Throughput Improvement in Gigabit DSL Communications

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Abstract – **In this paper we propose a scheme for throughput improvement in Gigabit Digital Subscriber Line (GDSL) systems by Radio Frequency Interference (RFI) mitigation, using an Identification and Cancellation algorithm. The research shows that the GDSL link performance depends strongly on the parameters of the Multiple Input Multiple Output (MIMO) DSL system as well as on the RFI suppression algorithm efficiency.**

Keywords – **Gigabit DSL, GDSL, DMT, RFI, MIMO**

I. INTRODUCTION

The rapid growth of communication technologies, digital signal processing (DSP) and computational power of microprocessors have made possible today's Gigabit DSL communications, offering throughput of several Gigabits, using more than one twisted pairs in the telephone cables.

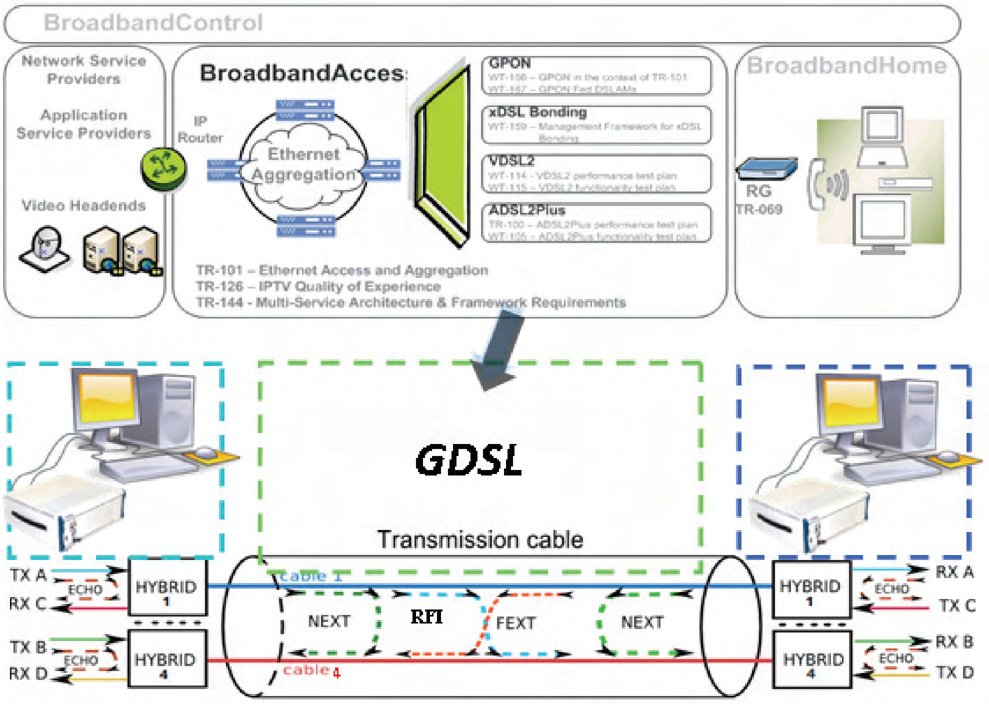

Fig. 1. Block diagram of MIMO DMT GDSL communication system

The multi-pair MIMO DSL vectored communication technology was originally proposed by Cioffi and Ginis [1, 2] in 2002. The method adopts common DSLAM equipment for all service providers in the Central Office, synchronised block transmission and Dynamic Spectrum Management algorithms. The theoretical studies prove that DSL loops can achieve data rates as high as 10 Gbps at 500 m using four twisted pair telephone cable, assuming DSLAM at both sides.

The Block Diagram of a GDSL communication system is presented on Figure 1.

Along with the methods typical for vectored DSL technology, GDSL benefits from Common Mode (CM) transmission due to its much lower attenuation. On the other side, in CM, the crosstalk disturbers are much stronger than in Differential Mode (DM). This phenomenon is utilized for transfer of additional information by applying appropriate precoding methods.

The transfer function of a MIMO DMT GDSL communication system can be described by the matrix equation [3]:

$$Y = HX + N \tag{1}$$

Where: **Y** is the output signal vector which components are the output signals of each twisted pair; **X** is the input signal vector which components are the inputs signals of each

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twisted pair; **H** is the transfer matrix of the MIMO DSL channel; **N** is the additive noise vector at the input of MIMO DSL channel, including AWGN, RFI, impulse noises. The crosstalk function between different wires, is included in the channel matrix **H**. Equation (1) is valid for each tone of the DMT symbol, therefore the tone index will be not be included in the analysis below.

In order to perform successful demodulation at the receiver, the channel transform matrix **H** of MIMO DSL channel must be known. Because of the physical nature of the cable cannel, it's assumed that the channel parameters are constant in time or vary slowly as a function of outside temperature. Therefore the MIMO cable channel parameters can be identified at the start-up initialization procedure.

GDSL DMT technology uses mainly the Common Mode transmission as shown on Figure 2 [2].

The matrix impedances $\mathbf{Z_L}$ and $\mathbf{Z_S}$ can have two main configurations: either both matrix impedances $\mathbf{Z_L}$ and $\mathbf{Z_S}$ to match the characteristic impedance matrix $\mathbf{Z_0}$ or the diagonal elements of $\mathbf{Z_L}$ and $\mathbf{Z_S}$ to match the diagonal elements of $\mathbf{Z_0}$.

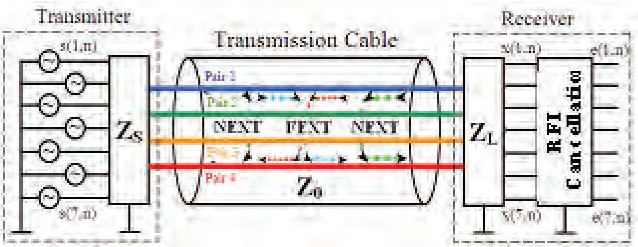


Fig. 2. MIMO GDSL Common Mode System Model [2]

The channel matrix **H** contains a frequency dependent transform function of the pair or wire at its main diagonal $T_{i,i}$ and a frequency dependent crosstalk transform function between pairs or wires. The channel matrix for Common Mode and Differential Mode in case of four twisted pairs can be written as:

$$H_{cm} = \begin{bmatrix} T_1 & FEXT_{12} & \cdots & FEXT_{16} & FEXT_{17} \\ FEXT_{21} & T_2 & \cdots & FEXT_{26} & FEXT_{27} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ FEXT_{61} & FEXT_{62} & \cdots & T_6 & FEXT_{67} \\ FEXT_{71} & FEXT_{72} & \cdots & FEXT_{76} & T_{77} \end{bmatrix} \quad (2)$$

Using Singular Value Decomposition (SVD) method, the cannel matrix **H** can be presented as [3]:

$$H(f) = U(f)S(f)V^*(f) \quad (3)$$

$$S(f) = diag\ (\lambda_1, \lambda_2, ..., \lambda_L) \quad (4)$$

Where: **U** and **V** are unitary matrixes and $\mathbf{UU^{-1}} = \mathbf{U^{-1}U} = \mathbf{VV^{-1}} = \mathbf{V^{-1}V} = \mathbf{I}$; $\mathbf{U^{-1}} = \mathbf{U^*}$; $\mathbf{V^{-1}} = \mathbf{V^*}$; L – number of twisted pairs; f – linear frequency and $f = n\Delta f$ for $n = 1,2,..., N_{sc}$; Δf – sub-tones bandwidth; λ_i – singular values of channel matrix per each tone. From equations (1-4) the input signal of the MIMO DMT receiver can be written as:

$$Y = U\ S\ V^* X + N \quad (5)$$

Multiplying (5) by $\mathbf{U^*}$ at left side, the received signal at the modem inputs is:

$$\tilde{Y} = S\ \tilde{X} + \tilde{N} \quad (6)$$

$$\tilde{y}_l = \lambda_l \tilde{x}_l + \tilde{n}_l, \qquad l = 1,2,..., L \quad (7)$$

$$\tilde{Y} = U^* Y; \quad \tilde{X} = V^* X; \quad \tilde{N} = U^* N \quad (8)$$

Equation (6) describes the MIMO DMT DSL system as a set of parallel scalar independent SISO DMT DSL communication systems. Consequently, the complexity of MIMO DMT GDSL system will be proportional to the complexity of L independent DMT DSL communication systems plus a little bit overhead due to the supervisor control algorithm and calculations required for matrixes: $\tilde{Y}$, $\tilde{X}$, $\tilde{N}$.

The Block Diagram in frequency domain of a single DMT DSL communication channel is presented on Figure 3 [2].

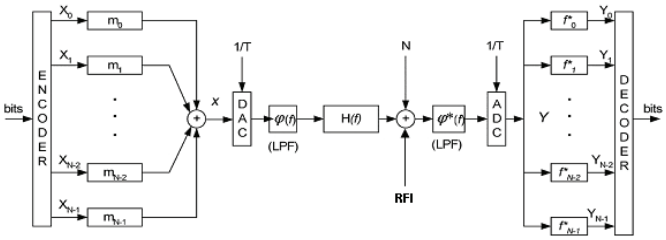


Fig. 3. Single scalar DMT DSL communication channel [2]

II. RFI CANCELLATION

The frequency identification and cancelation method is implemented as two phases algorithm. In the beginning of the first phase, the complex RFI frequency is estimated by finding maximum in oversampled signal spectrum [4]:

$$\omega_n = \arg(\omega) \in L_\infty \max(P_R(\omega)) \quad (9)$$

After this, the amplitude and phase estimation is done. The received sampled signal $r(k)$ can be expressed as:

$$r(k) = s(k) + n(k) + i_n(k) \quad (10)$$

The interference signal is defined as [4]:

$$i_n(k) = a_n \cos(\omega_n k / T) + jb_n \sin(\omega_n k / T) \quad (11)$$

On the basis of (11) a matrix form to represent the sampled interference can be used. In particular, it can be rewritten in matrix form as [4]:

$$I_n = MX \quad (12)$$

Where matrix ***M*** is defined as:

$$M = \begin{bmatrix} \cos(\omega_n k_1 / T) & j\sin(\omega_n k_1 / T) \\ \cos(\omega_n k_2 / T) & j\sin(\omega_n k_2 / T) \\ .... & .... \\ \cos(\omega_n k_N / T) & j\sin(\omega_n k_N / T) \end{bmatrix} \quad (13)$$

Vector ***X*** gathers the coefficients a_n and b_n:

$$X = \begin{bmatrix} a_n & b_n \end{bmatrix}^T \quad (14)$$

Applying Maximum Likelihood (ML) algorithm, the solution is given by [4]:

$$X = \left(M^T M\right)^{-1} M^T R \quad (15)$$

Where the input signal vector ***R*** is defined as:

$$R = \begin{bmatrix} r(k_1) & r(k_2) & .... & r(k_N) \end{bmatrix}^T \quad (16)$$

Thus the information about the complex amplitude of the RFI tone is derived.

The second phase of the algorithm uses the estimation results from the first phase, as initial conditions of NLS optimization procedure, applied to each scalar channel [4]:

$$f(\omega, A, \varphi) = \sum_{i=1}^{N} \left| r(t) - \sum_{m=1}^{M} A_m e^{j(\omega_m t + \varphi_m)} \right|^2 \qquad (17)$$

Here ω_m is the frequency of the m-th interfering tone and A_m and φ_m respectively are the amplitude and phase of the m-th interfering sinusoidal tone and M is the total number of interfering tones. The sum from 1 to N is referred to the N samples representing the sampled monocycle.

III. SIMULATION MODEL

To evaluate the performance of GDSL link, MATLAB simulations relative to the complex baseband presentation are conducted, assuming a typical MIMO DMT DSL receiver. The Channel Encoder is implemented as Convolutional Encoder with code rate: $R_C = 1/2$.The Interleaver – Deinterleaver is modeled as a permutation table random access algorithm. The Optimal Linear Precoder for complex signals is realized using the methods described in [2]. For the simulations, the number of used cable pairs is: $N = [1,2,3,4]$ and the corresponding number of MIMO inputs/outputs is: $K = 2N - 1$.The Digital Modulator is implemented as 8192-point Inverse Fast Fourier Transform (IFFT) process. The DMT symbol consists of up to 4096 tones. Each DMT data tone can use a different Grey encoded QAM modulation format which depends on the SNR of the data tone bandwidth. After the IFFT process, the prefix and suffix guard intervals are added.

The MIMO digital wire-line subscriber channel model is realized as given in [6].

$$y = H x + n + z \qquad (18)$$

Where: **y** is a $[K\times 1]$ output column vector whose components are the outputs of the individual transmission lines and **x** is a $[K\times 1]$ input column vector. In DM, the MIMO channel $[K\times K]$ transfer matrix **H** (typically constant or varying slowly with temperature) models the DSL cable test loop for common mode excitation, using the "ABCD" parameters block matrix [6, 7], **n** is a $[K\times 1]$ Complex Additive White Gaussian Noise (AWGN) column vector and **z** is a $[K\times 1]$ RFI column vector.

For the experiments, a 24-gauge cable segment (AWG 24) 300 m long, is chosen. The background noise with Power Spectrum Density (PSD) at -140 dBm/Hz is modeled as complex AWGN - $Nc(0,1)$.

By the time being, there is no globally accepted model for Common Mode transmission in twisted pair cables. In the proposed simulation model, the method for CM cable transfer function determination is realized by substituting the DM primary cable parameters [10, 11]:

$$R_C(f) = 0{,}55\, R(f)\,, \quad L_C(f) = 4{,}4\, L(f) \qquad (19)$$

$$G_C(f) = 2\, G(f)\,, \quad C_C(f) = 0{,}95\, C(f) \qquad (20)$$

Where: $R(f)$, $L(f)$, $G(f)$ and $C(f)$ are the frequency dependent primary DSL cable parameters in DM; $R_C(f)$, $L_C(f)$, $G_C(f)$ and $C_C(f)$ are frequency dependent primary DSL cable parameters in CM. Then, the CM MIMO DSL channel transform function can be written in a form [10]:

$$H_{CM} = H_{CM}^{D}\left(I + H_{CM\ NEXT} + H_{CM\ FEXT}\right) \qquad (21)$$

$$H_{CM\,NEXT_{m,n}}(f,L) = K_{NEXT}\, f^{3/2}\left(1 - C_{CM\,NEXT_{m,n}}(f,L)^4\right) \qquad (22)$$

$$H_{CM\,FEXT_{m,n}}(f,L) = K_{FEXT}\, f^{2}\left(1 - C_{CM\,FEXT_{m,n}}(f,L)^2\right) \qquad (23)$$

Where: $\mathbf{H^D_{CM}}$ is a $[2K\text{-}1\times 2K\text{-}1]$ diagonal matrix that contains the end to end complex line attenuations of $2K\text{-}1$ channels in CM, **I** is a $[2K\text{-}1\times 2K\text{-}1]$ identity matrix, $\mathbf{C_{CM\ NEXT}}$ and $\mathbf{C_{CM\ FEXT}}$ are $[2K\text{-}1\times 2K\text{-}1]$ "zero-diagonal" matrixes that reflect the NEXT and FEXT coupling in CM, L - the loop length and f - frequency. K_{NEXT} and K_{FEXT} are power normalization constants.

In the DMT Demodulator the guard prefix and suffix intervals are removed and 8192-point FFT is applied. Further, Frequency Domain Per-Tone Adaptive Channel Equalization and DMT demodulation are performed. Finally, OLP, 64-QAM demodulation and Error Correction Decoding are implemented.

IV. SIMULATION RESULTS

Using the above general simulation model of a MIMO Gigabit DSL system, different experiments have been performed, estimating the Bit Error Ratio (BER) and Throughput as a function of the Signal to Noise Ratio (SIR) and RFI presence. The RFI is modeled as a complex single tone, the frequency of which is located in the middle between two adjacent DMT tones. In respect of the number of used twisted pairs, four DSL systems are considered: Single Input Single Output (SISO) VDSL2 (1-pair), MIMO GDSL: 2, 3 and 4-pair. The DSL channels are subject to FEXT, NEXT and background AWGN with flat variable PSD.

In Figure 4 the complex MIMO DSL channel 24 AWG, 300 m long, without RFI suppression is considered. The background AWGN with Power Spectrum Density (PSD) at -140 dBm/Hz is considered. Unsurprisingly, 4-pair MIMO GDSL system achieves the best performance.

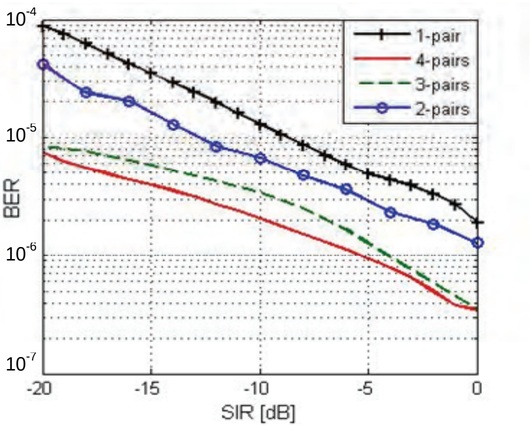
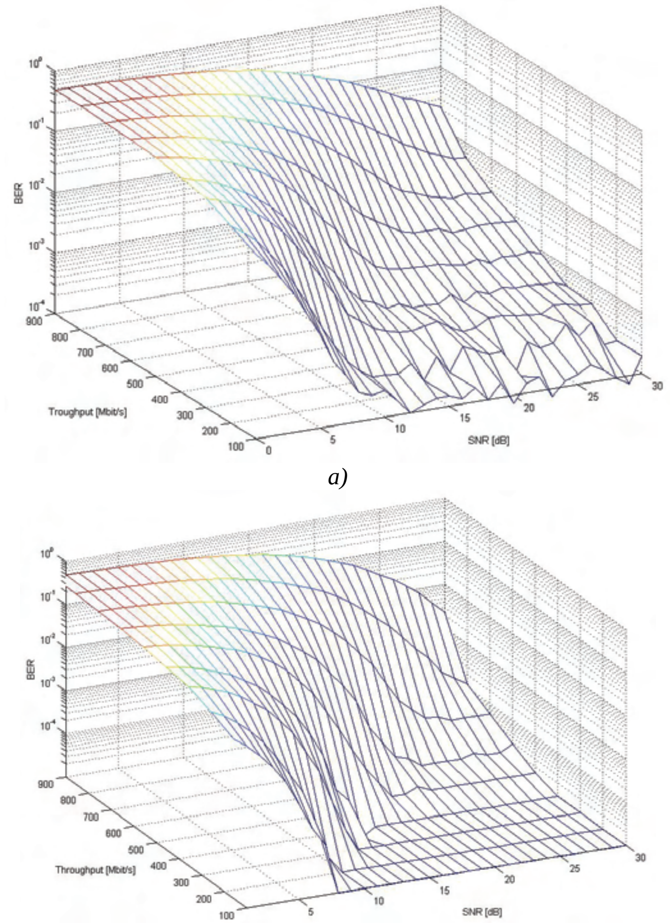


Fig. 4. BER as a function of SIR for GDSL

Figure 5 presents the relation between BER, Throughput and SNR for 4x4 MIMO GDSL DMT single user communication system: (a) – without RFI cancellation; (b) – with RFI cancellation.



a)

b)

Fig. 5. Relation between BER, Throughput and SNR for 4x4 MIMO GDSL DMT single user communication system for: SIR = -10dB, Cable 24 AWG, L = 300 m.

The GDSL system throughput as a function of SNR having:

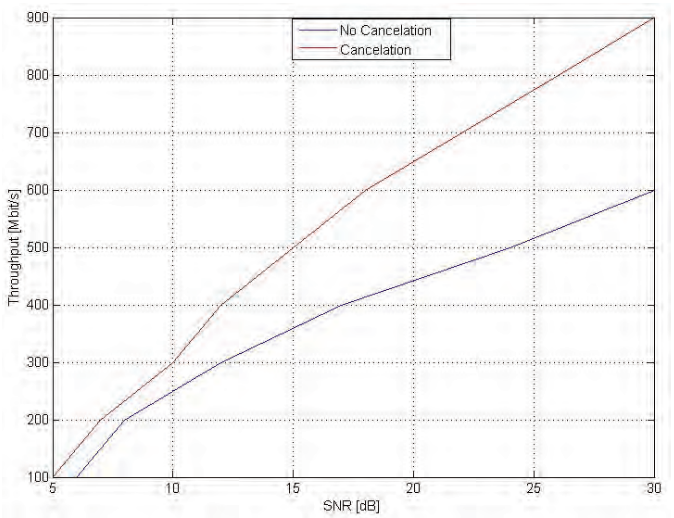


Fig. 6. Throughput as a function of SNR for 4x4 MIMO GDSL DMT single user communication system for: SIR = -10 dB, BER = 10^{-3}, Cable 24 AWG, L = 300 m.

RFI level fixed to SIR = -10 dB and BER fixed to BER = 10^{-3} is plotted in Figure 6. From the figure can be concluded that applying such a method of RFI cancellation leads to significant improvement in the throughput performance, up to a level where the system transmission speed is limited by the background AWGN.

V. CONCLUSIONS

In this paper a method for throughput improvement in MIMO Gigabit DSL DMT communication systems, using RFI filtering via frequency identification and cancellation, is proposed. Analyzed are the relations between BER and Throughput as a function of SNR for two cases: with and without RFI cancellation. The experimental results bring forward the significant improvement of GDSL link performance when applying such a RFI cancellation.

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