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CONTRIBUTION

TITLE: **Power and Rate Management for Level 3 DSM Vectored DSLs**

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ABSTRACT

This information-only contribution exhibits the benefits of Level 3 DSM in terms of power reduction. For upstream vectored DSL, power minimization problems can be solve at SMC; the power and bit distributions can be controlled by simply passing the Lagrange multipliers to the DSLAM. For downstream CuPON, similar control technique can be applied, while the extra dimensions from split-pair transmission can further reduce the transmit power over differentially-excited vectoring.

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Power and Rate Management for Level 3 DSM Vectored DSLs

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ABSTRACT
This information-only contribution exhibits the benefits of Level 3 DSM in terms of power reduction. For upstream vectored DSL, power minimization problems can be solve at SMC; the power and bit distributions can be controlled by simply passing the Lagrange multipliers to the DSLAM. For downstream CuPON, similar control technique can be applied, while the extra dimensions from split-pair transmission can further reduce the transmit power over differentially-excited vectoring.

1. Introduction

Level 3 Dynamic Spectrum Management (DSM), also called “vectoring,” enables signal-level coordination among DSL lines. With proper receiver or transmitter cooperation or both, FEXT and upstream out-of-domain interference can be canceled and significantly higher data rates can be achieved. Vectoring can also significantly reduce transmit power while achieving certain user data-rates. This contribution presents examples of showing the potential power reduction by using Level 3 DSM.

First, power reduction in upstream vectored DSL transmission is investigated. To minimize the power consumed, a power minimization problem is formulated and an algorithm to solve it is proposed. The complexity of the algorithm suggests the problem be solved by the Level 3 DSM Spectrum Management Center (SMC). Since the resulting power distribution, bit distribution, and decoding/precoding orders can be determined completely by the Lagrange multipliers, the only information that DSLAM needs from SMC is the Lagrange multipliers.

A second example is downstream “Copper-PON” (CuPON) systems [3]. In addition to the power reduction from crosstalk cancellation, the CuPON system creates extra transmit dimensions through the use of bonding and possibly even split-pair transmission. The distribution of data rates to these extra dimensions further reduces power consumption. Gains of up to 20 dB are obtained for the CuPON situation.

2. Power Minimization in Upstream DSL Systems

This section presents the upstream DSL power minimization problem. Upstream transmission is of greater interest for power minimization in non-bonded (or non-CuPON) transmission than is downstream: The downstream channel is diagonally dominant (DD), which allows independent treatment of each users power in overall power reduction, while the upstream channel is not DD. Thus, upstream power minimization requires a more sophisiticated SMC algorithm. Further, such an upstream problem also allows elimination of crosstalk and noises that come from outside the vectored lines (while downstream single-line transmission can only eliminate FEXT within the group of vectored lines). The tradeoffs among users becomes much more apparent.

2.1 Problem Formulation and Algorithms

In a vectored DSL system with K users and N tones, the power and number of bits allocated for user k at tone n are p_{nk} and b_{nk}, respectively. The power minimization problem can be thus formulated as:

$$\begin{aligned} \text{minimize} \quad & \sum_{k=1}^{K}\sum_{n=1}^{N} p_{nk} \\ \text{subject to} \quad & \sum_{n=1}^{\mathrm{N}} b_{nk} \geq R_k, \quad \forall k = 1,\cdots,K \\ & p_{nk} \geq 0, \qquad \forall k,\cdots,K, n = 1,\cdots,N. \end{aligned}$$

The objective function is the power sum over all the users, and the constraints are individual power constraints, where R_k denotes the minimum required rate for user k. The relation between p_{nk} and b_{nk} depends on the system. For example, the selection of minimum-mean-square-error generalized decision feedback equalizer (MMSE-GDFE) [1] or zero-forcing GDFE (ZF-GDFE) [2] results in distinct representations. But in general, supposing the SINR observed at tone n for user k is SINR_{nk}, the bit allocated becomes:

$$b_{nk} = \log_2\left(1 + \frac{\mathrm{SINR}_{nk}}{\Gamma}\right),$$

where Γ is the SNR gap.

Although the primal power minimization problem cannot be easily solved, its dual problem of an offset weighted rate-sum maximization can be solved efficiently by Lagrange dual-decomposition method. Moreover, the dual problem's solution is optimal when the number of tones goes to infinity (and typically converges to optimal easily with the numbers of tones used in VDSL systems). Following the derivations in [1] and [2], the dual problem can be written as:

$$\begin{aligned} \text{maximize} \quad & \sum_{n=1}^{\mathrm{N}} f_n(\boldsymbol{\mu}) + \sum_{k=1}^{K} \mu_k R_k \\ \text{subject to} \quad & \mu_k \geq 0, \quad \forall k = 1,\cdots K, \end{aligned}$$

where

$$f_n(\boldsymbol{\mu}) = \min_{p_{nk}\geq 0, b_{nk}} \left(\sum_{k=1}^{K} \left(p_{nk} - \mu_k b_{nk} \right) \right).$$

The optimization variables of the dual problem contain only the Lagrange multipliers μ_k. The problem is convex, and the objective function is possibly non-differentiable. Therefore, sub-gradient search methods (e.g. the ellipsoid method) can be applied to find the optimal Lagrange multipliers μ_k^*. These search methods iteratively update $\boldsymbol{\mu}$ based on the sub-gradient vector $\mathbf{d}$, which essentially indicates a descent direction of the dual objective. To be more specific, the sub-gradient can be expressed as:

$$d_k = \sum_{n=1}^{N} b_{nk} - R_{k,} \quad \forall k = 1, \cdots, K.$$

For each iteration, the sub-gradient depends on b_{nk} obtained from $f_n(\boldsymbol{\mu})$ at current stage. Therefore, N independent $f_n(\boldsymbol{\mu})$ need to be minimized. Simultaneously, the best decoding order of the users, which is the same on all DMT tones with MMSE-GDFE [1], is found. In MMSE-GDFE, the users with larger μ_k are decoded later, and thus all the tones use the same decoding order. When the optimal solution $\boldsymbol{\mu}^*$ is found, the power-minimizing bit-loading and decoding order can be computed based on the minimization inside $f_n(\boldsymbol{\mu}^*)$.

Although the original problem formulation does not include practical constraints such as PSD mask, bit cap, discrete bit-loading, and individual power constraint, they can be easily incorporated inside the search space of minimizing $\sum_{k=1}^{K}(p_{nk} - \mu_k b_{nk})$ inside $f_n(\boldsymbol{\mu})$. Therefore, this power minimization can be slightly modified to generate bit-loading results complying with the current standards' limitations on power spectral density, transmit power and bit caps.

In some cases, the set of data rates may not be achievable. SMC (service provider) determination of what rate tuples are achievable is here called the "admission problem." An SMC can determine whether a set of rates is achievable with a give set of constraints on PSD, bit caps, and transmit power. Furthermore, minimization of some users' power may be more important for reasons of emitted crosstalk into other systems or generally for emissions of any type. Thus, a weighted power sum may be desired by the service provider. Such weighting is a function of the desire of a service provider to trade power consumption for admissibility of a set of user data rates. It is a trade-off that only the service provider can determine based on the economics of their deployment desires.

2.2 Message passing between SMC and DSLAM

As mentioned in Section 2, the optimal bit and power distributions, as well as the optimal decoding order, are completely determined by the Lagrange multipliers. Traditionally, to find the optimal Lagrange multipliers requires hundred of iterations and updates and such complexity need not be endured by the DSLAM. This calculation should be taken inside the SMC where any high computational burden can be shared over a network of users, while simultaneously being considered with other SMC functions like Level 1 stability or Level 2 interference with other vectoring groups. Further, a weighted rate sum may be determined to be desirable by the service provider for a number of reasons and consequently the set of Lagrange multipliers used will change. To reduce the messages sent from SMC to DSLAM, it would best if only the Lagrange multipliers or their equivalent are sent. With the Lagrange multipliers and the à priori knowledge of the receiver type (e.g. MMSE-GDFE or ZF-GDFE), DSLAM can then calculate the required information by solving the much simpler $f_n(\boldsymbol{\mu})$ for each tone. Consequently, the system can be operated with the minimum (possibly weighted) total power achieving all the target rates with relatively low computational burden at the DSLAM and with service provider choice retained by the service provider. This contributionwill focus on even weighting of the power sum, so effectively total sum of analog transmitted power. However, the introduction of weighting is straightforward given the general problem posed above.

2.3 Examples

The following simulations show how the power-minimization problem can help reduce power in upstream vectored DSL system. The examples assume there are 12 DSL loops in a bundle, where not all of them are always vectored. Assume if there are K out of 12 users are vectored, and the remaining *(12-K)* users become disturbers that generate alien crosstalk into the vectored group of K users.. Also, another VDSL user from a different service provider is present and so is another source of alien crosstalk. The alien crosstalk is a correlated noise, which is characterized by a correlation coefficient ρ, varying from 0 to 0.99.

The remaining simulation parameters are:

gap-coding gain+margin = 9.5-4.5+6=12dB
bit cap = 15
N = 4096
VDSL2 12 MHz, North American bandplan is used
US0 is not used
Line type: 26 AWG
All lines are of the same loop length and same data rate

Figure 1 shows the average power used for achieving 3Mbps in a K = 6 system. It can be seen that even when the noise is completely uncorrelated, solving the power minimization problems can always save 2.5dB of power. If the noise is highly correlated, the power saving can be as high as 17dB (short loop) or a factor of 50. For long loops, vectoring can still reduce power by more than 7dB. On the other hand, Figure 2 shows how the power consumption changes with the target data rate. The loop length is 1500ft. The factor of power saved does not change too much with different target data rates. With different noise correlation, the power required for achieving 3Mbps in vectored DSL is from 2.5dB to 17dB less than non-vectored systems. Figure 3 presents the average power consumption versus the number of vectored lines (with loop length 1500ft). The target data rate is 3Mbps. As the number of vectored users increases, the required power continues to drop. When all the 12 lines are vectored, vectoring renders power reduction range from 11dB to 28dB, depending on the value of ρ.

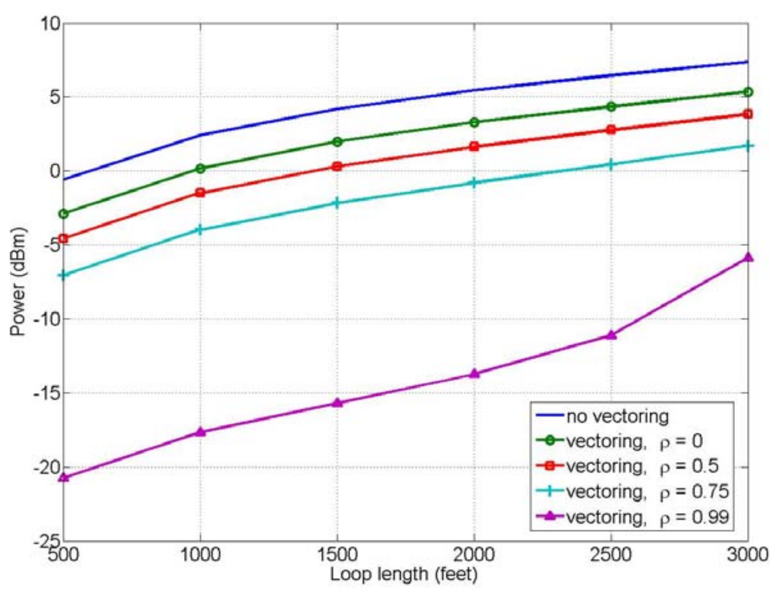

Figure 1: Power consumption per vectored line in upstream VDSL2. K = 6, Data rate = 3Mbps.

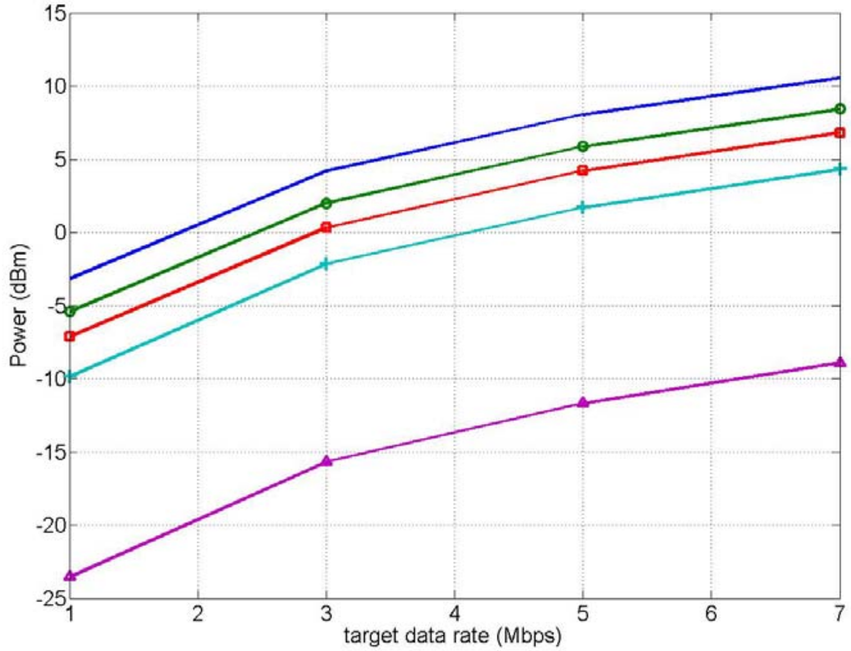

Figure 2: Power consumption per vectored line in upstream VDSL2. K = 6, Loop length = 1500ft.

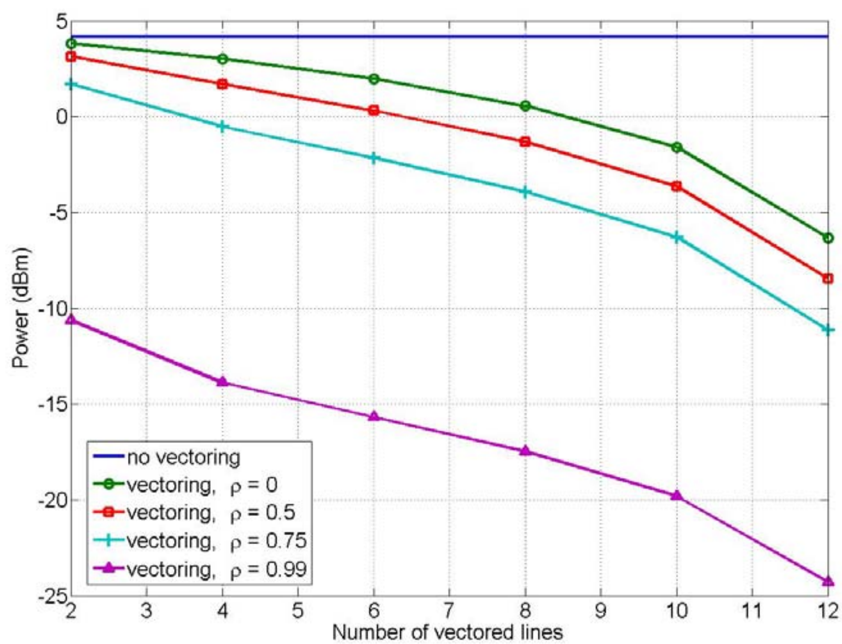

Figure 3: Power consumption per vectored line in upstream VDSL2. Data rate = 3Mbps, Loop length = 1500ft.

3. Downstream CuPON

3.1 CuPON

Figure 4 shows a CuPON structure with 200 copper lines [3]. It is originated from the PON (passive optical network) architecture, which consists of fiber and optical splitter circuits. Although the optical devices are very expensive, the junction boxes in Figure 4 can be implemented simply by connecting the wires. And the drops, containing two to four twisted pairs, can be shared by two or more homes. Moreoever, split-pair transmission [4] can be utilized to increase the degrees of freedom of the channel. For example, for a drop with four twisted pairs, split-pair transmission creates a 7-by-7 MIMO channel. With vectoring performed between groups, the whole system can achieve more than a 50Gb/s aggregate data rate [3].

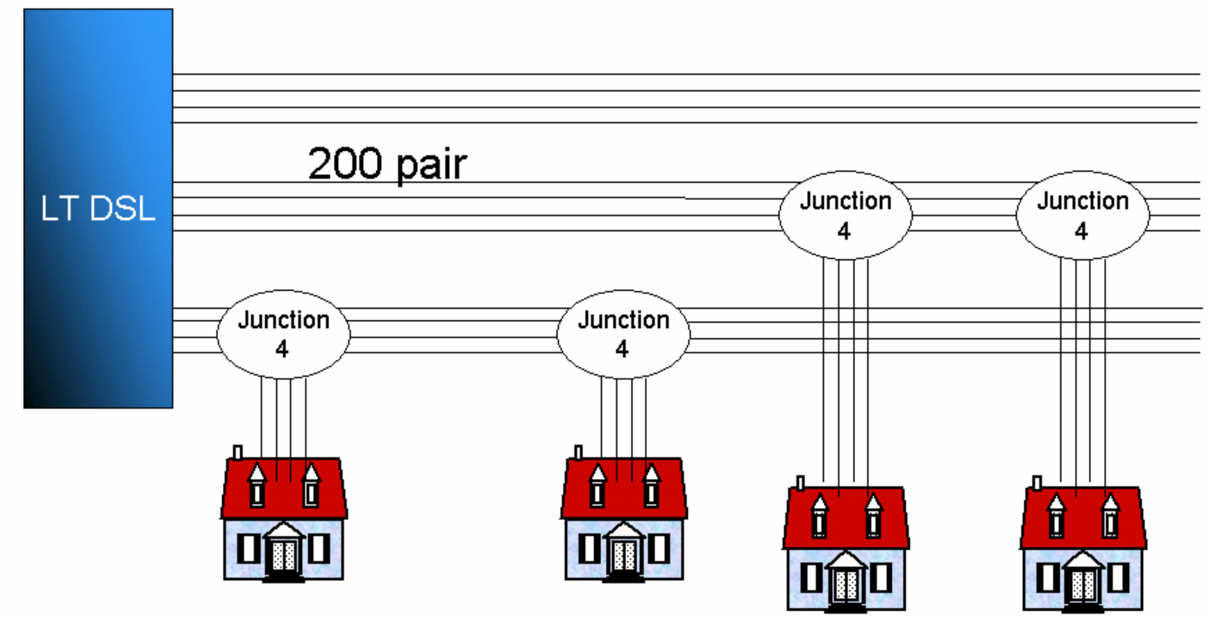

Figure 4: Basic CuPON architecture

3.2 Examples

Figure 5 shows a result on power consumption in a 2-user VDSL system with 300-meter lines. Three different transmission strategies, differential transmission without vectoring, differential transmission with vectoring, and split-pair transmission with vectoring (CuPON), are considered. The results in systems with 2 twisted pairs and 4 twisted pairs are presented. In differential excitation, it is assumed that both users have the same number of loops (each has 1 out of 2 or 2 out of 4 loops). Noise is AWGN with –140dBm/Hz PSD. Other simulation parameters are the same as 2.3.

From Figure 5, it can be observed that when target data rate is 50Mbps per user, using split-pair transmission in CuPON can save 6dB power for 2 loops and 5dB power for 4 loops over differential excited vectoring. When compared to non-vectoring case more power can be further saved. The power reduction becomes even more significant as the target data rate increases. For example, when 150Mbps per user is desired for a 4-loop system, the 7x7 split-pair transmission in CuPON needs transmit power 14dB smaller than differential excited vectoring. Besides power reduction, the data rate increase from using CuPON can also be verified. With transmit power 0dBm, the 7x7 split-pair CuPON can achieve a per-user data rate of 90Mbps more than 4x4 vectoring and 110Mbps more than no vectoring.

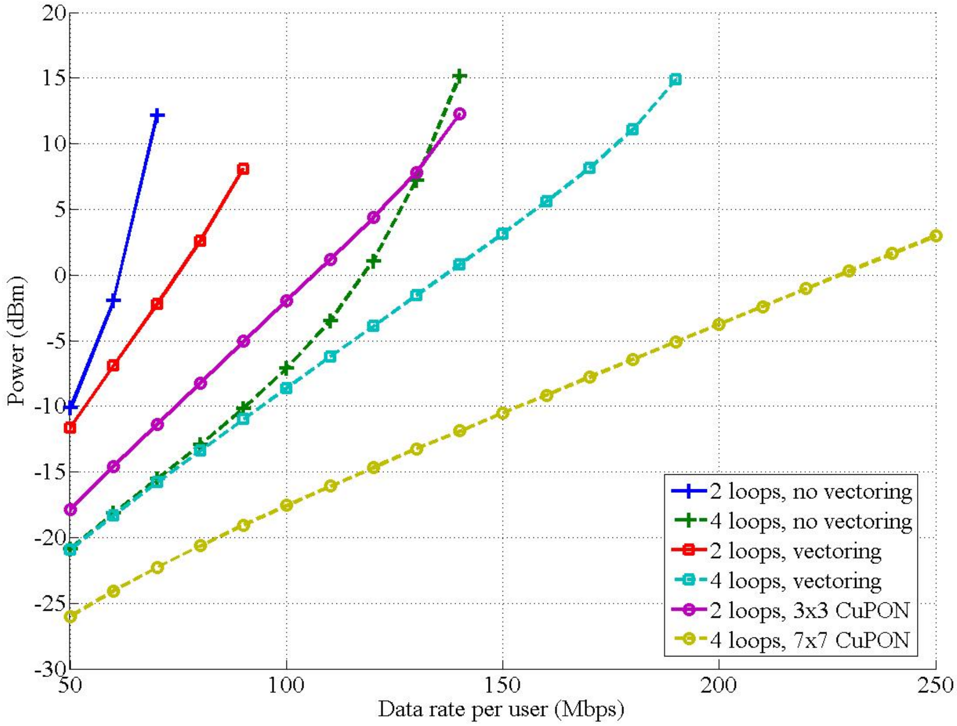

Figure 5: Power consumption for 300-meter lines

4. Conclusions

This contribution explains and verifies that DSM level 3 can help reduce power significantly in two applications. In upstream vectored DSL system, a power minimization problem can be solved at SMC. With only the knowledge of Lagrange multipliers, DSLAM can easily implement bit-loading to minimize the power. In downstream CuPON systems, the extra transmit dimensions obtained from split-pair transmission can further reduce the power consumption over differentially excited channel with vectored DSL.

5. References

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[2] C.-Y Chen, K. Seong, R. Zhang, and J. M. Cioffi, "Optimized Resource Allocation for Upstream Vectored DSL Systems with Zero-Forcing Generalized Decision Feedback Equalizer," to appear in *IEEE Journal on Selected Topics in Signal Processing*, December 2007.

[3] J. M. Cioffi, S. Jagannathan, M. Mohseni, and G. Ginis, "CuPON: The Copper Alternative to PON 100Gb/s DSL Networks," *IEEE Communication Magazine*, Vol. 45, No. 6, pp.132-139 June 2007.

[4] B. Lee, J. M. Cioffi, S. Jagannathan, and M. Mohseni, "Gigabit DSL," *IEEE Transactions on Communications*, Vol. 55, No. 9, September 2007.