DSM IN PRACTICE: ITERATIVE WATER-FILLING IMPLEMENTED ON ADSL MODEMS

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ABSTRACT

Dynamic spectrum management (DSM) is a new technique for multi-user power allocation and/or detection 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.

At the Alcatel Research and Innovation labs we have recently developed a DSM testbed which allows the performance of DSM algorithms to be evaluated in practice. This paper describes the development of this DSM testbed. With this testbed we have evaluated the performance of a DSM algorithm known as iterative water-filling. It has been demonstrated that iterative water-filling can yield data-rate gains of up to 500% in the real world.

Practical issues on the implementation of iterative water-filling are also discussed.

1. INTRODUCTION

Due to increasing line attenuation with increasing line length, the deployed services on long loops are low-bit-rate services. As each operator has a minimum-bit-rate service, customers on very long loops are not granted ADSL connections. Increasing the bit rate on long loops has thus a double effect: on the one hand it provides the customers on long loops with a higher bit rate, eventually enabling video-over-DSL, and on the other hand it increases the operator's DSL customer base. Indeed, increasing the bit rate on long loops is comparable to increasing the deployment range for a certain service.

The technology enabling an increase in bit rate is dynamic spectrum management (DSM) [2]. DSM is an adaptive form of spectrum management [3] and is based on automatic detection of interference caused by crosstalk. The entire twisted pair binder is considered as a shared resource and the overall bit rate is optimised. The optimisation can be done in different ways, depending on the level of coordination between the multiple DSL lines. We remark that the naming "dynamic spectrum management" originates from adaptive multi-user power allocation techniques, but the meaning of the term DSM has widened to include also multi-user detection techniques.

A distinction is made between DSM at level 0, 1, 2, and 3 according to the degree of coordination. *Level-0* DSM means no coordination between the lines. DSM at *level 1* means that the bit rates are reported to and controlled by a spectrum management center (SMC). It must be stated that the actual transmit PSDs are computed in each transceiver, hence the multi-user power control is distributed [4]. At *level 2* the received signal and noise power spectral densities (PSD) are reported to the SMC and the transmit PSDs are controlled by the SMC. Both level 1 and 2 gains in rate and reach are originating from adaptive multi-user power allocation techniques, resulting in crosstalk avoidance. *Level 3* is the highest DSM level at which all co-located transceivers jointly process the received symbols for upstream transmission and the transmit symbols for downstream transmission. At this level the gains are originating from multi-user detection techniques based on either crosstalk cancellation or crosstalk precompensation. An overview of the future of DSL implementing DSM with increasing coordination levels and migrating to remotely deployed DSL is given in [6].

In this paper we concentrate on DSM at level 1, and in particular on the specific algorithm called iterative water-filling. First we recapitulate in Section 2 the DSL channel characteristics, followed by the multi-user power allocation technique (iterative water-filling) in Section 3. In Section 4 we give an overview of iterative water-filling practically implemented on ADSL modems together with measurement results. Finally we draw a conclusion in Section 5.

2. THE DSL CHANNEL

ADSL modems use discrete multi-tone (DMT) modulation as adopted in the ADSL standard [5]. The 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.

$$\begin{aligned} b_k^1 &= \log_2\left(1+\frac{SNR_1(k)}{\Gamma_1}\right) \\ &= \log_2\left(1+\frac{|H_{11}(k)|^2 S_1(k)}{\Gamma_1\left(|H_{12}(k)|^2 S_2(k)+N_1(k)\right)}\right) \end{aligned} \tag{1}$$

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. 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.

3. MULTI-USER POWER ALLOCATION

In previous section the relation between both users has been shown. The goal is to optimise the overall bit rate by means of a cost 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. In recent work [7] one 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 existance of a spectrum management center (SMC). In this work we focus on a distributed algorithm which does not require a SMC. This algorithm is known as iterative water-filling algorithm [4]. This algorithm can be derived by making the assumption that the background noise is much larger than the crosstalk noise. It results in equation (3) with the optimum given by (4).

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

$$S_1(k) = \left[\frac{1}{\lambda_1} - \frac{\Gamma_1\, N_1(k)}{h_{11}^2(k)}\right]^+ \tag{4}$$

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

Therefore, after replacing the background noise with the total noise in equation (4), the optimal response of a modem to another modem interfering with it, under total power constraint, is known as the water-filling power allocation. Applying this power allocation iteratively converges to the Nash equilibrium [4].

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

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

The transmit PSD can then be approximated by the water-filling level (6) for all the usable tones because the PSD shaping would be limited to 3 dB and this is masked by the ripple on the PSD caused by the fine-tune gains. This decreases the power allocation complexity of DSM applied at level 1. The tones for which the SNR is not high enough are shut off.

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

In the following paragraph we give an overview of the operation modes of the ADSL transceivers and how to map iterative water-filling on it.

The DSL transceiver can be operated in 3 *adaptation* modes. In *rate-adaptive (RA) mode* the transceiver uses all available power to maximise the bit rate, while maintaining a fixed noise margin. In margin-adaptive (MA) mode the transceiver uses all available power to maximise the noise margin, while maintaining a fixed bit rate. In *power-adaptive (PA) or fixed-margin (FM) mode* the transceiver minimises the power consumption, while maintaining a fixed bit rate and noise margin. Currently most DSL lines are operated in MA mode, which means a lot of power is wasted on the short loops introducing unnecessary crosstalk on the longer loops. DSM at level 1 proposes to switch all DSL transceivers to PA (=FM) mode, which means that a DSL transceiver connected to a short loop will apply flat *power back-off* (PBO) in order to minimise power. Furthermore it is also proposed to abandon the idea of using spectral masks to ensure spectral compatibility with other DSL services, but only to restrict the total power. Hence a DSL transceiver connected to a long loop would be allowed to reallocate power from the higher tones, which are not used, to the lower tones, a technique called *boosting*. The resulting algorithm is equivalent to iterative water-filling.

4. ITERATIVE WATER-FILLING IN PRACTICE

Fig. 1 shows the *DSM (level 1) demonstrator* at Alcatel Research & Innovation labs, which has provided the results shown in Fig. 2 and Fig. 3. The demonstrator is based on a mixed deployment of central office (CO) distributed and remote terminal (RT) distributed lines in the same cable binder.

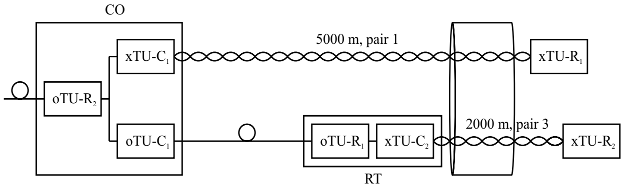

Fig. 1 DSM demonstrator at Alcatel Research & Innovation labs 1 long CO line of 5000 m and 1 short RT line of 2000 m.

The demonstrator allows switching from normal mode to DSM mode. In DSM mode some modem parameters are switched to ensure PA (=FM) operation and in addition the DSL transceivers switch from a normal modem software build to a DSM modem software build. Some changes have been made to the modem software to allow iterative water-filling.

The changes in the software consist of, in the first place, expanding the range of the average relative gain from initialisation to showtime from [0, -12] dB to [6, -20,5] dB. This means enhanced power back-off and boosting are made possible. A second topic of software changes concerns the sync symbols in showtime. Once in showtime, the modems react to upcoming and disappearing noises coming from neighbouring lines. In case a modem starts up with a high noise due to many disturbers, the transmit PSD will be calculated to achieve the needed SNR to attain the target bit rate. If the noise decreases due to neighbouring lines stopping transmitting power, the modem will automatically decrease its transmit PSD as the SNR is higher than needed. The transmit PSD of the sync symbols has to be low enough compared to the transmit PSD of the data symbols to avoid inter-symbol interference (ISI) from the sync symbols into the data symbols. This can be either achieved by ensuring a low transmit PSD of the sync symbols or by adapting the transmit PSD of the sync symbols according to the data symbol transmit PSD variation.

The performance of the demonstrator shows an important bit rate increase on the long loop. This results from, on the one hand, power back-off on the short RT loop and, on the other hand, boosting on the long CO loop. Fig. 2 illustrates boosting on the long loop.

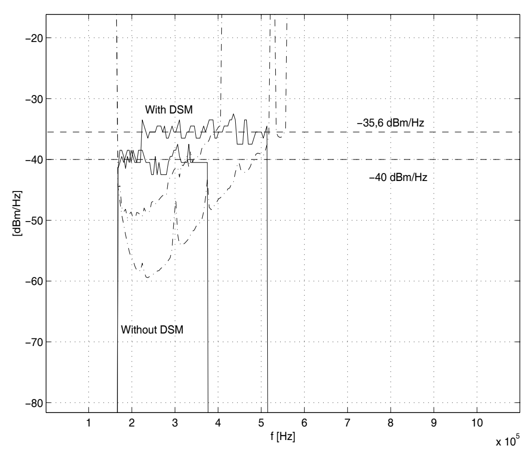

Fig. 2. Downstream ADSL transmit power spectral density (PSD) (solid) of the ATU-C transmitting over the 5000 m loop, which results from water-filling the noise-to-channel ratio (dotted).

Without DSM only 256 kbit/s is achieved on the long CO loop while the short RT loop operates at 4Mbit/s.

With DSM, not less than 1344 kbit/s is reached on the long CO loop with still 4 Mbit/s on the short RT loop. This is an increase of over 400 %. Extending this case to two long CO loops together with two short RT loops, the bit rates increase even more, from 208 kbit/s to 1280 kbit/s, an increase of over 500 %.

Fig. 3 depicts the *rate region* for the short and long line with and without DSM. It is clear that DSM allows extending the rate region substantially. Remark that these results are given here only to give an idea of the potential of DSM. The results achievable in the field will depend on the noise environment and the loop length distribution.

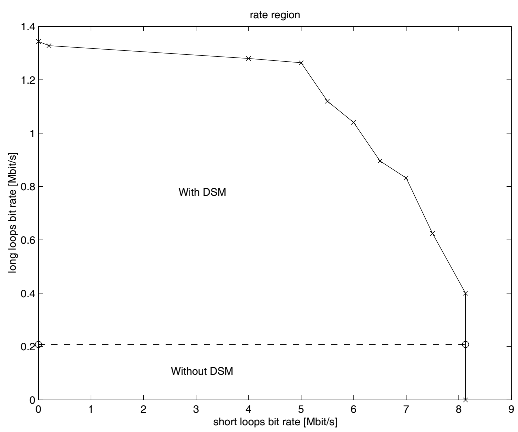

Fig. 3. Rate region for the short and long loop scenario: without DSM (dotted, circles) and with DSM (solid, plusses).

Although these results look very promising, iterative water-filling also has a number of drawbacks. Firstly as shown in Fig. 3 iterative water-filling means boosting on the long loops. Boosting implies breaking the spectral mask constraints, hence spectral compatibility with other services is not assured. Spectrally compatible DSM is currently under investigation by means of the American spectrum management standard [3] method B compliancy. Method B ensures spectral compatibility of a new technology not by imposing a spectral mask, but by ensuring that the new technology does not harm the specified basis systems by computing its impact on, for example, the bit rate of these basis systems

A second important drawback of iterative water-filling is the fact that DSM reduces the noise margin on the short line significantly, which means that, if, for example, a new DSL line is activated, the short line could go out of sync. We therefore implemented a new ADSL overhead channel (AOC) message enabling the modem to ask for an express boost. This express boost message is a very short message asking for an increase in PSD on all active tones. It makes it possible for the modems to react quickly to rapidly increasing noises such as a new upcoming disturber. The short length of the message decreases the probability of corrupt reception and as such enhances the stability.

Without special precautions DSM could introduce stability problems. So before DSM at level 1 can be introduced in the field, a more in-depth study on spectral compatibility and stability is required.

5. CONCLUSION

In this paper the practical implementation of iterative water-filling is investigated together with its performance on the cable farm at Alcatel's Research & Innovation lab. Taking into account the properties of the DSL channel together with the DMT modulation characteristics, the overall binder bit rate can be increased by applying multi-user power allocation techniques.

We have focused on DSM at level 1 more specifically on iterative water-filling. Water-filling results from a binder bit rate optimisation by introducing an approximation on the noise. Applying water-filling to DMT systems makes it possible to approximate it by flat transmit spectra decreasing consequently the complexity of the power allocation algorithm. Water-filling applied iteratively on the different modems converges towards the Nash equilibrium.

The results of iterative water-filling implemented on CO deployed ADSL modems show a significant performance increase compared to the actual deployment mode used by the operators (margin adaptive mode). The rate-region is plotted for a particular deployment case showing the huge advantages of iterative water-filling.

Finally some open question with relation to iterative water-filling are pinpointed as to be studied carefully to come up with spectrally compatible and stable implementations.

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