LOW COMPLEXITY CROSSTALK CANCELLATION THROUGH LINE SELECTION IN UPSTREAM VDSL

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ABSTRACT

Crosstalk is *the* major source of performance degradation in VDSL. A number of crosstalk cancellation techniques have been proposed to address this. Whilst these schemes lead to large performance increases they also have high run-time complexities, a problem which grows rapidly with the number of lines within a binder. Since the majority of crosstalk typically comes from only a few *dominant crosstalkers* it is possible to do partial crosstalk cancellation.

In this paper we present a low-complexity, partial crosstalk cancellation technique for VDSL based on line selection. We derive the optimal line selection technique, and several low-complexity selection algorithms which give near-optimal performance in most scenarios. These techniques lead to significant reductions in run-time complexity whilst giving similar performance to full crosstalk cancellation.

1. INTRODUCTION

VDSL is the next step in the on-going evolution of DSL standards and will support data rates up to 52 Mbps in the downstream. These rates are achieved by operating over short loop lengths and transmitting in frequencies up to 12 MHz.

Unfortunately the use of such high frequency ranges can cause significant electromagnetic coupling between neighbouring twisted pairs within a binder group. This electromagnetic coupling creates interference, referred to as crosstalk, between the systems operating within a binder. Over short loop lengths crosstalk is typically 10-15 dB larger than the background noise and is *the* dominant source of performance degradation.

Several schemes have been proposed for crosstalk cancellation in VDSL. These are typically based on joint processing at the central office (CO) of all lines within a binder. Whilst these schemes lead to significant performance gains their complexities are outside the scope of current implementation. We refer to these schemes as *full crosstalk cancellation*.

In this paper we investigate low complexity crosstalk cancellation for upstream communication which utilizes the concept of 'line selection'. It has been observed in many DSL systems that significant crosstalk often comes from only a small selection (typically 4-5) of the other lines within a binder. Using this observation, we propose a scheme which detects each user using only a sub-set of the lines present at the CO. This reduces complexity considerably whilst achieving virtually the same performance.

Similar schemes have been proposed in the wireless field referred to as hybrid selection/maximum ratio combining [1, 2]. These schemes typically involve antenna selection at the transmitter with the goal of reducing the required number of transmit RF chains. Here we are primarily concerned with selection at the receiver with the goal of reducing computational complexity. We also exploit certain properties of the DSL environment to gain a better understanding of optimal line selection in this context.

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2. SYSTEM MODEL

Through use of discrete multi-tone (DMT) transmission and synchronised reception it is possible to model crosstalk independently on each tone [3]. In this paper we concern ourselves only with crosstalk cancellation in upstream communication. The extension of line selection techniques to crosstalk pre-compensation in the downstream is also possible and is the subject of current work.

We model transmission on a single tone k as follows. $\mathbf{x}(k)$ is the set of QAM-symbols transmitted by each of the customer premises (CP) modems on tone k where $x_i(k) \triangleq [\mathbf{x}(k)]_i$ is the symbol transmitted by modem i. $\mathbf{y}(k)$ is the set of received signals on each of the modems at the CO where $y_i(k) \triangleq [\mathbf{y}(k)]_i$ is the signal received on modem i. $\mathbf{H}(k)$ is the channel matrix where $h_{i,j}(k) \triangleq [\mathbf{H}(k)]_{i,j}$ is the channel from CP transmitter j into CO receiver i. The receivers suffer from additive noise $\mathbf{z}(k)$ from e.g. alien crosstalk, RFI and thermal noise. $z_i(k) \triangleq [\mathbf{z}(k)]_i$ is the noise seen at receiver i which we assume to be Gaussian. There are N users in the binder so $\mathbf{x}(k)$, $\mathbf{y}(k)$ and $\mathbf{z}(k)$ are all vectors of length N, whilst $\mathbf{H}(k)$ is a matrix of dimension $N \times N$. Transmission of one DMT-block on tone k is modeled as

$$\mathbf{y}(k) = \mathbf{H}(k)\mathbf{x}(k) + \mathbf{z}(k)$$

For simplicity we assume identical noise power on all receivers at one tone $\mathcal{E}\left\{\mathbf{z}(k)\mathbf{z}^H(k)\right\} = \sigma^2(k)\mathbf{I}_N$ and normalised transmit powers $\mathcal{E}\left\{\mathbf{x}(k)\mathbf{x}^H(k)\right\} = \mathbf{I}_N$. Extensions to include non-white noise and spectral shaping are trivial, involving the use of an equivalent AWGN channel. We drop the tone index k in the following to clarify notation. An identical procedure is followed on each tone.

3. FULL CROSSTALK CANCELLATION

Many schemes for crosstalk cancellation have been proposed including linear MUD [4] and non-linear schemes based on decision feedback [3]. In upstream transmission due to the structure of the DSL channel there is often little difference in performance between linear and non-linear schemes. For this reason we restrict our attention to linear MMSE crosstalk cancellation.

Linear crosstalk cancellers form an estimate of the user of interest's signal, whom we denote user n, using a linear combination of the signals received on *all* lines

$$\widehat{x}_n = \mathbf{w}_n \mathbf{y}$$

The linear MMSE crosstalk canceller is a row-vector of size $1 \times N$ defined as

$$\mathbf{w}_n = \arg\min_{\mathbf{w}} \mathcal{E}\left|\mathbf{w}\mathbf{y} - x_n\right|^2 = \mathbf{e}_n^H \mathbf{H}^H \left(\mathbf{H}\mathbf{H}^H + \sigma^2 \mathbf{I}_N\right)^{-1}$$

where $\mathbf{e}_n$ is the n'th column of the identity matrix $\mathbf{I}_N$. Application of this leads to large performance gains, particularly over short loops where performance is interference limited. Unfortunately this leads to high run-time complexity and memory requirements. Full crosstalk cancellation has a complexity of $\mathcal{O}(N)$ multiplications/tone/DMT-block/user, leading to a total complexity $\mathcal{O}(KN^2)$ where K is the number of tones. This rapidly increases with the number of lines in a binder. For example, in a system with $K = 4096$, $N = 20$ and a DMT-symbol rate of 4 kHz, crosstalk cancellation has a run-time complexity of 6.55×10^9 mults/second. In binders consisting of hundreds of lines the complexity becomes completely unrealisable.

4. PARTIAL CROSSTALK CANCELLATION

This high complexity motivates the development of reduced complexity techniques. Typically, the majority of crosstalk experienced by a user comes from only a subset of lines within the binder. We refer to these lines as the *dominant crosstalkers*. These lines typically correspond to neighbouring pairs of a particular line within the binder geometry. In binders who's constituent lines have significantly different lengths, another source of dominant crosstalk is the near-far effect. In such scenarios, near-end users cause significantly more crosstalk than far-end users since the signals of far-end users attenuate before crosstalk coupling occurs.

For these reasons we can achieve a large performance gain just by cancelling crosstalk from dominant crosstalkers. This can be implemented by observing a sub-set of the lines when detecting each user. Specifically we observe the direct line of the user of interest, plus p additional lines. Due to the high SNR nature of the DSL channel, any interference on the line of interest which is correlated with interference on the p extra observation lines can be filtered out with minimal effect on signal power.

By observing only a subset of lines at the receiver, the complexity for crosstalk cancellation of a single user reduces from $\mathcal{O}(N) \rightarrow \mathcal{O}(p+1)$ which can be considerable for binders with a large number of lines N.

We denote the set of p extra observation lines $\mathbb{M}_n \triangleq \{m_n(1), \ldots, m_n(p)\}$, and the user of interest as user n. Observing line n and lines $\mathbb{M}_n$ in the detection of user n leads to the following reduced system model

$$\widetilde{\mathbf{y}}_n = \widetilde{\mathbf{H}}_n \mathbf{x} + \widetilde{\mathbf{z}}_n \tag{1}$$

where the set of signals on the observed lines $\widetilde{\mathbf{y}}_n \triangleq \left[y_n\ y_{m_n(1)} \cdots y_{m_n(p)}\right]^T$, noise on the observed lines $\widetilde{\mathbf{z}}_n \triangleq \left[z_n\ z_{m_n(1)} \cdots z_{m_n(p)}\right]^T$ and reduced channel $\widetilde{\mathbf{H}}_n \triangleq \left[[\mathbf{H}]^T_{\text{row } n}\ [\mathbf{H}]^T_{\text{row } m_n(1)} \cdots [\mathbf{H}]^T_{\text{row } m_n(p)}\right]^T$.

We form an estimate of the symbol of user n using a linear combination of the signals received on the *observed* lines only

$$\widehat{x}_n = \widetilde{\mathbf{w}}_n \widetilde{\mathbf{y}}_n$$

The optimal design for the linear partial crosstalk canceller $\widetilde{\mathbf{w}}_n$ in the MMSE sense is

$$\begin{aligned}\widetilde{\mathbf{w}}_n &= \arg\min_{\widetilde{\mathbf{w}}} \mathcal{E}\left|\widetilde{\mathbf{w}}\widetilde{\mathbf{y}}_n - x_n\right|^2 \\ &= \mathbf{e}_n^H \widetilde{\mathbf{H}}_n^H \left(\widetilde{\mathbf{H}}_n \widetilde{\mathbf{H}}_n^H + \sigma^2 \mathbf{I}_{p+1}\right)^{-1} \end{aligned}\tag{2}$$

5. OPTIMAL LINE SELECTION

Using (2) we can design a partial crosstalk canceller given any set of extra observation lines $\mathbb{M}_n$. The process for selecting these extra observation lines is now described. Our goal is to maximize data rate. Using information theory we can phrase the line selection problem as

$$\max_{\mathbb{M}_n} C_n \text{ s.t. } |\mathbb{M}_n| = p \tag{3}$$

where $C_n \triangleq I(\widetilde{\mathbf{y}}_n; x_n)$[1] and $|\mathbb{S}|$ denotes the cardinality of set $\mathbb{S}$. Rewrite (1) as a sum across transmitters

$$\widetilde{\mathbf{y}}_n = \sum_i \widetilde{\mathbf{h}}_i x_i + \widetilde{\mathbf{z}}_n$$

where $\widetilde{\mathbf{h}}_i \triangleq \left[h_{n,i}\ h_{m(1),i} \cdots h_{m(p),i}\right]^T$. Using this model

$$C_n = \log\left(1 + \widetilde{\mathbf{h}}_n^H \left(\sum_{i \neq n} \widetilde{\mathbf{h}}_i \widetilde{\mathbf{h}}_i^H + \sigma^2 \mathbf{I}_{p+1}\right)^{-1} \widetilde{\mathbf{h}}_n\right)$$

Define $\mathbf{Z} \triangleq \sum_{i \neq n} \widetilde{\mathbf{h}}_i \widetilde{\mathbf{h}}_i^H + \sigma^2 \mathbf{I}$. In DSL the direct channel from a given transmitter to its receiver is always much stronger than the channel from *that* transmitter to another receiver. We call this column-wise diagonal dominance since it ensures that $|h_{n,n}| \gg |h_{m,n}|\ \forall m \neq n$, ie. the diagonal element of each column has the largest magnitude. Hence we can approximate $\widetilde{\mathbf{h}}_n \simeq [h_{n,n}\ \mathbf{0}_{1\times p}]^T$. Using this observation we rewrite (3) as

$$\begin{aligned}\max_{\mathbb{M}_n} C_n \quad &\Leftrightarrow \quad \max_{\mathbb{M}_n} \widetilde{\mathbf{h}}_n^H \mathbf{Z}^{-1} \widetilde{\mathbf{h}}_n \\ &\Leftrightarrow \quad \max_{\mathbb{M}_n} |h_{n,n}|^2 \left[\mathbf{Z}^{-1}\right]_{1,1} \\ &\Leftrightarrow \quad \max_{\mathbb{M}_n} \left[\mathbf{Z}^{-1}\right]_{1,1}\end{aligned}$$

Now $\left[\mathbf{Z}^{-1}\right]_{1,1} = \left|\overline{\mathbf{Z}}_{1,1}\right| |\mathbf{Z}|^{-1}$ where $\overline{\mathbf{Z}}_{i,j}$, is defined as the matrix $\mathbf{Z}$ with row i and column j removed and $|.|$ denotes the determinant. We can re-write $\mathbf{Z}$ as follows

$$\mathbf{Z} = \begin{bmatrix} \overline{\mathbf{h}}_n^H \\ \mathbf{M}^H \end{bmatrix} \begin{bmatrix} \overline{\mathbf{h}}_n & \mathbf{M} \end{bmatrix} + \sigma^2 \mathbf{I}_{p+1} \tag{4}$$

where $\overline{\mathbf{h}}_i \triangleq [h_{i,1} \cdots h_{i,n-1}\ h_{i,n+1} \cdots h_{i,N}]^H$ and $\mathbf{M} \triangleq \left[\overline{\mathbf{h}}_{m(1)} \cdots \overline{\mathbf{h}}_{m(p)}\right]$. Note that $\overline{\mathbf{h}}_i$ contains the paths from the interferers to the receiver of line i. Decompose $\mathbf{Z}$ into sub-matrices

$$\mathbf{Z} = \begin{bmatrix} a & \mathbf{b}^T \\ \mathbf{c} & \mathbf{D} \end{bmatrix}$$

where $a \triangleq \left\|\overline{\mathbf{h}}_n\right\|^2 + \sigma^2$, $\mathbf{b}^T \triangleq \overline{\mathbf{h}}_n^H \mathbf{M}$, $\mathbf{c} \triangleq \mathbf{M}^H \overline{\mathbf{h}}_n$ and $\mathbf{D} = \mathbf{M}^H\mathbf{M} + \sigma^2 \mathbf{I}_p = \overline{\mathbf{Z}}_{1,1}$. Using the Schur complement we can write $\left[\mathbf{Z}^{-1}\right]_{1,1} = \left|\overline{\mathbf{Z}}_{1,1}\right| |\mathbf{Z}|^{-1} = \left(a - \mathbf{b}^T \mathbf{D}^{-1} \mathbf{c}\right)^{-1}$. We can rephrase our optimisation as $\min\left(a - \mathbf{b}^T \mathbf{D}^{-1}\mathbf{c}\right) \Leftrightarrow \max \mathbf{b}^T \mathbf{D}^{-1} \mathbf{c}$ since $a - \mathbf{b}^T \mathbf{D}^{-1} \mathbf{c}$ is positive. Thus our optimisation becomes

$$\max_{\mathbb{M}_n} \overline{\mathbf{h}}_n^H \mathbf{M}\left(\mathbf{M}^H \mathbf{M} + \sigma^2 \mathbf{I}_p\right)^{-1} \mathbf{M}^H \overline{\mathbf{h}}_n$$

[1] This can be related to the rate achieved using a conventional slicer through the SNR-gap to capacity.

Decompose $\mathbf{M}$ into an orthonormal set of basis vectors using the SVD, $\mathbf{M} \stackrel{\text{svd}}{=} \mathbf{USV}^H$ such that $\mathbf{U}$ has size $N-1 \times p$, $\mathbf{S} \triangleq \text{diag}\{s_1, \ldots, s_p\}$, and $\mathbf{V}$ has size $p \times p$. $\mathbf{U}$ contains the first p left singular vectors of $\mathbf{M}$ and spans the same column-space. Using this

$$\mathbf{M}\left(\mathbf{M}^H\mathbf{M} + \sigma^2\mathbf{I}\right)^{-1}\mathbf{M}^H = \mathbf{US}^2\left(\mathbf{S}^2 + \sigma^2\mathbf{I}\right)^{-1}\mathbf{U}^H$$

Thus our optimisation becomes

$$\max_{\mathbb{M}_n} \left\| \mathbf{S}\left(\mathbf{S}^2 + \sigma^2\mathbf{I}\right)^{-\frac{1}{2}}\mathbf{U}^H\overline{\mathbf{h}}_n \right\|^2$$

Each basis vector $\mathbf{u}_i$ is scaled by a penalty factor $\frac{s_i}{\sqrt{s_i^2+\sigma^2}}$. Basis vectors with larger singular values s_i introduce less noise when used for interference cancellation and hence have a light penalty.

Over short lines the interference is typically several orders of magnitude larger than the background noise. In this special case we can drop the noise term in (4) and approximate $\mathbf{S}^2 + \sigma^2\mathbf{I} \simeq \mathbf{S}^2$. Our optimisation then becomes

$$\max_{\mathbb{M}_n} \left\| \mathbf{U}^H\overline{\mathbf{h}}_n \right\|^2 \qquad (5)$$

Effectively we form a basis from the vectors $\overline{\mathbf{h}}_{m(1)}, \ldots, \overline{\mathbf{h}}_{m(p)}$ and use this to cancel the interference seen on line n (recall that $\overline{\mathbf{h}}_n$ is the interference seen on line n). The larger the projection of the interference $\overline{\mathbf{h}}_n$ onto the basis, the more interference we can remove and hence the larger the capacity.

Note that (5) must be evaluated over every possible subset $\mathbb{M}_n$ of cardinality p. There are $\binom{N-1}{p}$ such subsets which leads to a selection complexity of $\mathcal{O}\left(KNp^2\binom{N-1}{p}\right)$ mults/user. This can be extremely complex for large N e.g. with $p = 4$, $K = 4096$ and $N = 20$, line selection has a complexity of $\simeq 5.08 \times 10^9$ mults/user. Fortunately the DSL environment is quite stationary in time so subset selection doesn't need to be updated often. This reduces the impact of such a large selection complexity.

6. SIMPLIFIED LINE SELECTION

Since optimal line selection is highly complex we now present low-complexity selection algorithms which are near-optimal in most scenarios.

Greedy Algorithm (Basis Pursuit)

The greedy algorithm (also known as basis pursuit) is commonly applied to sub-set selection problems[5]. This algorithm works by selecting, at any one time, the best extra observation line as if this where the last extra observation line to be selected. As a result the algorithm is generally short-sighted and gives its best performance at low p.

The greedy algorithm is listed in Alg. 1 and operates as follows. We begin by defining the residual crosstalk $\mathbf{r}$. This contains all crosstalk which has not been captured in previously selected lines. The algorithm iterates p times. Each iteration, the algorithm selects the extra observation line which will capture the largest amount of residual crosstalk.

The algorithm has a selection complexity of $\mathcal{O}\left(\frac{1}{2}KN^3p^2\right)$ mults/user. In our previous example, selection would require $\simeq 2.62 \times 10^8$ mults/user, i.e. 19 times less complex than the optimal scheme. For comparison we also run simulations using the backwards greedy algorithm[5]. This algorithm is inherently long-sighted, giving best performance for large p.

Algorithm 1 Greedy algorithm

initialise
  residual crosstalk $\mathbf{r} = \overline{\mathbf{h}}_n$
  rel. basis vect. for each unselected line $\mathbf{u}_i = \overline{\mathbf{h}}_i / \left\|\overline{\mathbf{h}}_i\right\| \; \forall i \neq n$
  basis of selected lines $\mathbf{U}_s = [\,]$ (always orthonormal)
  set of unselected lines $\mathbb{S} = [1, N] - n$
for $j = 1 \ldots p$
  find line with largest projection $m_n(j) = \arg\max_{i \in \mathbb{S}} \mathbf{u}_i^H \mathbf{r}$
  update
    basis of selected lines $\mathbf{U}_s = \left[\mathbf{U}_s \; \mathbf{u}_{m_n(j)}\right]$
    set of unselected lines $\mathbb{S} = \mathbb{S} - m_n(j)$
    relative basis of each unselected line
      orthogonalize to selected basis $\mathbf{u}_i = \left(\mathbf{I} - \mathbf{U}_s\mathbf{U}_s^H\right)\mathbf{u}_i \; \forall i \in \mathbb{S}$
      normalize $\mathbf{u}_i = \mathbf{u}_i / \left\|\mathbf{u}_i\right\| \; \forall i \in \mathbb{S}$
end
$\mathbb{M}_n = \{m_n(1), \ldots, m_n(p)\}$

Dominant Lines

Partial crosstalk cancellation attempts to cancel interference from dominant crosstalkers only. In implementation this is done by only observing a sub-set of the lines at the CO when detecting each user. Except in extreme near-far scenarios, the best estimate of the dominant crosstalker's signals come from their direct lines hence these lines form a good basis for crosstalk cancellation.

In this scheme we simply observe the direct line of the user of interest and the direct lines of the p largest crosstalkers (largest $|h_{n,i}|$) on each particular tone. The complexity of this scheme is $\mathcal{O}(KN)$, the lowest of all schemes shown here. In our example, selection would require $\simeq 8.2 \times 10^4$ mults/user, ie. 62,000 times less complex than the optimal scheme.

7. PERFORMANCE

We now compare the performance of the different line selection schemes. In our simulations we use $K = 4096$, tone spacing 4.3125 kHz, DMT-block rate 4 kHz and Alien Crosstalk Type C as per ETSI standards. Coding gain is 3 dB, noise margin 6 dB and target symbol error probability $< 10^{-7}$. Flat transmit PSDs are employed at -60 dBm/Hz according to the 998 FDD band-plan. A set of measured channel transfer functions are used which were provided by British Telecom. The measurements were done on an 8-pair binder, consisting of 0.5 mm (24-Gauge) pairs.

Time/frequency-sharing (TS/FS) is used as a baseline comparison for the schemes. In time (frequency) sharing we simply do full crosstalk cancellation: $p = N - 1$, for some fraction of the time (on some fraction of the tones) and standard detection: $p = 0$, for the rest of the time (on the rest of the tones). This is the simplest form of partial cancellation available and gives a linear performance-complexity curve.

Distributed Scenario

In this scenario the lengths of the pairs are consistent with a distributed topology and range from 300m to 1000m in 100m increments. The measured crosstalk transfer functions from each of the shorter loops into the 1000m loop are shown in Fig. 1.

The performance vs. run-time complexity curves of the different schemes are shown in Fig. 2. As can be seen, line selection allows us to achieve 90% of the performance of full crosstalk cancellation with only 58% of the run-time complexity. It is expected that with larger binders this effect will grow considerably and measurements of these binders are currently underway. Little performance difference can be seen between the schemes and in our experience this is the case for all scenarios with lines < 1200m.

Extreme Near-Far Scenario

In extreme near-far scenarios with lines > 1200m, the performance difference between selection schemes grows considerably.

Over short lines, the direct lines of dominant crosstalkers usually form the best basis for estimating dominant crosstalkers' signals. However, this is not the case if the binder contains a long line with a weak direct signal, and interference signals which are highly correlated with the interference on the line of interest. In this case the long line will allow any correlated interference to be removed whilst introducing minimal extra interference from the (weak) direct channel. This only occurs in extreme near-far scenarios i.e. on line lengths > 1200m. Furthermore, the effect is only noticeable if $p <$ number of dominant crosstalkers.

We evaluated performance in an extreme near-far scenario with one 1800m line and 7×300m lines. The results are shown in Fig. 3. The greedy algorithm performs well for low p, whilst the backwards greedy and dominant lines algorithms perform well for high p. Outside of these ranges the algorithms can be significantly sub-optimal, even worse than time/frequency sharing in some cases. Note that in practice such extreme near-far scenarios rarely occur. Line lengths larger than 1200m are outside the range of any currently planned VDSL deployments.

8. CONCLUSIONS

Crosstalk is *the* dominant source of performance degradation in VDSL. Crosstalk cancellation has been proposed to address this and leads to large performance gains. Unfortunately it can also lead to large run-time complexity and memory requirements.

In this paper we have presented a reduced complexity, partial crosstalk cancellation scheme for upstream VDSL based on line selection. We presented the optimal scheme for line selection and a number of simplified schemes. It was seen that optimal line selection attempts to capture as much interference energy as possible on the extra observation lines. The simplified line selection schemes give near-optimal performance provided lines are less than 1200m which is virtually always the case in practice.

In this paper we focused on line selection to reduce crosstalk cancellation complexity. It has also been observed that the worst effects of crosstalk are limited to a small proportion of tones. With this in mind, the number of extra lines observed on each tone - p can be made a function of the tone index k and can vary according to the benefits of crosstalk cancellation on each tone. This is an interesting extension to this work and is currently being investigated.

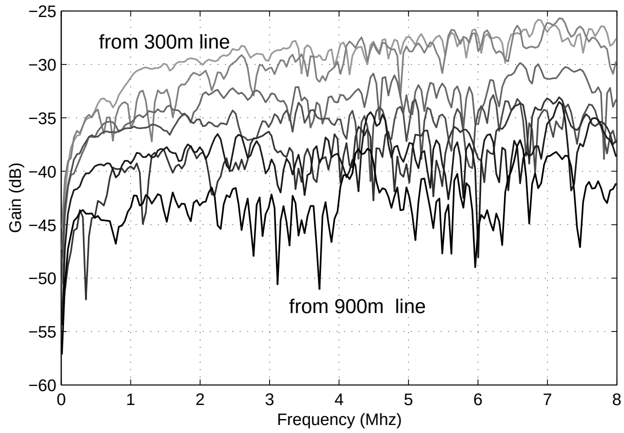

Fig. 1. Crosstalk Channels into 1000m Line

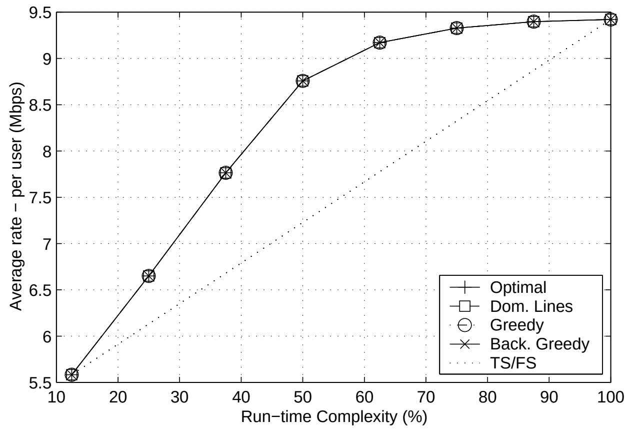

Fig. 2. Performance in Distributed Scenario

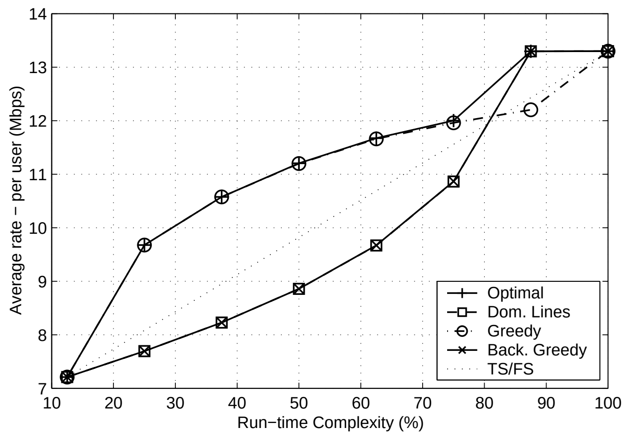

Fig. 3. Performance in Extreme Near-Far Scenario

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