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Title: **Example Improvements of Dynamic Spectrum Management (089)**

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Abstract:

This information-only contribution defines some potential dynamic spectrum-management methods and provides examples of potential improvements in their use. This contribution is not meant to provide sample text or methods for dynamic spectrum management, but rather to motivate study.

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Example Improvements of Dynamic Spectrum Management (089)

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ABSTRACT

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1. Introduction:

Spectrum management (SM) DSL standards and reports attempt to define the spectra of various DSL services. The reason for specifying the spectra of the various DSLs is to limit the crosstalk between DSLs that may be deployed in the same binder. Such crosstalk can be the limiting factor in determining the data rates and symmetries of offered DSL services at various loop reaches, so spectrum management finds some level of compromise between the various DSL service offerings that may be simultaneously deployed. Spectrum management studies have to date tended to specify some typical and worst-case loop situations, and then proceed to define fixed spectra for each type of DSL to compromise the mutual degradation between services. Such a fixed spectrum assignment consequently may not produce the desired level of compromise in situations different from those presumed in the studies. This information-only contribution attempts to expose the performance loss incurred by fixed spectrum assignment.

This contribution defines the current practice of fixed spectrum management as **static spectrum management.** By contrast, a system with adaptive determination of DSL spectra will be called **dynamic**

spectrum management. Necessarily, static SM is a special case of dynamic SM, so static SM can never outperform dynamic SM. The question then arises as to the level of improvement that dynamic SM can provide. This level of improvement varies with loop, crosstalk coupling function, and data rates/symmetries offered, but can be quite large as this contribution illustrates in Sections 2 and 3. The level of relative improvement increases as loop lengths get shorter and data rates get more symmetric, as is likely to be the case as DSL evolves. Importantly, dynamic spectrum management allows a greater mix of high-performance asymmetric and symmetric service in the same binder.

Within the context of dynamic SM, there are two unbundled situations of interest: line unbundling and packet unbundling [2]. Line unbundling occurs when different service providers place electronic physical-layer signals on lines within a telephone cable. This is the current practice when lines terminate in the central office. Packet unbundling occurs when service providers instead lease bit streams from a single common carrier who manages all signals on the cable. Table 1 illustrates the two types of dynamic SM that will be considered in these two cases, **vectoring and spectrum balancing.**

Table 1 – dynamic SM summary

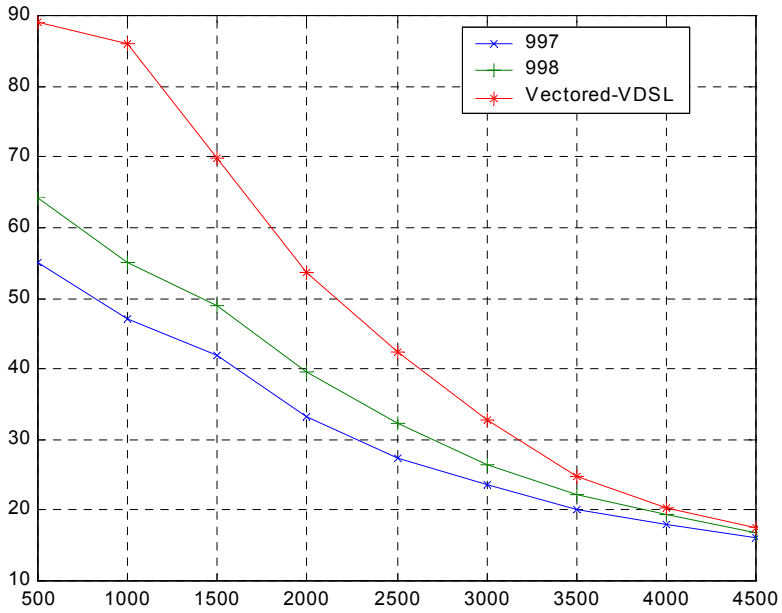
Unbundling	Dynamic SM name	Description of SM control	Sect
Packet	Vectoring	Line signals determined by common carrier's DSLAM	2
Line	Spectrum balancing	Line spectra recommended by 3rd opportunistic party	3

Section 2 reviews the basic vectoring line terminal (LT) for advanced DSL services, and then projects vectored DSL performance improvements with respect to static SM. The level of data rate and symmetry improvement is dramatic for this case, especially as line lengths get shorter and crosstalk is increasingly a factor. Large vectoring improvements occur even when all lines are assumed to have the same length, and of course further increase when line lengths are different. Vectoring is an example of a general adaptive form of code-division multiple access, and profits from the single packet-unbundled service provider's ability to monitor and control all lines' physical layer signals. Vectoring can thus be implemented efficiently in an LT that allows coordination among lines. By contrast in dynamic SM with different service providers collocating in an LT, a 3rd opportunistic/maintenance party can purchase/extract information from DSL modems, process that information, and send spectrum recommendations to all DSL modems determined to be mutually interfering. This spectrum-balancing of Section 3 also sees significant improvement, although not as much as vectoring. Spectrum balancing offers largest improvements when optimum line spectra for each line would be different, i.e. when line lengths and noise conditions within the binder are different. Spectrum balancing can be construed as an advanced spectrally flexible version of power back off. Section 4 concludes the document by trying to provide rules of thumb when improvements are large and suggests how DSL may evolve from current static spectrum management, to spectrum balancing, and then ultimately to vectoring.

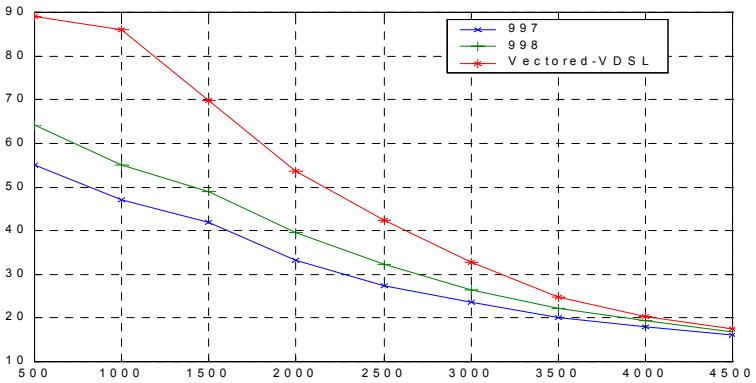
2. Vectoring for Packet Unbundling

The basic vectored DSL system is described in a previous contribution (99-559, Tampa, [3]) and will not be repeated here. However, LT NEXT is eliminated through the use of simple one-tap echo-canceller-like structures on each synchronized tone of common crosstalk between lines. NEXT at the customer-premises (or NT) of course remains when/if signal bands overlap, which will not be the case in this paper. FEXT is mitigated through vector precoding as described in [3] in the downstream direction, and is mitigated by block-DFE [3], possibly with error-propagation mitigated through any number of iterative multiuser schemes [4],[5]. However, in this contribution used a fixed-for-all-lines 4/5-band frequency plan that is described by upstream bands [0.03-0.138, 2.5-3.75, 7.5-14.5] and downstream in between those bands with vectoring. This band is not necessarily optimized, but we found it to be reasonably good for the common line lengths and Noise A used in all simulations. This band is common to all the lines in the simulation. This need not be the case and indeed it is possible to improve in situations where the lines have different lengths. We will leave further improvements to future contributions, but use this common plan here to illustrate the large improvement gained by allowing band use to be situation dependent, i.e. perhaps the simplest form of dynamic spectrum management. The choice for comparison was the existing two 4-band plans for VDSL, presumably a good choice to represent the current type of static spectrum management at its best.

A DMT system with a bit cap of 11 and up to 4096 4.3125 kHz-wide tones were used on each line. RFI band notching was included in all HAM bands. Average power per line is 11.5 dBm. Results appear in Figures 1(a) and 1(b). No power back-off is used in these Figures for the 997 (Europe) and 998 plans, so they perform worse in practice with PBO.



(a) downstream improvement of vectoring on short loops with respect to line-unbundled static VDSL



(b) upstream improvement of vectoring on short loops with respect to line-unbundled static VDSL

Figure 1 – example improvements with Noise A included for other DSL noises.

Evident in Figure 1 is the very large gain achieved at lengths of 3000 feet and below. Thus, at LT placements where packet unbundling is most likely to be of interest (see [1]), the largest gains are possible. Note the achievable data rates are symmetric because the downstream vectored results are the same as the upstream. Gains increase further in less symmetrical situations (where line lengths differ) and when actual measured crosstalking functions (typically larger than theoretical models in use today, thus magnifying effects of vectoring) can be included. Spectra 997 and 998 are examples of static spectrum management that tries to compromise several effects in determining the spectra – one might recall considerable consternation in the selection of these spectra while attempting to compromise diverse interests. It is clearly possible to do better with dynamic spectrum management.

One of the difficulties in specifying levels of improvement for situations in which line lengths differ is the choice of length and the corresponding desired data service, which can vary with customer. Information theory addresses this lack of specificity with what are known as "rate regions." A rate region is essentially a multidimensional plot of the mutually possible data rates on all lines. Anything inside a region bounded in this multidimensional space is possible, albeit with a different spectrum than any other point. The authors will present methods that always allow these mutually compatible spectra to be computed in later contributions, but a basic theory to do so was introduced by Cheng and Verdu in [6]. An example of a rate region for two lines of lengths 1000 and 1500 feet is shown in Figure 2.

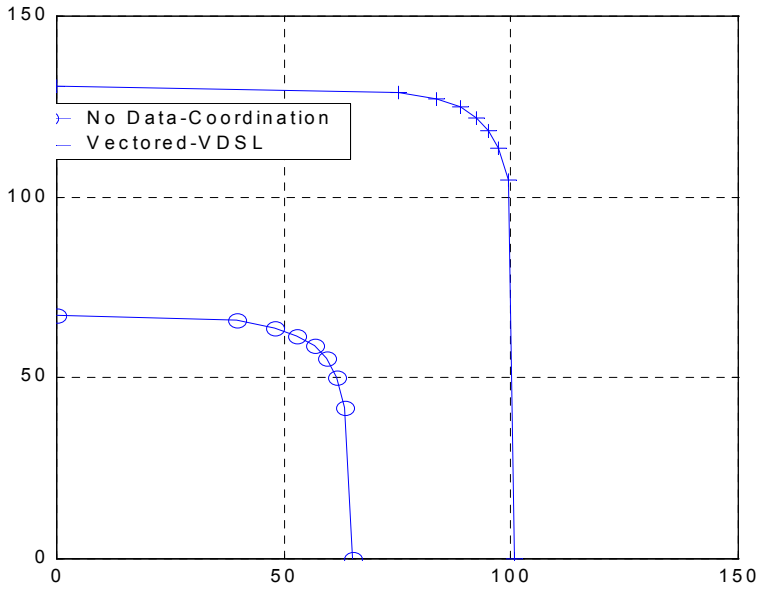


Figure 2 trade-off in Downstream data rate with power constraint for two users at 1000 and 1500 ft.

Each point inside the larger region is achievable with vectored VDSL and dynamic SM, although that point will have a unique spectrum for each line. More than 2 lines is hard to plot, but one could envision software within the service provider that evaluates customer-requested data rates, checks the rate region to

see if it is possible, and then commands each line to adjust its spectrum to the mutually best for the current request of data rates. Of course, a combination outside the region is not possible and would also then be immediately known as a problem situation to the service provider, eliminating the need in advance for maintenance to determine the field problem. The selection of spectrum for each point requires knowledge of the channel and noise for each line as well as of the crosstalk coupling functions between the affected lines. Figure 2 was plotted with only a total power constraint over all lines (which makes the plot easier to generate and may correspond to a desirable implementation), leading to higher data rates yet than Figure 1.

Figure 1 used a power constraint for individual lines. Instead, Figure 2 used an overall power constraint for all the two lines, and thus necessarily leads to yet higher rate projections.

One also envisions the problem in trying to respond to questions like "How much better can I get?" or "How much range improvement do I have?" because the answer depends heavily on the exact situation, but generally the answer for vectoring is ***"A huge improvement in rate and range, especially at shorter line lengths where wider spectra are used, and thus more potentially limiting crosstalking noise is generated."***

3. Spectrum Balancing Results

While vectoring with packet unbundling necessarily allows the highest data rates, it is possible that unbundling will remain at line level, at least transitionally in that some remote terminals or even central offices are likely to have uncoordinated line signals. For this configuration, Figure 3 below shows an opportunistic 3rd party that collects spectrum information (or computes it based on selected in/out measurements provided by the modem) and adaptively determines those lines that have significant mutual crosstalk. The spectrum on these "competing" lines is then balanced by the third party according to sophisticated signal processing algorithms, of which there are many choices possible. We used a method known as iteratively water-filling [7] to determine the individual line energy spectra, which amounts to essentially rerunning a loading algorithm for each line and updating its spectrum before using that new spectra to rerun water-filling on the other lines, which will converge to a competitively solution in all but aberrant situations [7]. There is less improvement in this case than with vectoring, but still an improvement with respect to the static spectrum management.

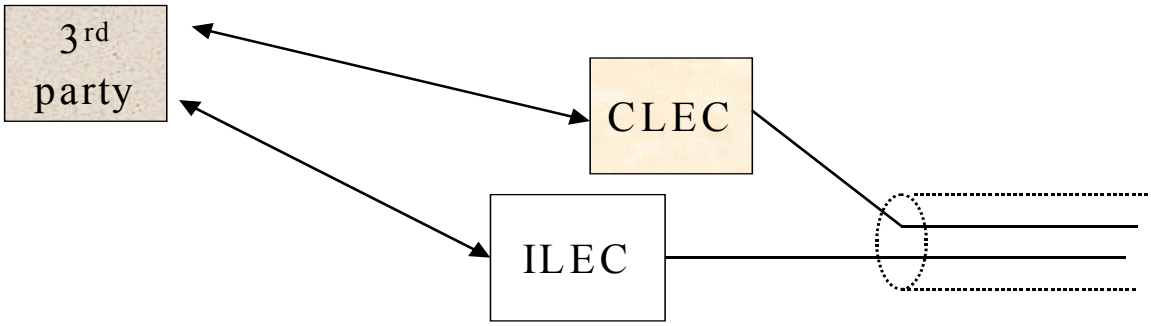


Figure 3– Basic concept of an opportunistic 3rd party.

Simulations in this section were performed essentially for two types of spectrum balancing, which are essentially equivalent to frequency-dependent power back off (PBO), a general topic that has been studied for VDSL. Power back off is typically implemented in the upstream direction in VDSL because a near-to-LT upstream transmitter's FEXT could potentially be a very large noise for a far-from-LT upstream receiver's detection of upstream signals. The downstream direction in VDSL was originally ignored for PBO, presumably because the FEXT is generated all in the same place (but one could argue still that the downstream signal power reduction on shorter lines would help longer lines – just not as much as

upstream). However, LT-based downstream VDSL emissions could be substantial noise also for central-office-based VDSLs or ADSLs. The flexible PBO here is implemented with iterative waterfilling, as in [7].

The simulations even just for the limited number of situations exposed here indicate large, one might say dramatic, improvements in achievable data rates for DSL. The authors are certain that yet larger gains are possible, but the area merits large investigation to determine those situations that have greatest and least benefits from spectrum balancing.

This section begins by looking at PBO methods that allow the spectra within existing standardized transmission bands to be changed in amplitude only (thus not violating any existing FDM spectrum management, which may be a good first step towards eventually dynamic spectrum management) – essentially power back-off or power boost subject to a common 11.5 dBm power constraint on each line. Improvements well beyond the best of current PBO methods are achieved by dynamically allocating spectra within these standardized bands (i.e., turning on/off different lines in different places, but maintain the direction consistent with current spectral specifications) in Section 3.1. Section 3.2 then proceeds to allow the bands themselves to be adjusted in terms of start/stop frequencies as well as be turned on/off within each band, but maintains a consistent set of bands for each binder group. Full-blown spectrum balancing would allow the band-edges on each line to be altered – however, we did not find this to provide significant improvement beyond that found in Section 3.2 unless we also introduce the vectoring of Section 3.1, except when the number of contributing crosstalkers is small. The authors suspect further improvements for full spectrum balancing when binders exhibit diverse line situations (radio frequency noise or bridged taps on some lines, but not all).

3.1 Flexible PBO with fixed bands

North America has standardized on a band usage plan known as plan 998 [9]. While this plan was conceived in VDSL studies, it applies and considers all other DSLs as well and is consistent with their band usage. Thus, the study of this section then uses this band also. This study first looks at 8 DSL lines emanating from an LT as an ensemble. Four of the lines are at 3000 ft in length and the other four are at 1500 feet in length. Only two lengths were selected to faciliate the plotting of rate regions, which will show the rate on the 3000 ft loops versus the rate on the 1500 ft loops. There will be one spectrum plan, but the relative magnitudes of transmitted signals in the used bands on the two different lengths are allowed to vary without PSD limit (above 1.1 MHz). other than each line's total power cannot exceed 11.5 dBm.

For comparison against traditional SM, this study uses each of the bands consistent with some fixed PBO criteria. This paper selects the reference noise method [8] where each line has its transmit spectra selected so that the FEXT it generates is equivalent to that of the 3000 ft line, using the standardized FEXT coupling function $\left(\frac{1}{49}\right)^{.6} \cdot 8 \times 10^{-20} \left|H(f)\right|^2 \cdot d \cdot f^2$ where $\left|H(f)\right|$ is the insertion loss of the 3000 ft line, and f is the frequency in Hz. Each FEXT is added to others for each line type considered. All spectra selected are consistent also with plan 998 of VDSL, which is upbands=[0.03,0.138; 3.75, 5.2 ; 8.5, 12.0] and downstream everywhere else. HAM radio bands are also silenced in any direction in this study, and so-called noise A of VDSL standards was used as a background crosstalk from other lines that could not be altered. This corresponds to a a rate pair for the short and long lines of

fixed plan 998, with reference noise power back-off:

On 3000' loops: (R_up, R_down) = (7Mbps, 23Mbps)
On 1500' loops: (R_up, R_down) = (9Mbps, 44Mbps)

The lines were all 26 gauge. The 998 plan emphasizes heavily an ability transmit at 22 Mbps downstream on the 3000 foot loop, and achieves that here. Instead, the simulations now are expanded within and consistent with the 998 plan, but allowing different loops to all optimize their spectra in cognizance of the power spectral transfer between the lines, which was assumed here to be the same model as above (in

practice yet greater gain can be achieved by measuring these functions and supplying them to the optimization program). Iterative water-filling [7] subject to the constraints of 998 band use and 11.5 dBm total power on any line is used. Noise A was left without alteration as a constant additive noise on all lines, but the FEXT generated by the 8 lines under study did vary with the choice of spectrum. Figures 4a and 4b show the achievable rate regions for upstream and downstream respectively. In particularly, one notes that the rates below are within the region:

fixed plan 998, with spectrum balancing within 998 bands:

On 3000' loops: (R_up, R_down) = (7Mbps, 24.5Mbps)
On 1500' loops: (R_up, R_down) = (19Mbps, 45Mbps)

The data rates have increased on all lines while spectum-plan-998 edge frequencies are maintained. In particular, the symmetric or upstream data rate possibility on the shorter lines has more than doubled while the asymmetric downstream data rate on the longer lines has increased! In fact, many other rate combinations are now possible also, as shown in Figures 4a and 4b.

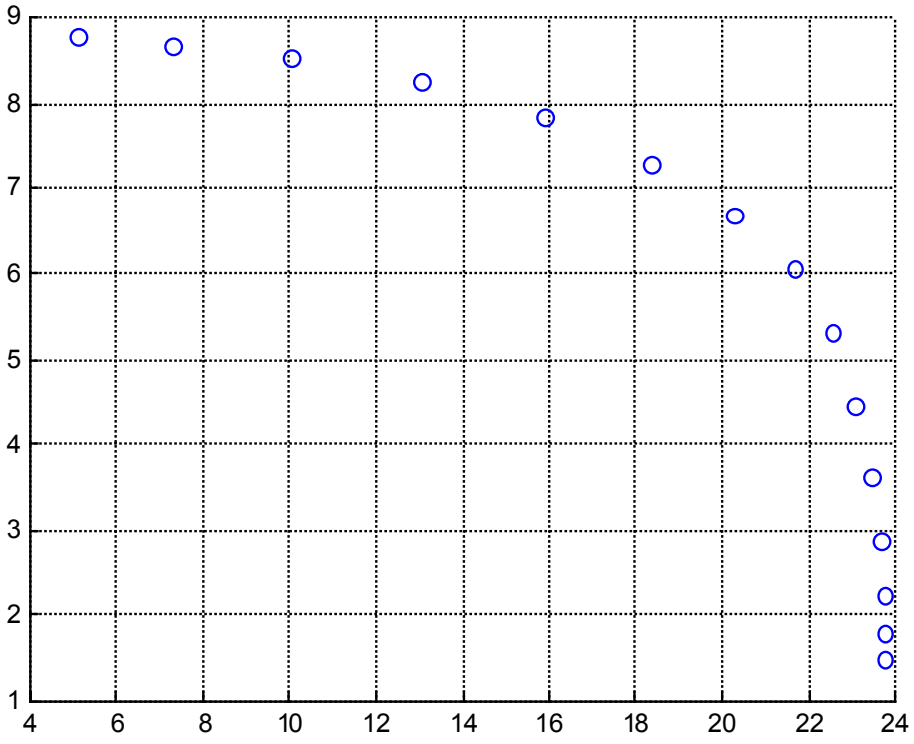


Figure 4(a) – Upstream data rates on 3000' (vertical axis) and 1500' (horizontal axis) 26-gauge loops with band-plan 998 and spectrum balancing (flexible power back off in this case).

One notes also that as much as 24 Mbps symmetric is possible on the shorter lines when the longer lines have very little upstream data rate and at least 24 Mbps downstream. Such a rate combination may be a very desirable trade-off between different service providers interests that could be implemented at least in some cases. The system entity that computes rate regions could determine if this combination is possible in a given binder and allow the implementation in those cases where it is. Indeed, we might argue that lines closer to a terminal or central office might be more likely to be businesses with symmetrical data service needs (voice, computer network connections) while those further away are residences with less symmetric

needs (video). Or it may be that only one residential customer is close, and the rest are far, while only one business is far. In this case, the service provider might find that there are 4 different spectra for the 4 cases, but that the needs of each customer can be satisfied – or pricing could be tiered on services to encourage data rates for a specific customer that are more accommodating for the overall benefit of the network (i.e., price symmetric services higher, and then tier that pricing).

In any case, what is clear is that the trade-offs may be limit less, but the basic data rate region can be determined for any line/binder and the provider can then proceed to make decisions that may enable far greater revenue generation and far more fair competition than any previously believed possible.

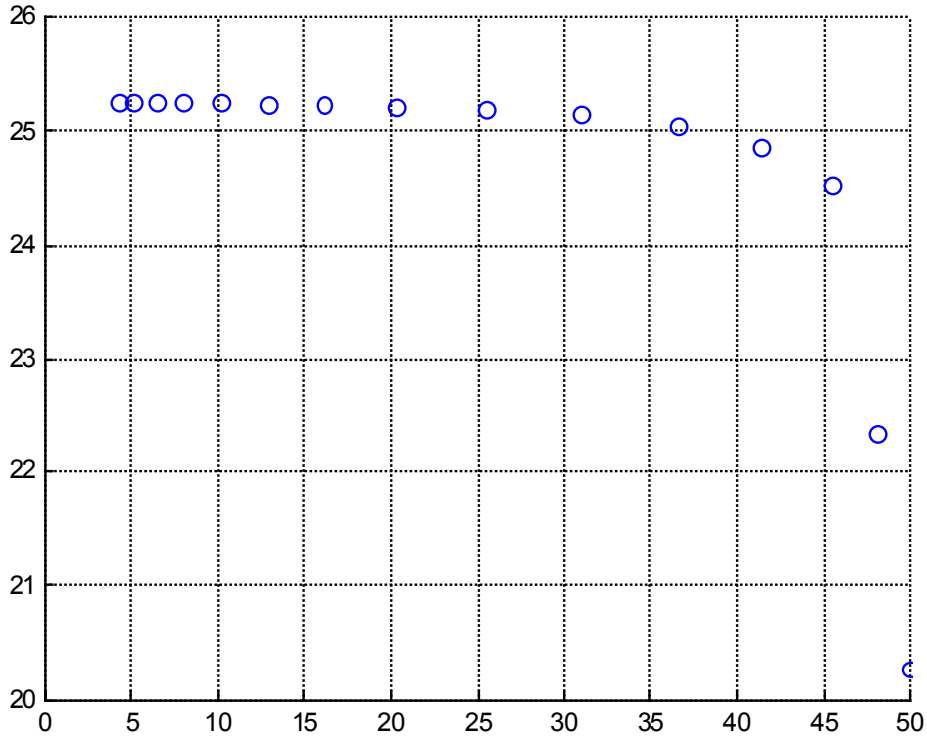


Figure 4(b) – Downstream data rates on 3000' (vertical axis) and 1500' (horizontal axis) 26-gauge loops with band-plan 998 and spectrum balancing (flexible power back off in this case).

3.2 Flexible PBO with variable bands

The allowable data rates improves more dramatically if the band plan above is allowed to have flexible corner frequencies. The simulations here maintained the use of 4 bands (and optional 5th upstream below 138 kHz), but allowed the frequency corner points to vary from the 998 plan – but the same plan was used for all the lines in the binder group, and flexible PBO was then applied within those consistent bands. The power constraints and noises are otherwise identical to those in Section 3.1, as are the 8 lines used. Figures 5(a) and 5(b) now illustrate the yet more dramatic improvement.

With the constant plan = [0.03, 0.138; 2.4, 5.0; 8.5, 12.0] upstream, a data rate combination now achievable is for instance:

Under **flexible spectrum, flexible power back-off**:

3000' loops: (R_up, R_down) = (14Mbps, 25Mbps)
1500' loops: (R_up, R_down) = (25Mbps, 47Mbps)

Note the asymmetric line now allows 14 Mbps upstream, double its previous value, while the downstream data rate on this line has again slightly increased. The 1500' foot line is now performing with 25 Mbps symmetric service or more – and enough downstream bandwidth for a business to watch TV on top of serving symmetric business demands (on their lunch hour of course)! Indeed, Figure 5a suggests that close to 34 Mbps symmetric service is achievable on the short loops while the longer loops still carry more than sufficient downstream data rate to carry 25 Mbps.

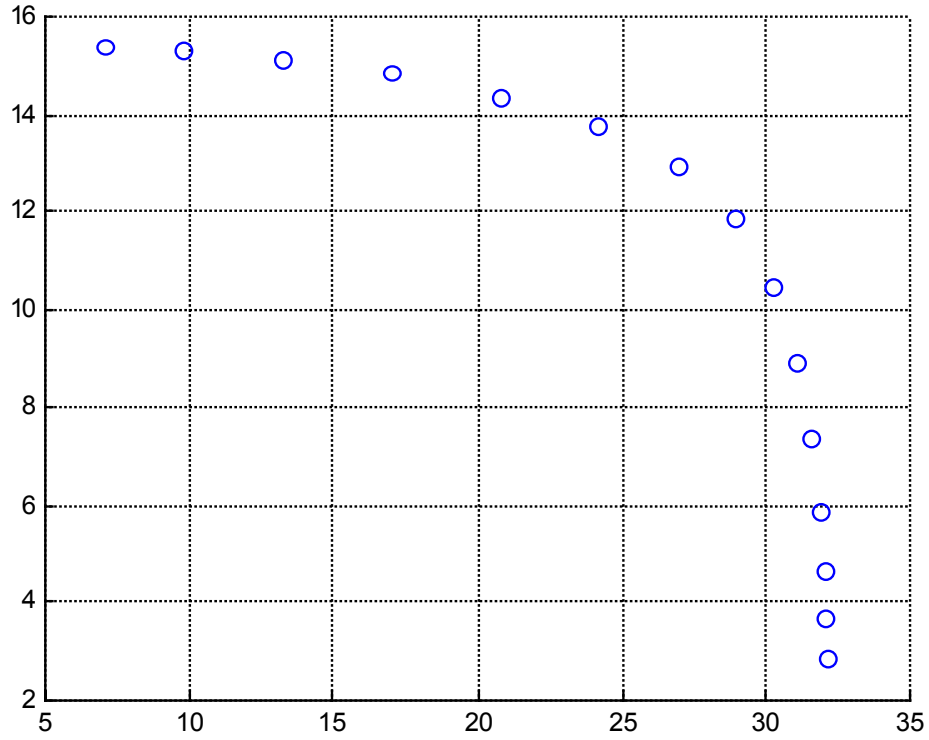


Figure 5(a) - Upstream data rates on 3000' (vertical axis) and 1500' (horizontal axis) 26-gauge loops with flexible band plan and spectrum balancing (flexible power back off in this case).

3.3 ADSL and VDSL iteraction and improvement

A classic recent problem in spectrum management [10],[11] has been the interaction of VDSL and ADSL. Specifically, VDSL FEXT from an ONU close to a customer can seriously degrade the downstream performance of a longer ADSL line that shares the same binder as the VDSL service. Such might be the case in which new VDSL service is early in deployment. Spectrum balancing is clearly the more prudent choice if the ADSL cannot be altered or changed. For this situation, we supply the rate regions of Figures 6a and 6b when ADSL are the only two services of concern and Figures 7a and 7b when 4 HDSL and 10 ISDN are also present. Two scenarios are plotted in figure a and b respectively in each case:

Scenario 1:
4 ADSL loops of lengths 12000ft are located from CO to CP.

4 VDSL 3000ft loops are located from ONU to CP.
VDSL and ADSL lines are co-located at CP. So the ONU is 9000ft from CO.

Scenario 2:
Same as above, except 4 VDSL loops of 4500ft are used. Thus, ONU is assumed to be 7500ft from CO.

Evident from Figures 6a and 6b is that the situation with dynamic spectrum management, even if executed just for the VDSL line is a dramatic improvement from the correctly studied and often-quoted results of Dr. Krista Jacobsen of TI in [10],[11] where she studied static spectrum management. The conclusions are also far more optimistic. [10], for example showed, that when VDSL operates at circa 20+ Mbps downstream, the ADSL at 9000 ft. (3000m) and 12000 ft. (4000 m) was able to only achieve 2.8 Mbps and 2.5 Mbps, respectively. The comparable situation in Figures 6a and 6b show 5 Mbps is possible, basically doubling the achievable rate and making it appear like the VDSL system is not present as a disturber.

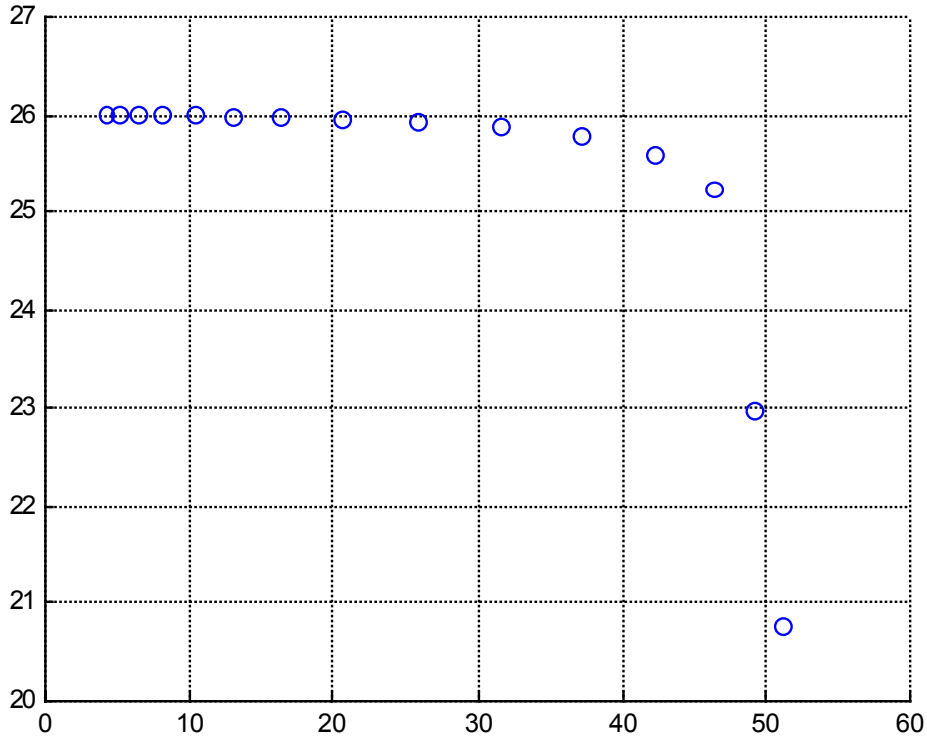


Figure 5(b) - Downstream data rates on 3000' (vertical axis) and 1500' (horizontal axis) 26-gauge loops with flexible band plan and spectrum balancing (flexible power back off in this case).

Figures 7a and 7b appear to be the first report of range loss when HDSL and ISDN are also present, which reduces the ADSL range further, and it appears that it is possible to service VDSL, with existing ADSL, HDSL, and ISDN at nearly 3 Mbps rate in ADSL and 20+ Mbps rates in VDSL with no degradation, but only if dynamic spectrum management is used (in this case we used spectrum balancing).

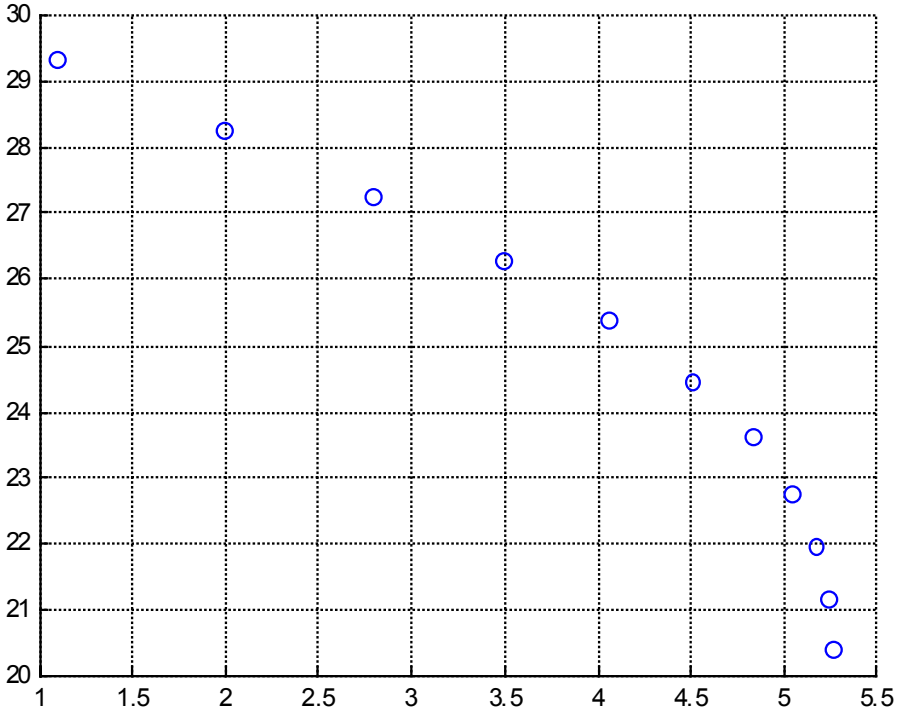


Figure 6a – VDSL downstream data rate (Mbps – vertical) vs ADSL downstream data rate for Scencario 1 and spectrum balancing.

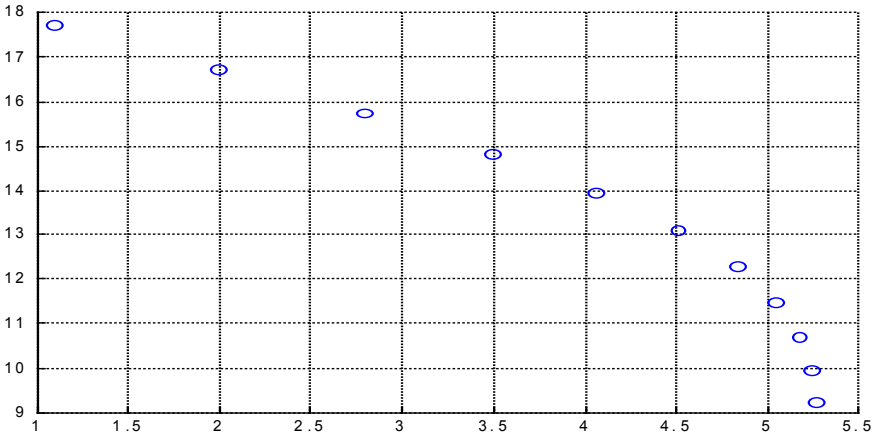


Figure 6b – VDSL downstream data rate (Mbps – vertical) vs ADSL downstream data rate for Scencario 2 and spectrum balancing.

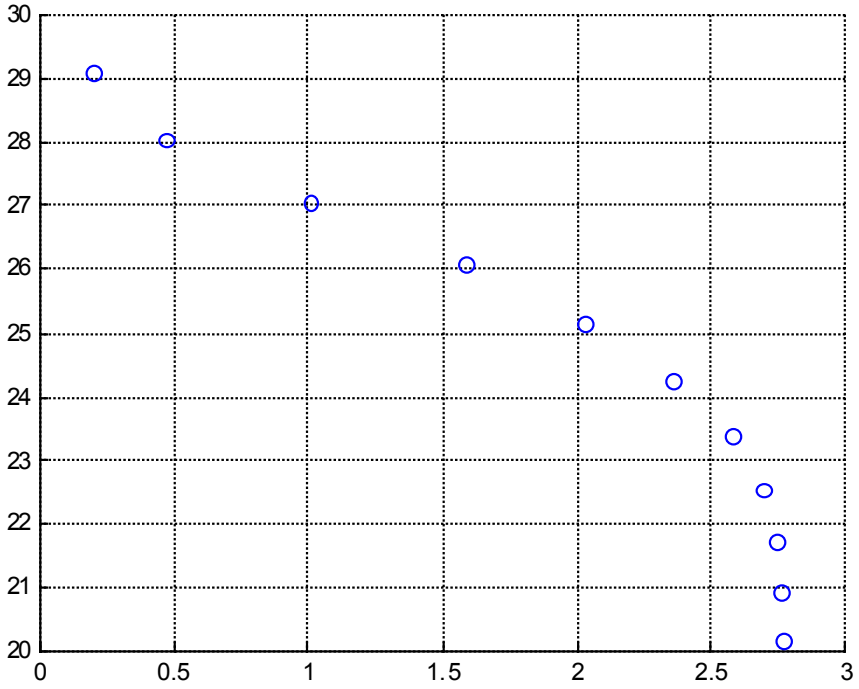


Figure 7a – VDSL downstream data rate (Mbps – vertical) vs ADSL downstream data rate for Scencario 1 and spectrum balancing, with 4 HDSL and 10 ISDN also present.

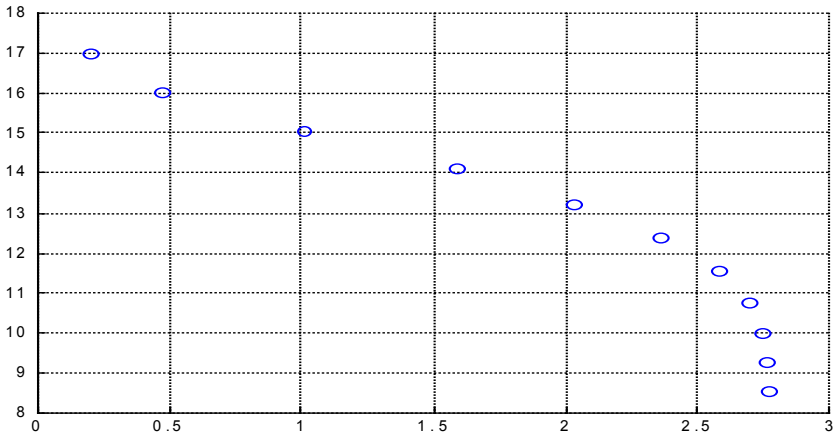


Figure 7b – VDSL downstream data rate (Mbps – vertical) vs ADSL downstream data rate for Scencario 2 and spectrum balancing, with 4 HDSL and 10 ISDN also present.

4. Conclusion

This contribution shows that increasing amounts of dynamic spectrum management can lead to dramatic improvements in the future achievable data rates of DSL, especially as line lengths get shorter and fiber-fed remote terminals are used in DSL Large increase in symmetric and asymmetric data rate combinations and possibilities is permitted in a spectrally consistent and mutually collaborative manner. As the needs of the DSL industry increase with time and the steady consumer march of the past half-century towards increasing bandwidths occurs, methods like those shown here and the general methods of dynamic spectrum management can vastly improve the service providers ability to meet these needs.

Spectrum management may initially allow different line types within a binder to optimize their spectra with knowledge of the rates desired and general characteristics of the other lines in the binder group, allowing that some of those lines may not be able to optimize correspondingly to the same extent. This may progress to full dynamic ability of most of the lines or all of the lines to optimize their transmit spectra collaboratively under recommendations sent by a 3rd party. Eventually, coordination of line signals (and thus consequently spectra also) at the LT can lead to the largest improvements of all, especially at shorter line lengths.

This contribution is not meant to attempt to specify the the data rates that should be attempted, but rather to support and motivate the proposal for study of dynamic spectrum management in [1]. The DSL industry is growing and healthy (after many projections that it would never occur, some by some of the industries biggest advocates today), but will undergo the inevitable growth pains of childhood and adolescence as it progresses with crosstalk being one of the greatest technical challenges. The parentage of standards-group spectrum management needs to grow with its DSL child and nuture its finest possibilities. Such nutured growth necessarily mandates an increasingly sophisticated network maintenance, monitoring, and control facility as a basis of DSL traffic and demand – not together all that different in concept from what has happened to the switching industry over the years. Just now, that facility will progress into the access links also.

5. References

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