cost function given by equation (2).

$$
\begin{aligned}
&J(S_1(k),S_2(k))= \\
&\sum_k \log_2\left(1+\frac{S_1(k)\cdot h_{11}^2(k)}{\Gamma_1\left(N_1(k)+S_2(k)\cdot h_{12}^2(k)\right)}\right) \\
&+\sum_k \log_2\left(1+\frac{S_2(k)\cdot h_{22}^2(k)}{\Gamma_2\left(N_2(k)+S_1(k)\cdot h_{21}^2(k)\right)}\right) \\
&+\lambda_1\cdot\left(P_1-\sum_k S_1(k)\right)+\lambda_2\cdot\left(P_2-\sum_k S_2(k)\right)
\end{aligned} \tag{2}
$$

Equation (2) is the sum of the bit rates of both users together with the Lagrange multipliers taking into account the total power restriction of both users. This is a non-convex optimisation problem. Hence finding the global optimum requires an exponential complexity in K, with K the total amount of tones. Recent work [3] has looked at numerically tractable ways of solving this problem through use of a dual decomposition. While this algorithm demonstrates large performance gains, it is centralized and requires the existence of a spectrum management centre (SMC). In this work we focus on a distributed algorithm, known as iterative water-filling, which does not require a SMC.. This algorithm can be derived by fixing the PSD of the interferers. It results in equation (3) with the optimum given by (4).

$$
\begin{aligned}
&J(S_1(k),S_2(k))= \\
&\sum \log_2\left(1+\frac{S_1(k)\cdot h_{11}^2(k)}{\Gamma_1 N_1(k)}\right) \\
&+\sum \log_2\left(1+\frac{S_2(k)\cdot h_{22}^2(k)}{\Gamma_2 N_2(k)}\right) \\
&+\lambda_1\cdot\left(P_1-\sum_k S_1(k)\right)+\lambda_2\cdot\left(P_2-\sum_k S_2(k)\right)
\end{aligned} \tag{3}
$$

If $\widetilde{N}_1 = N_1(k)+h_{12}^2(k)S_2(k)$,

$$
S_1(k)=\left[\frac{1}{\lambda_1}-\frac{\Gamma_1\,\widetilde{N}_1(k)}{h_{11}^2(k)}\right]^+ \tag{4}
$$

where $[x]^+=\max(0,x)$.

If each user successively optimizes its own spectrum while regarding other user's interference as fixed noise, this results in an iteration of modems doing water-filling, hence Iterative Water-filling.

Looking to equation (1), to have one bit on a carrier, the SNR must be at least as big as Γ_1. Combining this with equation (4), the transmit PSD on tones loaded with 1 bit will be given by equation (5).

$$
S_1^{\min}(k)=\frac{\Gamma_1\left(N_1(k)+h_{12}^2(k)\,S_2(k)\right)}{h_{11}^2(k)}=\frac{1}{2\,\lambda_1} \tag{5}
$$

The transmit PSD on tones with very low Noise-to-Channel ratio (NCR) will be approximated by equation (6), hence the transmit PSD only varies with at most 3 dB.

$$
S_1(k)=\frac{1}{\lambda_1} \tag{6}
$$

The transmit PSD can then be approximated by a flat PSD for all the usable tones, because the g_i gain scaling mechanism will anyhow adapt the PSD within a range of -2.5 to 2.5 dB. Hence no PSD shaping is required for IWF. The tones for which the SNR is not high enough are shut off. Basically, IWF consists in shutting off tones and boosting for long lines, and power back-off for short lines. Overall, the PSD of modems doing IWF is practically flat [4].

3. SPECTRAL COMPATIBILITY

The T1E1.4 working group of the T1 committee (ANSI) has adopted a “Spectrum Management for Loop Transmission Systems” standard [2]. This standard provides spectrum management requirements and recommendations for the administration of services and technologies that use metallic subscriber loop cables. Spectrum management is the administration of the loop plant in a way that provides spectral compatibility for services and technologies that use pairs in the same cable.

In order to achieve spectral compatibility, the ingress energy that transfers into a loop pair, from services and transmission system technologies on other pairs in the same cable must not cause an unacceptable degradation of performance of the DSL service of the loop under consideration. In addition, the egress energy from a particular loop pair must not transfer into other pairs in a manner that causes an unacceptable degradation in the performance of services and technologies on those pairs.

There are basically two ways to ensure spectral compatibility with the existing protected services: Method A and Method B. Method A consists of a series of fixed masks (management classes). In order to encourage innovation, Method B was proposed. This method provides a generic analytical method (instead of a fixed masks), for determining spectral compatibility. This method is more complicated that Method A, and consists in fact of a series of tests which are done on a technology by technology basis. There are several “basis systems” defined, and for each one a specific test is performed.

4. COMPUTING SPECTRALLY COMPATIBLE MASKS

In order to implement the Method B tests, a software tool (in Matlab) has been developed, following the specifications of [2]. In order to check the accuracy of the tool, the results have been compared with the Telcordia tool (Telcordia DSL Spectral Compatibility Computer) [5]. The comparison has been made for an extensive number of cases, and there is a very good agreement between the results of both tools.

Alcatel's tool works as follows: a “new service” is defined: a PSD (Power Spectral Density) in upstream and downstream. Then, by using a user interface one selects the basis systems

(protected services) to be tested with. For spectral compliance, throughout this contribution, all the protected services will be tested against.
Simulations have shown that Method A limits the performance of iterative water-filling (IWF). Boosting (exceeding the Method A specified mask) on certain tones is quite common for IWF, and leads to increased performance.
A new set of spectrally compatible masks have been calculated, following the reasoning illustrated in Fig. 1.

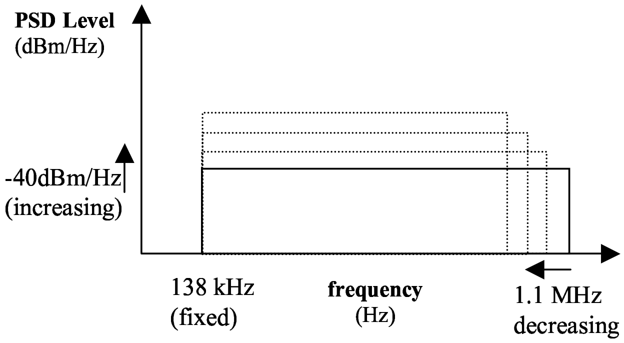

Figure 1: Downstream masks for ADSL, respecting the total power constraint

The original downstream ADSL mask is presented in Fig. 1 with a solid line. It spans from 138 kHz up to approximately 1.1 MHz, and has a level of –40 dBm/Hz. If the maximum frequency is reduced and the total transmit power constraint is respected (19.85 dBm), then new masks can be calculated. Obviously, all the new masks will exceed the Method A requirements, and therefore Method B will be employed for insuring spectral compatibility.
Each mask is first tested with Method B. If it is not spectrally compatible, the PSD level is reduced with a value ΔPSD, and tested again. The procedure is repeated until the resulting mask is spectrally compatible.
All the above procedures were automated in a Matlab script, interfacing with Alcatel's Method B tool.
Sidelobes have been calculated for the PSD of the new system. With these sidelobes the effect of energy spreading of the DMT modulation is taken into account. This is very important to model the energy on the tones that have been switched off. The sidelobes have been calculated using matrix A from [6], appendix IV.
The resulting spectrally compatible masks are presented below in Fig. 2.

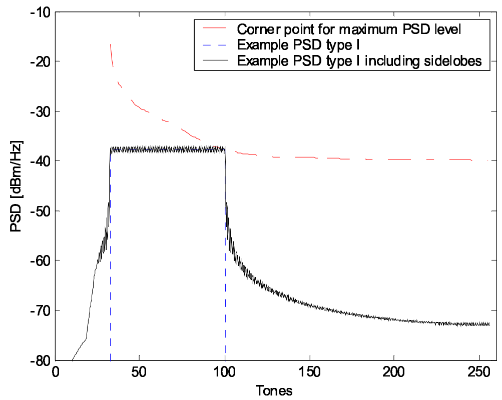

Figure 2: Spectrally compatible masks with sidelobes

Since IWF has practically flat masks, the new set of masks calculated will 'fit' with the IWF masks.
These results will give more "room" for the IWF algorithm to boost, while respecting Method B.

5. RESULTS OF IWF WITH SPECTRALLY COMPATIBLE MASKS

The scenario simulated is described in Fig. 3:

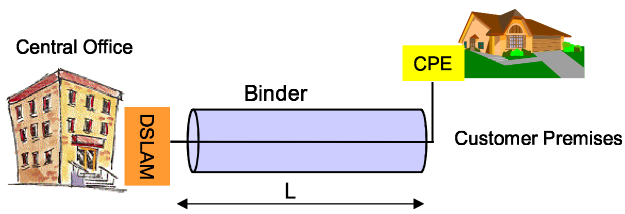

Figure 3: Scenario to be simulated

One ADSL modem doing IWF is simulated, and two type of noise environments are considered: first only white noise (AWGN), and second the ETSI FB noise. The ETSI FB noise is described in Table 1.

Table 1: ETSI FB noise

Nr. disturbers	Type disturbers
10	ISDN 2B1Q
4	HDSL 2B1Q (2 pairs)
15	ADSL
15	SDSL (2.3 Mb/s)

Only one line was considered, because most of the gains of IWF come from boosting, which is the focus of this contribution.
In Fig. 4 the rate-reach curve is plotted for the case of AWGN noise, and the ADSL modem is doing IWF. The length L varies from 2000 meters, until 7000 m (in increments of 200 m).

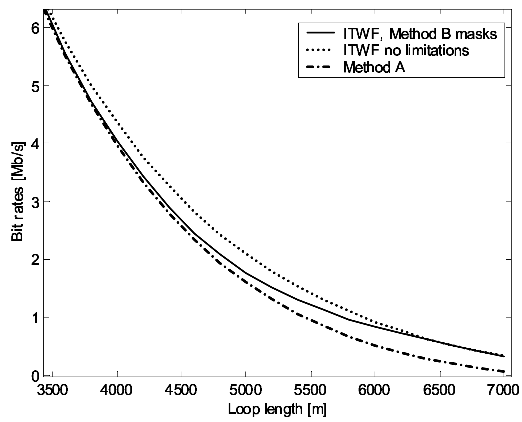

Figure 5: Rate reach plots for ITWF with and without the Method B constrains and Method A for AWGN noise

The results of Fig. 5 are summarised in Table 2.

Table 2: Reaches for several bit rates (IWF), AWGN noise

Bit rate [Mb/s]	Reach [m], 26 AWG		
	Method A	IWF, Method B	IWF, no restrictions
3	4323.5	4365.4	4520.35
2	4772.4	4852.6	5064.6
1	5459.7	5752.5	5917.3
0.5	6021	6635.4	6647

In Figure 6, the same comparison is made for the ETSI FB noise.

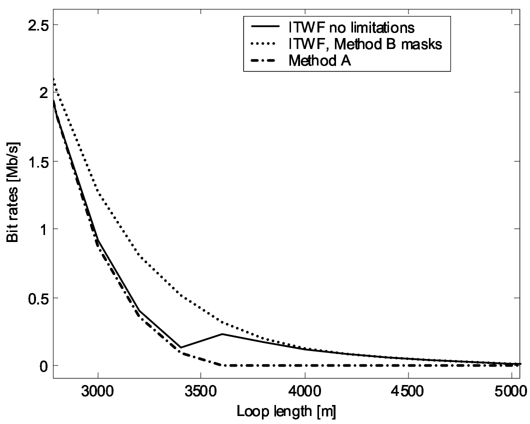

Figure 6: Rate reach plots for ITWF with and without the Method B constrains and Method A for ETSI FB noise

The results from Fig. 6 are summarised in Table 3.

Table 2: Reaches for several bit rates (ITWF), ETSI FB noise

Bit rate [Mb/s]	Reach [m], 26 AWG		
	Method A	ITWF, Method B	ITWF, no restrictions
1	2973.1	2982.2	3116.1
0.5	3145.3	3162.8	3417.4
0.2	3321.2	3530.8	3798.3

6. CONCLUSIONS

The DSM algorithms provide a way to increase the bitrate and as such making way for new services. The issue of spectral compatibility is a sensitive one, and needs to be addressed.

The present contribution addresses the spectral compatibility requirements described in the T1E1.4 ANSI standard, which is valid for North America. This standard specifies a Method A (fixed masks) and a Method B (series of tests) as possibility to ensure spectral compatibility. In Europe, the regulations vary from country to country and are in fact related to Method A (with modifications related to specific deployment conditions, such as legacy systems).

Since Method A is too restrictive for IWF, a set of masks were developed using Method B, allowing boosting under controlled conditions.

IWF was implemented for ADSL [7], but without any spectral compatibility constrains. The next step will be to implement the masks calculated in this contribution in the IWF demonstrator.

The simulation results show that IWF still gives increases in performance and is spectrally compatible. The set of spectrally compatible masks presented in Fig. 2 have the advantage of being simple, but are by no means unique, and perhaps other masks can be computed that yield even better results for IWF.

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