ISSN XXXX XXXX © 2017 IJESC

Research Article Volume 7 Issue No.5

A Zero-Forcing Crosstalk Canceler for Upstream VDSL with Optimized Spectra

Deepika[1], Virender kumar[2]
M.Tech Student[1], Assistant Professor[2]
Department of ECE
HCTM Technical Campus kaithal, Haryana, India

Abstract:
The primary contribution of this research is to remove crosstalk problem. Crosstalk is a serious problem in next generation DSL Systems such as VDSL. Several non-linear cancellers have been proposed. But they suffer from high complexity, error propagation and long latency. So we here describe a zero forcing crosstalk canceler and it has low complexity, low latency and optimal performance. A lower bound on the performance of the linear ZF canceler is developed. This bound shows that the Linear ZF canceler operates close to the single-user bound. Here assume the combination of spectral optimization and crosstalk cancellation. We formulate a bound and show that in 99% of upstream DSL channels the linear zero-forcing canceler achieves 97% of the theoretical capacity. Since the linear ZF canceler decouples transmission on each line, optimized spectrum is developed, leading to reduction in complexity.

Keywords: DFC, DSL, DSM, VDSL, ZF canceler

I. INTRODUCTION

VDSL is an extension of ADSL technology with a shorter loop length and uses higher data rate than ADSL. DSL systems such as VDSL uses high data rates from 13Mbps to 52 Mbps in downstream and data rate from 1.6 Mbps to 26 Mbps in upstream. In this high data rates electromagnetic coupling between neighbouring twisted pairs that creates crosstalk. Crosstalk is 10-15 db larger than background noise. If one pair interfere then the voltage and current induced by the interferer on to the other pair travel in both directions result in NEXT and FEXT. Due to crosstalk performance is degraded [17]. In upstream communications, the receiving modems are collocated at the central office(CO) or at an optical network unit(ONU) located at the end of street. This allows joint reception of the signals transmitted on the different lines, thereby enabling crosstalk cancellation. Several crosstalk canceler designs are there. One of them is a *decision feedback canceler* **(DFC)** which is used to achieve close to the theoretical channel capacity [1]. To get the error free decisions a perfect channel code must be used, which has infinite decoying complexity and delay [14]. But decoying of each user's codeword must be done before decisions get feedback. Due to this there exists long latency and high complexity that grows with the number of u8sers in the binder. In VDSL, codeword may be interleaved across several DMT blocks to add robustness against impulse noise [15]. By this the codeword having long length and latency is typically at the limit required for most applications. So DFC canceler cannot be used in real time application such as voice over IP or video conferencing. To attain cancellation one more technique is there and that is turbo coding principles [2], [3]. But these techniques are extremely complex and give poor performance when more than one crosstalk exists. One more technique is using of coordination on both ends of link. But this is not possible since different customers are situated at different locations. So it does not create improvement in performance. In this paper, we describe a linear zero-forcing crosstalk canceler. It has a low complexity, low latency and does not suffer from error propagation. It offer high data rate from 13 to 53 Mbps in downstream and 1.6 Mbps to 26 Mbps in upstream. It removes all crosstalk. Due to this near optimal performance is performed. The linear ZF canceler operates close to the single user bound in VDSL channels. These bounds allow the performance of the linear ZF canceler to be predicated without explicit knowledge of the crosstalk channels. The remaining part of this paper is described as follows. In section 2, the system model for a network of VDSL is given. Here in this *column-wise diagonal dominance* (CWDD) property is defined. In section 3, consider the single user bound, which is the capacity achieved when only one user transmits and all receivers are used to detect that user. In section 4, describes a simpler linear design, the linear ZF canceler, that has low complexity, no latency and free from error propagation. In this section we also conclude the proof on the lower bound of the linear ZF canceler. In section 5, explains power loading algorithms for use with the linear canceler. As a result the PSD for each line can be determined through a low complexity water filling procedure. With optimized spectra the performance of near optimal linear canceler is also described here. In section 6, compare the performance of the different cancellers. In section 7, we give conclusion of our performance.

II. SYSTEM MODEL

One of the major impairments of DSL systems is crosstalk. The crosstalk signal has a large bandwidth and its spectra in the main lobe is strongly correlated. So to estimate the crosstalk we use crosstalk cancellation system. Assuming that the modems are synchronized and discrete multi-tone (DMT) modulation is employed we can model transmission independently on each tone

$$y_k = H_k . x_k + z_k \qquad (1)$$

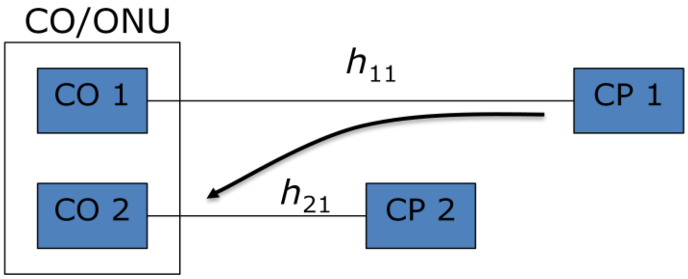

Figure. 1. [7]

In equation 1, Where $x_k = \left[x_k^{\ 1}, x_k^{\ 2}, x_k^{\ 3}, ...x_k^{\ N} \right]^T$ contains transmitted signals on tone k , here the tone index lies in the range $1......K$. There are N lines in the binder and $x_k^{\ n}$ is the signal transmitted onto line n at tone k . The received vector y_k and additive noise vector z_k have similar structures. The vector y_k contains the received signals on tone k . The vector z_k contains the additive noise on tone k and is comprised of thermal noise, alien crosstalk, RFI etc. The $N \times N$ matrix H_k is the crosstalk channel matrix on tone k . We denote the transmit PSD of user n on tone k as $S_k^n \triangleq \varepsilon\left\{ \left| x_k^n \right|^2 \right\}$

In fig. 1 CP 1 is the disturber and CO 2 is the victim. Here we use CWDD property. The crosstalk channel matrix H_k is CWDD (Channel wise Diagonally Dominant), since on each column of H_k the diagonal element has the maximum magnitude.

$$\left| h_k^{\ n,m} \right| \ll \left| h_k^{\ m,m} \right|, \forall m \neq n \qquad (2)$$

The diagonal elements of H_k contain direct channels while off diagonal element contain crosstalk channel. The degree of CWDD can be characterized with the parameter α_k

$$\left| h_k^{\ n,m} \right| \leq \alpha_k . \left| h_k^{\ m,m} \right|, \forall m \neq n \qquad (3)$$

Note that crosstalk cancellation is based on joint reception. So it requires the collocation of receiving modems. So in all channels where crosstalk cancellation can be applied the CWDD property holds.

In 99% of lines α_k is bounded

$$\alpha_k \leq Kxf \,.\, f_k . \sqrt{d_{coupling}} \qquad (4)$$

Where $Kxf = -22.5dB$ and f_k is the frequency on tone k in MHz [7]. Here $d_{coupling}$ is the coupling length between the disturber and the victim in kilometers. The coupling length can be upper bounded by the longest line length in the binder. Hence

$$\alpha_k \leq Kxf \,.\, f_k . \sqrt{l_{\max}} \qquad (5)$$

Where $l_{\max}$ denotes the length of the longest line in the binder. To find a value for α_k that is independent of the particular binder configuration, $l_{\max}$ can be set to 1.2 km, which is the maximum deployment length for VDSL [9]. On typical lines α_k is then less than -11.3 dB.

III. THEORETICAL CAPACITY

In this we will define what we actually want in our result and what kind of error is arisen. Now we consider the single user bound condition that is only one user transmits and all receivers are used to detect that user. Using the single bound the capacity of user *n* on tone ***k*** is limited to

$$b_k^n \leq \Delta f . I\left(x_k^n ; y_k \right)$$

$$= \Delta f . \log_2 \left(1 + \frac{S_k^n \left\| h_k^n \right\|^2}{\sigma_k} \right) \qquad (6)$$

In eq. 6, Where $I\left(a;b\right)$ denotes the mutual information between a land b . To account for the sub optimality of practical coding schemes, we include the SNR-Gap to capacity Γ [8]. This results in the following achievable bit loading of user n on tone k .

$$b_k^{\ n} = \Delta f . \log_2 \left(1 + \frac{S_k^{\ n} . \left\| h_k^{\ n} \right\|^2}{\Gamma . \sigma_k} \right) \qquad (7)$$

Where Δf is the tone Spacing, σ_k is Noise power on tone k, Γ is SNR Gap to Capacity, $S_k^{\ n}$ is Transmit Power by user n on tone k, $h_k^{\ n,n}$ is Direct Channel of user n, $h_k^{\ n,m}$ Crosstalk Channel from user m to n.

In the single-user case with spatially white noise, the single user bound can be achieved by applying a matched filter to the received vector y_k . The CWDD property (3.3) leads to the bound

$$\left\| h_k^n \right\|_2^2 = \left| h_k^{n,n} \right|^2 + \sum_{m \neq n} \left| h_k^{m,n} \right|^2,$$

$$\leq \left| h_k^{n,n} \right|^2 \left[1 + \alpha_k^2 \left(N - 1 \right) \right] \qquad (8)$$

This leads to

$$b_k^n \leq b_{k,bnd}^n \left(s_k^n \right) \qquad (9)$$

where

$$b_{k,bnd}^n \left(S_k^n \right) \triangleq \Delta f \, \log_2 \left(1 + \frac{S_k^n \left| h_k^{n,n} \right|^2}{\Gamma \sigma_k} \left[1 + \alpha_k^2 \left(N - 1 \right) \right] \right) \qquad (10)$$

IV. NEAR OPTIMAL LINEAR CANCELER

In this section we describe a linear crosstalk canceler. This system has low complexity, no latency and no error propagation. And it removes all crosstalk. Due to the well conditioned structure of the VDSL channel matrix, the ZF design causes negligible noise enhancement. The combination of spectral optimization and crosstalk cancellation is also considered. We also develop bounds to show that the linear ZF canceler operates close to the single-user bound in VDSL channels. These bounds allow the performance of linear ZF canceler to be predicated. The structure is based on the *zero-forcing* (ZF) criterion, which leads to the following estimate of the transmitted vector

$$\hat{x}_k = H_k^{-1}.y_k \quad (11)$$

Each user then has a crosstalk free channel, affected only by the filtered background noise. So after cancellation from eq. 11, after application of the linear ZF canceler, the soft estimate of the transmitted symbol is

$$\hat{x}_k^n = x_k^n + \left[H_k^{-1}\right]_{row-n}.z_k \quad (12)$$

Hence the post cancellation signal power is S_k^n, the post cancellation interference power is zero and the post cancellation noise power is

$$\tilde{\sigma}_{k,n} \triangleq \varepsilon\left\{\left|\left[H_k^{-1}\right]_{row-n}.z_k\right|^2\right\}$$

$$= \left\|\left[H_k^{-1}\right]_{row-n}\right\|^2.\sigma_k \quad (13)$$

In eq. 13 [11] we define the noise power. Hence Data rate achieved by Linear ZF Canceler is given by

$$b_{k,ZF\,Bound}^n(S_k^n) \triangleq \Delta f.\log_2\left(1+\frac{S_k^n}{\Gamma.\tilde{\sigma}_{k,n}}\right) \quad (14)$$

Since H_k is well conditioned Column wise diagonally Dominant Matrix, the noise enhancement caused by ZF canceler is negligible and achieved Data rate is nearly equal to

$$b_{k,ZF}^n(S_k^n) \triangleq \Delta f.\log_2\left(1+\frac{S_k^n.\left|h_k^{n,n}\right|^2}{\Gamma.\sigma_k}\right) \quad (15)$$

Since the linear ZF canceler operates generally close to the single user bound. So we can say that it is a near optimal design. The bound depends on the binder size, direct channel gain and background noise power. One main point here is to note that CWDD applies to all lines when receivers are collocated. No knowledge of the actual binder configuration is necessary. The performance of a line can be estimated using only information about the line itself, such as its direct channel attenuation and background noise.

V. SPECTRA OPTIMIZATION

DSL modems should not transmit more power than necessary to achieve their target data rates with good quality of service and should not use more bandwidth than useful for communication. In order to accomplish such transmission efficiency, adaptive allocation techniques, known as dynamic spectrum management (DSM) [14], can be applied for shaping the transmitted power spectrum density(PSD) In DSL lines. This section investigates the optimization of transmit spectra for use with the linear ZF canceler. Each transmitter is subject to a total power constraint

$$\Delta f \sum_k S_k^n \le P_n, \forall n \quad (16)$$

The goal is to maximize a weighted sum of the data rates of the modems within the network

$$\max_{s_1,\ldots\ldots,s_N} \sum_n w_n R_n \quad \text{s.t.} \quad \Delta f \sum_k S_k^n \le P_n, \forall n \quad (17)$$

In eq. 17 ,Where vector $S_n \triangleq \left[S_1^n, S_2^n, \ldots\ldots S_K^n\right]$ contains the PSDs of user n on all tones. The weights $w_1,\ldots\ldots\ldots w_N$ are used to ensure that each modem achieves its target data rate. The data rate R_n is a function of the transmit PSDs $s_1,\ldots\ldots\ldots s_N$ and also depends on the type of crosstalk canceler used [17]. PSD shows the strength of variations (energy) as a function of frequency. When the ZF canceler is applied, all crosstalk is removed, and the spectra optimization decouples into an independent power loading for each user. It reduces complexity. Water filling is a well known algorithm to decide the power allocation and the information distribution of a communication system. As one of the most prosperous algorithms for DSM level 1, water filling utilize fast bit loading techniques based on channel signal to noise ratio, described as signal to noise ratio with unit signal power across the entire frequency band.

A. Theoretical capacity

Here we extend the single user bound that may vary their transmit spectra under total power constraint. Denote R_n as the data rate of user n. When the transmit PSD S_n^k is allowed to vary under a total power constraint (4.15), the capacity for user n in a CWDD channel is bounded

$$R_n \le \max_{\sum_k S_k^n \le P_n} \sum_k b_{k,bnd}^n(S_k^n) \quad (18)$$

In eq. 20[1], Where $b_{k,bnd}^n\left(S_k^n\right)$ is defined (11). In this optimization, the objective function is concave, and the total power constraint forms a convex set. Hence, the Karush–Kuhn–Tucker (KKT) conditions are sufficient for optimality. Examining the KKT conditions leads to the following bound for CWDD channels:

$$R_n \le \sum_k b_{k,bnd}^n(S_{k,bnd}^n) \quad (19)$$

Where single user water-filling PSD is defined by

$$S_{k,bnd}^n \triangleq \left[\frac{1}{\lambda_n} - \frac{\Gamma.\sigma_k}{\left|h_k^{n,n}\right|^2\left[1+\alpha_k^2.(N-1)\right]}\right]^{\dagger} \quad (20)$$

In eq. 22[7], The function $[x]^{\dagger} \triangleq \max(0,x)$ and λ_n is chosen such that power constraint on tone n is tight that is

$$\Delta f \sum_k S_{k,bnd}^n = P_n \quad (21)$$

B. Near optimal linear canceler

Here we describe the linear canceler with transmit spectra optimization. The ability to set the PSD level of each frequency carrier individually gives to DSM techniques to improve the achievable rates [12]. Equation (16) implies that (19) is equivalent to

$$\max_{s_1,\ldots\ldots,s_N} \sum_n \sum_k w_n b^n_{k,ZF}\left(S^n_k\right)$$

$$\text{s.t.} \quad \Delta f \sum_k S^n_k \le P_n, \forall n \qquad (22)$$

So by using this technique the optimization problems now decoupled between users, allowing the optimal power allocation to be found independently for each user. This also implies that these PSDs are optimal regardless of the choice of weights w_n.

When transmit PSD is allowed to vary under a total power constraint, the capacity of user n can be given by

$$R_n \le \sum_k b^n_{k,ZF}(S^n_{k,ZF})$$

(23)

Where single user water filling PSD [17] is defined by

$$S^n_{k,ZF} \triangleq \left[\frac{1}{\lambda_n} - \Gamma.\sigma_{k,n}\right]^{\dagger} \qquad (24)$$

$[x]^{\dagger} \triangleq \max(0,x)$ and the water filling level λ_n must be chosen such that power constraint on tone n is tight that is

$$\Delta f \sum_k S^n_{k,ZF} = P_n \qquad (25)$$

So the approach proposed in for power allocation with the zero-forcing DFC is also valid here with the linear ZF canceler. Conventional water-filling algorithms can be applied to find the correct water-filling level with complexity [17]. As a result, during power allocation each user need only concern themselves with maximizing their own data rate. All crosstalk in the system will be completely removed at the receiver side with negligible impact on the direct channel gains. This can be clearly seen in (25) where the weights have no influence on the final power allocation. This implies that the same operating point is near-optimal regardless of the choice of priorities amongst the users, which simplifies power allocation. As a result of CWDD, the linear ZF canceler operates close to the single-user bound. So using the linear ZF canceler in combination with the power allocation (25) gives near-optimal performance.

VI. PERFORMANCE

Certain properties of DSL channels ensure that these simple linear designs lead to near optimal performance. We formulate a bound on the performance of these schemes and show that in 99% of upstream DSL channels the linear zero forcing canceller achieves 97% of the theoretical channel capacity. This section evaluates the performance of the linear ZF canceller in a binder of 8 VDSL lines. The line lengths range from 150 meter to 1200 meter in 150 meter increments, as shown in Fig. 2. For all simulations the line diameter is 0.5 mm (24-AWG). The target symbol error probability is 10^{-7} or less, the coding gain is set to 3 dB, and the noise margin is set to 6 dB, which results in an SNR-gap Γ 12.9 dB. As per the VDSL standards the tone- spacing Δf is set to 4.3125 kHz [15] [9]. The modems use 4096 tones, and the 998 FDD band plan. Background noise is taken as -130 dBm/Hz and Performance is compared with the single-user bound.

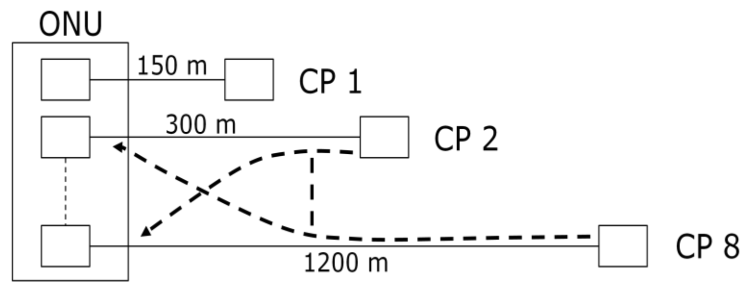

Figure.2. Upstream VDSL scenario

Table.1. Numeric values used for various simulations [15]

N	Δf (K Hz)	P_n (dBm/H z)	Γ	σ_K (dBm/ Hz)	PSD mask (dBm/ Hz)	Band Plan
8	4.3 125	11.5	12. 9 dB	-130	-60	998 FDD

A. Fixed tansmit spectra

Current VDSL standards require that modems transmit under a spectral mask of -60 dBm/Hz[15][9]. Spectral mask is used for a definition of the standardized bandwidth in order to minimize interference. It shows how steep is the curve. This section evaluates the performance of the linear ZF canceler when all modems are operating at this mask. Fig. 3 shows the data-rate achieved by each of the lines with crosstalk cancelers. The linear ZF canceler achieves substantial gains, typically 30 Mbps or more, over conventional systems with no cancellation. As can be seen the linear ZF canceler achieves near-optimal performance, operating close to the single-user bound. This is a direct result of the CWDD of H_k, which ensures that the linear ZF canceler causes negligible noise enhancement. Fig. 4 shows the data-rate achieved by the linear ZF canceler as a percentage of the single-user bound. Performance does not drop below 99% of the single-user bound. The lower bound on the performance of the linear ZF canceler is also included for comparison. As can be seen the bound is quite tight and guarantees that the linear ZF canceler will achieve at least 94% of the single-user bound. It is interesting to note in Fig. 4 that the bound drops to its lowest value at 900 m. The reason for this is as follows. On short lines, the coupling length $d_{coupling}$, as defined is short. This results in a low value for α_k, and as a result, the linear ZF canceler causes negligible noise enhancement. On longer lines α_k is larger so we should expect to see the noise enhancement increase. However, as the line length increases, the direct channel attenuation becomes so bad in the high frequencies that these tones are shut off. The majority of data transmission then occurs in the low frequencies, where the crosstalk coupling and α_k are low. So on long lines, the noise enhancement at the higher frequencies has negligible impact. It is thus on the intermediate-line lengths, such as 900 m, where the noise enhancement of the linear ZF canceler will result in the largest performance degradation, as seen in Fig. 4.

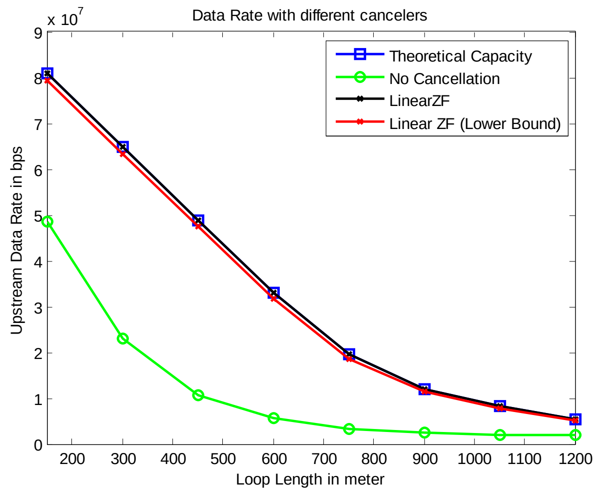

Figure.3. Data Rate with Linear ZF Canceler for Fixed Spectra

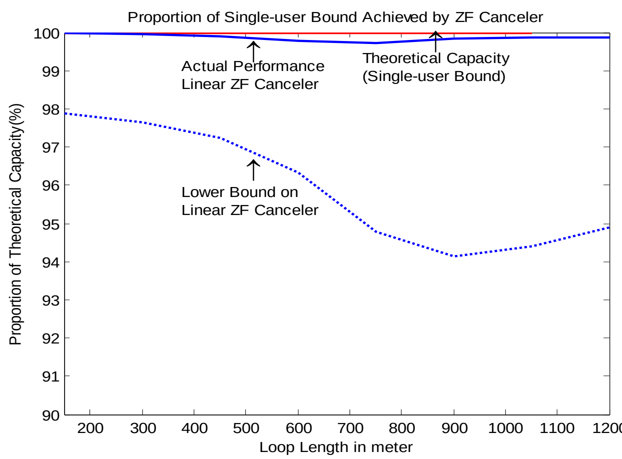

Figure.4. Proportion of Single User Bound achieved by ZF Canceler

B. Optimized transmit spectra

This section investigates the performance of the linear ZF canceler with optimized spectra. A total power constraint of 11.5 dBm/Hz is applied to each modem as per the VDSL standards [15] [9]. Spectral mask constraints are not applied. Fig. 5 shows the data-rates achieved on each line. The use of optimized spectra yields a gain of 5-12 Mbps. The benefit is more substantial on the longer lines, where a 5 Mbps gain can double the data-rate. Fig. 5 shows that spectra optimization gives maximum benefit on long lines. This is to be expected since on long lines the direct channel gain decreases more rapidly with frequency. Note that the benefit of adaptive spectra, when crosstalk has already been cancelled, comes primarily from the modem loading power in the best parts of the channel, which are typically in the lower frequencies

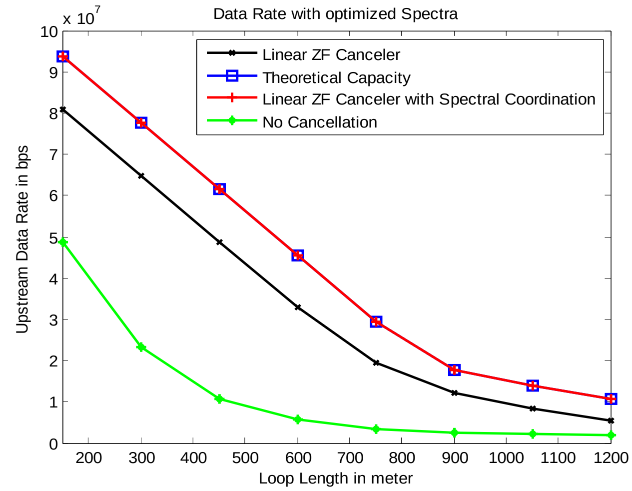

Figure.5. Data Rate with Optimized Spectra

VII. CONCLUSION

This dissertation investigated the design of crosstalk cancelers for upstream VDSL. Several non-linear crosstalk cancellers and pre-compensators suffer from high complexity and error propagation. The linear zero forcing canceller is a low complexity, low latency design, near optimal performance. The combination of spectral optimization and crosstalk cancellation was considered. Existing designs based on decision feedback suffer from error propagation, high complexity and long latency. A linear ZF canceler is proposed, which has a low complexity and no latency. An oft-cited problem with the ZF design is that it leads to severe noise enhancement in ill-conditioned channels. Fortunately VDSL channels with co-located receivers are column- wise diagonal dominant. This ensures that the VDSL channel is well conditioned, and noise enhancement caused by the ZF design is negligible. An upper bound on the capacity of the multi-user VDSL channel was derived. This single-user bound shows that spatial diversity in the VDSL environment is negligible. Therefore the result of this canceler is the complete suppression of crosstalk without noise enhancement. A lower bound on the performance of the linear ZF canceler was derived. This bound depends only on the binder size, direct channel gain and background noise for which reliable models exist. As a result the performance of the linear ZF canceler can be accurately predicted. This bound shows that the linear ZF canceler operates close to the single-user bound. The bounds were extended to VDSL systems with optimized spectra. Since the linear ZF canceler decouples transmission on each line, the spectrum on each modem can be optimized independently, leading to a significant reduction in complexity.

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