SIMULATOR OF ADSL PHYSICAL LAYER

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Abstract

This paper presents simulation results accomplished within ADSL toolbox, which was developed in our institute. The toolbox simulates physical layer of ADSL communication chain, where the main efforts are given to equalization techniques at receiver, proper channel partitioning at transmitter and channel modeling.

Equalization efforts consist in time domain algorithms and appropriate filters - time domain equalizers (TEQ). Evaluation of TEQs is presented as a bit error ratio (BER) as function of SNR.

Bit-loading (partitioning) of the channel at transmitter is also important for optimal utilization and achievement of higher data-rates. Water-filling bit-load method, we use, is discussed and compared to other simpler methods.

Last part of this paper present ADSL channel model based on measurements of real metallic cable (binder).

1 Introduction

During last few years the development of the technology in the domain of computer science, communication and signal processing was a key enabling factor resulting in the widespread of broadband data communication systems. Recently, more and more broadband communication standards use OFDM type of modulation (DVB-T, DVR, IEEE 802.16, WiMax, ADSL2+, VDSL etc.). The reason is, that OFDM effectively use the wide frequency band and the relative simplicity receiver design.

Asymmetric digital subscriber line (ADSL) systems are wire-line based and using discrete multi-tone modulation (DMT). The crucial task of such systems is restoration of degraded signal at receiver modem. ADSL modems equalize response of line (channel) to fight with interferences and line dispersion, which down the bit-rate of transmission. Main equalization principle is “Channel shortening”, which is the base for time domain equalizers (TEQ). Channel shortening means that the effective channel response, composed of channel response and equalization filter, is to be shortened to length of cyclic prefix [2].

Optimal utilization of the channel demands bit-loading methods, which examine channel properties in per-tone sense. Such a methods stand on water-filling principle, which examines per-tone SNR and results in per-tone number of bits and energy levels that should be optimally used. Along with examining properties of implemented rate adaptive water-filling (RA-water-filling) several discussions about results came up. Resulting error ratios have shown that the RA-water-filling tends to overestimate channel capacity. With these findings a custom bit-load correction was applied to algorithm.

Integral part of a communication system model is properly designed channel model. Developed toolbox allows to choose simplified channel model, where the far-end and near-end cross-talks (FEXT, NEXT) are simulated by spectrally shaped noise. Second choice offers a channel model, which was created of true characteristics (transfer and crosstalk) measured on real metallic cable (binder). These measurements was provided by Department of telecommunication engineering at CTU Prague. Considering computational complexity, it has been decided to develop a peripheral accelerator of the channel.

1.1 Water-filling

Within initialization of ADSL connection, channel partitioning (bit-loading) is done. Water-filling algorithm examines per-tone SNR and result in per-tone number of bits and energy levels that should be optimally used.

Generally for multi-tone, the optimum water-filling transmit energies then satisfy ([4]):

$$\mathcal{E}_n + \Gamma \cdot \frac{\sigma_n^2}{|H_n|^2} = \text{constant} \tag{1}$$

for each tone n,
where $\mathcal{E}_n$ is the per-tone energy, σ_n^2 and $|H_n|^2$ are power spectral densities of noise and channel, Γ is the SNR gap.

Such a condition (1) leads to a set of linear equations with boundary constraints.

There are two types of loading algorithms - those that try to maximize data rate and those that try to maximize performance at a given fixed data rate. The first one, Rate-Adaptive loading criterion, maximizes (or approximately maximizes) the number of bits per symbol subject to a fixed energy constraint:

$$\max_{\mathcal{E}_n} b = \sum_{n=1}^{N} \frac{1}{2} \left(1 + \frac{\mathcal{E}_n \cdot \ g_n}{\Gamma} \right) \tag{2}$$

$$\text{subject to:} \quad N\bar{\mathcal{E}}_x = \sum_{n=1}^{N} \mathcal{E}_n \tag{3}$$

where $g_n = \frac{|H_n|^2}{\sigma_n^2}$.

As noted above, the solution lead to a set of linear equations. The set of equations to solve has form of (4), where are $\mathrm{N}+1$ equations that have $\mathrm{N}+1$ unknowns, which are the energies $\mathcal{E}_n$ and the constant. Solution is then found recursively [4].

$$\begin{aligned} \mathcal{E}_1 + \Gamma/g_1 &= K \\ \mathcal{E}_2 + \Gamma/g_2 &= K \\ \vdots &= \vdots \\ \mathcal{E}_N + \Gamma/g_N &= K \\ \mathcal{E}_1 + \ldots + \mathcal{E}_N &= N\bar{\mathcal{E}}_x \end{aligned} \tag{4}$$

Example bit-load of channel provided by RA-water-filling is shown on figure 1. Selected CSA loop #3 (see sec. Channel model) has several taps and thus bit-load respects this property, where the effect dominates at higher tones.

2 Simulation results

All the equalizer algorithms, we had implemented, were tested within our toolbox. Set of implemented algorithms include: MMSE Unit energy constraint (UEC), MMSE Unit tap constraint (UTC), Maximum Shortenig SNR (MSSNR), Minimum Intersymbol Interference (MinISI), Maximum Bitrate (MBR), Maximum Geometric SNR (MGSNR), Minimum Delay Spread (MDS) and Carrier nulling Algorithm (CNA). An example simulation results are presented on next figures. Figures 2a and 2b show results for reference channel loop "CSA #6". Figures 3a and 3b show results for reference channel loop "CSA #3".

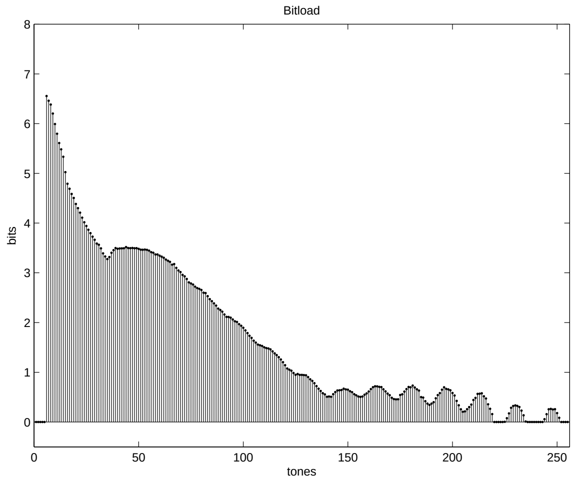

Figure 1: Bit-loading example with water-filling (SNR=45dB, CSA loop #3, lower 10 tones unused)

Simulation conditions common for both reference loops were:

- Random user data was given by normally distributed random sequence which were partitioned to 500 of different data symbols.
- Channel noise was shaped type according to noise profile A (see sec. Channel model).
- SNR of transmitted signal and added noise was set in range from 30 to 90dB.
- Each simulation for particular equalizer and SNR was repeated ten-times to reach some statistical independence.
- Bit-loading was computed for each channel loop with the bit-load correction (see below). Each carrier had the capability to carry up to 11 bits, i.e. up to 2048-QAM could be used on each carrier.
- Lower band of twenty carriers was left unused as ISDN/POTS band. Total number of usable carriers was then 235.
- Dimension of FFT in DMT (de)modulator was 512. Length of cyclic prefix was 40 samples long, i.e. each symbol was 552 samples long.
- Lengths of equalizer filter TEQ and target impulse response TIR were set to 32. System delay could vary from 3 to 39 samples.

Both figures on the left side (2a and 3a) show a bit-rates which were achieved by RA-water-filling with our customized bit-loading correction for given channel loop. Figures on the right (2b and 3b) show the graphs of bit-error ratio established for varied SNR.

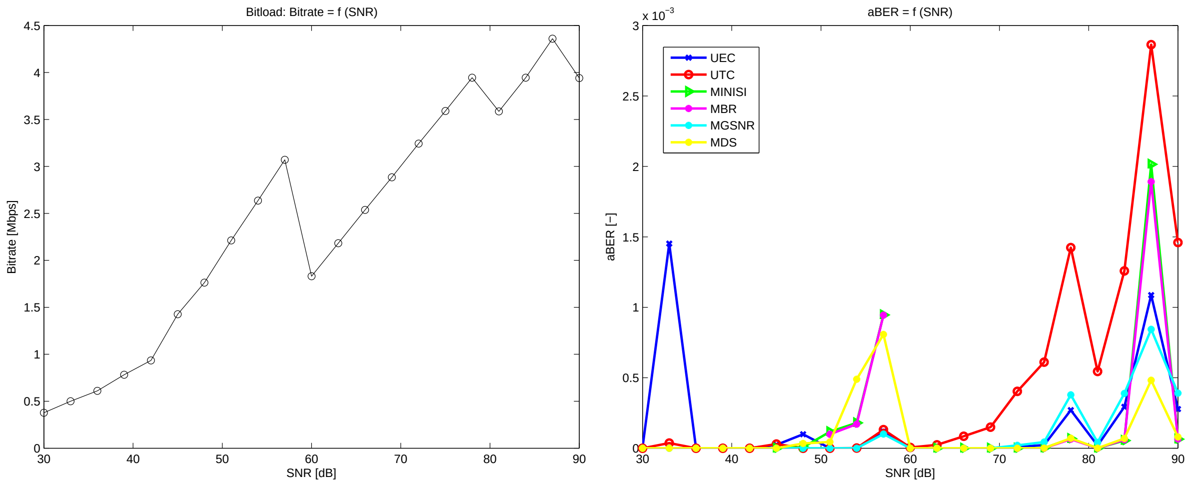

Figure 2: Example simulation results for CSA #6: a) achieved bit-rates for given SNR, b) average system bit-error ratios for given SNR

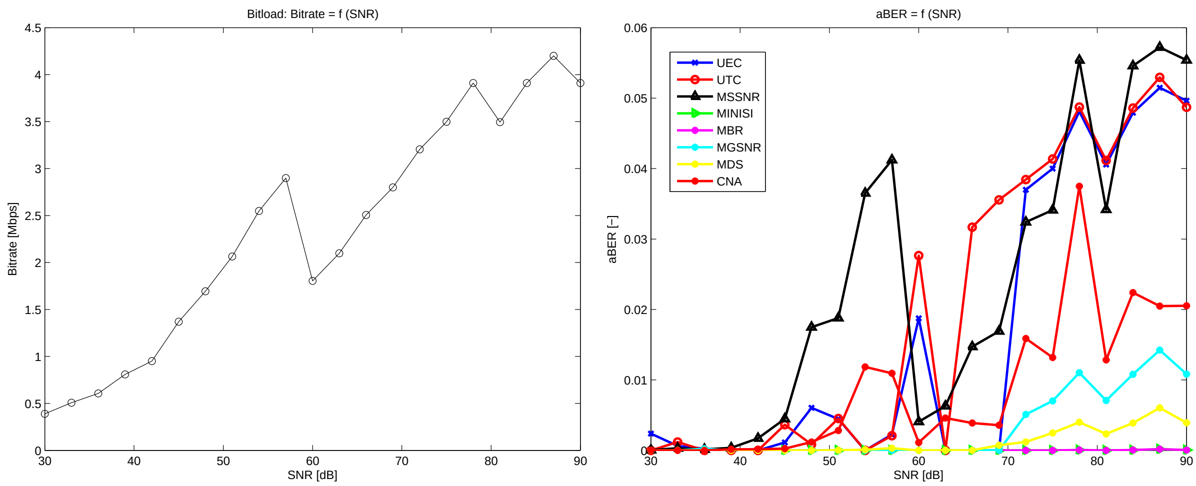

Figure 3: Example simulation results for CSA #3: a) achieved bit-rates for given SNR, b) average system bit-error ratios for given SNR

2.1 Bit-load correction

Since the water-filling has tendency to overestimate channel capabilities, we proposed experimental bit-load correction. The correction, simply, lower the bit-load towards to higher SNR. Such a correction holds resulting error ratios in useful range of values. Obviously, lowering the bit-load cause some twists on relation between achieved data-rates and given SNR. The correction is shown on figure 4.

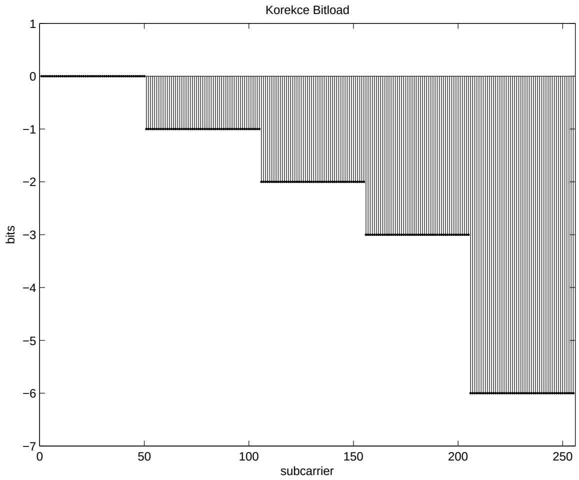

Figure 4: Bit-load correction applied on water-filling results

2.2 Comparison to other bit-loading algorithms

In effort to compare water-filling results, we made simulations with two other bit-loading algorithms. Both algorithms have been configured in order to achieve bit-rate approximately 5 Mbps and with respect to ISDN/POTS lower 20 tones have left unused.

The first bit-load has decreasing stairs-like character (fig. 5a), maximum number of bits per-tone is $b_n = 11$, achieved bit-rate is 5.02 Mbps. Other bit-load is simply flat with bit configuration $b_n = 6$ constant and achieves bit-rate 5.26 Mbps. Resulting error ratios for mentioned bit-loads are shown on figures 6a and 6b. Stairs-like bit-load respects channel property in way of decreasing bit-load with growing frequency, thus its error ratios resulted lower than the flat bit-load case.

Finally, table 1 presents the listing of achieved error ratios for RA-water-filling with correction, decreasing stairs and flat bit-load.

TEQ alg.	Bit-load type					
	water-filling		stairs		flat	
	CSA #6	CSA #3	CSA #6	CSA #3	CSA #6	CSA #3
	BER [-]	BER [-]	BER [-]	BER [-]	BER [-]	BER [-]
UEC	2.7E−04	0.05	5.1E−03	0.06	0.04	0.06
UTC	1.5E−03	0.05	8.5E−03	0.06	0.04	0.06
MSSNR	0.1	0.06	0.1	0.13	0.08	0.1
MinISI	6.4E−05	4.6E−05	4.5E−03	1.2E−03	0.04	0.05
MBR	6.5E−05	4.6E−05	4.5E−03	1.2E−03	0.04	0.05
MGSNR	3.9E−04	0.01	3.1E−03	0.02	0.04	0.05
MDS	8.0E−05	3.9E−03	5.9E−03	0.01	0.04	0.05
CNA	0.03	0.02	0.05	0.05	0.06	0.06

Table 1: Comparison of bit-loading algorithms, average error ratios for SNR $=$ 90 dB.

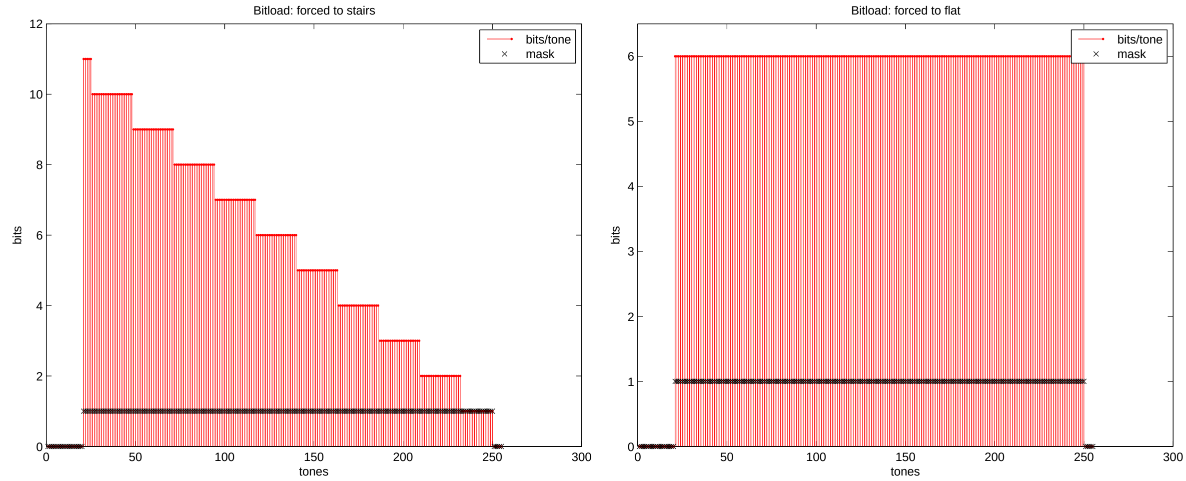

Figure 5: Bit-load forced to: a) decreasing stairs: max. $\mathrm{b_n} = 11$, b) flat: $\mathrm{b_n} = 6$

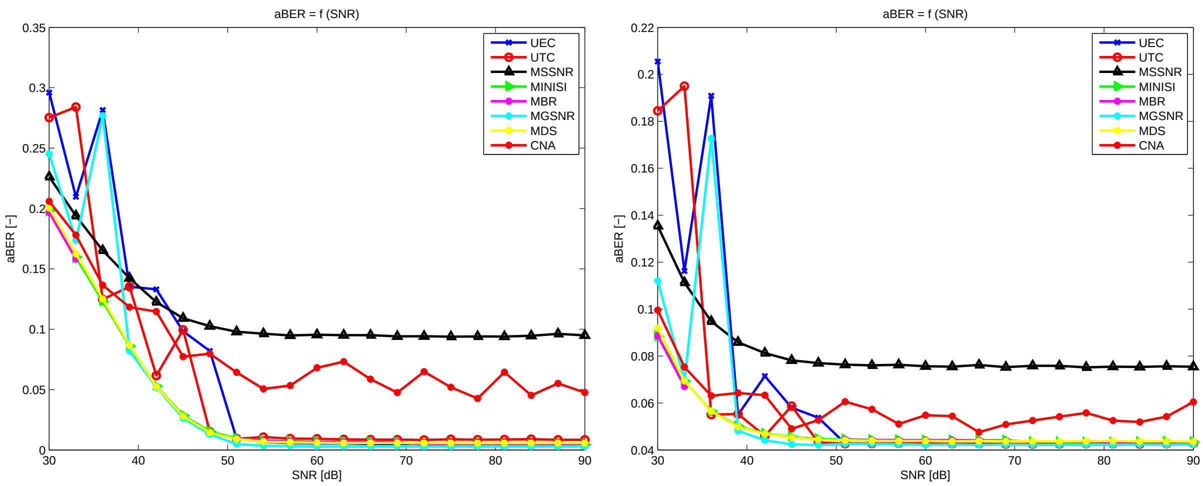

Figure 6: Resulting BERs for CSA #6 forced bit-load: a) decreasing stairs: max. $\mathrm{b_n} = 11$, b) flat: $\mathrm{b_n} = 6$

3 Channel model

Integral part of toolbox are proper channel models. The first, simplified, model use reference CSA# loops as channel response. These reference loops are recommended by ITU-T ADSL standards [3]. Noise added to channel could be modeled by white gaussian noise or spectrally shaped noise profile based on modeling of xDSL trunks [1]. This model (fig. 7) was generated with following setup: ADSL2+ over ISDN, frequency division duplex, interference profile type A. Near-end and far-end cross-talks (NEXT, FEXT) are simulated by the same noise models in this case.

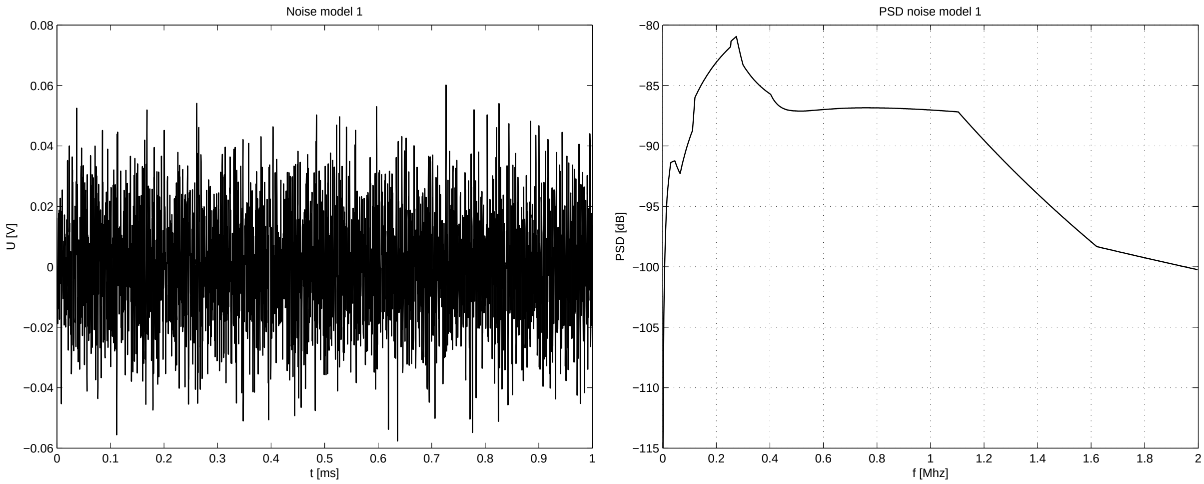

Figure 7: Noise model - spectrally shaped profile

More advanced model was created of true characteristics (transfer and crosstalk) measured on real metallic ADSL cable (binder). The cable has the following parameters:

- cable type: TCEPKPFLE 25 x 4 x 0,4
- 50 twisted pairs
- length = 400m ($\approx 1300\,$ft)

Attenuation of each pair was measured up to 34.5 MHz with frequency step equal to four DMT tones $f_{step} = 4 \cdot 4.3125\,$kHz. Coupling between different pairs was also measured within equal range of frequencies. These measurements led to total amount of 1275 characteristics. With regards to ADSL toolbox, all characteristics were interpolated to frequency step equal to one DMT tone 4.3125 kHz and bandwidth was taken only up to approximately 8.8 MHz. Interpolation was done in frequency domain and interpolation FIR filter optimized by `intfilt` function was used. Also the impulse responses were enumerated for time domain analysis using inverse FFT. Example characteristics are depicted below, figure 8. shows magnitude of a pair and its channel response, figure 9. shows coupling between a pairs and corresponding impulse response. Model, we use in toolbox, takes the first 2048 tones ($\approx 8.8\,$MHz) of each magnitude and 256 useful samples of each impulse responses.

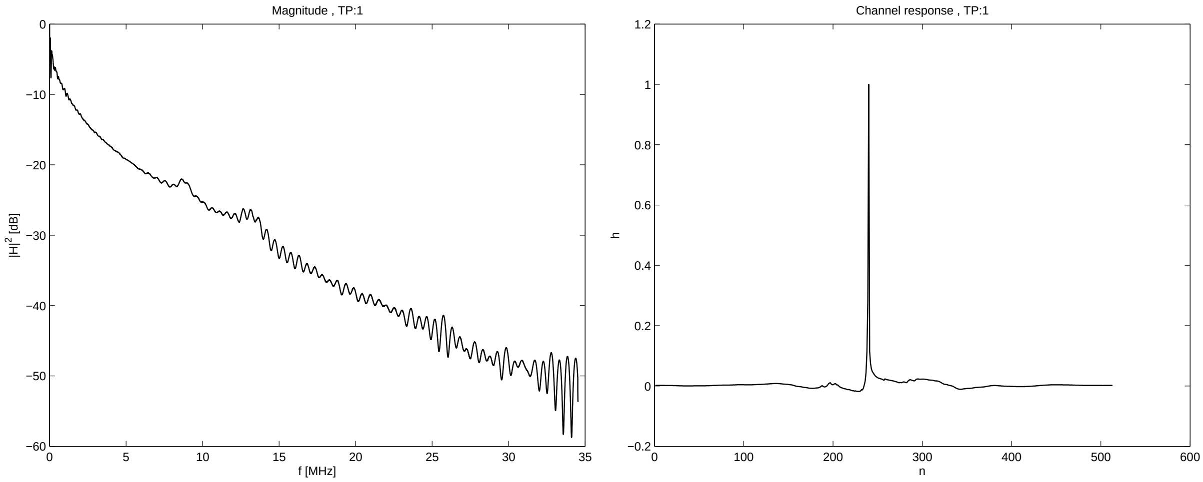

Figure 8: Magnitude and channel response of pair No.: 1

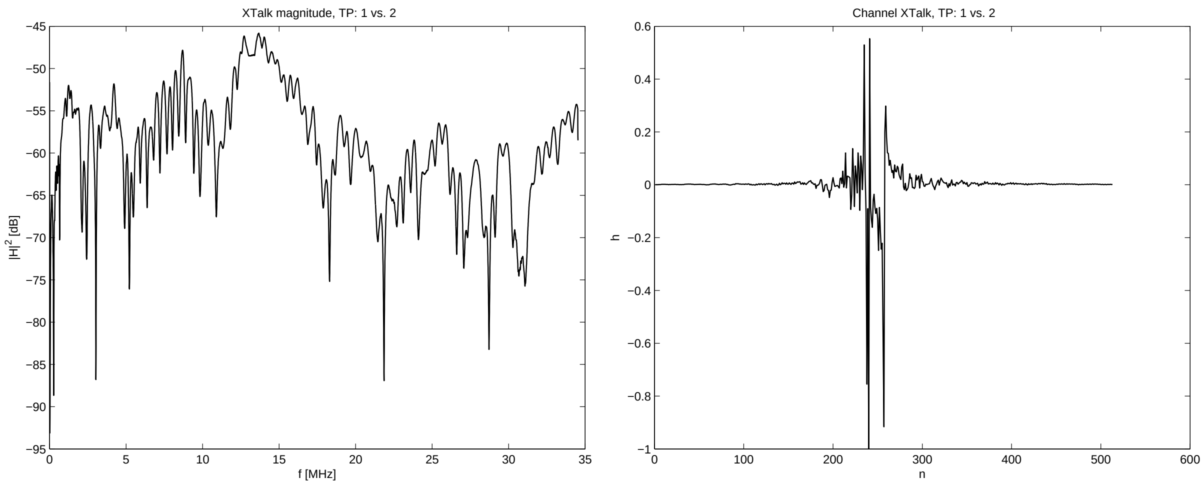

Figure 9: Coupling magnitude and impulse response, pair No.: 1 vs. 2

3.1 Hardware accelerator

Considering computational complexity and amount of coupling twisted pairs, it has been decided to develop a peripheral accelerator, which should relieve the load of simulation environment.

The accelerator will be FPGA based peripheral connected through serial bus (USB 2.0). Since ADSL communication resolves frames/symbols, the accelerator should operate in frame mode too. Equalization algorithms suggest two-stage functionality: setup and computation. Setup will manage loading of all transfer and coupling functions, while computation stage will enumerate desired transfers and cross-talks of selected users for each incoming data frame.

Computational complexity graduate with involved groups of neighbouring users. It's assumed that there should be allowed configurations which involve smaller groups of users. Computational mode involving all fifty users at binder is the most accurate and also the highest complexity mode. Next, we have chosen groups of four and sixteen neighbouring users, in order to manage lower complexity simulations for testing purposes.

4 Conclusions

Bit-loading algorithm has a significant influence on bit-error ratio (BER). Bit-load correction serves as a little aid to achieve better results. Its usage is more suitable than re-evaluation of transmission gap in experimental background. Lowering the bit-load cause some twists on relation between achieved data-rates and given SNR, this side effect can be seen on figures 2a and 3a.

According to table 1., resulted error ratios confirms that the water-filling algorithm finds satisfying optimum for bit-load. Flat bit-load leads to the worst results because it doesn't respect channel's natural property of decreasing capacity with higher frequency.

New channel model allows to enumerate real cross-talks between channels and also implies efforts on multi-user optimizations. Multi-user view of ADSL system, where provider parts are centralized, led our efforts to methods close to wireless MIMO problems.

Acknowledgements

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References

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