Dynamic Resource Allocation Based Partial Crosstalk Cancellation in DSL Networks

Beier Li*, Paschalis Tsiaflakis*, Marc Moonen*, Jochen Maes†, and Mamoun Guenach†
* Electrical Engineering, Katholieke Universiteit Leuven, Belgium, email: {bli,ptsiafla,moonen}@esat.kuleuven.be
† Alcatel-Lucent Bell Labs, Belgium, email: jochen.maes@ieee.org, guenach@ieee.org

***Abstract*—The design of crosstalk mitigation techniques for DSL broadband access systems has mainly focused on physical layer transmit rate maximization. However, for certain applications, upper-layer performance metrics like network throughput, stability and delay performance may be more relevant. In this paper, we present a number of dynamic resource allocation based algorithms for partial crosstalk cancellation (PCC) that focus on these upper-layer metrics. A first algorithm focuses on preserving transmission queueing stability while maximizing the transmit rate. This is then extended towards budget adaptive algorithms, which dynamically adapt the PCC so as to improve the resource efficiency and to obtain a desirable trade-off between delay performance and resource consumption. Simulation results demonstrate the improved stability of the proposed algorithms and the obtained trade-off between delay performance and resource consumption.**

I. INTRODUCTION

Digital subscriber line (DSL) technology is one of the most widely deployed broadband access technologies worldwide. Current DSL networks suffer from crosstalk between the copper-lines in the same cable binder, which can result in a huge performance degradation. In order to reduce the effects of the crosstalk, one can resort to two types of crosstalk mitigation techniques. The first is dynamic spectrum management (DSM), also known as spectrum balancing [1] [2], The second is signal coordination, also known as crosstalk cancellation, precoding or vectoring [3][4][5].

Many applications provided over the access network, such as IPTV and online-gaming not only require a high transmit rate, but also a low transmission delay, to realize a high quality service and real-time interaction. When provided with a freedom in the physical layer resource allocation, a transmit rate adaptation subject to the user priorities is able to reduce the delay of the arrival data, i.e. the time between arrival and transmission of the data at the modems. It was recently shown that dynamic spectrum balancing, i.e. dynamic transmit power allocation, can take the problem of queueing and network throughput into account [6]. Also the possibility of integrating Queueing Proportional Scheduling proposed in [7] with a general decision feedback equalizer is discussed in [8]. In this paper we focus on partial crosstalk cancellation (PCC) [3][4], which consists of linear crosstalk cancellation where only a portion of the crosstalk is cancelled. PCC significantly reduces the computational complexity with respect to full crosstalk cancellation schemes.

Existing crosstalk cancellation techniques for DSL systems assume that each user has infinite data to transfer. In practice, however the workload is finite and it is therefore more realistic to model the system as a time-slotted system with a first-in-first-out (FIFO) queue, whose output is defined by the physical layer transmit rate and whose input is modeled as a random data arrival process. This layered system model with dynamic queueing is introduced in Section 2.

In Section 3 we propose the Max-Weight Partial Crosstalk Cancellation (MW-PCC) algorithm, which is a dynamic partial crosstalk cancellation algorithm, that focuses on network throughput and stability, i.e. it prevents the queues from growing to infinity when possible. The channel uncertainty problem, especially the issue of alien crosstalk in MW-PCC is also discussed in Section 3.

In Section 4, MW-PCC is extended towards budget adaptive schemes so as to dynamically adapt the resource budget to the application needs. This is further extended towards an algorithm that adopts a specific delay performance target.

Section 5 contains simulation results, that demonstrate the improved stability of the proposed algorithms and the obtained trade-off between delay performance and resource consumption. Conclusions are given in Section 6.

II. SYSTEM MODEL

A. Physical Layer Resource Allocation

The DSL system considered here consists of N users, and each user transmits over K orthogonal tones. We assume an accurate knowledge of the channel state information (both direct and crosstalk channels) at the Central Office (CO). The vectored channel model for each tone can be then given as follows,

$$\vec{y}_k = H_k \vec{x}_k + \vec{z}_k$$

The vector $\vec{x}_k = [x_k^1, ..., x_k^N]^T$ denotes the transmitted signals from N users on tone k. Vectors $\vec{z}_k$ and $\vec{y}_k$ have the

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same structure as $\vec{x}_k$. Vector $\vec{z}_k$ denotes the additive noise, which consists of thermal noise and other background noise. Vector $\vec{y}_k$ denotes the received signal vector. $\mathbf{H}_k$ is an $N \times N$ matrix, whose element $h_k^{n,m}$ represents the channel from user m's transmitter to user n's receiver.

To process the vectored signal, we use partial linear zero-forcing crosstalk cancellation for upstream communication and pre-coding for downstream communication, as introduced in [3] [4]. A digital signal processing (DSP) complexity is deployed in the Digital Subscriber Line Access Multiplexer (DSLAM) to remove the crosstalk. These work under the same principle, i.e. when a crosstalk canceller or precoder tap is deployed on a specific tone from a disturber user to a victim user, the corresponding crosstalk will be removed. The resulting bit rate on tone k of user n can be given as follows,

$$b_k^n = f_s \log_2 \left(1 + \frac{1}{\Gamma} \frac{|h_k^{n,n}|^2 s_k^n}{\sum_{m \neq n} (1 - c_k^{n,m}) |h_k^{n,m}|^2 s_k^n + \sigma_k^n} \right)$$

$c_k^{n,m} \in \{0, 1\}, \forall m \neq n$,
$c_k^{n,m} = 1$: if the crosstalk from user m to user n on tone k is cancelled,
$c_k^{n,m} = 0$: if the crosstalk from user m to user n on tone k is not cancelled,
where f_s denotes the symbol rate, s_k^n and σ_k^n denote the transmit power and the noise power of user n on tone k. Throughout this paper we assume fixed PSDs, i.e. fixed s_k^n, $\forall n, k$. For user n, the total transmit rate is:

$$R^n = \sum_{k=1}^{K} b_k^n.$$

The physical layer resources of partial crosstalk cancellation (PCC) are the crosstalk canceller taps $c_k^{n,m}$, $\forall k, n, m \neq n$, and are constrained by a crosstalk canceller budget for all users in the system, denoted by C^{total}. The PCC resource consumption is constrained as follows,

$$C = \sum_{k=1}^{K} \sum_{m=1}^{N} \sum_{n=1}^{N} c_k^{n,m} \leq C^{total}. \quad (1)$$

By distributing the PCC resources to different users on different tones, we can obtain a different trade-off in the transmit rate vector $\vec{R} = [R^1, ..., R^N]$. The rate region, which characterizes the trade-off between the transmit rates of the users, depends on the allocated PCC resources and can be defined as follows:

Definition 1: (Physical Layer Rate Region). The rate region is the finite set of all possible achievable transmit rate combinations:

$$\mathbb{R} = \{\vec{R} : C \leq C^{total}\}.$$

B. Dynamic Traffic Model

We assume the DSL system is time-slotted, indexed by t. The arrival data of each user is stored in a FIFO queue before entering the physical layer. $Q^n(t)$ denotes the queue length of user n at time slot t.

At each time slot, a certain amount of data (the physical layer transmit rate, denoted as $R^n(t)$) will be transmitted and subtracted from the queue. $A^n(t)$ denotes the arrival data rate of user n in time slot t, which can be modeled by a random process, whose expectation is denoted by $\mathbb{E}[A^n(t)] = \lambda^n$. Moreover, we choose the time slot to be sufficiently small, so that $A^n(t)$ is bounded to a constant, ω^n, i.e. $A^n(t) \leq \omega^n, \forall n \in N, \forall t \geq 0$.

At each time slot, the queue length of user n is then updated as:

$$Q^n(t+1) = [Q^n(t) - R^n(t)]^+ + A^n(t) \quad (2)$$

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

C. Transmission Queueing Stability

Our goal is to prevent the transmission queues Q^n from growing to infinity. The stability of the transmission queueing system is defined as follows:

Definition 2: (Transmission Queueing Stability). A multi-user system is called stable, if the following is satisfied:

$$\limsup_{t \to \infty} \frac{1}{t} \sum_{\tau=0}^{t} \mathbb{E} \left[\sum_{n \in N} Q^n(\tau) \right] < \infty \quad (3)$$

Calculating how long exactly the data stays in the queue is not possible, due to the stochastic arrival process and the dynamic transmit rate. We define the system delay as a systematic metric for the delay performance.:

Definition 3: (System Delay). The system delay Ψ represents a DSL system's delay performance under a specific arrival process. It is calculated as:

$$\Psi(t) = \frac{1}{t} \sum_{\tau=0}^{t} \mathbb{E} \left[\sum_{n \in N} Q^n(\tau) \right]. \quad (4)$$

However, constrained by the physical layer resources, the system is not able to stabilize any arrival data process with an arbitrarily large expectation value. We define the set of all arrival data process with expectation vector $\vec{\Lambda} = [\lambda^1, ..., \lambda^N]^T$ that can be stabilized by the system as the throughput region.

Definition 4: (Throughput Region). The throughput-region $\vec{\Lambda} \subset \mathbb{R}_+^N$ is the set of all arrival vectors for which there exists a resource allocation algorithm stabilizing the system.

Intuitively, if the arrival vector $\vec{\Lambda}$ is located within the physical layer rate region, in an arbitrary time period, there must be a combination of transmit rates $[R^1, ..., R^N]$, such that the transmit rates are higher than the arrival data rates, so that the system can be stabilized. In [9], the achievable throughput region is characterized as :Λ = convex-hull($\mathbb{R}$), where $\mathbb{R}$ is the physical layer rate region.

III. Max-Weight Partial Crosstalk Cancellation

In this section we propose a dynamic resource allocation algorithm, which will be referred to as Max-Weight Partial Crosstalk Cancellation (MW-PCC). The algorithm dynamically allocates the crosstalk canceller taps, based on the instantaneous queue lengths $Q^n(t)$.

A. MW-PCC Algorithm

The objective is to preserve the stability of the transmission queue, under the dynamic queueing model (2). The Max-Weight (MW) scheduling algorithm [9] is proven to maximize the throughput region. Here we extend the MW algorithm to PCC, to dynamically allocate the PCC resources, i.e. the crosstalk canceller taps, so as to maximize the throughput region of the DSL systems. This enables a proper interaction between the queueing status and the transmit rates. The instantaneous queue lengths are used to represent the priority of the individual user, and the instantaneous throughput of the whole DSL system is optimized correspondingly.

Definition 5: (Max-Weight Partial Crosstalk Cancellation (MW-PCC)). For each time slot, the optimal resource allocation of the PCC is computed as:

$$\forall t : c^{opt}(t) = \underset{\{c_k^{n,m},\forall k,m,n\neq m\}}{\operatorname{argmax}} \sum_{n=1}^{N} Q^n(t)R^n \qquad (5)$$
$$\text{s.t.} : \sum_{k=1}^{K}\sum_{m=1}^{N}\sum_{n=1}^{N} c_k^{n,m} \leq C^{total}.$$

Remark 3.1: By applying MW-PCC, the throughput region of the DSL system is maximized to the *convex hull* of its rate region for the given resource budget (1). When the expected value of the arrival process $\vec{\lambda}$ is strictly interior to the throughput region, the transmission queues will not grow to infinity and are upper bounded.

The MW-PCC algorithm requires problem (5) to be solved for each time slot. We use a Lagrange dual decomposition approach to solve the optimization problem efficiently. This consists of moving the budget constraint (1) into the objective function with the introduction of a Lagrange multiplier $\pi \geq 0$ as follows,

$$c^{opt}(t) = \min_{\pi} \underset{\{c_k^{n,m},\forall k,m,n\neq m\}}{\operatorname{argmax}} \Big(\sum_{n=1}^{N} Q^n(t)R^n + \pi\big(C^{total} - \sum_{k=1}^{K}\sum_{m=1}^{N}\sum_{n=1}^{N} c_k^{n,m}\big)\Big).$$

For a fixed π, the problem is decoupled over tones. Furthermore, unlike in spectrum balancing, increasing the number of crosstalk canceller taps for a user will not cause any damage to other users, which makes a further decoupling over users possible. The resulting per-tone search space is then dramatically reduced from $(2^{N-1})^N$ to $N-1$, which can be solved using an exhaustive search over N possibilities [5]. The Lagrange multiplier π is updated using a subgradient approach with an adaptive stepsize as proposed in [10]. A complete description of the MW-PCC algorithm with dual decomposition is presented in Algorithm 1.

Algorithm 1 MW-PCC

while $C \neq C^{total}$ **do**
  for $n = 1$ *to* N **do**
    for $k = 1$ *to* K **do**
      $$c_k^{n,opt} = \underset{\{c_k^{n,m},\forall m,n\neq m\}}{\operatorname{argmax}} Q^n(t)b_k^n - \pi\sum_{m=1}^{N} c_k^{n,m}$$
    end for
  end for
  update π
end while The C converges to C^{total}
Update the queue length by (2)

B. Robustness against alien crosstalk and channel estimation errors

In practice, the assumption of perfect channel state information is not always valid, i.e. there may be channel estimation errors and channel changes, e.g. an alien crosstalker may join the cable binder and cause severe crosstalk. The physical layer performance will be degraded by inaccurate channel state information due to the non-optimal resource allocation.

This issue is investigated with respect to the throughput region and transmission queueing stability. We have observed that, restrained by the reduced physical layer rate region, the throughput region is also reduced. However the arrival processes within the reduced throughput region are still stabilizable through MW-PCC, at the cost of delay performance. As a result, MW-PCC is observed to be robust against small channel changes. This will be further demonstrated in the simulation section.

IV. Budget Adaptive Approaches for MW-PCC

Under a fixed crosstalk canceller budget, for any stabilizable arrival process, the resulting transmit rate vector of MW-PCC is always restrained to the boundary of the rate region. Therefore MW-PCC is not resource-efficient as it always uses all the available resources. In this section we propose two budget adaptive MW-PCC algorithms, to address the above points.

A. Budget Adaptive MW-PCC

We define a cost constant V, which is a positive number, and the instantaneous crosstalk canceller usage $C(t)$, which is the PCC resource consumption C (1) at time slot t.

We introduce an additional term $-VC(t)$ into the objective function of (5), to penalize the allocation of crosstalk cancellers taps. This allows the instantaneous resource usage $C(t)$ not to be restrained to the total resource budget C^{total}. Therefore the transmit rate vector is no more restrained to the boundary of a fixed rate region, but can be located within the rate region. For a large V, the number of the allocated crosstalk canceller taps will be reduced, resulting in a lower transmit rate and a larger system delay, and for a small V, many crosstalk canceller taps will be allocated, which results in a high transmit rate and a small system delay. The procedure of the Budget Adaptive MW-PCC (BA-MW-PCC) is now as follows:

For each time slot, we allocate the crosstalk canceller taps according to the following optimization problem:

$$\forall t : c^{opt}(t) = \underset{\{c_k^{n,m}, \forall k,m,n \neq m\}}{\operatorname{argmax}} \sum_{n=1}^{N} Q^n(t) R^n - VC(t)$$
$$\text{s.t. } : \sum_{k=1}^{K} \sum_{m=1}^{N} \sum_{n=1}^{N} c_k^{n,m} \leq C^{total},$$

where C^{total} is the maximal crosstalk canceller budget. In order to achieve the largest possible throughput region, in the rest of the paper we choose the $C^{total} = K \times N \times (N-1)$, which corresponds to full crosstalk cancellation.

Remark 4.1: With an arbitrary positive number V, the queues can always be stabilized, as long as the arrival vector is strictly interior to the throughput region of the maximal canceller budget. The proof is omitted due to space limitation.

B. System Delay Tracking BA-MW-PCC

We introduce a further extension of the BA-MW-PCC algorithm. Any cost constant V corresponds to a relative distance between the dynamic arrival vector and the transmit rate vector. A large V leads to a low resource consumption and a low delay performance, and vice versa. However, the delay performance has an obvious but non-analytic relation to the resource budget. Therefore we replace the cost constant V by a dynamic cost index $V(t)$, which is updated subject to a target "instantaneous system delay" $\Psi^{target} = \sum_{n=1}^{N} Q^{n,target}$, as follows,

$$V(t) : V(t) = V(t-1) + \epsilon(\Psi^{target} - \sum_{n=1}^{N} Q^n(t-1)), \quad (6)$$

where ϵ is the stepsize, which is a positive number. After updating the cost index $V(t)$, the remaining procedure is the same as BA-MW-PCC. With this dynamic cost index $V(t)$, the crosstalk canceller usage is controlled by the difference between the instantaneous system delay and the desired system delay. Therefore the instantaneous system delay will be kept at the desired value, and on the long term the system delay converges to the target Ψ^{target} . Note that this scheme is only able to track a desired system delay, but not precisely constrain to it, due to the stochastic arrival process. The significance of this dynamic cost function is that the highly coupled relationship between the delay performance and the resource budget is bypassed.

Remark 4.2: The cost index $V(t)$ is not necessarily positive. The objective function to maximize is monotonically increasing with respect to the crosstalk canceller budget after decoupling over users and tones, and so a negative or zero $V(t)$ leads to full crosstalk cancellation, i.e. $C(t) = C^{full}$.

Remark 4.3: The desired system delay is lower bounded. If the transmit rate can always empty the queue before the new data arrives, which implies a minimal queue length, then the lower bound of the desired system delay is as follows,

$$\Psi^{target} \geq \sum_{n=1}^{N} \mathbb{E}(A^n).$$

A too small Ψ^{target} will not affect stability but results in full cancellation.

V. SIMULATION RESULTS

The simulations are performed for a four-user upstream VDSL2 scenario, as shown in Figure 1. The diameter of the twisted pair lines is 0.5 mm. The coding gain is set to 3 dB and the noise margin is set to 6 dB. The target error probability is 10^{-7}. The tone spacing Δ_f is 4.3125 kHz and the users use 2786 tones ranging from 0 to 12 MHz, with a symbol rate f_s of 4000 symbols per second. We fix the transmit power at -60 dBm/Hz on all the tones.

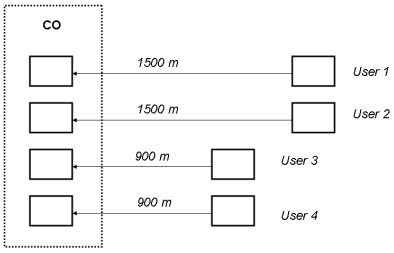


Fig. 1: Simulation Scenario

A. Performance of MW-PCC

The variation of the queue lengths of user 1 and 3 as a function of time is shown in Figure 2.

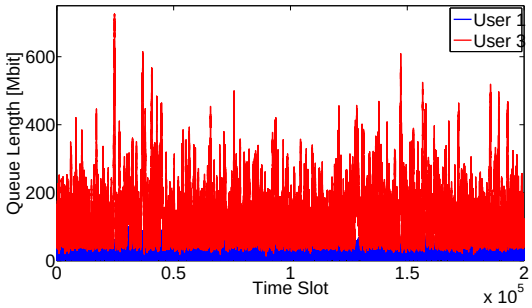


Fig. 2: Dynamic Queues

In Figure 3, we demonstrate the relationship between system delay and resource budget. The arrival vector is close to the boundary to the throughput region for 30% crosstalk cancellation. By increasing the budget from 30% to 40% and 50%, the system delay is improved.

To evaluate the robustness against alien crosstalk, simulation begins without any alien crosstalk. In the first stage of Figure 4, the system delay is stable. Then a 600m user is added to the system, which creates alien crosstalk. Although the system delay increases rapidly, it converges to a new stable level. Thus we can say, in this scenario, the MW-PCC is robust against unknown alien crosstalk up to a certain degree.

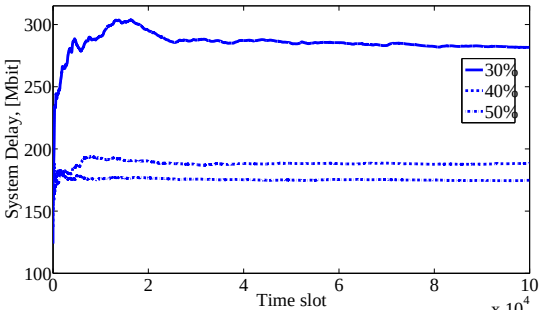


Fig. 3: System Delay versus Crosstalk Canceller Budget

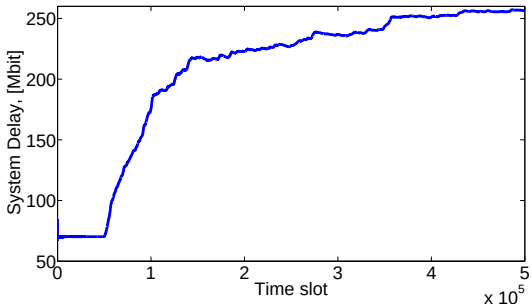


Fig. 4: System Delay under Alien Crosstalk

B. Performance of BA-MW-PCC

Here the performance of the budget adaptive algorithms is investigated. Figure 5 contains the system delay for an arrival vector out of the boundary of the throughput region for 30% crosstalk cancellation (high workload), and for an arrival vector close to the boundary (low workload). The MW-PCC with a fixed budget (30%) can only stabilize the low workload arrival process (unstable procedure not shown). The BA-MW-PCC can stabilize both arrival processes, by tuning the instantaneous budget adaptively. This shows that the throughput region is enhanced by BA-MW-PCC, by dynamically adjusting the physical layer resource budget to the arrival process.

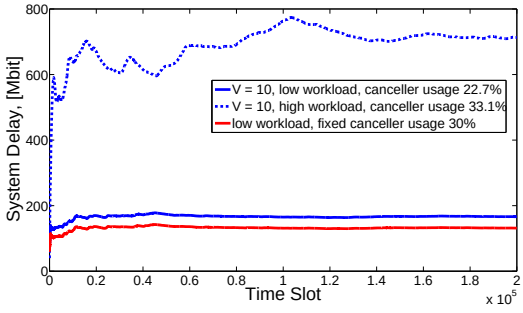


Fig. 5: Comparison of BA-MW-PCC and MW-PCC

The resource efficiency of the system delay tracking BA-MW-PCC is demonstrated in Figure 6. Reaching the same system delay as MW-PCC with fixed budget, the system delay tracking MW-PCC significantly reduces the crosstalk canceller consumption from 10015 to 5904 on average.

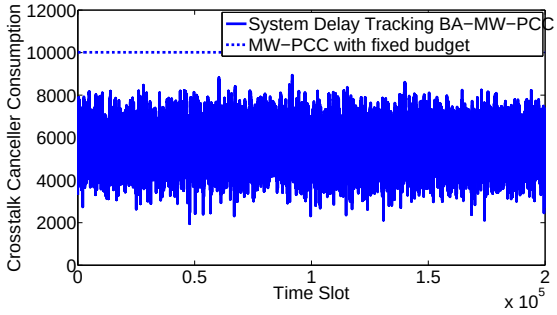


Fig. 6: Crosstalk Canceller Consumption

VI. Conclusion

A dynamic resource allocation based PCC algorithm is proposed, referred to as MW-PCC, that dynamically allocates crosstalk canceller taps so as to stabilize the dynamic arrival data and so as to maximize the throughput region. To the best of our knowledge, this is the first scheme that uses a dynamic cross-layer approach for DSL PCC. Extension towards budget adaptive schemes are also proposed that dynamically adapt the resource budget so as to obtain a better resource efficiency, and further to enable an explicit delay performance target.

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