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ENVIRONMENTAL INFLUENCES ON THE POWER SPECTRAL DENSITIES OF VDSL SIGNALS

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For successful analyzing of the VDSL transmission on metallic homogeneous symmetric lines, it is necessary to know basic features of the VDSL environment. This article introduces characteristics of the VDSL environment and shortly discusses duplex methods and proposed modulation techniques. In addition, particular service types of VDSL transmission rates and spectral characteristics of the VDSL signals together with demands on VDSL frequency spectrum allocations are presented. The main part of the article is focused on modeling of the VDSL environment and on analyzing of environmental influences on the power spectral densities of VDSL signals, especially in the access network in Slovakia. The results of this our modeling are used in a following detailed analysis of the VDSL system performance.

Keywords: the VDSL environment, VDSL transmission rates, the VDSL frequency spectrum, the power spectral density of the VDSL signal

1 INTRODUCTION

With a progress in telecommunication access networks, a great attention is dedicated to technologies that can achieve a broadband data communication delivering to common customers. In present days, a large growth of Internet services is arising and a market of potential customers for high-speed data transmissions is increasing. From viewpoint of a total number of potential customers and a rate of deployments, the xDSL technologies seem to be as the most advantageous from a variety of access technologies.

In the Slovak Republic, the HDSL (High-speed Digital Subscriber Line) technology is utilizing already many years and the ADSL (Asymmetric Digital Subscriber Line) technology is just emerging in practice. In this paper, we focus on the VDSL (Very high-speed Digital Subscriber Line) technology [1]. The VDSL technology can be considered as a final evolution step of xDSL modems that will provide maximum transmission rates at minimum possible costs to customers. The VDSL system is designed for providing a choice between symmetric and asymmetric services. It is necessary to highlight that a standardization process for the VDSL is not finished. Producers of VDSL modems are formed into two associations. First — VDSL Alliance — asserts as a basic modulation scheme the DMT (Discrete Multitone) modulation. Second — VDSL Coalition — asserts as a basic modulation scheme the CAP (Carrierless Amplitude/Phase) modulation. Into the VDSL standardization process, a group of operators — FSAN (Full Services Access Network) — is also included. For the VDSL, technical specifications and recommendations are published by standardization organizations ETSI, ANSI and ITU. In our analysis, we are coming out from specifications issued by ETSI [2], [3] and DSL Forum [4].

2 THEORETICAL PART

2.1 Characteristics of the VDSL environment

The VDSL environment on metallic homogeneous symmetric lines is influenced by several additive noise components, including an electronic noise (generally white), a crosstalk coupled from adjacent loops in the cable bundle between the customer premises and the central office (usually non-white) and a residual echo noise remaining after any echo cancellations.

The simplest case of the noise is the additional white Gaussian noise (AWGN) with the fixed standard level $\sigma_1^2 = -140$ dBm/Hz. In our analysis, we use the increased level for the AWGN $\sigma_2^2 = N_0/2 = -110$ dBm/Hz. The crosstalk is a case of the noise that arises from the electromagnetic coupling of signals in various transmission paths where both pairs — the first pair (disturbing) and the second pair (disturbed) of lines — are situated in the same telephone cable bundle. At the information signal transport, we distinguish two types of crosstalks:

- the near-end crosstalk (NEXT) — the NEXT transmission path can be modeled using its transmission function $\mathcal{H}_{NEXT}$ in the form
$$|\mathcal{H}_{NEXT}(f)|^2 = K_{NEXT} \cdot f^{3/2} \tag{1}$$
where $K_{NEXT} = 0.882 \times 10^{-14} N_d^{0.6}$ and N_d is the number of disturbing pairs (disturbers).
- the far-end crosstalk (FEXT) — the FEXT transmission path can be modeled using its transmission function $\mathcal{H}_{FEXT}$ in the form
$$|\mathcal{H}_{FEXT}(f)|^2 = K_{FEXT} \cdot l \cdot 3280 \cdot f^2 \cdot ||H_C(f)|^2 \tag{2}$$

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Table 1. Frequency allocations with the maximum utilization of the SCM subbands

Subbands	Symbol rate R_S (Mbaud)	Carrier frequency f_C (MHz)	Lowest frequency f_{LOW} (MHz)	Highest frequency f_{HIGH} (MHz)
1D f_1–f_2	2.16	2.2275	0.93	3.52
2D f_3–f_4	2.16	6.885	5.59	8.18
1U f_2–f_3	0.945	4.5225	3.96	5.09
2U f_4–f_5	2.16	10.53	9.23	11.83

where $K_{FEXT} = 3.083\times10^{-20}$ and l is the line length in km.

From the analysis of frequency characteristics of the white noise, both types of the crosstalks and their combinations for the homogeneous symmetric lines introduced in [5], it is clearly to see that the largest noise power contains the NEXT crosstalk and, in the comparison with it, AWGN and FEXT noise powers are neglected. Moreover, the noise power of the FEXT crosstalk for longer line lengths is expressively decreased.

Except influences of the white noise and both types of the crosstalks, homogeneous symmetric lines transmitting information signals at very high-speed rates by means of xDSL technologies are also affected by impulse noises. The influence of impulse noises on the performance of xDSL systems in the environment of metallic lines is a content of another study that calls for a construction of other mathematical techniques and simulation methods. Another part of the noise in the VDSL environment can be created by the radio frequency interference (RFI). This type of the noise is involved in our analysis by using of appropriate spectral masks. For more information, solving of the RFI issue is introduced in the work [6].

In our analysis, the NEXT crosstalk is not considered because this one can disable a communication in the VDSL frequency bandwidth. For avoiding the NEXT influence in the VDSL signal transmission, the FDD or TDD duplex methods can be used [7]. A duplex method determines how the overall throughput of the channel path is shared between two directions of the transmission and how the asymmetry ratio is achieved by the ratio of upstream and downstream data rates. If the same frequency bands are used simultaneously for both directions, the available VDSL capacity will be heavily affected by the NEXT crosstalk resulting from VDSL modems operating in neighboring pairs. There exist two main fundamental duplex principles for avoiding the NEXT influence.

If upstream and downstream transmissions are partitioned in time, the entire frequency band can be used in both directions in separate time epochs. When all upstream/downstream transmissions within a cable binder are time-synchronized, the NEXT influence is avoided. This particular duplex method is called the time-division duplex (TDD).

The other fundamental method is the frequency-division duplex (FDD). In the FDD, the NEXT is avoided via a division of the available spectrum in distinct frequency bands where each band is used uniquely for either upstream or downstream transmissions. This requires that all systems in the same binder use the same frequency plan.

For calculating transmission functions of homogeneous lines and for describing characteristic features of the AWGN noise and the FEXT crosstalk, we use relationships that are introduced in [5] adjusted for the VDSL environment.

Proposed modulation techniques for the VDSL system can be divided into 2 main groups. A singlecarrier modulation (SCM) group introduces above all the CAP/QAM combination. A ground is using only one carrier frequency. Allowable bandwidth is divided into 4 subbands restricted for particular directions of transmission. A multicarrier modulation (MCM) group is creating from various variations of the DMT modulations in synchronous or asynchronous versions, respectively the DWMT (Discrete Wavelet Multitone) modulation. In this case, allowable frequency bandwidth is divided into a large number of subchannels (minimally 256) that are processing in a digital area.

For particular SCM subbands and MCM subchannels, the signal-to-noise ratio (SNR) can be determined based on known parameters — a power spectral density (PSD) of the VDSL signals, a transmission function of the transmission channel and frequency characteristics of the AWGN noise and the FEXT crosstalk. In our analysis, we are also using a linear equalization (LE) process by a reason of eliminating influences of the intersymbol interference (ISI). The power level of the VDSL signal can be acquired by integrating of its PSD characteristic at the end of the transmission path, respectively of its PSD characteristic adjusted by the correction. For each established subband in the SCM, limits of the integral present values of highest and lowest frequencies (Tab. 1) [3]. For each subchannel n in the MCM, the interval of frequencies is allocated between $\langle n\cdot\Delta f, (n+1)\cdot\Delta f\rangle$, where $\Delta f = 4.3125\,\text{kHz}$ is the DMT subchannel bandwidth. The power level of noises can be calculating by integrating of the AWGN noise and the FEXT crosstalk power spectral characteristics for the given frequency area. If the received VDSL signal is adjusted by the correction, also noise characteristics must be adjusted.

Table 2. Transmission rates in dependence on the reach defined by ETSI

Service type	Downstream transmission rates (Mbit/s)	Upstream transmission rates (Mbit/s)	Reach in the best and in the worst case (PSD with apertures) (m)	Reach in the best and in the worst case (PSD without apertures) (m)
Asymmetric (A4)	23.268	4.096	894/453	995/534
Asymmetric (A3)	14.464	3.072	1294/729	1344/820
Asymmetric (A2)	8.576	2.048	1592/789	1691/882
Asymmetric (A1)	6.4	2.048	1689/843	1791/936
Symmetric (S5)	28.288	28.288	Not available	298/212
Symmetric (S4)	23.168	23.168	Not available	397/261
Symmetric (S3)	14.464	14.464	796/580	845/575
Symmetric (S2)	8.576	8.576	1245/820	1294/820
Symmetric (S1)	6.4	6.4	1392/881	1444/876

Table 3. Transmission rates in dependence on the reach defined by ANSI

Service type	Downstream transmission rates (Mbit/s)	Upstream transmission rates (Mbit/s)	Reach (m)
Asymmetric short	52	6.4	300
Asymmetric short	38.2	4.3	300
Asymmetric short	34	4.3	300
Asymmetric medium	26	3.2	1000
Asymmetric medium	19	2.3	1000
Asymmetric long	13	1.6	1500
Asymmetric long	6.5	1.6	2000
Asymmetric long	6.5	0.8	2000
Symmetric short	34	34	300
Symmetric short	26	26	300
Symmetric short	19	19	300
Symmetric medium	13	13	1000
Symmetric long	6.5	6.5	1500
Symmetric long	4.3	4.3	1500
Symmetric long	2.3	2.3	1500

2.2 Characteristics of VDSL transmission rates

A difference between the VDSL modem and other xDSL modems is mainly defined in providing of extremely high-speed transmission rates. Transmission rates in dependence on the reach defined by ETSI [2], [3] distributed according to service types are shown in Tab. 2. The ANSI T1 commission proposed bit rate groups also based on the line lengths (short, medium and long). For every defined line length, there are also distinguishable symmetric and asymmetric traffic modes. Proposed transmission rates in dependence on the reach defined by ANSI [4] are shown in Tab. 3.

2.3 Spectral characteristics of the VDSL signals

The VDSL modem uses a frequency bandwidth up to 20 MHz. From this reason, the VDSL transmitter must solve situations that are not emergent in other xDSL modems. To these problems belong a spectral compatibility and cooperation with installed xDSL systems and a high level of different crosstalks.

In VDSL modems, various types of duplex methods and proposed modulation techniques are considered in [7], [8] and [9]. The ETSI recommendation binds producers to keep an established frequency plan [2]. The VDSL system can work in a frequency band bounded by frequencies f_{LOW} and f_{HIGH} (Fig. 1). In this band, the power of the VDSL signal must be adjusted to a level that can ensure the spectral compatibility with older xDSL systems (BA ISDN, HDSL and ADSL). Alike, the signal level must be decreased in given frequency areas to obviate undesirable emissions (RFI), concretely caused by amateur radio stations.

The lower frequency f_{LOW} is given by the spectral compatibility with narrowband services POTS and BA ISDN. The VDSL frequency plan depends on installation variations, on crosstalks from different sources and on the existence of narrowband services. Therefore, PSD masks of the VDSL signal are defined on the base of specific criteria. By [2], we can discriminate between the VDSL deployment with or without the existence of narrowband services in the same cable and with or without the possibility for creating frequency apertures. The FTTEx variation seems to be the most probably variation of the VDSL deployment scenario where the line termination transceiver is placed in the central office exchange. Therefore, in our analysis, we used the FTTEx power spectral density mask. A graphical representation of the selected variation is shown in Fig. 2. If necessary, it is possible to assign any other standard spectral mask for the considered VDSL signal.

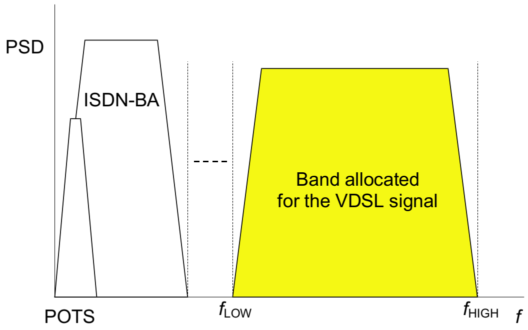

Fig. 1. The general frequency plan for the VDSL system

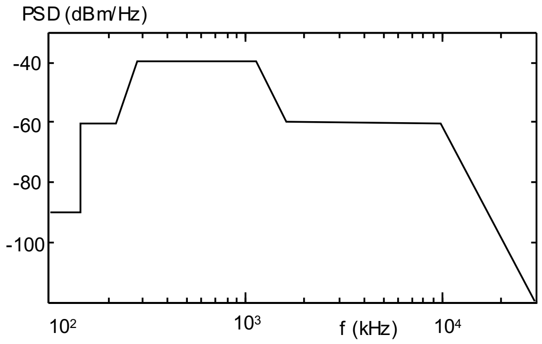

Fig. 2. The PSD mask of the VDSL signal for the FTTEx variation with narrowband services and the ADSL presence

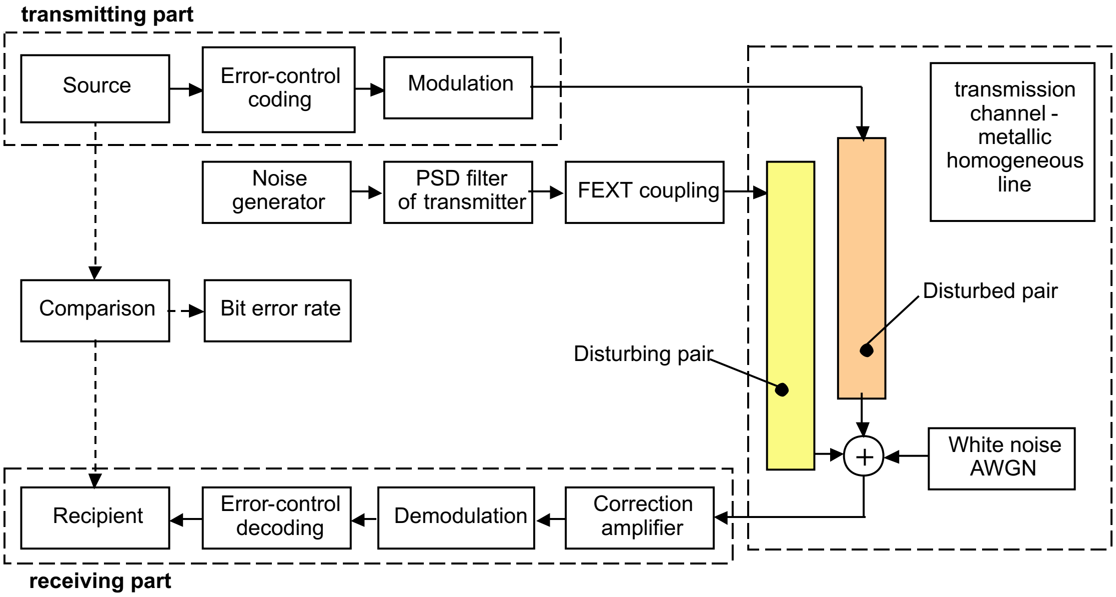

Fig. 3. The block scheme of the VDSL simulation model

3 EXPERIMENTAL PART

3.1 Modeling of the VDSL environment and a basic scheme of the model

For considering of the signal transmission on metallic homogeneous lines by means of the VDSL technology, it is necessary comprehensively to know characteristics of negative environmental influences and features of applied modulation techniques. It is difficult to realize the exact analytical description of complex systems such as the VDSL system in the real environment of local access networks. In addition, due to dynamical natures of some processes, it is not suitable. For analyzing of various signal processing techniques used by the VDSL technologies, a suitable and flexible enough tool are computer simulations and modeling schemes of real environmental conditions at the signal transmission.

For our modeling of the transmission path, we used the software program *Matlab* v5.3 together with the dynamic system simulation environment *Simulink* 3.0. *Matlab* is a powerful collection of tools for an algorithm development, computation and visualization. It provides more control and flexibility compared to a traditional high-level programming language and is based on fields and matrixes equipped with many functions for program-run controlling and data structures processing. From additional libraries *Signal Processing Toolbox* 4.2 and *Communication Toolbox* 1.4, functions for signal processing were utilized [11].

A proposed and realized modeling scheme represents a transmission of high-speed data signals in the downstream or in the upstream directions by means of the VDSL technology utilizing of metallic homogeneous lines. This model was based on the ADSL simulation model introduced in [10]. Basic functional blocks realized in our simulation model are shown in Fig. 3. The VDSL simulation model can be divided into three main parts — a transmitter, an environment of a transmission channel and a receiver. The transmitter is primarily responsible for the transmitted data protection and for the modu-

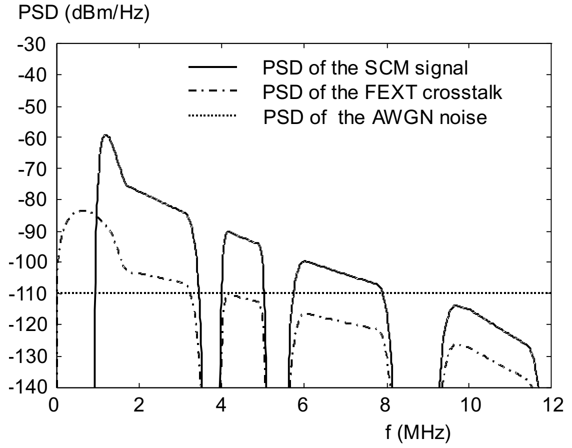

Fig. 4. The PSD characteristics of the SCM signal, the FEXT crosstalk and the AWGN noise attenuated at the end of the line

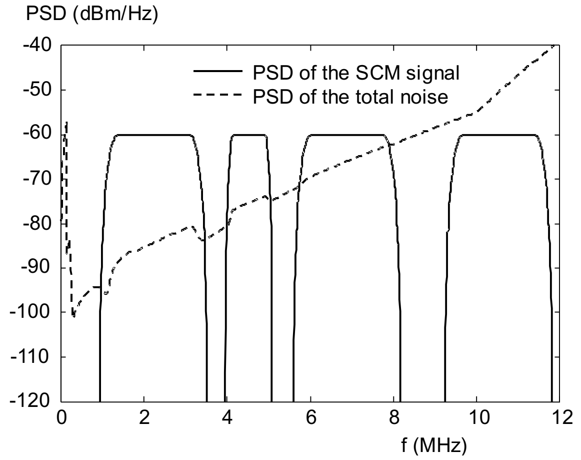

Fig. 5. The PSD characteristics of the SCM signal and the total noise adjusted by the corrector

Table 4. Band transition frequencies for the SCM FDD subbands according to the ETSI

Band transition frequencies	f_1 (kHz)	f_2 (kHz)	f_3 (kHz)	f_4 (kHz)	f_5 (kHz)
VDSL subbands	138	3000	5100	7050	12000
Optional subbands	138	3750	5200	8500	12000
Utilization of frequencies below f_1 and above f_5 but within the overall PSD masks although possible, is not covered [3].					

lation of a signal into the form possible for a transport through the line. Except the propagation loss, the signal transmission environment in the local subscriber loop is characterized also by negative influences of crosstalk noises from neighboring pairs and by activities of the impulse noise. Because these negative influences expressively interfere into the communication and represent its main limiting factors, they constituted a critical part of the model and, therefore, it is necessary exactly to recognize and express their characteristics by correct parameters. The receiver is conceptually inverse to the transmitter. Its main functions are the demodulation and the correction of corrupted information bits. Before the demodulation, a received signal is amplified for compensating of the propagation loss arisen in the transmission line.

3.2 The analysis of environmental influences on the PSD of the VDSL signal

At the analysis of the signal transmission through metallic homogeneous lines in the VDSL environment, we need to know three basic parameters - properties of the signal transmitted into the line (mainly its PSD), a transmission function of the transmission channel and features of the noise and crosstalk environmental influences.

In [5], particular relationships and frequency characteristics of basic noises and crosstalks occurred at the signal transmission through metallic homogeneous lines in the environment of xDSL technologies are introduced. The analysis of negative influences of noises and crosstalks on qualitative parameters of homogeneous lines can be extended to the VDSL environment. In our analysis, the NEXT crosstalk is not considered because this one can disable a communication in the VDSL frequency bandwidth. With respect to the possible VDSL deployments in conditions of the ST access network, we use a spectral mask defined for the FTTEx variation and for the coexistence with narrowband services in the same pair. In this spectral mask variation, the ADSL presence is supposed.

For the SCM modulation, four individual subbands are given alternatively for upstream and downstream directions of the transmission. Band transition frequencies are introduced in Tab. 4.

Using a transmission function of the raised cosine filter and on the base of known values of carrier frequencies and symbol rates for particular subbands (Tab. 1), we can express an ideal PSD characteristic of the SCM signal. A signal transmitted into the metallic homogeneous lines must comply with the defined FTTEx spectral mask, so that a spectrum of the ideal SCM signal from the modulator must be digitally adjusted using FIR filters before transmitting. From this adjusted PSD, moreover, frequency components equivalent to subbands allocated for amateur radio stations should be eliminated [2]. Using appropriate FIR filters, the SCM signal can be also adjusted with respect to other FTTx spectral masks.

For the MCM modulation, a way to form the PSD of the signal transmitted from the transmitter is defined in the ETSI standard [3]. After simplifying, it is multiplying of every complex coefficient $Z_i = X_i + jY_i$ by a constant g_i and resulting complex coefficients $Z_i' = g_i \cdot Z_i$ enter into the IFFT block. By this way, the transmitter can easy adapt any PSD characteristic of the transmitted VDSL signal for satisfying demands that are established by a chosen spectral mask. Alike, it is easy to keep frequency apertures in given subbands at occurrences of disturbing frequencies of the RFI type. Therefore, the MCM allows

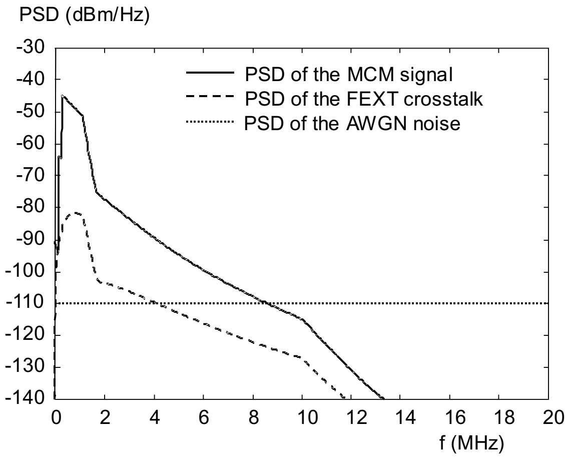

Fig. 6. The PSD characteristics of the MCM signal, the FEXT crosstalk and the AWGN noise attenuated at the end of the line

a high flexibility of the PSD transmitted signal and tries as effective as possible utilizations of the available bandwidth. We can therefore suppose that the transmitted VDSL signal will achieve maximum allowable levels in particular subchannels according to the FTTEx spectral mask (Fig. 2).

In Figs. 4 and 5, results of PSD characteristics of VDSL signals for the line length 0.5 km, the core diameter 0.4 mm with 24 ADSL and 9 VDSL disturbers and with the FTTEx spectral mask are introduced. In Fig. 4, the power spectral density of the SCM signal, the AWGN noise and the FEXT crosstalk are considered at the end of the line. All these characteristics are attenuated from a reason of transmitting signals through metallic homogeneous lines and, therefore, their corrections are needed. We are also using a linear equalization process to eliminate influences of the intersymbol interference (ISI). We can imitate this process by a corrector in the frequency area with a transmission function inverted to a channel transmission function. The output from this corrector is a signal with a balanced spectrum satisfying the Nyquist criterion. This correction in the frequency area eliminates aftereffects of the nonlinear signal attenuation by amplifying of higher frequency components. However, the correction of the received signal amplifies also the influence of noises and interferences. In Fig. 5, the PSD of the SCM signal and the total noise adjusted by the corrector are specified.

In Fig. 6, results of PSD characteristics of the MCM signal, the AWGN noise and the FEXT crosstalk for the line length 0.5 km, the core diameter 0.4 mm with 24 ADSL and 9 VDSL disturbers and with the FTTEx spectral mask are introduced. A received signal is sampled and processed by the FFT block without a correction in the frequency area. Therefore, the SNR can be calculated in particular subchannels directly from the MCM signal power and the noise powers at the end of the line.

A sense of the analysis of environmental influences on the power spectral densities of VDSL signals is to identify all substantial noise resources and at the same time to determine a way for calculating of the signal-to-noise ratio for various proposed modulation techniques. For our following analysis of the VDSL system performance, the parameter SNR is very important. The signal-to-noise ratio for the subband given by the lowest f_{LOW} and the highest f_{HIGH} frequencies can be expressed as:

$$SNR = \frac{\int_{f_{LOW}}^{f_{HIGH}} PSD_S(f)\mathrm{d}f}{\int_{f_{LOW}}^{f_{HIGH}} PSD_N(f)\mathrm{d}f} \tag{3}$$

where $PSD_S(f)$ is the VDSL signal power spectral density and $PSD_N(f)$ is the noise power spectral density. The SNR ratio must be calculated from the adjusted SCM signal power and the noise powers.

4 CONCLUSION

This paper introduces the analysis of environmental influences on the power spectral densities of VDSL signals. The knowledge of the PSD characteristics of the

APPENDIX —— ABBREVIATIONS

ADSL	Asymmetric DSL	HDSL	High bit rate DSL
ANSI	American National Standard Institute	ISDN	Integrated Services Digital Network
AWGN	Additive White Gaussian Noise	ISI	Intersymbol Interference
BA ISDN	Basic Access ISDN	ITU	International Telecommunication Unit
CAP	Carrierless Amplitude/Phase	MCM	Multicarrier Modulation
DMT	Discrete Multitone	POTS	Plain Old Telephone Service
DSL	Digital Subscriber Line	PSD	Power Spectral Density
DWMT	Discrete Wavelet Multitone	RFI	Radio Frequency Interference
ETSI	European Telecommunication Standard Institute	SCM	Singlecarrier Modulation
FDD	Frequency Division Duplex	SNR	Signal-to-Noise Ratio
FIR	Finite Impulse Response	ST	Slovak Telecom
FSAN	Full Service Access Network	TDD	Time Division Duplex
FTTEx	Fiber To The Exchange	VDSL	Very high bit rate DSL

VDSL signal can be very effectively utilized for characterizing the VDSL signal transmission on metallic homogeneous symmetric lines, especially for a determination of the SNR ratio. In addition, the PSD characteristics of the VDSL signal for singlecarrier and multicarrier modulation techniques are used in our following analysis of the overall VDSL system performance including theoretical and practical limits of transmission channels used by the VDSL technology.

Basic features and characteristics of negative environmental influences at the signal transmission in the VDSL environment and spectral characteristics of the VDSL signals can be used for modeling of the VDSL transmission path. This analysis allows determining main problems that can arise at the VDSL signal transmission. From our analysis, we can see that higher frequency areas (around the 8 MHz) are better utilized by the MCM. However, a utilization of those duplex and modulation techniques that minimize, eventually eliminate the NEXT crosstalk is an imperative condition.

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