1. Introduction

In May 2011, installation of VDSL2 (Very-high-speed digital subscriber line) was started by Telefonica Czech Republic. The spectral profile 998ADE17 was chosen for VDSL2 lines operating in the access network owned in the Czech Republic [1]. In a year of operation, practical experience with the operation of VDSL is already available and we proceeded to correct our simulation model for digital subscriber lines [2]. The VDSL lines are widely used for the transmission video-streams of IPTV (Internet Protocol Television). The required bandwidth and quality of video stream on higher layers of communication model is researched in many works, for example [3]. This article is focused to transmission directly on the physical medium and the physical layer. Two major problems were identified with precision modelling of digital subscriber lines on the physical layer.

Firstly, transmission function of the line must be accurate. A real telecommunication line can be simplified as a homogeneous line with evenly distributed electrical parameters. As the frequency grows, the inhomogeneities along the line have more influence.

Secondly, code gain of the modem must be updated. The code gain is depended on a vendor and its error correction and equalization algorithms implementation.

Both problems are described and analysed in this article and practices are recommended to address them. Another big problem of metallic lines is crosstalk, which was addressed in many articles, such as [4] and [5].

2. Types inhomogeneities

The telecommunications practice uses the following classification for specific types of inhomogeneities that can appear in subscriber lines in local access networks; they have originated from the analogy technology:

- Inhomogeneities of type 1 – they include transitions between different core diameters, transitions between different materials (copper–aluminium), and transitions between different cable arrangements (pairs–quads).
- Inhomogeneities of type 2 – representing “broken” quads, pairs, pair with bad insulation, interruptions.
- Inhomogeneities of type 3 – they originate from disobedience of rules for connecting groups (bundles) and layers (positions).

This classification is, however, insufficient for digital subscriber lines that occupy the frequency bands up to tens of MHz, and therefore it is desirable to introduce the classification according to Table 1. The authors have further divided the individual types into subtypes that are identified by lower-case letters.

It is particularly important to introduce the inhomogeneities of Type 0 that are characterized by inhomogeneity of the cable section itself resulting from imperfect manufacturing and installing, and also from unmatched characteristic impedances of terminal devices and the line section in the operating frequency range (compromise termination) due to extremely wide band.

Type 1 inhomogeneities are caused by the branched access network topology and they must be taken into account in real oper-
3. Model of line with inhomogeneities

The transmission function of a line is influenced by many factors, and the first option is to model it according to [6] as an environment with multipath propagation:

$$H(f) = \sum_{i=1}^{N} g_i \cdot e^{-\alpha_i l_i} \cdot e^{-\beta_i l_i^2}$$  \hspace{1cm} (1)

where $g_i$ is the path weight, $T_i$ is the delay of a path with length $l_i$, $N$ is number of paths and $\alpha$ is specific attenuation.

Another modelling option is to use the telegraph equations, in this case not with constant coefficients, but with variable ones, i.e. primary parameters RLCG depending on the position within the line. Simplified model can be used for practical applications, which is based on real conditions in access networks – the inhomogeneities are not simulated continuously, but discretely, as a limited number of impedance mismatches on the line. In such a case we can model the line as a cascade of individual sections with different parameters and lengths.

If we want to determine the transmission function of a line composed of several sections with different parameters and containing also taps or other elements, we can express it from the product of matrices describing the individual cascaded sections. We should use the cascade parameters of a two-port network $ABCD$ [7]. The resulting matrix of the cascade will be given by the product of the sectional matrices:

$$A = A_1 \cdot A_2 \cdot \ldots \cdot A_n = \begin{bmatrix} a(f) & b(f) \\ c(f) & d(f) \end{bmatrix}$$  \hspace{1cm} (2)

where $A_1$ to $A_n$ are matrices describing the cascaded elements and $a(f)$ to $d(f)$ are the resulting parameters of the entire cascade.

Similar procedure can be applied also to modelling of lines with inhomogeneity. The model will be formed by matrices describing homogeneous sections of various lengths. Between each two homogeneous sections there will be inserted inhomogeneities of different nature. The entire cascade will be terminated by a homogeneous section. There are two possibilities of defining the inhomogeneities: either using the impedance defects as combinations of serial and parallel impedances (suitable for less serious defects), or using electrically short sections with different secondary parameters; also, a combination of both methods can be used (suitable for strong inhomogeneities).

Then we can describe a section of a homogeneous line with length $l$, characteristic impedance $Z_o$, and propagation coefficient $\gamma$, using the following matrix:

$$A_o = \begin{bmatrix} \cosh(\gamma (f) \cdot l) & (Z_o(f) \sinh(\gamma (f) \cdot l)) \\ \sinh(\gamma (f) \cdot l) & (Z_o(f) \cosh(\gamma (f) \cdot l)) \end{bmatrix}$$  \hspace{1cm} (3)

Impedance $Z_o$ that is in series between the input and output contacts will be expressed using the matrix (4); it can be used if
there is an inhomogeneity caused by increased specific resistance 
or inductance (e.g. contact resistance in cross-connect and distri-
bution frames).

\[
A_z = \begin{bmatrix} 1 & Z_p \\ 0 & 1 \end{bmatrix}
\]  

(4)

Impedance \( Z_p \) that is in parallel with the common input and 
output contacts will be expressed using the matrix (5); it can be 
used if there is an inhomogeneity caused by increased specific 
leakage or capacitance (e.g. capacitance of cross-connect and distri-
bution frames).

\[
A_p = \begin{bmatrix} 1 & 0 \\ \frac{1}{Z_p} & 1 \end{bmatrix}
\]  

(5)

The resulting matrix will be calculated as a product of odd 
number of partial matrices \((1+2\pi)\) as follows:

\[
A = A_{L_i} \prod_{i=1}^{2\pi} (A_{D_i}, A_{L_i})
\]  

(6)

where \( A_{L_i} \) are matrices describing homogeneous sections (Lines) 
and \( A_{D_i} \) are matrices modelling the inhomogeneities (Defects), but 
with different secondary parameters \( Z_{ci} \) and \( \gamma_i \) than in the matrix 
\( A_{L_i} \). The number of matrices depends on the required nature 
of inhomogeneities. For practical use, modelling of inhomogene-
ity by electrically short sections of lines with different secondary 
parameters can be recommended. The formula (6) can then be 
rewritten as a product of matrices, as follows:

\[
A = A(\gamma_{L_i}, Z_{L_i}, l_{L_i}) \prod_{i=1}^{2\pi} A(\gamma_{D_i}, Z_{D_i}, l_{D_i}) A(\gamma_{L_i}, Z_{L_i}, l_{L_i})
\]  

(7)

where \( l_{L_i} \) are the homogeneous sections lengths and \( l_{D_i} \) are the 
lengths of sections modelling the inhomogeneity.

In order to approach the pseudo-random nature of inhomoge-
neity originating by cable manufacturing and installing, it is 
advisable to choose the lengths so that they are not integer multi-
ples of each other. An example of modelling a line with inhomoge-
neity and added components (e.g. capacitance of cross-connect 
and distribution frames, patch cords, connection from main dis-
tribution frame to DSLAM) is shown in Figs. 1 and 2 where the 
value of a 500m section is compared to that of a homogeneous 
line in a TCEPKPFLE 75×4×0.4 local cable.

4. Improvement code gain calculation

Mentioned more precise calculations for line transmission para-
eters were implemented into Simulator xDSL program [2]. The 
simulation program is designed to perform calculations within the 
spectral compatibility sphere in a metallic access network and cal-
culations concerning a transmission performance for several types 
of digital subscriber lines.

The simulation program allows performing simulation of all 
lines xDSL. For each transmission technology it is possible to set 
up an additional parameter. For example, for VDSL2 it is neces-
sary to set up frequency band and PSD mask (Power Spectral 
Density). The transmission environment is modelled with the use 
of the noise profiles A, B, C, D, defined by ITU-T for each tech-
nology. However, it is also possible to use one’s own combination 
of different transmission technologies.

For more precise calculations of transmission performance in 
Simulator xDSL program, there was a gain code correction applied. 
The code gain (CG) of modem depends on how the subscriber’s 
data are protected during the transmission. What is more, a value 
of code gain affects bits allocation in each sub-channel of DMT.
(Discrete Multi-tone) modulation. Number of allocated bits for i tone (channel) is determined by (8) [5]:

$$b_i = \log_2 \left( 1 + \frac{S_i}{N_i} k_i \right)$$  \hspace{1cm} (8)

where, $b_i$ is the number of allocated bits, $S_i$ is a signal power, $N_i$ is a noise power. Constant $k_i$ is given by (9):

$$k_i = \frac{S\cdot NM}{CG}$$  \hspace{1cm} (9)

where $S\cdot G$ is Shannon Gap 9.55 for BER $= 10^{-7}$. NM is Noise Margin (usually for xDSL NM $= 6$ dB). Figure 3 shows a dependence of signal to noise ratio (SNR) on a number of channel. Blue curve is again measured, while red comes from theoretical simulation.

An example of code gain calculated from measured values of noise margin is shown in Fig. 4. The noise margin value varies because of the user modem that is trying to provide a maximum bitrate, which depends on the actual SNR value for a given tone. The noise margin is not really constant, but varies between the minimum and maximum values around the desired value of 6 dB. The calculated code gain from noise margin and SNR values is around 6 dB.

5. Conclusion

Two major problems were identified with precision modelling of digital subscriber lines: inhomogeneity along the line and code gain vendor dependence. The updated classification and inhomogeneity was used to refine model lines. In result, code gain value differs, depending on a vendor and algorithms implemented into the end user modem. For that reason, improvements can be applied only to a specific modem. Despite these conditions, Simulator xDSL allows to perform calculations according to specific conditions and obtain exact values for transmission performance of xDSL system. Table 2 summarizes the results before correction and after correction of the downstream bitrate modelled values for both the intended effects. Parameters of local cable TCEPKFLE 75×4×0.4, spectral profile 998ADE17 to 17 MHz and noise model B (ETSI) were used for all cases. The noise model B is calculate from typical crosstalk from other 15 lines with VDSL2 modems and mix of SHDSL and ADSL modems in reference cable with 50 pairs.

![Fig. 3 Dependence of SNR on order of DMT tones](image1)

![Fig. 4 Dependence of noise margin (blue) and code gain (red) on order of DMT tones](image2)

| Description                                  | Downstream bitrate |
|----------------------------------------------|--------------------|
| Effect of inhomogeneity:                     |                    |
| Without inhomogeneity                        | 16 Mbps            |
| With inhomogeneity                           | 12 Mbps            |
| Effect of code gain correction:              |                    |
| Original value of code gain = 3 dB           | 12 Mbps            |
| New value of code gain = 6 dB                | 16 Mbps            |

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