Technology White Paper

Dynamic Spectrum Management for Digital Subscriber Lines – Edition 2

Crosstalk is one of the main limitations of DSL performance today. Static Spectrum Management (fixed spectral masks) ensures that DSL lines in the same cable are spectrally compatible under worst-case crosstalk assumptions. Dynamic Spectrum Management (DSM) increases capacity utilization by adapting the transmit spectra of DSL lines to the actual time-variable crosstalk interference.
The gains in rate/reach performance are most significant for deployment scenarios where crosstalk is the dominant noise source and where a substantial reduction in crosstalk can be achieved. This is the case for MIMO (Multiple-Input, Multiple-Output) transmission. Also for crosstalk avoidance gains are large, especially when the transmitters are not collocated, like in mixed CO/RT (Central Office / Remote Terminal) downstream transmission and upstream transmission in general. DSM is also beneficial on long CO lines, but then it requires boosting – which can be done to a certain extent without giving up spectral compatibility. When applying DSM, care also has to be taken to ensure the stability of the DSL lines.

ALCATEL

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As DSL has reached the mass deployment stage, telecommunications operators now want to increase their ARPU by adding new multimedia services, such as Video-on-Demand (VoD), on top of their basic HSI offering. However, these services require more bandwidth than HSI alone, despite improvements in source coding techniques. In addition, competition from cable operators is a major driver to increase DSL capacity.

The crosstalk between pairs in the same binder presents a severe limitation to rate/reach performance. Static Spectrum Management (SSM) ensures that DSL lines present in the same cable are spectrally compatible assuming a worst-case crosstalk environment. However, the actual crosstalk coupling depends very much on the victim and disturber pair under consideration. Moreover, the crosstalk interference may vary significantly from one binder to another and over time due to, for example, the on/off-switching of DSL modems. Therefore, because it uses fixed spectral masks, SSM wastes channel capacity.

Dynamic Spectrum Management (DSM) exploits this opportunity to optimize capacity by adapting the transmit spectra of all DSL lines to the actual time-variable crosstalk interference. The meaning of the term DSM has gradually broadened to include also techniques that aim at crosstalk mitigation by jointly processing the signals of multiple DSL lines.

Spectacular gains in rate/reach performance have been reported in the literature on this subject: [2] [3] [4] [7] [12] [13]. However, these gains depend very much on the deployment scenario. This paper assesses the potential of several DSM methods based on extensive simulations over thousands of different network environments. Secondly, it proposes a methodology to ensure spectral compatibility of DSM-enabled lines. Thirdly, it elaborates on how to protect the stability of DSL lines when DSM is applied. Finally, the paper indicates how DSM algorithms can be implemented in practice and which DSM functionality will be supported by Alcatel products.

The need for speed

Operators are introducing new value-added multimedia services as a consequence of competition from other access providers, the desire to generate additional revenues, and the increasing end-user appetite for media-rich content. This results in an accelerating demand for more bandwidth, especially in the last mile.

In principle there are five ways to increase the capacity of DSL lines:

1. Improving the DSL transmission technology,
2. Increasing the DSL transmission bandwidth,
3. Increasing the DSL transmit power and/or Power Spectral Density (PSD),
4. Reducing the subscriber loop attenuation, and
5. Reducing the noise level received by the DSL modem.

ADSL2, the successor of ADSL, is an example of technology improvement (1). It adds an average of 50 to 80 kbits/s of capacity to a typical line compared to ADSL, for example, by exploiting tones previously unused for data transport, such as the pilot tone [11]. Closing the remaining SNR gap[1] further would require a huge increase in the complexity, and cost, of the DSL transceiver.

[1] The SNR gap expresses how closely a transmission technology approximates to the maximum capacity achievable over a communications channel with a certain SNR, according to the Shannon limit: the smaller the SNR gap, the better the transmission technology.

Short loops with a useful transmission band larger than the band currently exploited by ADSL may benefit from the introduction of new DSL technologies with extended bandwidth, such as ADSL2+, VDSL and VDSL2 (2) [1].

Long loops with a useful transmission band smaller than the band currently used by ADSL may benefit from the introduction of new DSL technologies with boosted transmit PSD, such as RE-ADSL2 (3) [11]. However, increasing the DSL transmit power and/or PSD on a particular line could harm neighboring lines because of crosstalk. Hence this is not normally allowed, although exceptions such as RE-ADSL2 may be justified. This will be explained in the section on spectral compatibility.

The loop attenuation (4) can be reduced by shortening the loop length by RT deployment such as FTTArea, FTTCab, FTTCurb, or FTTBuilding. To maximize the benefit, this RT deployment is combined with the introduction of ADSL2+ and VDSL at the RT, which have extended bandwidth (2) [1].

Noise reduction (5) is possible, for example, by removing (S)HDSL repeaters, reallocating repeatered DSL to isolated pairs, or replacing HDSL by more spectrally friendly SHDSL lines.

Although these solutions may be very effective, they might not always be feasible. Dynamic Spectrum Management (DSM) proposes an alternative solution, which aims at avoiding crosstalk interference by adapting the transmit spectra to the actual time-variable crosstalk environment to maximize the utilization of the overall binder capacity [2]. As DSM proposes, in principle, to adjust the transmit spectra freely, taking only the total power constraint into account, some of the resulting spectra may be boosted (3). However, this can be avoided by forcing DSM to comply with static spectrum management rules (see the section on spectral compatibility). DSM can, of course, be combined with all the solutions mentioned above to increase capacity.

DSM levels of coordination

In [2] a distinction is made between DSM at level 0, 1, 2, and 3 according to the degree of coordination between multiple DSL lines:

- level 0: Static Spectrum Management (SSM)
- level 1: autonomous (single-user) power allocation aiming at crosstalk avoidance
- level 2: coordinated (multi-user) power allocation aiming at crosstalk avoidance
- level 3: multi-user transmission aiming at crosstalk mitigation

DSM level 0 corresponds to Static Spectrum Management (SSM), which means that a DSL line maximizes its own performance without considering the performance of neighboring lines. Spectral compatibility between lines in the same binder is ensured by restrictions imposed on the transmit power and spectrum. Examples of DSM level 0 are the Margin-Adaptive (MA) and Rate Adaptive (RA) modes of operation. MA operation means that all available power is used to maximize the noise margin, while maintaining a fixed bit rate. When configured in RA mode, the DSL line will use all available power to maximize the bit rate at initialization, while ensuring the configured noise margin.

DSM level 1 is achieved when the power of a DSL line is allocated in such a way that unnecessary crosstalk to its neighbors is avoided. This leads to increased capacity of the complete

binder, if applied by all, or most, of the lines in the binder. At level 1 the power allocation of a DSL line is computed only based on its own line condition and service requirements, that is, without coordination with the other lines in the same binder.

A first example of DSM level 1 is the Power Adaptive (PA) mode of operation, which means that the power is minimized, while maintaining a fixed bit rate and noise margin within a configured range. The PA mode is also called Fixed Margin (FM). A second example is Iterative Water Filling (IWF) [4], which is in fact nothing more than an extension of the PA mode. The only difference between IWF and PA is that IWF does not adhere to the fixed-mask constraint. As a result IWF allows boosting, which means that power is reallocated from unused to used tones.

Like level 1, DSM level 2 also aims at crosstalk avoidance by adapting transmit spectra, but the power allocation of a DSL line is based not only on its own line condition and service requirements, but also on those of other lines. This requires coordination between the lines in the same binder. DSM level 2 ultimately allows the optimal spectrum allocation for each line in the binder to be computed, such that the total binder capacity is maximized.

An example of a DSM level 2 is the Optimal Spectrum Balancing (OSB)[2] algorithm described in [7].

The goal of DSM level 3 is to mitigate crosstalk. Where DSM level 2 acts on the PSD level, DSM level 3 will reduce crosstalk by jointly processing the actual signals of multiple lines in a binder. To make such joint processing possible, either all transmitters and/or receivers must be co-located. The crosstalk mitigation method will depend on the co-location, as can be seen in Table 1.

Table 1: Crosstalk mitigation method vs. co-location of transmitters and receivers

	Co-located receivers	Non-co-located receivers
Co-located transmitters	Crosstalk cancellation	Crosstalk pre-compensation
Non-co-located transmitters	Crosstalk cancellation	DSM level 3 not possible

DSM level 3, therefore, can both be used for point-to-point and for point-to-multipoint connections (see Figure 1). In the case of point-to-point connections, all processing can be done at the receivers. In point-to-multipoint connections (e.g., one CO with multiple CPEs), all processing is done at the CO. In DSM level 3, the binder is considered as a whole, instead of looking at each line of a binder individually. That is why DSM level 3 is also often referred to as "MIMO" (Multiple-Input, Multiple-Output) or "Vectoring". These names both indicate that the signals of all lines should be combined in a vectored signal and should be processed together.

In fact, crosstalk cancellation uses techniques very similar to those of an echo canceller. The crosstalk coupling channel varies only slowly in time, so it can be modeled as a digital filter. Since the reference signals on the other lines are known (thanks to the joint processing of signals), it is possible to predict the induced crosstalk on the other lines. This crosstalk signal prediction value can then be subtracted from the actual received signal to reduce the amount of crosstalk.

DSM level 3 is rather complex. All lines in a binder have to be processed by one entity. So, either all the lines have to be processed on one chip, or the various chips that process all the lines have to be endowed with fast data connections (to exchange the crosstalk information).

Figure 1: Illustration of point-to-multipoint and point-to-point connections

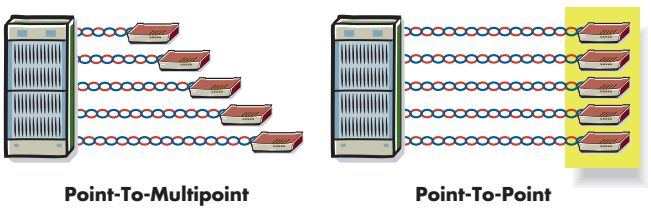


Figure 2: IWF and OSB transmit spectra for a case of mixed CO/RT deployment.

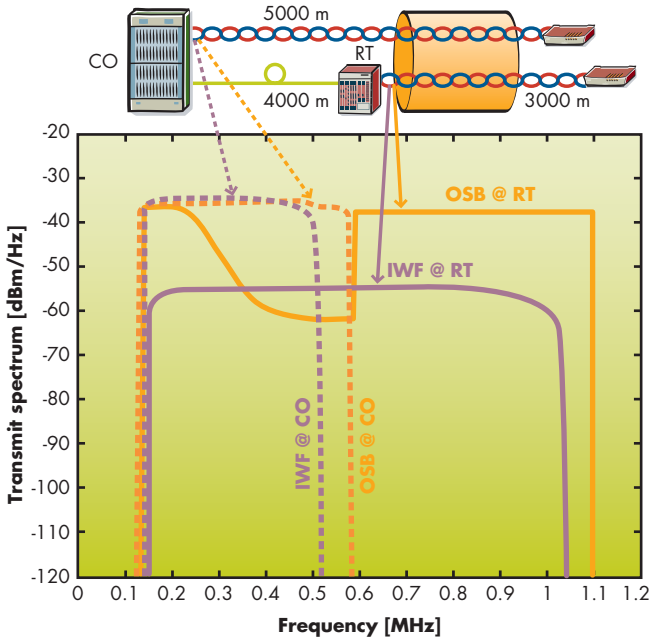


Figure 2 and Figure 3 illustrate DSM levels 0, 1, and 2. Figure 2 depicts the deployment scenario. A 5000 m 0.5 mm CO ADSL line is present in the same binder as a 3000 m 0.5 mm RT ADSL line. The fiber-fed RT is located 4000 m from the CO. The bit rate of the RT line is maximized, while guaranteeing 1 Mbits/s on the CO line. In addition, there are 10 SSM ADSL, 10 ISDN, and 4 HDSL crosstalkers present in the same binder. When the CO and RT lines operate in MA mode, they transmit at a nominal level of -40 dBm/Hz over the entire downstream band. The IWF and OSB transmit spectra are depicted in Figure 2. IWF boils down to flat Power Back-off (PBO) on the short RT line and boosting on the long

[2] OSB is the same as OSM, Optimal Spectral Management.

CO line. The OSB transmit spectrum of the CO transmitter very closely resembles the CO IWF transmit spectrum, but the OSB transmit spectrum of the RT transmitter is shaped more intelligently than its IWF counterpart. In the band where the CO line does not transmit, the RT line boosts. In the band where the CO line is active, the RT line boosts in the lower part of the band where the crosstalk coupling is small. In the higher part of the band where the CO line is active, the RT line applies severe PBO to avoid crosstalk interference to the CO line.

Figure 3: Rate region of a CO and RT line operating in MA mode (yellow), applying IWF (purple), and OSB (orange).

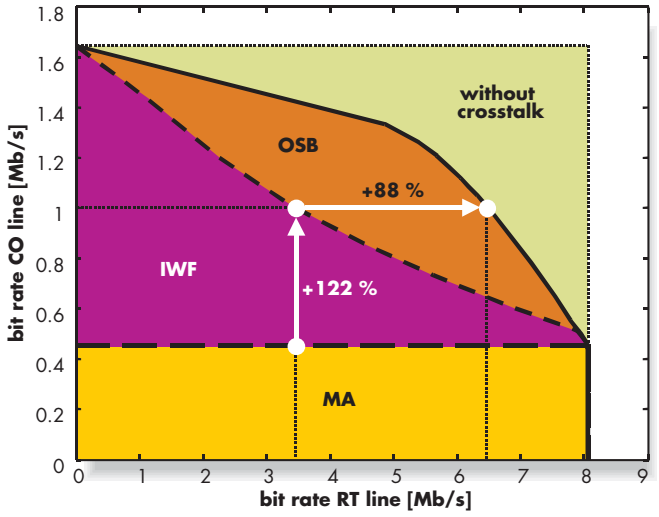


Figure 3 shows the, so-called, "rate region" for the CO and RT line, which is the set of all combinations of bit rates on the two lines, achievable with a particular noise margin and for a specified maximum transmit power for each of the DSL lines. From the figure it is clear that the rate region increases from DSM level 0 (MA), over DSM level 1 (IWF), to DSM level 2 (OSB). The rectangle shows the theoretical rate region in the absence of crosstalk between the CO and RT line. On the plot, the operating points corresponding to the transmit spectra of Figure 2 have also been depicted. For example, OSB allows an 88% increase in the bit rate of the RT line (from 3.4 Mbits/s to 6.4 Mbits/s), while maintaining the CO line at 1 Mbits/s.

DSM rate/reach performance gains

DSM level 1

The rate/reach performance gains of DSM level 1 depend on the deployment scenario, and particularly on the following parameters:

- mix of CO and RT lines in a binder
- DSL technology
- target bit rates of the different DSL bandwidth tiers[3] [1]
- loop length distribution
- number of DSM and SSM DSL lines in the binder
- number and type of alien crosstalkers
- DSM algorithm

To obtain a more realistic picture of the DSM performance gains for level 1, tens of different deployment scenarios were simulated, varying all parameters above. Moreover for every case, tens of 50-pair binders were simulated, where the length of every pair was randomly chosen according to the loop length distribution under consideration. Finally, each binder consisted of 16 DSL lines under test. The remaining 34 lines are considered as noise source for these 16 lines under test. This means that, in total, thousands of DSL lines were simulated, which should give reliable results.

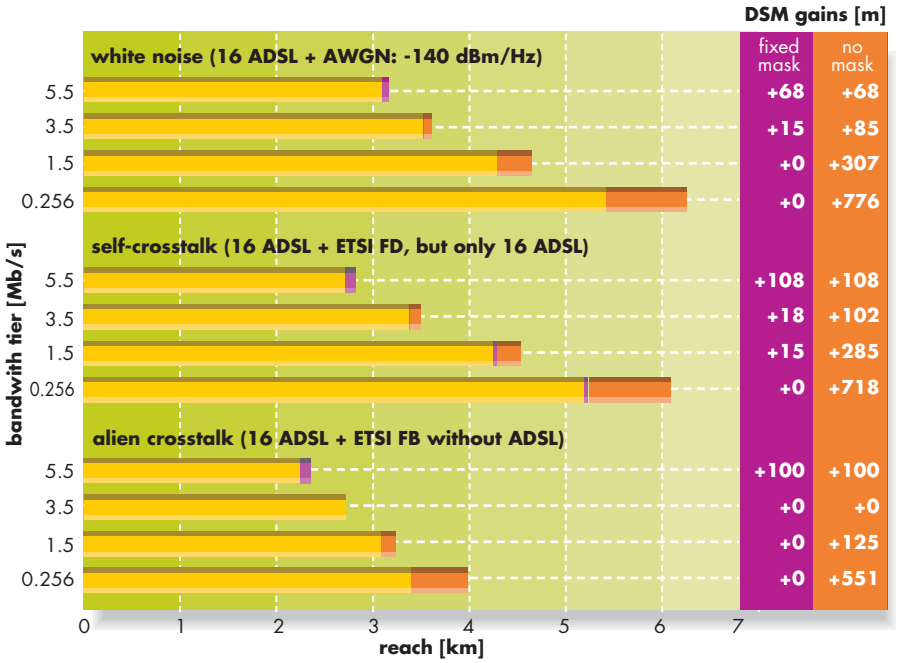
The simulation results are presented below, firstly for CO-fed ADSL and secondly for mixed CO/RT-fed ADSL. Note that focus is on downstream transmission, because crosstalk is less of an issue in the lower ADSL upstream band.

For CO-fed ADSL, IWF is presented. A distinction is made between IWF limited by the fixed masks of ADSL (so only applying flat power back-off), and IWF not limited by the mask (applying flat power back-off and boosting).

For mixed CO/RT-fed ADSL, DSM is only applied at the RT, to clearly illustrate where the gains come from. Applying DSM at the CO, too, would even improve the performance gains. The following algorithms are presented: IWF and Autonomous Spectrum Balancing (ASB). For IWF, only flat power back-off is used (boosting does not make sense on a short RT line), but a distinction is made between ADSL1 and ADSL2, since the amount of power back-off that can be achieved by each

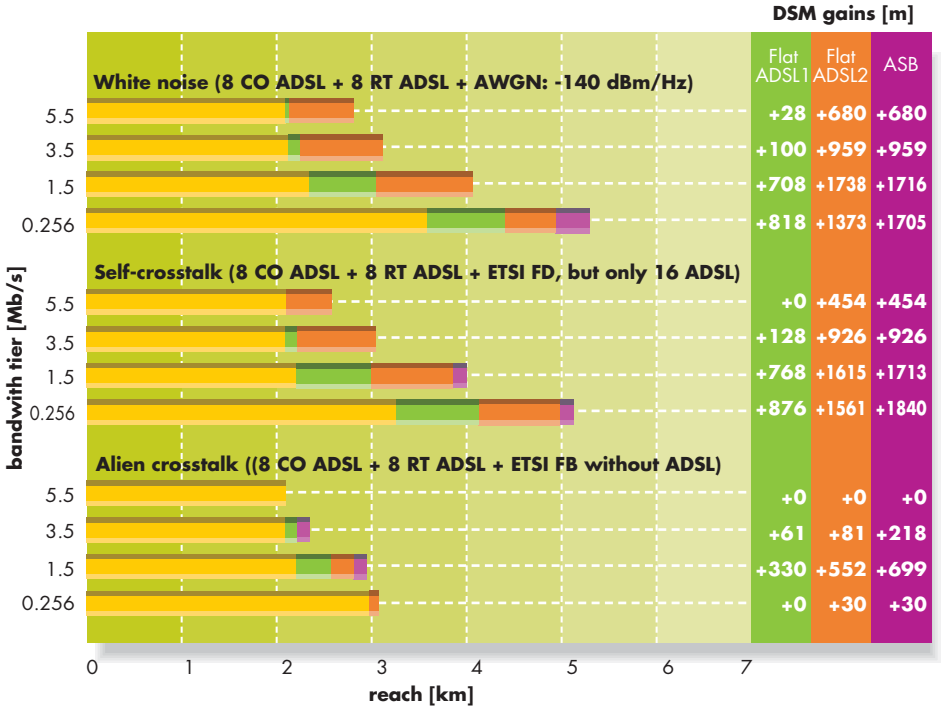
[3] To map services and revenue potential to bandwidth, it is expected that operators will define their services in terms of bandwidth tiers. (see also figure 2 in [1])

Figure 4: DSM level 1 performance gains for CO-fed ADSL: MA (yellow), IWF with fixed mask (green), and IWF without mask (orange).



of these technologies is different. ASB is an autonomous algorithm derived from OSB, where only the actual distance between CO and RT is taken into account. Since no knowledge on the other lines is taken into account, the PSD from ASB is calculated by defining a worst-case "virtual" victim line that is deployed from the CO. Consequently, ASB will show a better performance than IWF, but less good than OSB, from which it is derived. Finally, the simulations presented are based on the North-American loop length distribution [15]; however, the results for Europe are similar.

Figure 5: DSM level 1 performance on the CO lines for mixed CO/RT-fed ADSL MA (yellow), ADSL1 flat power back-off (green), ADSL2 flat power back-off (orange), Autonomous Spectrum Balancing (purple).



CO-fed ADSL

Figure 4 shows to what extent DSM allows an increase in the reach of the four bandwidth tiers typical for ADSL, namely tier 0 (256 kbits/s), tier 1 (1.5 Mbits/s), tier 2 (3.5 Mbits/s), and tier 3 (5.5 Mbits/s). As DSM considers the impact of lines in the same binder on one another, there are 16 lines under test instead of just one. The results are presented for three different noise environments: white noise (-140 dBm/Hz AWGN), self-crosstalk (ETSI-FD, but only 16 ADSL lines instead of 49), and alien crosstalk (ETSI-FB, but the 15 ADSL lines are under test instead of noise). Two different versions of IWF are compared: fixed mask (-40 dBm/Hz: no boosting) and full-fledged IWF (with boosting, no mask limitation).

An important conclusion is that, without boosting, IWF does not increase the reach of any of the tiers significantly, whatever the noise environment. If boosting is allowed, then, in terms of reach, tier 0 and, to a lesser extent tier 1, benefit from applying IWF.

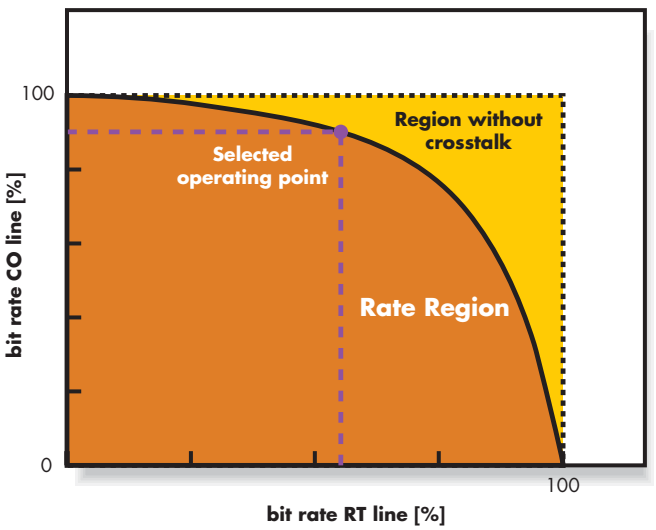
Mixed CO/RT-fed ADSL

Figure 5 shows to what extent DSM allows an increase in the reach of the four bandwidth tiers on the CO lines for mixed CO/RT downstream transmission. There are again 16 lines under test, eight CO lines and eight RT lines. Only the RT lines apply DSM, namely IWF or ASB. The CO lines have been kept in MA mode, such that the gains on the CO lines are only due to the change in PSD on the RT lines - flat power back-off for IWF or a shaped PSD for ASB. For ADSL1, the PBO is limited to 12dB (minimum PSD at a level of 52dBm/Hz). For ADSL2, the PBO is limited to 40dB (minimum PSD at a level of 80dBm/Hz), which results in performance identical to unlimited PBO (not indicated on the figure). It can be seen that there is a big difference between the performance of ADSL1 and ADSL2, owing to the difference in PBO.

When comparing Figure 4 (curves in yellow) and Figure 5 (curves in yellow), it can be seen that mixed CO/RT deployment (deploying users from an RT in a binder with existing users from the CO) with overlapping spectra will reduce the reach of the CO-deployed lines. However, by applying DSM at the RT one can recover the loss of reach of the CO deployed lines. Since only DSM at RT is considered in Figure 5 and not at the CO, the curves of Figure 5 should only be compared with the yellow curve of Figure 4. It can be concluded that flat PBO (IWF) applied to RT lines is very effective in recovering the reach of the CO lines. Flat PBO works very well in this case because the DSL transmitters are not co-located. Note that the gains diminish as the alien crosstalk pollution increases.

ASB can deliver additional gain in reach compared to IWF, but mainly on tier 0 (256 kbits/s). This is due to the fact that

Figure 6: Rate region and trade-off between CO-RT bit rate



the PSD of ASB is very similar to flat PBO for an RT, which is close to the CO, resulting in performance similar to that of IWF applied at the RT. When the distance between RT and CO increases, there is more shaping in the PSD of ASB; hence its performance improves compared to IWF. Note that for these performance simulations, the rate of the RT lines is kept constant at 5.5 Mbits/s (the highest bandwidth tier). When looking at a rate region (like the one in Figure 6), it becomes clear that the actual gain of the CO lines is highly dependent on the rate chosen for the RT line. Performance gains for ASB will improve if a lower bit rate at the RT is chosen. A lower bit rate at the RT is needed, for example, when full protection of the CO lines is requested (DSM allows a trade-off between the bit rates at the CO and the bit rates at the RT).

DSM level 2

DSM level 2 takes into account the actual crosstalk coupling, the actual deployment scenario, the actual noise environment, etc. This means the gains of DSM level 2 are at least as good as DSM level 1, but in most cases they will be even better.

As indicated before, ASB can only take into account a worst-case victim line, whereas Optimal Spectrum Balancing (OSB) will be able to take into account the actual victim lines deployed from the CO and the actual crosstalk coupling. So performance of OSB will always be better than ASB.

DSM level 3

For DSM level 3, simulations have been done for VDSL. It is assumed that all VDSL lines in a binder are part of a MIMO system, such that the crosstalk from all VDSL lines in this binder can be cancelled. Only the noise of non-VDSL lines (e.g., ADSL, HDSL, etc.) remains, but since these alien systems have only a small part of the available spectrum in common with VDSL, their influence is minimal.

For the performance curves in Figure 7, several simulations have been performed. For each simulation, a point-to-multi-point configuration was used, with all CPE modems at the same distance from the CO, but without joint processing at the CPE. Although the actual bit rates vary slightly, the gains are similar for a point-to-multi-point configuration with all CPE modems at a different distance (e.g., equally spread) from the CO. That is why, for DSM level 3, no statistical processing of network-wide simulations needs to be done, and simulations can be limited to a co-located scenario. Simulation results for an equally spread loop length distribution are similar, but not shown here. In both cases (CPE co-located or not), all the processing is done at the CO: crosstalk cancellation for the upstream transmission and crosstalk pre-compensation for the downstream transmission.

Two different noise scenarios have been considered: AWGN-only at a level of –140dBm/Hz and AWGN at –140dBm/Hz with additional ANSI-alien crosstalk noise model A, which includes the noise from ADSL, ISDN-BA and HDSL.

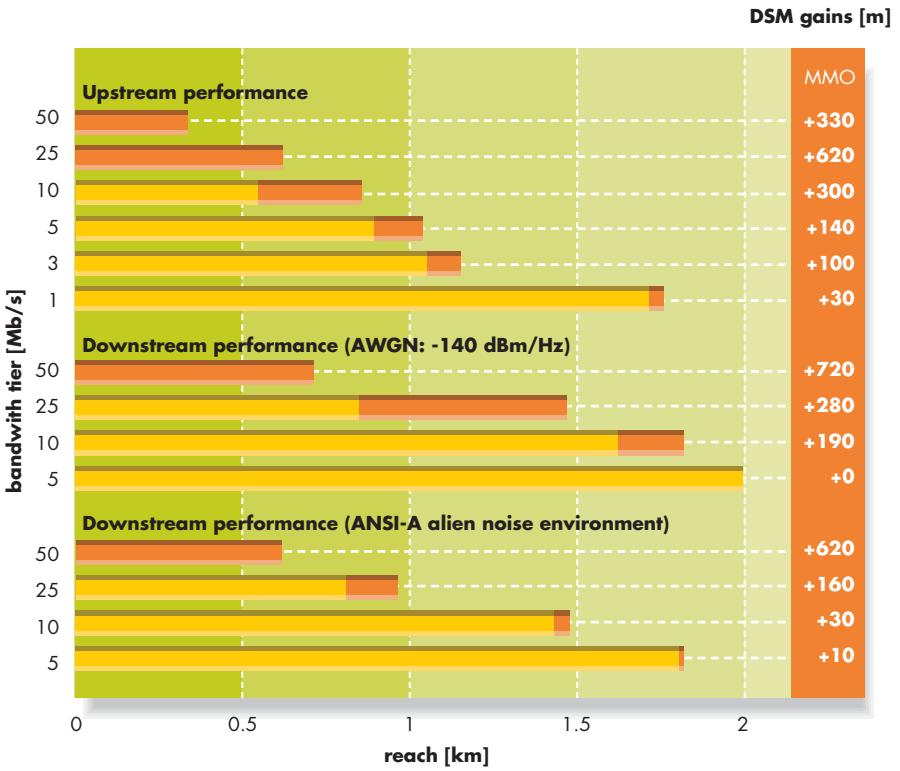
Figure 7 shows the gains for DSM level 3, compared to the current VDSL deployment practice with maximum power in downstream and with upstream power back-off (UPBO). UPBO is needed so as to have acceptable reach for VDSL deployment without DSM level 3. Deployment of upstream without UPBO would result in a very high upstream bit rate on short loops but a very low bit rate on longer loops. Without UPBO, the reach increase of DSM level 3 would be even higher, as can be seen from the figure.

The bit rate increase for downstream is significant, and even greater for upstream deployment. Bit rates of 25Mbits/s to 50Mbits/s in upstream are possible by using DSM level 3, even up to 600m and 300m, respectively. Without DSM level 3, the maximum tier for upstream is 10 Mbits/s. For downstream transmission, a tier bit rate of 50 Mbits/s is now available up to 700m.

The increase in reach is considerable, especially on the shorter loops. For longer loops the increase in reach is rather limited. On long loops, the amount of crosstalk decreases (compared to the fixed noises), but at the same time the gain that can be achieved with DSM level 3 decreases.

As can be seen, the dependence on the alien crosstalkers (ADSL and HDSL) is very small. There is no significant difference for upstream performance (so only 1 figure is shown), since the upstream bands U1 and U2 have negligible spectral disturbance from these ADSL / HDSL systems. In downstream, the influence of the alien crosstalkers is more evident, but still limited.

Figure 7: DSM level 3 performance gains for VDSL



Ensuring spectral compatibility of DSM-enabled lines

In principle DSM is a new way of looking at spectrum management. The transmit spectra are adjusted to the actual crosstalk environment, rather than using a fixed spectral mask for a certain DSL technology in a network. Fully-fledged DSM would require new spectrum management standards. As long as agreement on such new standard has not been reached, DSM has to be forced to comply with the transmit spectra restrictions imposed by Static Spectrum Management rules. One option is to restrain DSM, in the case of ADSL, to the –40 dBm/Hz transmit mask, which implies that no boosting is allowed. But then nearly all gains in reach vanish when applied to the CO-fed deployment scenario (Figure 4). A more advantageous solution could be found by exploiting the so-called analytical method B of the North-American T1.417 spectrum management standard, which allows boosted transmit masks that do not harm the legacy DSL lines to be designed. For example, the boosted mask of RE-ADSL2 has been designed according to this method B.

When only flat power back-off is used, spectral compatibility is not an issue, since the transmit spectrum is then lower than what is allowed in T1.417. However, when mixed CO/RT deployment or boosting is considered, spectral compatibility is essential.

As far as boosting is concerned, the best strategy is to define a set of masks that are spectrally compatible. Then it is up to the modem (i.e., DSM level 1) or a spectral management center (SMC) (i.e., DSM level 2) to decide which mask will be used. The main advantage of such an approach is that it is manageable (limited number of masks), and spectral compatibility can be explicitly tested (in simulation or in the lab). With an infinite number of masks, manageability becomes very difficult.

In a mixed CO/RT deployment where protection of the CO lines is needed, more information is needed to set the PSD of the RT lines. DSM will not guarantee full protection by default, but it does allow a trade-off between CO and RT bit rates by selecting a certain point on the rate region (see Figure 6). A possible solution to ensure spectral compatibility is to use a spectral management center (DSM level 2) to select a good PSD for each line, while taking into account the effect on other lines.

The stability of DSL lines when applying DSM

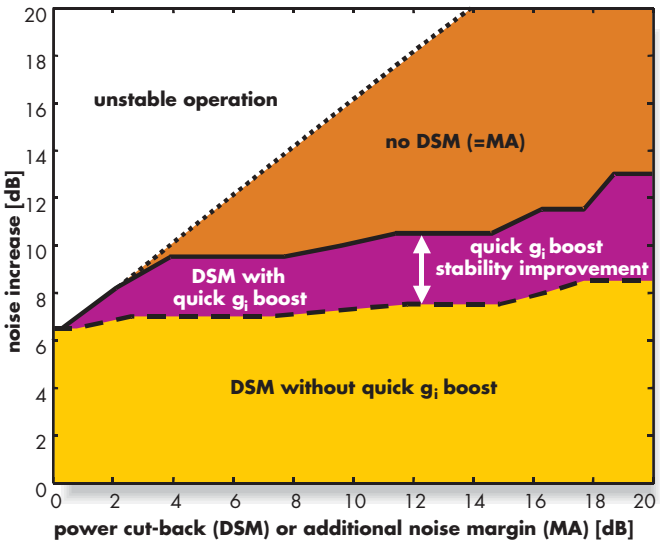
Currently most DSL lines are configured in Margin-Adaptive (MA) mode, which means that all available power is used to maximize the noise margin while maintaining a certain fixed bit rate. A DSL line becomes more robust against non-stationary noise, and hence more stable, as its noise margin increases. However, it has been reported [14] that the majority of lines operating in MA mode have excessive noise margins and hence cause unnecessary crosstalk interference.

As DSM aims at minimizing crosstalk interference, it limits the noise margin to the target noise margin (mostly 6 dB). However, to ensure stability, it might be wise to set the maximum additional noise margin not to 0 dB, but at a higher value, as indicated by [14].

Another approach would be to replace the static additional noise margin (partially) by a more dynamic form of robustness, namely a so-called quick g_i boost procedure [8] [16]. This would allow a DSL transceiver experiencing a drop in noise margin to send a short message to its peer transceiver to request that all tones be boosted with x dB such that its noise margin is restored.

The quick g_i boost procedure was implemented in a DSM test bed consisting of a 7300 ASAM, Thomson SpeedTouch CPEs, and a cable farm containing France Telecom and British Telecom cable sections. Both the CO and CPE modem software required adaptations to enable this quick g_i boost procedure. This means the quick g_i boost procedure cannot be used on existing installed lines (it requires an upgrade of the CPE). The stability of a DSL line was tested by instantaneously increasing the noise level after the line had reached

Figure 8: Improving stability by introducing the quick gi boost when applying DSM. Note that the horizontal scale has a different meaning for DSM and for MA mode: PCB for DSM (dashed line and full line) and additional noise margin for MA mode (dotted line).



show time. Figure 8 shows up to which noise increase the line remains stable as a function of the power cutback applied by DSM or the additional noise margin available in MA mode. Note, therefore, that the horizontal scale has a different meaning for DSM and MA mode: PCB for DSM, and additional noise margin for MA mode. For example, for a short line there could be a large additional noise margin of 15 dB when operating in MA mode, or equivalently this additional noise margin might have been converted into 15 dB of PCB when applying DSM. In MA mode, the noise resilience increases proportionally with the increase in additional noise margin. When applying DSM, the noise resilience is expected to remain flat at a little above 6 dB (the target noise margin plus additional noise resilience thanks to the bit swap mechanism), but it slightly increases with increasing power back-off because of a reduction in internal noise. The introduction of a quick g_i boost procedure improves the stability of a DSM-enabled line by about 3 dB.

One of the reasons the quick g_i boost is not able to completely follow the MA stability performance is that the AOC channel, which transports the boost message, is rather slow. Fortunately, the speed of the AOC channel has been improved in ADSL2, so an even larger improvement in stability could be possible by using the quick g_i boost.

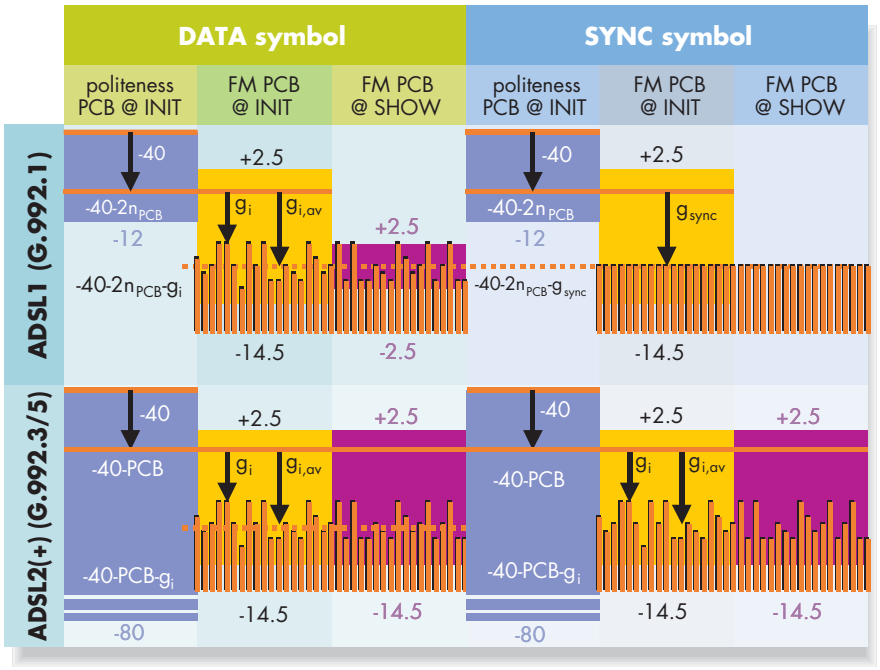
Note that the quick g_i boost, while protecting one line, could harm neighboring lines. However, the impact of a quick g_i boost is still smaller than the impact of a new line that is switched on.

Implementation of DSM

DSM level 1 – distributed DSM (implemented in the DSL transceiver)

In ADSL1, power allocation is based on water filling and is constrained by the mask. When the maximum additional noise margin is set to zero, the ADSL1 line operates in PA mode, approximating IWF, except for boosting. Figure 9 shows the Power CutBack (PCB) procedures in ADSL1: politeness PCB, FM-based PCB at initialization, and FM-based PCB during show time. The FM-based PCB is controlled by the maximum additional noise margin. It is limited from -14.5 dB to +2.5 dB at initialization and from -2.5 dB to +2.5 dB during show time. The latter is because the SYNC symbols do not scale with the DATA symbols during show time, as indicated by Figure 9. Note that FM-based PCB is optional in ADSL1 (ITU G.992.1), which means it is not supported by all ADSL1 CPEs. In addition, some ADSL1 CPEs apply FM-based PCB, but do not respect the range from -2.5 dB to +2.5 dB during show time.

Figure 9: Transmit power control in ADSL1 and ADSL2(+)



In ADSL2 (G.992.3), the FM-based PCB is mandatory. In addition, the SYNC symbols do scale with the DATA symbols such that the range of the FM-based PCB during show time equals the range of the FM-based PCB during initialization, as indicated by Figure 9.

In addition, Reach-Extended ADSL2 (RE-ADSL2) is specified in ITU G.992.3 annex L. Using the same reasoning as in the section on spectral compatibility, RE-ADSL2 allows an automatic switch between the normal ADSL mask and one boosted mask. This has been proven spectrally compatible with the basis systems according to method B of T1.417. Hence RE-ADSL2 captures part of the gains shown in the section on the DSM performance gains for CO-fed ADSL (see section "CO-fed ADSL", page 4).

DSM level 2 – centralized DSM (implemented near the DSLAM element manager)

A distributed implementation of DSM has the advantage of allowing optimal spectrum adaptation during show time. However, this distributed DSM functionality in ADSL1 is quite limited, and not all CPEs implement it. As DSM has most value if all DSL lines apply it, a DSM solution should also cover the legacy ADSL lines. Therefore a centralized implementation of DSM is preferable. Centralized DSM consists of a software module that communicates with the DSLAM via the Management Information Base (MIB).

In ADSL1 there are two MIB transmit spectrum control parameters: the maximum nominal PSD for downstream transmission (MAXNOMPSDds) and the carrier mask (CARMASKds), which allows tones to be shut off. ADSL2 (in fact ADSL2+, G.992.5) offers greater flexibility to control the transmit PSD because it introduces a downstream PSD mask (PSDMASKds) parameter that allows a piecewise linear transmit PSD to be set.

MIMO (implemented in the DSL line card and transceivers)

MIMO for DSL is still in an experimental phase.

Conclusion

DSM allows rate/reach performance of DSL to be increased by either avoiding crosstalk by autonomous (level 1) or coordinated (level 2) power allocation techniques, or mitigating crosstalk by multi-user transmission methods (level 3). For level 1, in-depth performance results are presented using Iterative Water-Filling (IWF) and Autonomous Spectral Balancing (ASB). ASB is an autonomous, but limited version of the DSM level 2 Optimal Spectral Balancing (OSB) algorithm. For DSM level 2 (OSB), it is argued that the results are at least as good as ASB. For level 3, again some performance results are presented.

For CO-fed ADSL, IWF provides most significant gains in reach for low-bit-rate services thanks to boosting. If boosting is not allowed, then DSM does not achieve significant gains in reach in the case of CO-fed ADSL. For mixed CO/RT-distributed ADSL, IWF applied to the RT lines is most beneficial for the reach of the higher-bandwidth tiers on the CO lines. ASB can even do slightly better, especially as the distance between CO and RT becomes larger, since in that case the effect of shaping the transmit PSD becomes more important.

IWF and ASB can be either implemented in a distributed fashion, i.e., on the DSL transceiver, or in a central-

ized way as a software application running near the DSLAM element manager and communicating with the DSL lines through the DSLAM MIB. Both for distributed (level 1) and centralized DSM (level 2), Alcatel solutions are or will be available under the form of ADSL2, RE-ADSL2, CO modem software updates, MIB software updates, and the 5530 NA.

DSM level 2 has better performance than DSM level 1, since more information is incorporated in the design of the optimal transmit PSD, such as the exact configuration of the binder (loop lengths and flavors of all lines), the exact crosstalk coupling between the lines, etc. There will be a gradual transition from DSM level 1 algorithms that are implemented in a centralized way to fully DSM level 2 algorithms when more information about the network becomes available.

DSM level 3 differs from levels 1 and 2 insofar as it requires that all DSL lines in the same binder jointly process their transmission signals. This requires that the DSL transceivers be co-located and hence is only possible at the network side, except if multiple lines are bonded. This intense coordination between the lines allows crosstalk mitigation, which means crosstalk cancellation in upstream and crosstalk pre-compensation in downstream. The requirement to connect all lines in the same binder to the same DSL transceiver implies that DSM level 3 is only possible at a remote terminal, because from that point binder integrity is more likely. DSM level 3 is also called vectoring [13] or MIMO (Multiple-Input Multiple-Output). DSM level 3 is currently still too complex for implementation on the available DSL digital chips.

Abbreviations

ADSL Asymmetric DSL
AOC ADSL Overhead Channel
ARPU Average Revenue Per User
ASAM Advanced Services Access Manager
ASB Autonomous Spectrum Balancing
CO Central Office
CPE Customer Premise Equipment
DRM Dynamic Rate Management
DSL Digital Subscriber Line
DSLAM DSL Access Multiplexer
DSM Dynamic Spectrum Management
FM Fixed Margin
FTTArea Fiber-To-The-Area
FTTBuilding Fiber-To-The-Building
FTTCab Fiber-To-The-Cabinet
FTTCurb Fiber-To-The-Curb
HDSL High-bit-rate DSL
HIS High-Speed Internet
ISDN Integrated Services Digital Network
IWF Iterative Water Filling
MA Margin-Adaptive
MIB Management Information Base
MIMO Multiple-Input Multiple-Output
NA Network Analyzer
OSB Optimal Spectrum Balancing
OSM Optimal Spectrum Management
PBO Power Back-Off
PCB Power Cutback
PSD Power Spectral Density
RA Rate-Adaptive
RE-ADSL Reach-Extended ADSL
RT Remote Terminal
SHDSL Single-pair High-speed DSL
SMC Spectrum Management Center
SNR Signal-to-Noise Ratio
SSM Static Spectrum Management
TMM Thomson MultiMedia
UPBO Upstream Power Back-Off
VDSL Very-high-speed DSL
VoD Video-on-Demand

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