Software for Estimation of xDSL Service Quality

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***Abstract* – In this paper, estimation of xDSL service performances is presented. Since the transmission medium quality is one of the key requirements for performance capabilities of these services, an analytical method for modelling of primary per-unit length parameters of twisted pair is described. This model is implemented in the existing software extended to allow for estimation of data rates on telephone subscriber loops for xDSL service. For the example of particular twisted pair telephone cable, an experimental measurement of its parameters is done, which is followed by their modelling using described software. At the end, comparison of experimental and modelled results of capacity for specific cable is presented.**

***Keywords* – xDSL, twisted pair, modelling, estimation, characterization.**

I. INTRODUCTION

The demand for high-speed data communications has been on the increase over the past several years due to drivers such as the internet, including the World Wide Web (WWW), video service, consumer services, and entertainment to name a few. High-speed voice band modems have reached a maximum transfer rate of 56 Kbps and alternative ISDN technology (*Integrated Services Digital Network*) access speeds reaching rates of 144 Kbps. Due to bandwidth limitations, new technologies are desired to exceed this limitation. There are different broadband access technologies on the market that are capable of transferring voice, data and multimedia content with high speed. These technologies can be classified in three groups due to transmission medium used: twisted pair, cable (fiber and coaxial) and wireless.

DSL (*Digital Subscriber Line*) technologies, called xDSL, which are equivalent to broadband access technology on twisted pair, are developed by telecommunication industry in order to use millions of kilometers of existing twisted pair infrastructure. One of the main advantages of DSL technology is equal usage and sometimes even sharing of telephone lines (local loops) with plain old telephone service (POTS) [1]. However, due to narrowband nature of POTS (0-4 kHz for voice signals), local loops are not suitable for broadband xDSL service.

The main idea of xDSL technology development is using existing infrastructure of telephone subscriber loops. Performance analysis of DSL technologies is of vital importance to DSL service providers. This type of analysis requires accurate prediction of the local loop structure and precise identification of the cable parameters.

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Different models of cables have been derived in order to accurate describe the behaviour of primary parameters using transmission line model [2]. Although many of them are rather empirical [3], there is also an analytical model based on physical and electromagnetic characteristics of twisted pair [4]. Both empirical and analytical models are implemented in developed software used for characterization of twisted pairs on physical layer [5-6]. In addition, by using these models, it is possible to estimate achievable capacity of DSL systems, as illustrated in this paper. Data rates for xDSL service are calculated using power spectral densities (PSD) given in ITU-T 996.1 Recommendation [7]. Number of bits per subchannel and data rates for twisted pair are the characteristics that are incorporated in modified software for estimation of xDSL performances. The software is developed in MATLAB programming environment [8]. Based on available input parameters, software calculates the twisted pair characteristics and compares them with available measured characteristics. Verification of software is given on an example of particular twisted pair in frequency band of interest for xDSL service.

II. TWISTED PAIR MODELLING AND DATA RATE CALCULATION

The electrical characteristics of the twisted pair cables are defined using the classical transmission line model. This model incorporates a set of four parameters per unit length, including a series inductance and resistance and a shunt capacitance and conductance, also known as the RLCG parameters of the cable. The series inductance represents the total self-inductance of the two conductors, and the shunt capacitance is due to the close proximity of the two conductors. The series resistance is due to the finite conductivity of the conductors, and the shunt conductance is due to the dielectric loss in the material between the two conductors. Graphical representation of a segment of twisted pair cable per unit is given on a figure 1.

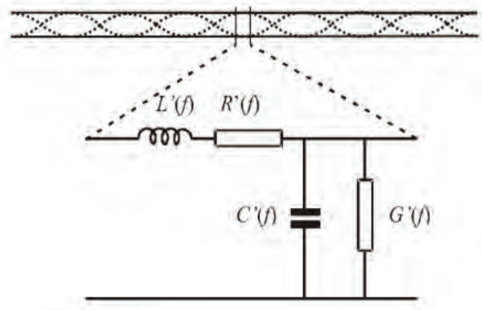

Fig.1 Segment of twisted pair modelled with transmission line model

Although physical principles have inspired the models, many are rather empirical. The empirical models are developed by fitting of measured primary and secondary parameters. These kind of models cannot be used for some frequency characteristics of the twisted pair, like crosstalk and transfer function. Their main deficiency is that they are not based on physical characteristics of twisted pairs. In reference [4], an example of an analytical model is described.

This model, which includes the skin effect and the effect of permittivity of isolation material, can precisely define primary parameters of twisted pair on frequencies of interest for xDSL service. Figure 2 shows physical characteristics of a cross section the twisted pair cable, which consists of two conductors with the diameter d and distance D between their centers. Conductivity of the metallic conductor is σ while permittivity of the insulating material is $\varepsilon_r' - j\varepsilon_r''$.

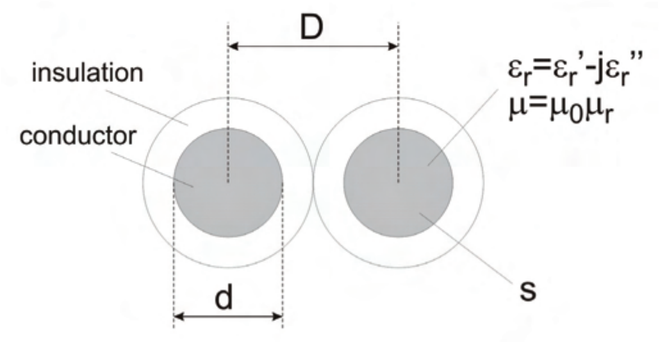

Fig.2 Physical characteristics of a cross section of twisted pair cable

Primary parameters per unit length according to analytical model can be calculated as (1-4):

$$C'(f) = \frac{\pi\varepsilon_0\varepsilon_r'}{\cosh^{-1}(D/d)}, \qquad (1)$$

$$L'(f) = \frac{\mu_0}{\pi}\cosh^{-1}(D/d) + \frac{R_s(f)}{2\pi^2 fd}\frac{D/d}{\sqrt{(D/d)^2-1}}, \qquad (2)$$

$$R'(f) = \frac{R_s(f)}{\pi d}\frac{D/d}{\sqrt{(D/d)^2-1}}, \qquad (3)$$

$$G'(f) = \frac{2\pi^2 f\varepsilon_0\varepsilon_r''}{\cosh^{-1}(D/d)}, \qquad (4)$$

Parameter R_s in equations (2) and (3) represents resistance which is frequency dependable as:

$$R_s(f) = \sqrt{\pi f \mu/\sigma}\ , \qquad (5)$$

Using primary parameters, secondary parameters of twisted pair, characteristic impedance Z_c and propagation constance $\gamma=\alpha+j\beta$, can be calculated.

$$Z_c(f) = \sqrt{[R'(f) + j2\pi f L'(f)]/[G'(f) + j2\pi f C'(f)]} \qquad (6)$$

$$\gamma(f) = \sqrt{[R'(f) + j2\pi f L'(f)][G'(f) + j2\pi f C(f)']} \qquad (7)$$

Uniform portion of line of length l can be modelled as a two-port network, where voltage V_1 and current I_1 of the left-hand port are linked to the voltage V_2 and current I_2 of the right-hand side port through so-called ABCD model:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}\begin{bmatrix} V_2 \\ I_2 \end{bmatrix}, \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cosh(\gamma l) & Z_0\sinh(\gamma l) \\ \frac{1}{Z_0}\sinh(\gamma l) & \cosh(\gamma l) \end{bmatrix} \qquad (8)$$

The values A, B, C and D are dependent only on the secondary parameters; they are independent of the termination impedance. Insertion loss can be computed according to:

$$H_{iloss}(f) = \frac{Z_S(f) + Z_L(f)}{Z_s(f)(CZ_L(f) + D) + AZ_L(f) + B} \qquad (9)$$

where $Z_s(f)$ and $Z_L(f)$ are the source and termination impedances at the ends the loop. Power spectral density (PSD) of the received signal is then given by:

$$S_p(f) = S_x(f)\left|H_{iloss}(f)\right|^2 \qquad (10)$$

,where $S_x(f)$ is the PSD of the transmitted signal.

Crosstalk is the primary noise source in DSL systems. For the purpose of estimating the performance of a DSL system, the crosstalk PSD, $S_n(f)$, needs to be computed, in most cases using the models presented in [7]. The crosstalk noise is modelled as additive Gaussian noise.

For ADSL and second-generation VDSL (VDSL2), DMT (*Discrete Multi Tone*) technology of multi-carrier modulation is standardized. In DMT systems, a discrete Fourier transform (DFT) is used to combine many narrowband signals to form one broadband signal. For each narrowband channel (each subchannel or tone), the signal and noise are almost white within the band. Therefore, data rate for each subchannel can be approximated by:

$$C_k = \frac{1}{T}\log_2(1 + \frac{SNR_k}{\Gamma}) \qquad (11)$$

where 1/T is the data symbol rate of each subchannel, SNR_k is the average signal-to-noise ratio in the subchannel and Γ is the overall gap from Shannon capacity at the desired error rate. Based on the assumption of almost flat signal and noise spectrum within each channel, the SNR of each channel can be approximated by:

$$SNR_k = \frac{S_p(f_k)}{S_n(f_k)} \qquad (12)$$

where f_k is the sub-carrier (center) frequency for each subchannel. If DMT system operates with a noise margin or if coding is used, then the margin and coding gain are incorporated into Γ factor according to:

$$\Gamma = \frac{\Gamma(P_e)\cdot\gamma_m}{\gamma_c} \qquad (13)$$

where $\Gamma(P_e)$ is a constant reflecting the Shannon gap (for a bit error rate of 10^{-7} this constant is approximately $\Gamma(P_e) = 9.89$, γ_m is noise margin (typically 5-6 dB) and γ_c denotes to coding gain (due to trellis coding it is typically in the range from 3 dB to 5 dB).

The aggregate data rate using all the narrowband subchannels is the sum of the data rates of the individual subchannels:

$$C = \sum_{k=K_0}^{K_1} C_k = \frac{1}{T}\sum_{k=K_0}^{K_1}\log_2(1 + \frac{SNR_k}{\Gamma}) \qquad (14)$$

III. SOFTWARE FOR DATA RATE CALCULATIONS

In order to calculate capacity of twisted pairs for xDSL service, the existing software for modelling of primary and secondary parameters [5,6] is modified to allow transmission rate calculation. For software design, the option of creating Graphical User Interface (GUI) in MATLAB programming environment is used.

An analytical model based on physical and electromagnetic characteristics of twisted pair is implemented in software. Besides physical characteristics, other input parameters are length of line, system margin, error probability and coding gain. As output characteristics, user can choose among primary parameters (RLCG parameters), secondary parameters, insertion loss, transfer function, signal and noise power spectral densities, number of bits per channel and data capacity for twisted pair. If capacity of transfer is chosen, user needs to know which systems may interfere with the line of interest. In addition, software can give comparison of the modelled and measured results for characteristics of interest.

IV. MEASUREMENTS OF TWISTED PAIR PARAMETERS

In order to experimentally obtain primary parameters per unit length, measuring of input impedance of tested twisted pair in frequency band of interest is done. Impedance is measured when line has short and open end. Devices and instruments used for calibration and measuring are shown on figure 3.

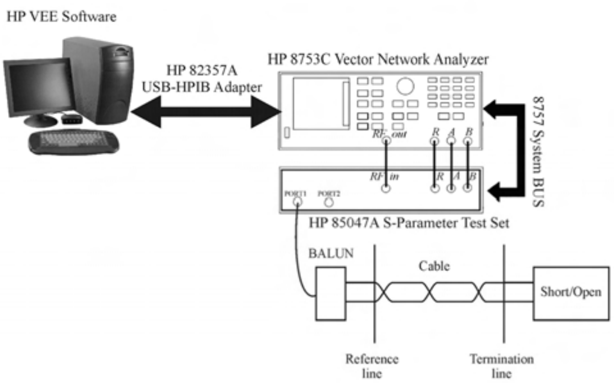

Fig 3. Measuring system

Through these measurements it is possible to calculate secondary parameters in frequency band of interest: Zc(f) i γ(f). As input impedance of twisted pair of length l in the case of open end is: Zoc(f)=Zc/tanh(γl)), and in the case of short end is: Zsc(f)=Zctanh(γl); characteristic impedance and the constance of propagation can be calculated as:

$$Z_c(f)=\sqrt{Z_{oc}(f)Z_{sc}(f)}, \tag{15}$$

$$\gamma(f)=\frac{1}{l}\tanh^{-1}\sqrt{\frac{Z_{sc}(f)}{Z_{oc}(f)}}, \tag{16}$$

Based on these results, primary parameters can then be calculated as:

$$R'(f)=\mathrm{Re}\{\gamma(f)Z_c(f)\}, \tag{17}$$

$$L'(f)=\frac{1}{2\pi f}\mathrm{Im}\{\gamma(f)Z_c(f)\}, \tag{18}$$

$$C'(f)=\frac{1}{2\pi f}\mathrm{Im}\left\{\frac{\gamma(f)}{Z_c(f)}\right\}, \tag{19}$$

$$G'(f)=\mathrm{Re}\left\{\frac{\gamma(f)}{Z_c(f)}\right\}, \tag{20}$$

Other characteristics of interest can then be computed by using equations (8)-(14).

V. NUMERICAL ANALYSIS

For the verification of analytical model implemented in software described on Section 3, twisted pair of the following physical characteristics is analyzed: d=0.65 mm and D=1.35 mm. Conductor of twisted pair is copper with specific conductance σ=5.65·107 S/m. Real part of insulating material permittivity is $\varepsilon_r' = 2.4$. Primary and secondary parameters of the described twisted pair are computed using equations (1)-(4) and equations (6)-(7), respectively. To verify modelled parameters, experimental analysis of considered twisted pair in frequency band up to 10 MHz is done too. Secondary parameters are extracted from measurements results as described in Section 4, and then primary parameters are calculated using equations (17)-(20). Either using modelled or measured parameters, other twisted pair characteristics can be easily obtained through equations (9-14). Comparison of the modelled and measured results for some of the software output characteristics is shown on figures 4-7.

Number of bits per channel for FDD (Frequency-Division Duplexing) and EC (Echo Cancelling) techniques, obtained using modelled and measured parameters, is shown on figs. 4 and 5, respectively.

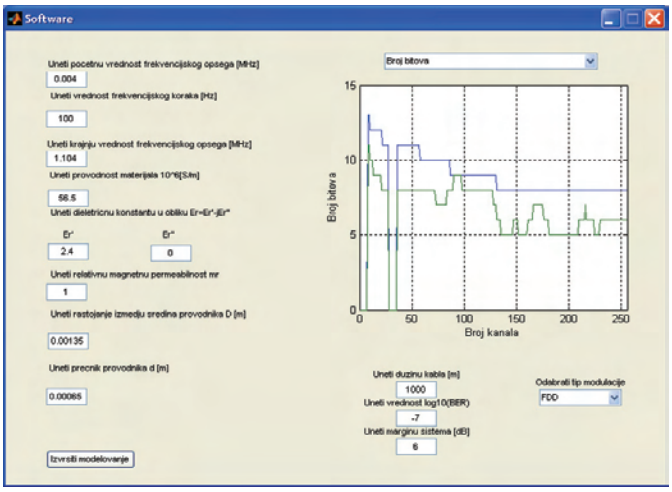

Fig 4. Number of bits per channel for FDD technique
(modelled parameters – blue; measured parameters - green)

FDD channels, that are used for xDSL service, are from 8 to 27 for upload and from 36 to 256 for download transfer. Channel between 28 and 35 are not used for this service. Channels used for EC are between 8 and 31 for upload and between 8 and 256 for download transfer. For number of used channels, estimated data rate for EC is greater than for FDD.

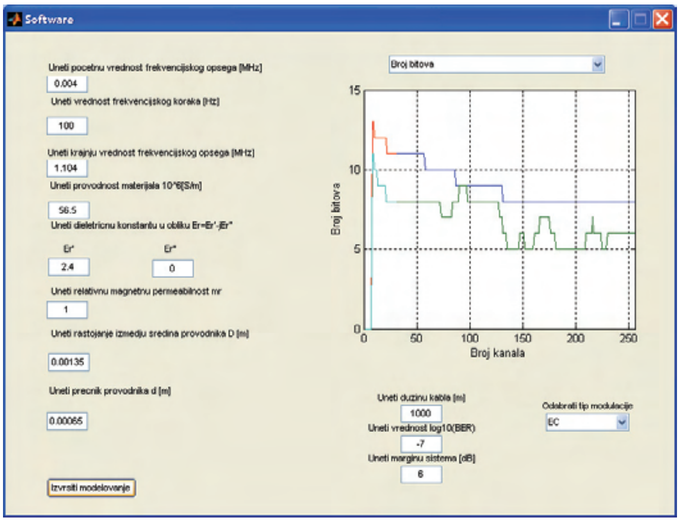

Fig 5. Number of bits per channel for EC technique (modelled parameters: red - upstream, blue – downstream; measured parameters: cyan – upstream, green - downstream)

Power Spectral Densities (PSD) of signal and noise for FDD and EC techniques are given on figs. 6 and 7, respectively, where modelled parameters are marked with red line for signal and green line for noise and measured parameters are marked with blue line for signal and cyan line for noise. Data rates for upstream and downstream, obtained from modelled and measured parameters, are given for a system with Bit Error Probability $BER=10^{-7}$ and system margin of 6 dB. Length of the local loop is l=1000 m.

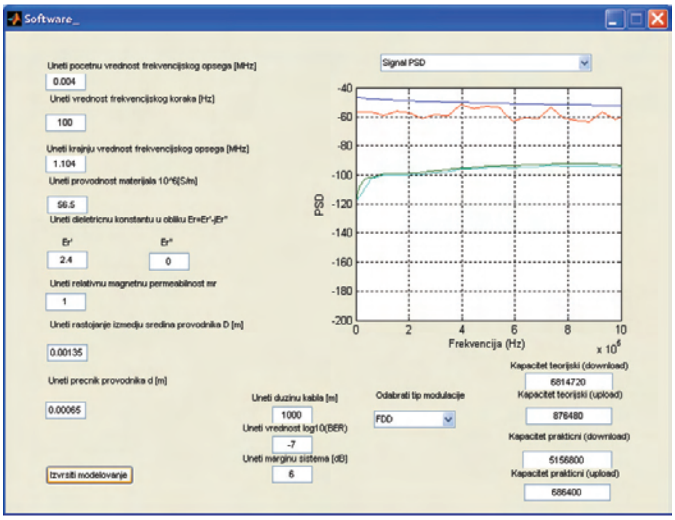

Fig 6. PSD and data rates for FDD technique

For FDD, data rates calculated from modelled parameters are 6.499 Mbit/s for download and 856 kbit/s for upload transfer. Data rates computed from measured parameters for specific cable are 4.918 Mbit/s for download and 670 kbit/s for upload. As mentioned before, capacities are greater for EC for the same cable and the same system. For EC, estimated data rates from modelled results are 7.63 Mbit/s and 1007 kbit/s for download and upload direction, respectively. Data rates calculated form measured results are 5.80 Mbit/s and 780 kbit/s for download and upload transfers, respectively.

VI. Conclusion

In this paper estimation of performances for telephone local loop, as the key component of xDSL service is presented. For the purpose of modelling of twisted pair, theory of transmission lines and analytical model based on physical and electromagnetic characteristics are used. Calculations of power spectral densities and data rates are based on ITU-T Recommendations. These characteristics, as well as primary and secondary parameters, transfer function and insertion loss, are implemented in developed software for evaluation of xDSL service quality. Through this software operaters of xDSL service are able to get an overview of the estimated performances of xDSL access technology on existing local loops.

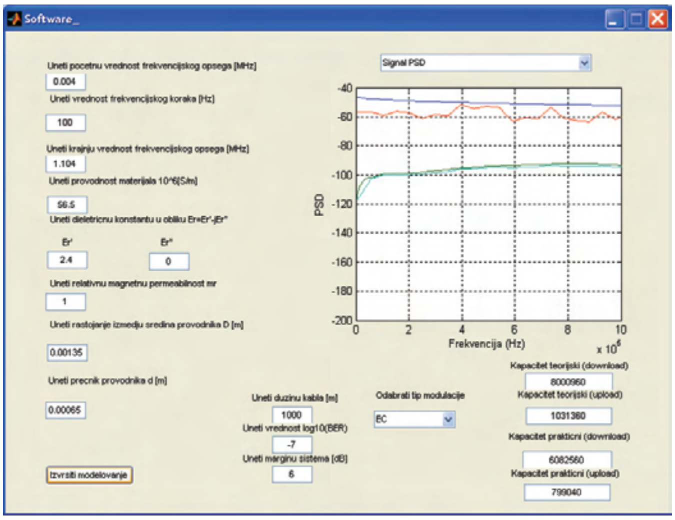

Fig 7. PSD and data rates for EC technique

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