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Compatibility of Vectored and Non-Vectored VDSL2

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***Abstract*—Vectoring cancels the crosstalk between multiple VDSL2 lines and can greatly improve performance, particularly on short loops. Crosstalk cancellation can only be performed on lines within a vector group and vectored lines may experience uncancelled crosstalk from nearby lines that are non-vectored or in a separate vector group. This paper shows that a substantial consensus exists on the possibility of mitigating the impact of this uncancelled crosstalk on the vectored lines. Among the possible mitigation techniques, we show here that very good levels of compatibility between vectored and non-vectored VDSL2 can be achieved with Dynamic Spectrum Management (DSM]).**

I. Introduction

Very-high rate Digital Subscriber Line (VDSL2) technology uses high frequencies and short loop lengths to transmit at speeds up to several hundreds of Mbps. VDSL2 uses frequency-division duplexing, upstream and downstream, to avoid near-end crosstalk. However, VDSL2 can still be limited by far-end crosstalk (FEXT). Vectoring, as defined by the ITU-T G.993.5 standard, can greatly improve the performance of VDSL2 [1]. Vectoring removes the FEXT created within a vectored group (*self*-FEXT) by processing at the transmitter (downstream) or at the receiver (upstream).

The benefits of vectoring are immediately appreciated by looking at Figure 1. The downstream rate-reach plot for 48 non-vectored VDSL2 lines shows that 100 Mbps can be achieved only out to 150m for 50% of subscribers. Furthermore, the VDSL2 lines exhibit a wide range of achievable data rates especially for shorter loops (note the wide variation between the 1% and the 99% data rate percentiles) thus confirming the non-uniformity of the effects of FEXT which depends on a large number of factors, e.g. loop length, frequency, cable geometry, density of active lines, etc. If all 48 lines were vectored, then all lines would *ideally*[1] achieve the same "FEXT-free" performance and it would then be possible to offer 100 Mbps to 100% of users out up to 550m. Note also that, as crosstalk is removed with vectoring, also the variation of performance across lines is reduced so that it is possible to offer higher data rates to a wider percentage of users.

In addition to the DSL lines belonging to a specific vectored group, there may also be additional non-vectored lines or additional lines belonging to other (disjoint) vectored groups. This is a practical scenario that is likely to arise in early phases of vectored deployment as the introduction of vectoring will be gradual. This scenario may also happen when the other non-vectored lines or the other vectored groups are run by competitive operators in the same DSL binder - this is the typical case where Sub-Loop Unbundling (SLU) is allowed by the regulatory framework. Although vectoring is able to cancel self-FEXT, crosstalk from non-vectored VDSL2 lines or from lines belonging to other vectored groups within the same cable or binder (*alien*-FEXT) may not always be removed within a vectored group. Since this alien crosstalk may cause performance degradation to vectoring, the important question on whether it is possible to reap the benefits of vectoring in the presence of alien crosstalk naturally arises[2].

Besides being an important topic for practical reasons as deployment of vectoring is about to start, a better understanding of this technical issue can also be helpful for guiding regulators in setting the appropriate regulatory framework, e.g. by understanding whether SLU is detrimental or not to achieving the full benefits that vectoring allows. If technical clarity on this matter is not made soon, there is the risk that market competition restrictions may be imposed by regulators in such way that only a single operator (usually the incumbent) will be allowed to manage all vectored lines.

In this paper, we address the topic of compatibility, or coexistence, of vectored and non-vectored lines by surveying the existing literature (both scholarly papers and standards contributions), by categorizing the available results, and by reporting new simulation results. Note that this paper does not address mitigation techniques based on re-arranging the outside plant or performing binder management. Since it may often be the case that there are only a few non-vectored VDSL2 lines that create significant crosstalk into vectored lines, their impact can be ameliorated by physical-plant re-arrangement such as swapping pairs. However, such solutions can be expensive and/or labour intensive, so that they tend to be not favored by operators [9].

The literature on the topic of compatibility is scarce and

[1]Note that in the presence of impulsive noise, RFI, etc., the data rates achieved by vectoring would be lower than the "FEXT-free" case so that the full benefits of vectoring are never attained - even if all lines are controlled by a single operator.

[2]While the impact on vectored lines of crosstalk created by non-vectored lines could be substantial, the impact of crosstalk from vectored lines to non-vectored lines is similar to the conventional case where all lines are non-vectored.

Table I: Summary of available studies that address the issue of the impact of alien crosstalk on vectored lines.

	No mitigation	Mitigation via DSM or other methods
Upstream	–	[2], [3], [4], [5], [6], [7], [8], [9], [10]
Downstream	[11]	[9], [10], [12], [13], [14]

very few scholarly papers or standard contributions are available. Furthermore, a unitary framework for assessing the impact of alien crosstalk on vectoring is still lacking. This has created confusion in the industry and has often led to the overly-conservative conclusion that vectored lines cannot operate in the presence of alien crosstalk thus implying that vectoring can be successful only in unbundled environments. However, we have ascertained that the vast majority of published results actually points to the opposite conclusion: there are indeed successful mitigation techniques that allow coexistence between vectored lines and alien disturbers. In fact, we have found that all the available contributions can basically be categorized as shown in Table I. Furthermore, there is also a wide consensus that it is possible to mitigate the effects of alien crosstalk on vectored lines via Dynamic Spectrum Management (DSM) [15], [16] or other techniques such as advanced signal processing. In the next Sections we will discuss in depth the papers listed in Table I.

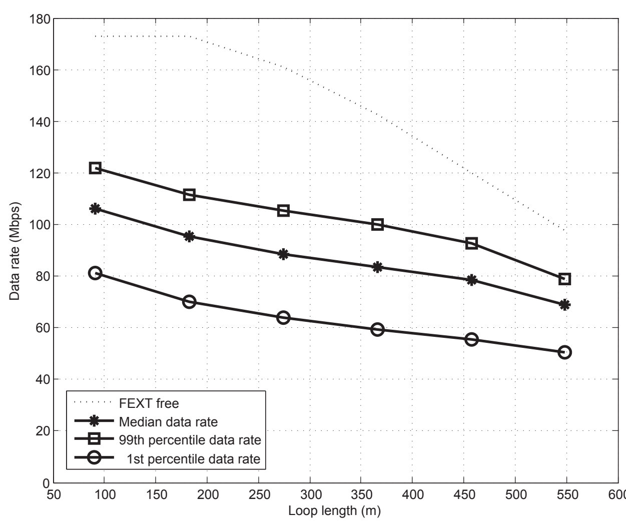

Figure 1: Rate-reach plot for a group of 48 non-vectored lines. If all lines were vectored, then they would all achieve the *ideal* performance shown by the “FEXT free” curve. For details on the simulations, see Sect. IV.

II. Impact of Alien Crosstalk: the Non-Managed Case

When no form of mitigation is adopted, VDSL2 crosstalk from lines outside of a vectoring group can strongly decrease the performance of vectored VDSL2. In this unmanaged case, the performance of vectored VDSL2 can become almost as low as that of non-vectored VDSL2; but not lower.

For example, Figure 2 shows the case when, among 48 lines, 24 are vectored lines mixed with 24 non-vectored VDSL2 lines. Comparing these simulation results to Figure 1, we can notice that the performance of the vectored lines is now only marginally better than that of the non-vectored lines; this is primarily due to the fact that the unmanaged non-vectored lines transmit at full rate and full power and creating strong alien crosstalk. Furthermore, now that we have alien crosstalk present, we can also notice that vectored lines exhibit a spread in performance similar to VDSL2. There is consensus on the above results. The fact that vectored lines can be significantly impacted by non-vectored lines when no form of mitigation is adopted has also been known for some time in standardization groups.

Similar conclusions have also been recently reported in a paper by Alcatel-Lucent [11], where simulations and also lab measurements for mixtures of vectored and non-vectored lines in downstream VDSL2 are given. For example, Figure 3 shows the Cumulative Distribution Function of *measured* data rates when vectoring is operated in the presence of unmanaged alien crosstalk. However, the conclusion reached by the authors that *“To take full benefit of vectoring technology, it is of utmost importance that all lines at a given site are controlled by a single operator”* appears to be misleading as it does not explicitly state the underlying assumption that nothing is done to mitigate alien crosstalk. This matter will be addressed in depth in the next Section, where we will report a wide consensus on the existence of mitigation techniques that range from advanced alien crosstalk cancellation to DSM techniques.

III. Impact of Alien Crosstalk: the Managed Case

The vast majority of published results shows that mitigation techniques that mitigate the effects of alien crosstalk are indeed available. Some of them report the beneficial effects of advanced crosstalk cancellation techniques that are able to eliminate both self and alien crosstalk. However, most contributions report on the use of DSM as a means to mitigate alien crosstalk and this benefit adds to the many other well known benefits that DSM can bring across the entire network [17], [18], [19].

A Spectrum Management Center (SMC) can use appropriate DSM techniques to control the impact of crosstalk. In unbundled environments, each operator may have their own SMC, but if each of those SMCs independently follows certain “politeness” rules then it is still possible for all service providers to enjoy the majority of the benefits of vectoring and mitigate the non-vectored crosstalk. Even better results can be achieved if the SMCs of the various operators can exchange information, or if the DSL access infrastructure is shared among the various providers and is managed by a single

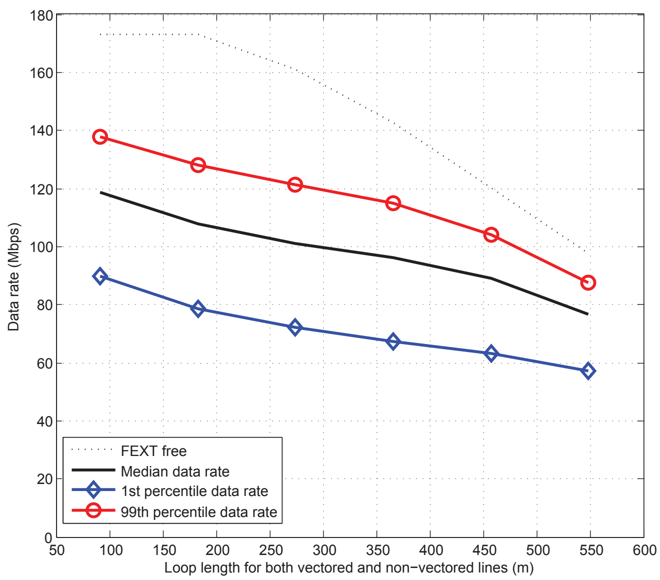

Figure 2: Rate-reach plot for a group of 24 vectored lines mixed with 24 non-vectored lines, for the case when all lines are not managed. For simulation details, see Sect. IV

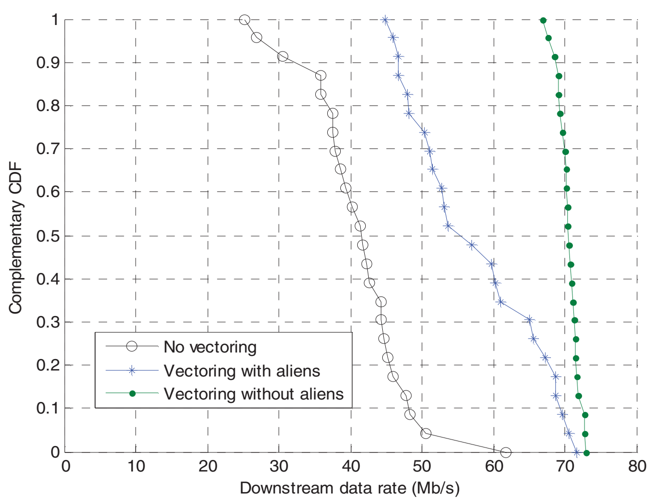

Figure 3: From [11], Figure 6 – Lab measurements: Complementary Cumulative Distribution Function (CDF) of the data rate for 500 m cable of 0.4 mm gauge in a non-branched topology. It shows the impact of aliens (non-vectored VDSL2) on the vectoring performance. It assumes a 24 line platform, with 5 non-vectored lines.

management system that has a full view of the network.

Specifically, good results have been reported on mitigation techniques that are based on DSM Level 1 (rate limiting, flat power back-off) and DSM Level 2 (spectrum balancing). DSM-based techniques can be used for mixed deployments in both upstream and downstream directions and do not require adding any complexity in the transceivers.

Similar conclusions have been reported by Ericsson in [20], where the authors state that "*partial vectoring or independent cancellation by different operators provide significant improvement over non-vectored systems*."

A. The Downstream case

In [12], authors showed that the performance gains for downstream vectored DSL systems can be maintained in a mixture of vectored and non-vectored lines if SMCs are assigned to control the impact of crosstalk from the non-vectored into the vectored lines. The presented simulations results were for downstream VDSL2 profile 17a, in a binder with 20 vectored lines and 5 non-vectored lines. A target bit rate was set for non-vectored lines and, with this restriction, Iterative Water-Filling (IWF) was performed to optimize the transmit spectra of the vectored and non-vectored lines. With this spectral optimization the performance of vectored lines is degraded by less than 10% for most loop lengths, much less than the degradation when no DSM is enabled, which can be 50% or more as seen in Figure 2 of [12]. Authors of [12] also show that IWF (which is essentially DSM Level 1) is nearly as effective as DSM Level 2 Optimal Spectrum Balancing (OSB) for downstream compatibility of non-vectored lines with vectored lines. Another interesting result is that the variability of the data rate of vectored lines tends to be small when DSM is used to control the alien crosstalk, just like it would be in a completely vectored system.

Baldi et al. report that unmanaged alien noise can cause a great reduction in the achievable bit rate of vectored lines, particularly for the shortest loop lengths [10]. However, authors also point out that "*new architectures have been proposed, that permit to cancel both in-domain and out-of-domain crosstalk, at the expense of increased complexity,*" and that complexity can be limited by the use of partial cancellation techniques.

A joint optimization framework for using DSM Level 2 in mixed deployments of vectored and non-vectored lines is proposed in [13]. The proposed framework allows a joint optimization of vectoring and spectral balancing of both vectored and non-vectored lines. The optimization problem is solved finding a sub-optimal solution called IF/MAC which groups users together. The developed solution addresses the case where there are multiple vector groups, vectoring is applied within each group only and the developed spectral balancing optimization mitigates crosstalk between the groups. Both analytical and simulation results show that advanced DSM can effectively manage crosstalk between multiple, disjoint vector groups. For example, Figure 4 shows that DSM increases speed and allows trade-offs between vector groups.

The results reported in [13] on the compatibility of multiple vectored groups yields an additional degree of flexibility in handling the DSL lines located at a (large) access node. Board Level Vectoring (BLV, vectoring of all lines in a line card) or System Level Vectoring (SLV, vectoring across line cards) are valid solutions for avoiding alien crosstalk and indeed several companies have already announced the availability of BLV/SLV equipment. Furthermore, even cross-DSLAM vectoring (at least across single-vendor equipment) may soon become a reality as it seems that several companies have added this functionality to their product roadmap. The results in [13] suggest that coordinating all lines in a single large vectoring group is not the only solution available to operators. In fact, DSM Level 2 can allow multiple vectored groups to coexist and also extend their rate region by limiting the crosstalk they cause to each other. This increases the degrees of freedom that operators may have in planning their deployments, especially when considering large access nodes with hundreds of ports where there is a higher probability of finding either lines controlled by multiple operators or legacy (non-vectored) lines. It is important to recognize that the technical feasibility that allows exercising these degrees of freedom is ensured by the use of appropriate management techniques like DSM [9].

Besides the classical VDSL2 cases examined so far, authors in [14] address the case of mixed G.fast deployments. G.fast is a new ITU-T project developing a standard for transmitting up to 1 Gbps on loops shorter than 200m and using frequencies up to hundreds of MHz. The solution being pursued for G.fast is OFDM-based and similar to DSL, thus the problem of compatibility is comparable. As seen in Figure 11 of [14], applying DSM Level 2 to the non-vectored lines appreciably increases vectored G.fast bit rates.

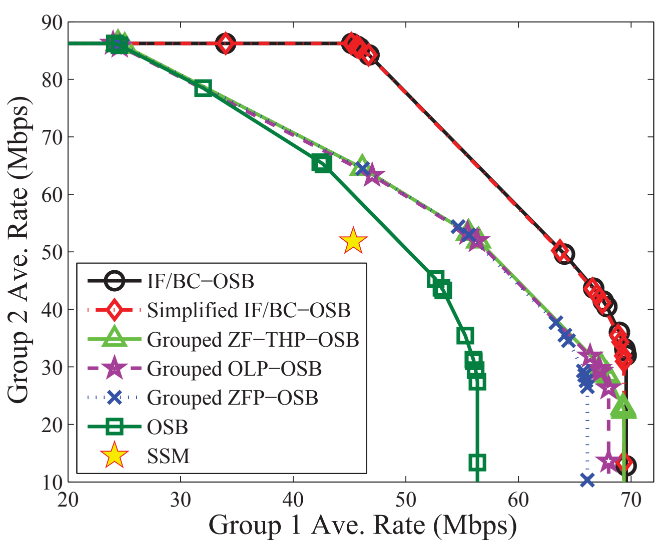

Figure 4: From [13], Figure 3 – Average achievable bit rate of the vectored group 1 with 400 m and 800 m lines vs. achievable bit rate of the 400 m group 2, comparing static spectrum management (SSM) to DSM using different crosstalk mitigation schemes.

B. The Upstream case

Upstream vectored VDSL2 signals are received at a single location, where the vectored receiver can cancel self-FEXT and, in some cases, also alien-FEXT that is correlated across the different pairs. If alien crosstalk is absent, it has been shown that linear receivers (ZF or MMSE) are able to remove self-FEXT almost completely due to the column-wise diagonal dominant nature of the DSL channel matrix. However, when alien crosstalk is present, the linear receivers are sub-optimal and one must resort to more sophisticated receivers such as the Generalized Decision Feedback Equalizer (GDFE) or a turbo receiver. Cancellation of alien FEXT is most effective if the number of aliens is lower than or at most equal to the number of vectored lines.

Recent contributions targeting specifically alien crosstalk cancellation can be found in [7], [8]. In [7], authors propose an LMS receiver structure that effectively cancels much of the non-vectored crosstalk into vectored lines. This proposed approach allows low complexity implementation using adaptive filters and is blind, i.e. does not require the knowledge of the transfer function of self and alien FEXT. The authors of [8] use an iterative receiver to perform self and alien crosstalk cancellation. In the absence of alien crosstalk, authors claim that FEXT can be cancelled with complexity similar to that of existing linear receivers whereas the cancellation of alien crosstalk only requires little extra complexity.

Crosstalk cancellation as described above, can be successfully coupled with DSM Levels 1 and 2 to further mitigate the effects of alien disturbers. For such upstream mixed deployment scenarios, DSM Level 2 spectral optimization techniques have been shown to greatly improve the spectral compatibility of vectored and non-vectored VDSL2 lines – especially when a near-far scenario is considered [2], [4], [5], [6]. For example, Figure 5 shows that DSM Level 2 dynamic-band Multi-Level Water-Filling (MLWF) algorithm, which dynamically optimizes the cut-off frequencies in the MLWF algorithm, is particularly effective compared to DSM Level 1 techniques such as IWF or UPBO.

Figure 5 illustrates the rate region for the situation of an upstream VDSL2 mixed deployment (profile 17a) when two 300m vectored lines and one 1200m non-vectored line coexist in a binder. UPBO is a single point that is determined by the VDSL2 upstream default PBO settings. DSM Level 1 using IWF has a rate region that extends the single point of static VDSL PBO. Level 2 DSM using MLWF with both static selection (preferred loading band being US2) and with dynamic selection of a frequency in band US1 or US2 (above which is the preferred loading band) further extend the rate region. However, there is a small loss when static cut-off frequency selection is performed.

The above performance shows that, in the upstream case, DSM Level 2 outperforms DSM Level 1 for the case of mixed deployments. This conclusion is different from the downstream case where it was noted that DSM Level 1 techniques, such as capping the non-vectored bit rates, are nearly as good as DSM spectral optimization techniques such as OSB. This is because, in upstream near-far scenarios, spectral optimization techniques such as MLWF allow vectored groups to be polite to non-vectored groups and, therefore, extend the rate region. This effect is similar to the near-far scenarios observed in non-vectored DSL systems.

When dealing with near-far effects, it has been found that the use of UPBO for upstream vectoring benefits mixed deployments. Forouzan et al. conclude that it is generally safer to always enable the UPBO unless one is sure that all loops will be managed by the same SMC [6]. If this is not the case, the achievable bit rates for the long (and managed) loops when UPBO is disabled are significantly smaller than when

UPBO is enabled due to higher crosstalk originating from the unmanaged loops. For fully vectored system, the UPBO could be disabled as also argued in [3].

ITU-T Contribution C-1530 [3] shows that dynamically adjusting the UPBO of non-vectored lines can strongly improve performance of vectored lines compared to using static UPBO. Figure 6 shows that dynamic UPBO (labeled as Vectored UPBO 1 and Vectored UPBO 2) has better performance than static UPBO. The authors argue that this may be due to the fact that "*the optimal setting of UPBO parameters for vectoring depends (among other things) on the FEXT cancellation capability of the vectored system.*"

The capability of dynamically adjusting the UPBO has been acknowledged as very important also for non-vectored systems and has been recently incorporated in the new UK Access Network Frequency Plan ratified in Sep. 2011 [21]. According to the new ANFP, an operator may either use a static configuration for the UPBO or a dynamic configuration that also allows to exceed the mask under some average constraint (see [21], Sect. C.3).

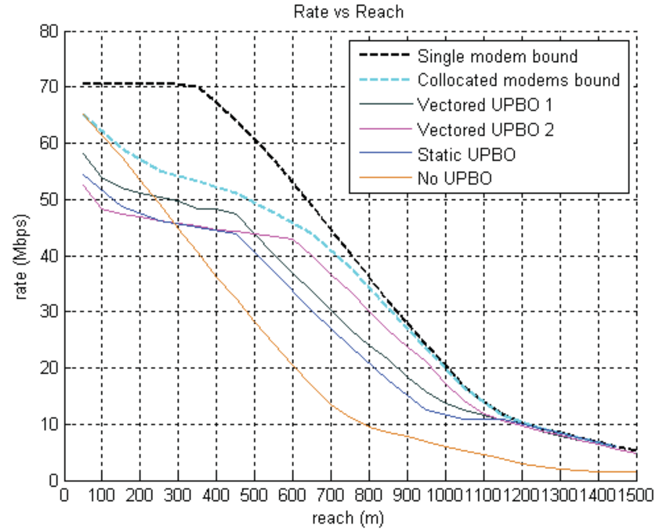

Figure 6: From [3], Figure 2 – Partial vectoring - 32 dominant disturbers cancelled out of 63 lines.

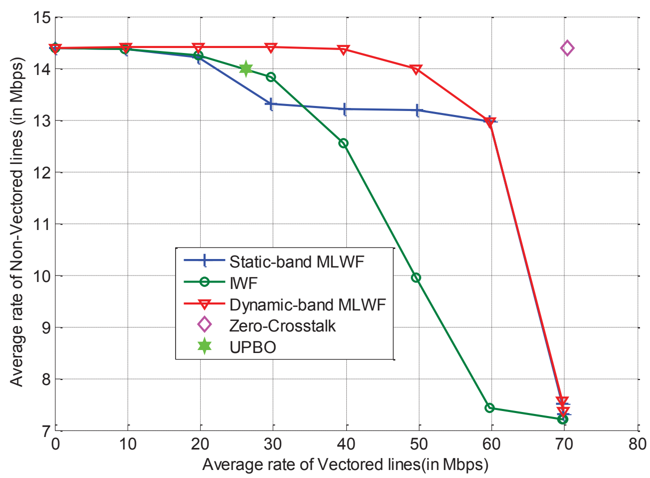

Figure 5: From [4], Figure C-13.(a) – Various rate regions under different SMC strategies for a configuration of two 300m vectored lines and one 900m non-vectored line. The difference between the green and red curves is the gain in compatibility from DSM Level 2.

IV. New Simulation Results

New simulations were performed and are reported here. These simulations are for downstream VDSL2 profile 17a with crosstalk modeled according to the ATIS model for MIMO channels in ATIS-0600024. 48 DSL pairs were selected randomly from a cable with 100 pairs and four binders. Out of these, 24 pairs were assigned to a single vector group and 24 pairs were non-vectored. For each loop length, a set of pair-to-pair couplings were randomly generated from the ATIS model and 500 random pair selections were made to generate statistics representing different assignments of vectored and non-vectored lines. VDSL2 profile 17a was simulated with PSD limit mask 998ADE17-M2x-B (B8-12). Dynamic Power Back-off (DPBO) was not enabled and the background noise was assumed to be equal to -140 dBm/Hz. Non-vectored lines had a fixed downstream rate with 6 dB margin, consistent with the application of DSM Level 1 for INP management, and power management was applied to the non-vectored lines only. The results presented here differ from those reported in [12]: simulated scenarios include more non-vectored lines and account for more statistical runs; various data rate percentile are now reported, not only the worst cases; we here exclusively focus on DSM Level 1 (power management).

Figures 7 and 8 show results in a mixture of 24 vectored lines and 24 non-vectored lines where the transmit power of the non-vectored lines is managed by limiting their transmission rate at 6 dB margin. Statistics are presented for vectored pairs for the 1st-percentile, the 50th percentile (median), and the 99th-percentile of all the different random pair selections. Figure 7 shows that vectored lines can achieve 100 Mbps downstream out to 500m for 99% of subscribers if the vectored lines are rate limited to 25 Mbps. Figure 8 shows that vectored lines can achieve 100 Mbps downstream out to 350m for 99% of subscribers if the non-vectored lines are rate limited to 45 Mbps. These should be compared to the unmanaged cases in Figure 1 and Figure 2 where 100 Mbps downstream is only achieved out to 150m for 50% of subscribers. Note that for a quantitative assessment of the impact of alien crosstalk on vectored lines, more scenarios should be considered.

V. Conclusions

On the basis of the presented literature survey and our own simulation results we conclude that alien crosstalk can be detrimental to vectoring only when the lines are left completely *unmanaged*. If the non-vectored lines or the other vectored groups are properly managed with DSM, advanced signal processing or a combination of both, then the impact on

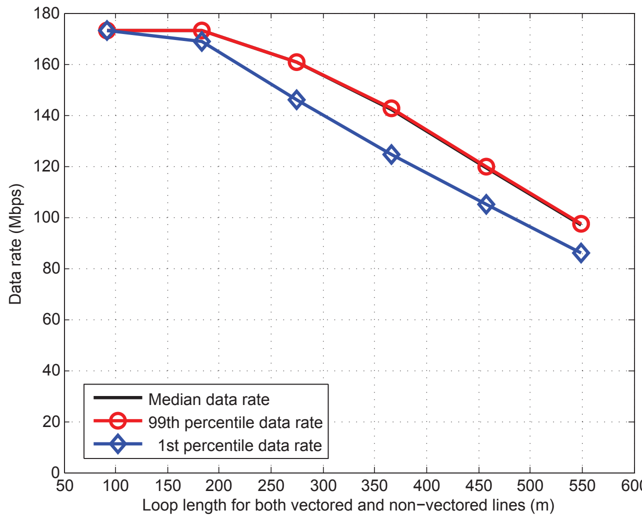

Figure 7: Rate-reach plot for a group of 24 vectored lines when 24 non-vectored lines are also present in the same binder and their data rates are capped at 25 Mbps.

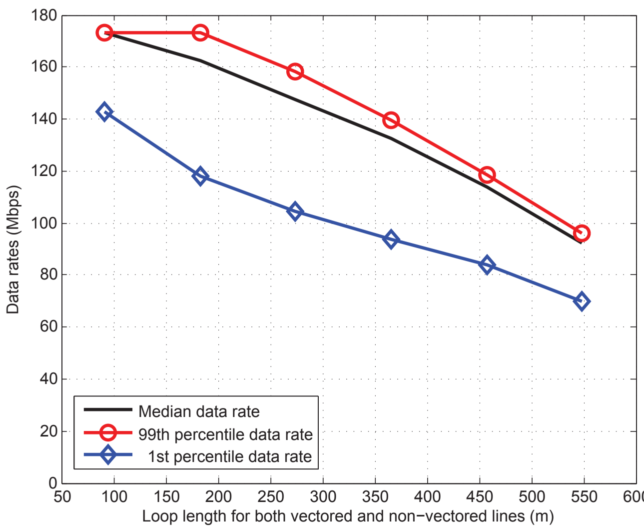

Figure 8: Same as in Figure 7, but for data rates capped at 45 Mbps.

the vectored lines is limited and coexistence is indeed possible.

We also found a wide consensus that DSM Level 1 (power management) and DSM Level 2 (spectral shaping) can be successfully applied to non-vectored lines to make them compatible with vectored lines as well as to the case of multiple vector groups. Thus, vectored lines deployed along-side non-vectored lines can achieve excellent performances and retain most of the benefits of vectoring when an appropriate use of DSM techniques is made. Furthermore, besides resorting to BLV, SLV or even the possibly upcoming cross-DSLAM vectoring when dealing with large access nodes, operators may also use DSM as an alternative to adding extra DSLAM functionality at the access node.

We conclude pointing out that DSM provides benefits to vectored deployments that go beyond ensuring compatibility with alien disturbers. Vectored systems can be managed to allow improved diagnostics based on the knowledge of crosstalk couplings between pairs and improved mitigation of the effects of impulse noise and of other time-varying noise sources [9]. Thus, DSM can be very effective even in the case that all lines are either controlled by a single operator or vectored in a single large group via SLV or cross-DSLAM vectoring.

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