# INVESTIGATION OF VDSL2 DIGITAL LINES PERFORMANCE WITH BRIDGED TAPS

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***Abstract.*** *Modern Very-High Speed Digital Subscriber Lines (VDSL2) can potentially increase the transmission rates in access networks up to tens of Mbps in both directions. However, the real transmission performance of VDSL2 technology is heavily influenced by real conditions of symmetrical pairs and quads in local metallic cables. This paper is primarily focused on the bridged taps and their influence on transmission performance of VDSL2 lines. The presence of bridged taps can complexly affect resulting attenuation, impedance and also crosstalk characteristics of transmission lines, moreover while this influence may differ for various types of metallic cables. That is why a comparison for several typical cables used in last-mile segments was performed and is presented here. The simulations and calculations presented in this paper are based on ABCD matrices, and thanks to that the simulations can be performed for various scenarios and situations.*

## Keywords

***Attenuation, bridged taps, FEXT, metallic lines, VDSL2.***

## 1. Introduction

Today, the second generation of Very-High Speed Digital Subscriber Lines (VDSL2) is currently being deployed in Czech Republic to replace old ADSL2+ lines. These xDSL technologies effectively exploit existing symmetrical pairs of local metallic cables and lines [1], [2] and thanks to that they are typically used to provide data connection for households or small companies. Modern VDSL2 lines can potentially offer transmission rates up to tens of Mbps in both directions, however their real performance is significantly dependent on conditions and real transmission parameters of used lines and cables, especially the attenuation, crosstalk and other disturbances [3], [4].

The bridged taps represent another potential problem especially in local access networks in last-mile segment [5]. They can complexly influence the overall transmission parameters of metallic lines, because their presence affects the attenuation, impedance and crosstalk characteristics. The bridged taps can be easily formed and caused usually during the process of repairing the metallic cable or due to replacing the old cables with new lines, when old unused parts of previous cables are not properly removed. Specific bridged taps can be also created in subscriber premises by incorrect splitting of the feeder cable or by using improper home communication systems over telephone wires.

The attenuation characteristic of a transmission line with bridged tap depends on the length of a tap, however, the impedance and crosstalk is also influenced by its position. The problem of bridged taps in access networks and their influence was partially studied and reported in several papers [6], [7], which introduced some basic conclusions. The simulation technique used in this paper is based on the **ABCD** matrices of transmission lines and bridged taps [8]. These **ABCD** matrices can be easily adapted for any scenario and simply cascaded in case of multiple bridged taps or taps with various parameters, which makes the resulting method more versatile. Moreover, the influence of bridged taps on transmission parameters is different for various types of metallic cables and lines. This influence is given mainly by the primary $R$, $L$, $C$ and $G$ parameters of lines and also by their crosstalk characteristics. Therefore, several typical metallic cables used in access networks or local data networks specified by ITU-T rec. G. 996.1 [9], and used in last-mile networks in Czech Republic were used in simulations. Thanks to that, this article contains the comparisons of achievable VDSL2 performance for various metallic cables and the influence of bridged taps on their transmission characteristics.

The first part of this article is focused on the introduction of presented model and method of calculations and the description of used metallic cables. The second part consists of simulations of VDSL2 for lines with bridged taps based on the presented models.

## 2. Modeling of Transmission Lines with Bridged Taps

First, a model based on **ABCD** cascaded transmission matrices is necessary to describe. The general situation for two symmetrical pairs is presented in the following Fig. 1. These two pairs are located in one cable and the second pair contains a bridged tap.

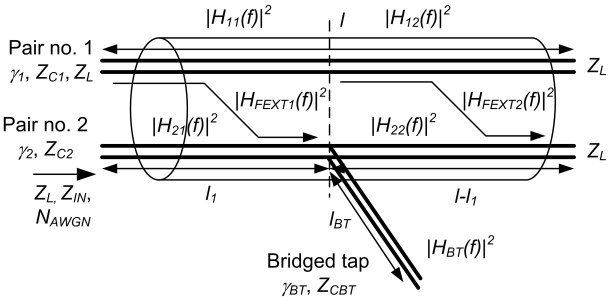

**Fig. 1:** The schematic illustration of a situation with bridged tap.

The propagation constants and characteristic impedances of both pairs are $\gamma_1$, $\gamma_2$ and $Z_{C1}$, $Z_{C2}$ respectively. The propagation constant of a bridged tap is $\gamma_{BT}$ and char. impedance $Z_{CBT}$. The length of both pairs is $l$, the length of a bridged tap is $l_{BT}$ and the beginning of a tap is located at the distance $l_1$ from the beginning of the second pair. This point is marked with dashed line in previous Fig. 1 and it divides both pairs into two sections, which will be further used in the following calculations. The power transfer functions of these sections are $|H_{11}(f)|^2$, $|H_{12}(f)|^2$, $|H_{21}(f)|^2$ and $|H_{22}(f)|^2$ respectively, the power transfer function of a bridged tap is $|H_{BT}(f)|^2$. The power transfer function of FEXT crosstalk in the first section is $|H_{FEXT1}(f)|^2$ and $|H_{FEXT2}(f)|^2$ in the second section. Both pairs are terminated with load impedance $Z_L$ on both sides, $Z_{IN}$ is the input impedance of the pair with a bridged tap. The spectral density of additive white Gaussian noise in the second pair with a bridged tap is $N_{AWGN}$. The **ABCD** matrix of a transmission line and bridged tap are specified in [3], as well as the resulting power transfer function for the situation described in previous Fig. 1 [10]. The far-end crosstalk (FEXT) was estimated using model presented in [8] together with cascading FEXT elements as described in [11]. The summary FEXT power function consists of a part, which is generated before the bridged tap and is affected by the presence of bridged tap, while the second part represents FEXT crosstalk generated after the bridged tap and not influenced by its presence. This conclusion was also provided in [6].

The load impedance $Z_L$ of both pairs in previous Fig. 1 is constant and $Z_L = 100\ \Omega$ in all following simulations and calculations. This is a typical value for VDSL2 lines. The bridged tap is considered to be unloaded (opened) in all simulations, therefore its load impedance is $Z_{LBT} = \infty$. The calculations of input impedance $Z_{IN}$, power transfer functions of both pairs and FEXT crosstalk are based on the cascaded **ABCD** matrices. According to the [3], the general **ABCD** matrix of simple transmission line (metallic pair), $\mathbf{ABCD}_L(f)$, can be expressed as:

$$\mathbf{ABCD}_L(f) = \begin{pmatrix} cosh(l,\gamma(f)) & Z_C sinh(l,\gamma(f)) \\ \dfrac{sinh(l,\gamma(f))}{Z_C(f)} & cosh(l,\gamma(f)) \end{pmatrix}$$

$$\mathbf{ABCD}_L(f) = \begin{pmatrix} a_L(f) & b_L(f) \\ c_L(f) & d_L(f) \end{pmatrix}, \tag{1}$$

where $l$ is the length of a pair, $\gamma(f)$ its propagation constant, $Z_C(f)$ represents a characteristic impedance and $f$ frequency, because all these terms are frequency dependent. The **ABCD** matrix of a bridged tap, $\mathbf{ABCD}_{BT}(f)$, is defined as:

$$\mathbf{ABCD}_{BT}(f) = \begin{pmatrix} 1 & 0 \\ \dfrac{1}{Z_{CBT} coth(l_{BT},\gamma_{BT}(f))} & 1 \end{pmatrix}$$

$$\mathbf{ABCD}_{BT}(f) = \begin{pmatrix} a_{BT}(f) & b_{BT}(f) \\ c_{BT}(f) & d_{BT}(f) \end{pmatrix}. \tag{2}$$

In which $l_{BT}$ stands for the length of bridged tap, $Z_{CBT}(f)$ and $\gamma_{BT}(f)$ for its characteristic impedance and propagation constant respectively. The situation in Fig. 1 for the pair no. 2 with one bridged tap can be described using **ABCD** matrices (1), (2), as:

$$\mathbf{ABCD}(f) = \mathbf{ABCD}_{L1}(f)\mathbf{ABCD}_{BT}(f)\mathbf{ABCD}_{L2}(f)$$

$$\mathbf{ABCD}(f) = \begin{pmatrix} a(f) & b(f) \\ c(f) & d(f) \end{pmatrix}, \tag{3}$$

where **ABCD**(f) represents the resulting matrix for cascaded situation, $\mathbf{ABCD}_{L1}(f)$ and $\mathbf{ABCD}_{L2}(f)$ are matrices of two sections of transmission lines divided by a bridged tap in Fig. 1 and $\mathbf{ABCD}_{BT}(f)$ stands for the matrix of a bridged tap. In case of multiple bridged taps or elements of transmission line, simply more **ABCD** matrices can be cascaded in (3). The input impedance $Z_{IN}(f)$ of the second pair with a bridged tap can be expressed according to [9] and previous matrices (1), (2) and (3) as:

$$Z_{IN}(f) = \frac{Z_L a(f) + b(f)}{Z_L c(f) + d(f)}, \tag{4}$$

**Tab. 1:** The parameters of #BT9 model for all types of cables used for simulations.

| | **ITU-T G.996.1 0.32** | **ITU-T G.996.1 0.4** | **ITU-T G.996.1 0.5** | **UTP cat. 5e** | **TCEPKPFLE 75 × 4 × 0.4** |
|---|---|---|---|---|---|
| $r_{0c}$ | 409 | 280 | 179 | 178 | 280 |
| $a_c$ | $0,3822$ | $0,0969$ | $0,0561$ | $0,019$ | $0,26566$ |
| $l_0$ | $607,5^{-6}$ | $587,13^{-6}$ | $673,6^{-6}$ | $50^{-6}$ | $787^{-6}$ |
| $l_\infty$ | $500^{-6}$ | $427^{-6}$ | $544,25^{-6}$ | $390^{-6}$ | $745^{-6}$ |
| $b$ | $5,2464$ | $1,395$ | $1,3013$ | $0,3$ | $4,133$ |
| $f_m$ | $609^3$ | $739^3$ | $580,92^3$ | $25^6$ | $8,5268^6$ |
| $c_\infty$ | $40^{-9}$ | $50^{-9}$ | $50^{-9}$ | $38^{-9}$ | $35,42^{-9}$ |
| $g_0$ | 0 | 0 | 0 | $7e^{-12}$ | 0 |
| $g_e$ | 0 | 0 | 0 | $1,02$ | 0 |

where $Z_{IN}(f)$ is an input impedance of pair no. 2 (with bridged tap), $Z_L$ is a load impedance (here $Z_L = 100\,\Omega$) and $a(f)$, $b(f)$, $c(f)$ and $d(f)$ are the elements of $\mathbf{ABCD}(f)$ matrix (3). Generally, the transfer function of a cascaded line $H(f)$ can be calculated as:

$$H(f) = \frac{Z_L}{Z_L a(f) + b(f) + Z_L Z_S c(f) + Z_S d(f)}. \quad (5)$$

In which $Z_S$ is the impedance of a signal source and its value in this paper is considered $Z_S = Z_L$.

## 2.1. Parameters of Metallic Cables

The following simulations of VDSL2 lines were performed for 5 different metallic cables, which are specified in ITU-T G.996.1 rec. [9] or are often used for access or local data networks in Czech Republic. Thanks to that, the influence of bridged taps on resulting transmission characteristics of these cables can be easily compared and decided. These cables are specified as: ITU-T G.996.1 0.32 cable, ITU-T G.996.1 0.4 cable, ITU-T G.996.1 0.5 cable, UTP cat. 5e cable and TCEPKPFLE $75 \times 4 \times 0.4$ cable, where the last number represents the diameter of a Cu core.

The calculation of primary $R$, $L$, $C$, $G$ parameters of all cables was based on British Telecomm. model #BT9 and parameters specified in ITU-T G.996.1 and in [13] as Tab. 1. The #BT9 model estimation defines $R$, $L$, $C$ and $G$ as:

$$R(f) = \sqrt[4]{r_{0c}^4 + a_c f^2}\,[\Omega/km], \quad (6)$$

$$L(f) = \frac{l_0 + l_{\text{inf}}\left(\dfrac{f}{f_m}\right)^b}{1 + \left(\dfrac{f}{f_m}\right)^b}\,[H/km], \quad (7)$$

$$C(f) = c_\infty\,[F/km], \quad (8)$$

$$G(f) = g_0 f^{g_e}\,[S/km], \quad (9)$$

where $R$ [$\Omega$/km], $L$ [H/km], $C$ [F/km], $G$ [S/km] are the primary parameters of metallic lines, f is a frequency in Hz and all parameters used in (6), (7), (8) and (9) were specified in previous Tab. 1. Using previous $R$, $L$, $C$ and $G$, propagation constant $\gamma(f)$ and characteristic impedance $Z_C(f)$ of a line segment can be calculated as:

$$\gamma(f) = \sqrt{(R + j\omega L)(G + j\omega C)}, \quad (10)$$

$$Z_C(f) = \sqrt{\frac{R + j\omega L}{G + j\omega C}}. \quad (11)$$

These formulas were used to calculate the parameters of each segment in cascaded scenario, while the resulting transfer functions, input impedances and FEXT transfer functions were determined by applying **ABCD** matrices together with formulas (1), (2), (3), (4) and (5) to obtain the results for each situation.

## 3. VDSL2 Performance over Lines with Bridged Tap

This section contains the description and results of simulations of VDSL2 lines with bridged tap. All following calculations were performed for VDSL2 lines with frequency plan B8-12 for Europe up to 17 MHz and spectrum profile 998ADE17, which is currently used in Czech Republic. The simulations were performed for all 5 types of metallic cables with parameters presented in Tab. 1, so it is possible to compare the influence of bridged tap on resulting transmission performance of each cable. Due to that, the estimation of transmission rates was calculated for a scenario without any bridged tap and then the following graphs contain the relative rates in % expression. Generally, the simulations were performed for two different scenarios. The first scenario is focused on AWGN as a dominant source of disturbance, therefore it illustrates a situation with one single VDSL2 line in a cable without any FEXT influence. The second scenario is based on

FEXT crosstalk as a major disturbing source, when simulations for 10 and 50 disturbing VDSL2 systems in the same metallic cable were performed. Thanks to that, the results for different cables can be easily compared and decided, which cable is more influenced by the presence of bridged tap in case of FEXT crosstalk or in case of AWGN as a dominant source of noise.

Downstream and upstream directions were analyzed and separate graphs for both directions are always presented. The calculations and simulations of VDSL2 lines were performed according to the models and methods presented in [3] and [8] with parameters of VDSL2 lines specified in ITU-T rec. G.993.2 [12]. The value of load impedance ZL was considered as 100 Ω (typical value for VDSL2 lines) and the value of $N_{AWGN}$ was constant and according to [3] $N_{AWGN} = -140$ dBm. The value of $K_{FEXT}$ crosstalk parameter was used individually for each metallic cable according to the parameters provided in [9] and [13].

## 3.1. The Results for a Scenario without FEXT Influence

In this scenario, the metallic cable contains only one symmetrical pair, therefore no FEXT crosstalk is presented. Moreover, this pair contains one single bridged tap with variable length and variable position. The length of a cable is $l = 0,8$ km, the length of a bridged tap $l_{BT}$ varies from 0,002 to 0,1 km and its position $l_1$ varies from 0,008 km to 0,79 km.

First, the values of upstream/downstream transmission rates of VDSL2 lines without any bridged tap were calculated for each type of metallic cable and are presented in Tab. 2.

**Tab. 2:** Calculated transmission rates for VDSL2 lines without any bridged tap and FEXT crosstalk.

| Type of a cabel | Transmission rate [Mbps] | |
|---|---|---|
| | Upstream | Downstream |
| ITU-T G.996.1 0.32 | 13,792 | 52,16 |
| ITU-T G.996.1 0.4 | 22,58 | 64,596 |
| ITU-T G.996.1 0.5 | 41,908 | 92,532 |
| UTP cat. 5e | 26,248 | 67,144 |
| TCEPKPFLE 75 × 4 × 0.4 | 39,672 | 88,692 |

Next, the simulation for the pair with a bridged tap was performed. The following Fig. 2 contains the results of relative transmission rates in % expression simulated for upstream direction, while Fig. 3 illustrates the results for downstream direction.

For better interpretation of simulated results, following set of graphs in Fig. 4 and 5 contains selected characteristics for the position of a bridged tap $l_1 = 16$, 238, 476 and 714 meters. The types of cables are presented with the same colors used in previous figures.

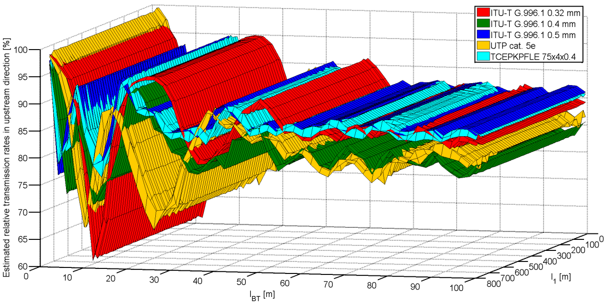

**Fig. 2:** The result of calculation of relative VDSL2 transmission rates in upstream direction for all metallic cables in the first scenario with single bridged tap.

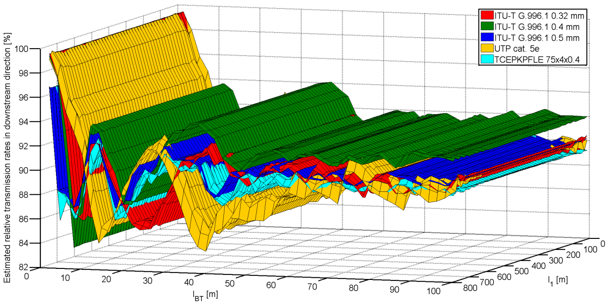

**Fig. 3:** The result of calculation of relative VDSL2 transmission rates in downstream direction for all metallic cables in the first scenario with single bridged tap.

The previous results illustrate the negative influence of a bridged tap on transmission rates of VDSL2 lines. As it was expected, the position of a bridged tap does not influence the resulting attenuation characteristic of a line, which is affected only by the length of a tap $l_{BT}$. This conclusion results from (5), where no position $l_1$ of a bridged tap is presented. This conclusion also corresponds with the results provided in [6]. Therefore in case of AWGN environment without any FEXT influence, the resulting transmission rates are constant and independent on the position of a tap $l_1$ and are influenced only by its length $l_{BT}$. It can be also deduced, that especially short bridged taps can cause significant narrow frequency peaks in attenuation characteristic according to the ratio between the length of a bridged tap and the wavelength of propagating electromagnetic signal for specific VDSL2 frequency profiles [6]. This conclusion is illustrated in the following Fig. 6, where the attenuation characteristic for various lengths of a tap $l_{BT}$ for a TCEPKPFLE cable is presented (the results for other cables are similar).

Due to that, all graphs in previous Fig. 2, 3, 4 and 5 contain narrow peaks for short taps with lengths up to 30 meters, which may decrease the resulting transmission rates by 30 % in upstream and by 20 % in downstream direction compared to the situation without any bridged tap.

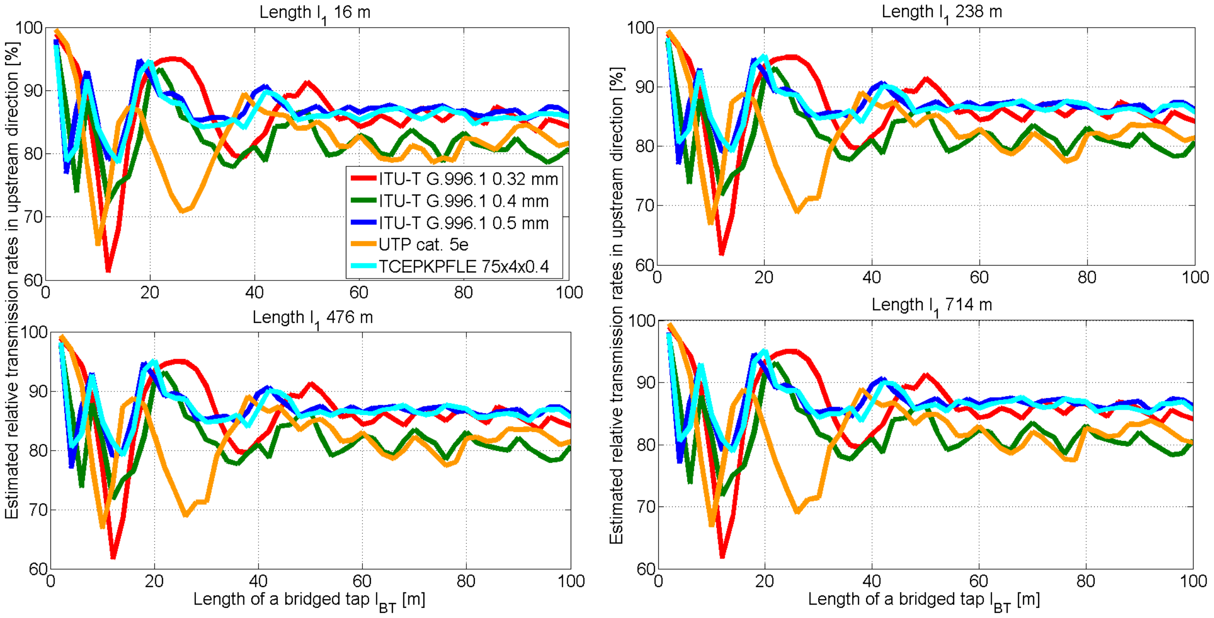

**Fig. 4:** Relative transmission rates of VDSL2 in upstream direction selected for 4 different positions $l_1$ of a bridged tap.

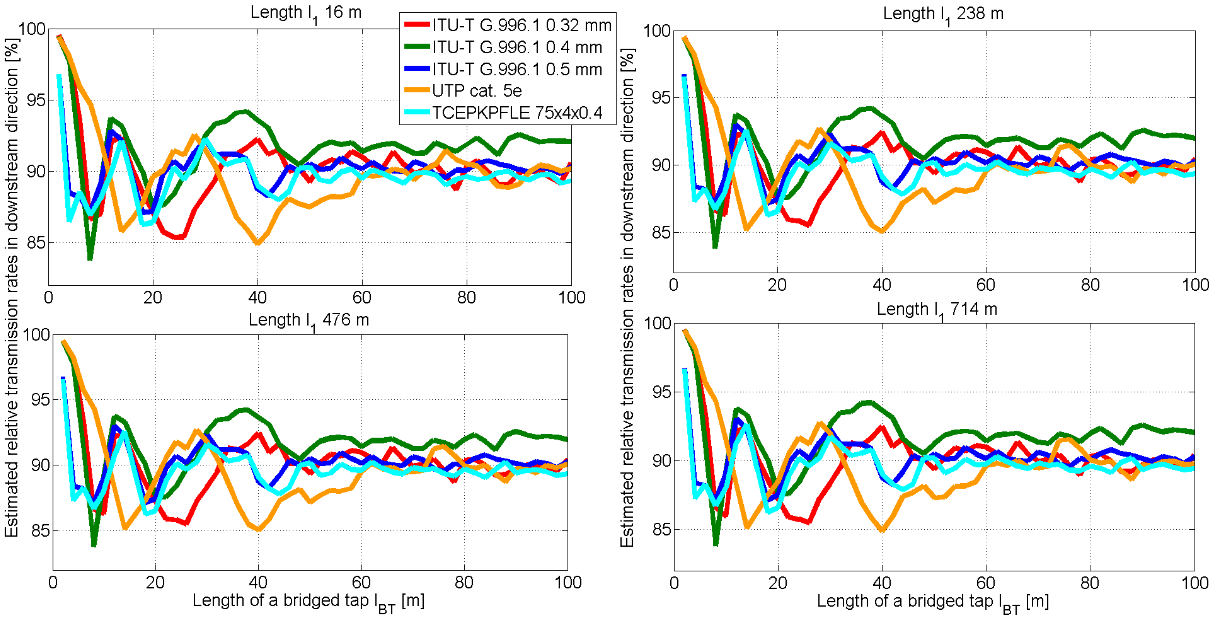

**Fig. 5:** Relative transmission rates of VDSL2 in downstream direction selected for 4 different positions $l_1$ of a bridged tap.

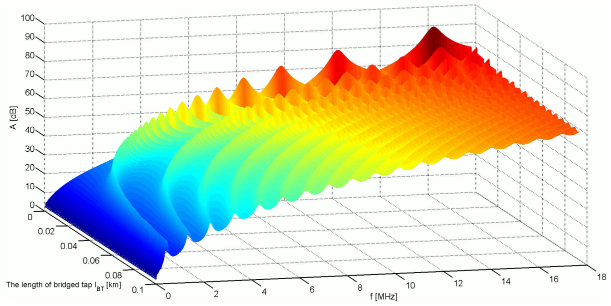

**Fig. 6:** Relative transmission rates of VDSL2 in downstream direction selected for 4 different positions $l_1$ of a bridged tap.

The input impedance $Z_{IN}$ and resulting characteristic impedance $Z_C$ of cascaded elements of transmission lines with bridged taps also play an important role and significantly influence the resulting transmission rates of VDSL systems. To illustrate the frequency dependence of input impedance of a pair no. 2 containing a bridged tap, the following graph in Fig. 7 was prepared, where $Z_{IN}$ in upstream direction for various lengths of a bridged tap $l_{BT}$ and its fixed position $l_1$ was calculated for TCEPKPFLE cable (the input impedance characteristics for other cables are similar).

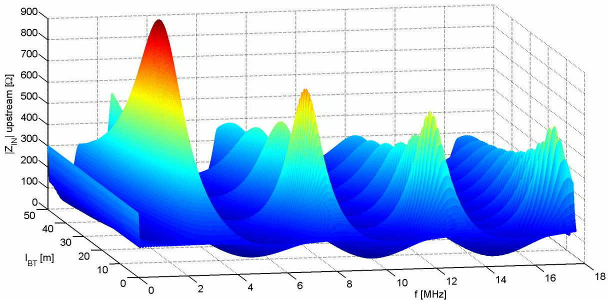

**Fig. 7:** Relative transmission rates of VDSL2 in downstream direction selected for 4 different positions $l_1$ of a bridged tap.

The input impedance of cascaded transmission line with bridged taps (pair no. 2 in this case) is significantly dependent on the position of a tap $l_1$, its length $l_{BT}$ and on the relation between the characteristic impedance of a tap $Z_{CBT}$ and the pair no. 2 $Z_{C2}$. However, all simulations performed in this paper are based on the **ABCD** matrices, therefore, all these influences were properly considered and included in the presented results of VDSL2 transmission performance.

The resulting transmission rates presented in Tab. 2 also illustrate that the upstream performance of VDSL2 lines with B8-12 profiles is affected by the presence of a bridge tap more compared to the downstream results. The longer bridged taps with the lengths $l_{BT}$ more than 50 meters also negatively influence the transmission performance of VDSL2 lines, however, the degradation is not as dramatic as in case of short bridged taps, while the transmission rates are decreased by 20 % in upstream and by 10 % in downstream direction in average.

The relative transmission rates for different metallic cables are quite similar without any significant differences. The UTP cat. 5e cable together with ITU-T G.996.1 0.32 cable show the highest sensitivity and their transmission parameters are influenced by the presence of a bridged tap the most, especially in the upstream direction. On the other hand, the performance of a VDSL2 line via TCEPKPFLE 75 × 4 × 0.4 cable is not very degraded in case of a bridged tap and AWGN environment in both directions.

## 3.2. Simulations for FEXT Environment

The previous simulation was performed for a theoretical situation with only a single VDSL2 line in a cable. However, in practice, typical cables used in access and local networks are usually occupied with many xDSL systems, therefore FEXT crosstalk is a dominant source of disturbance. To conclude its influence in case of lines with bridged taps, the following simulations were performed for 10 disturbing lines (summary FEXT crosstalk of 10 VDSL2 systems) and for 50 disturbing lines (summary FEXT crosstalk of 50 VDSL2 systems).

First, the simulation for 10 disturbing VDSL2 lines is presented. The following Tab. 3 contains the estimated transmission rates for all types of presented cables in case of lines without any bridged tap.

**Tab. 3:** Estimated transmission rates for VDSL2 lines disturbed by 10 identical VDSL2 disturbing systems in a same cable without any bridged tap.

| **Type of a cabel** | **Transmission rate [Mbps]** | |
|---|---|---|
| | Upstream | Downstream |
| ITU-T G.996.1 0.32 | 6,824 | 23,044 |
| ITU-T G.996.1 0.4 | 8,96 | 24,184 |
| ITU-T G.996.1 0.5 | 10,308 | 26,108 |
| UTP cat. 5e | 15,124 | 36,008 |
| TCEPKPFLE 75 × 4 × 0.4 | 7,436 | 23,472 |

It is evident, that the achievable transmission rates are significantly lower compared to the previous values presented in Tab. 2. The UTP cat. 5e cable has the highest FEXT attenuation, due to that the VDSL2 performance in its case is the highest in both directions. The simulations of a bridged tap for this scenario were performed again with the length of a cable $l = 0,8$ km and the variable length of a bridged tap $l_{BT}$ from 0,002 to 0,1 km and its variable position $l_1$ from 0,008 km to 0,79 km. The results are presented in the following Fig. 10, 11, 8 and 9.

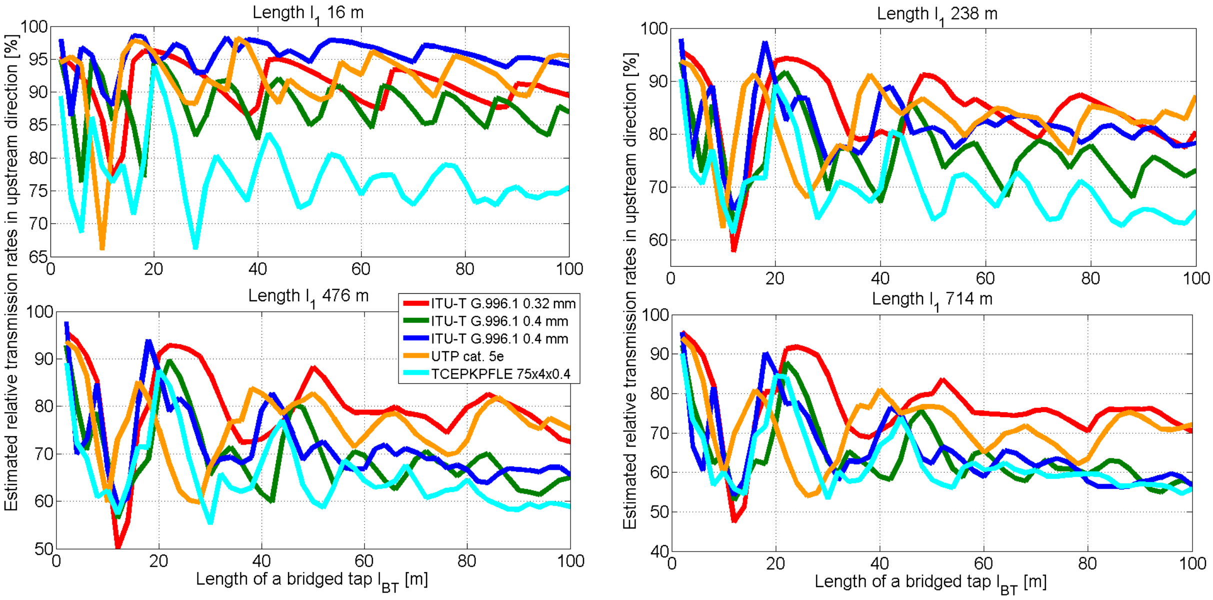

**Fig. 8:** Relative transmission rates of VDSL2 in upstream direction selected for 4 different positions $l_1$ of a bridged tap in this scenario.

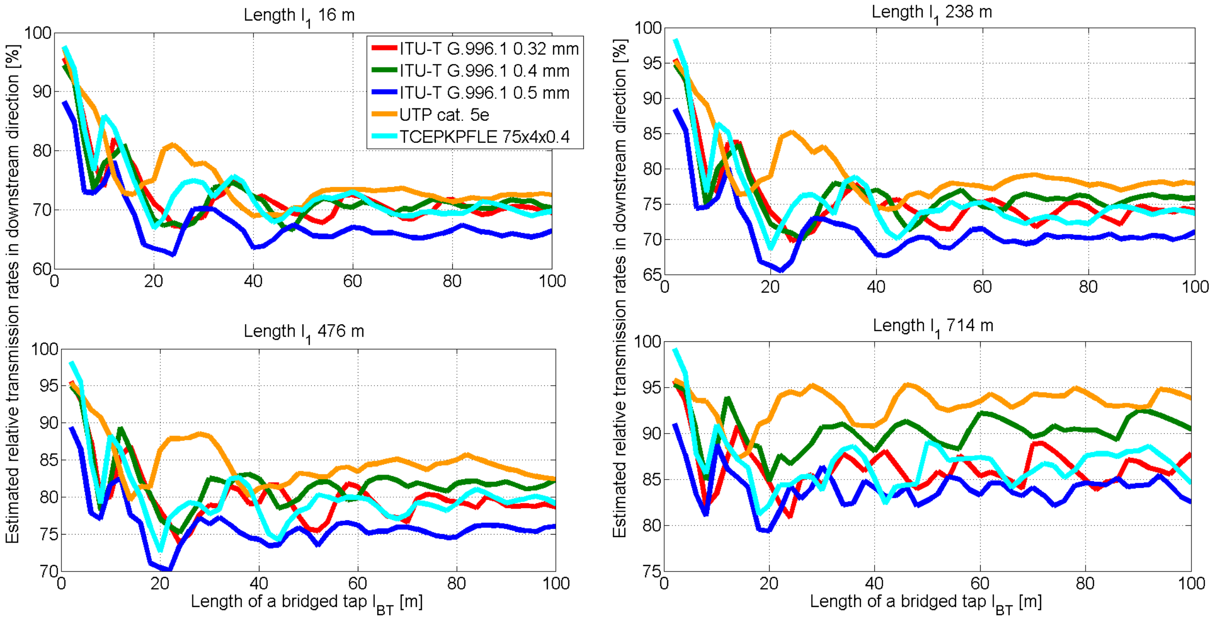

**Fig. 9:** Relative transmission rates of VDSL2 in downstream direction selected for 4 different positions $l_1$ of a bridged tap in this scenario.

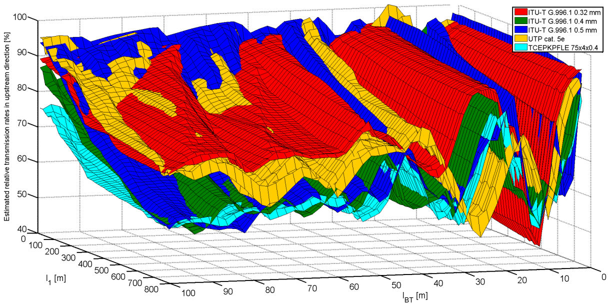

**Fig. 10:** The relative transmission rates of VDSL2 lines in upstream direction for all selected cables with 10 disturbing VDSL2 lines.

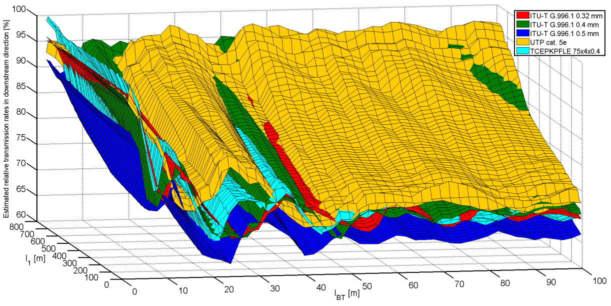

**Fig. 11:** The relative transmission rates of VDSL2 lines in downstream direction for all selected cables with 10 disturbing VDSL2 lines.

As it was expected, the FEXT attenuation depends both on the length of a tap $l_{BT}$ and also on its position $l_1$ in a cable. Due to that, the performance of VDSL2 is generally influenced by both parameters $l_{BT}$ and $l_1$ and it can be concluded that the closer the bridged tap is located to the transmitter (VDSL2 modem in case of upstream, or VDSL2 central office in case of downstream), the more negative influence it causes. Therefore, the presence of bridged taps located close to the central office negatively influences mainly the downstream transmissions, while the bridged taps located near the subscribers (end-users) primarily affect upstream transmission performance. This fact is also presented in all graphs in Fig. 10 and 11, where in case of upstream direction the degradation of transmission rates is by 10–15 % for tap located at the beginning of a line ($l_1 = 16$ meters), while for tap located at the end of a line ($l_1 = 714$ meters) the average degradation is approx. 35 %. The downstream characteristic shows the inverse dependence. These conclusions generally correspond with the results provided in [6], [7] and [10].

The comparisons between different types of cables illustrate, that due to the differences between FEXT attenuation characteristics, the presence of a bridged tap in case of UTP cat. 5e cable together with ITU-T G.996.1 0.32 cable has the lowest impact on resulting transmission rates, on the other hand, the TCEPKPFLE cable shows significant sensitivity on the presence of a bridged tap and its length, especially in upstream direction. The last scenario and simulation is also based on FEXT dominant environment with 50 disturbing VDSL2 lines.

**Tab. 4:** Estimated transmission rates for VDSL2 lines disturbed by 50 identical VDSL2 disturbing lines in a same cable without any bridged tap.

| Type of a cabel | Transmission rate [Mbps] | |
|---|---|---|
| | Upstream | Downstream |
| ITU-T G.996.1 0.32 | 5,064 | 16,348 |
| ITU-T G.996.1 0.4 | 5,196 | 17,188 |
| ITU-T G.996.1 0.5 | 5,524 | 17,228 |
| UTP cat. 5e | 10,972 | 27,12 |
| TCEPKPFLE 75 × 4 × 0.4 | 4,224 | 14,652 |

The results of simulations are presented in following Fig. 12, 13, 14 and 15.

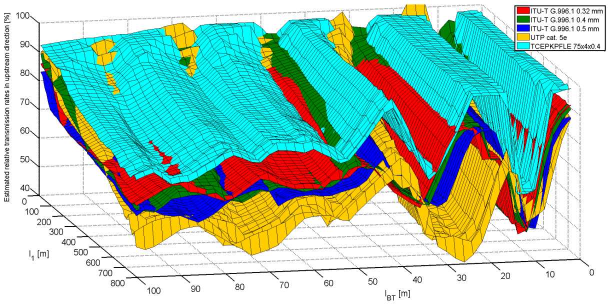

**Fig. 12:** Estimated relative transmission rates of VDSL2 lines in upstream direction for a scenario with 50 disturbing VDSL2 lines.

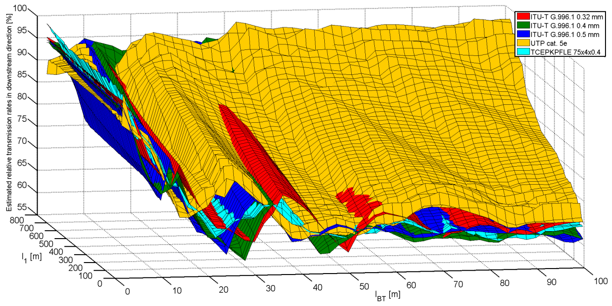

**Fig. 13:** Estimated relative transmission rates of VDSL2 lines in downstream direction for a scenario with 50 disturbing VDSL2 lines.

The more intensive noise caused by the FEXT crosstalk from 50 VDSL2 lines further decreased the achievable transmission rates as can be seen by comparing the values in Tab. 3 and 4. The results of relative transmission rates for different cables with variable bridged tap verify previous conclusions for a situation with 10 disturbing VDSL2 lines. The degradation of transmission rate in upstream direction is between 15–40 % approx. for ITU-T cables as well as TCEPKPFLE cable, the UTP cat. 5e cable thanks to its higher FEXT attenuation reaches better results,

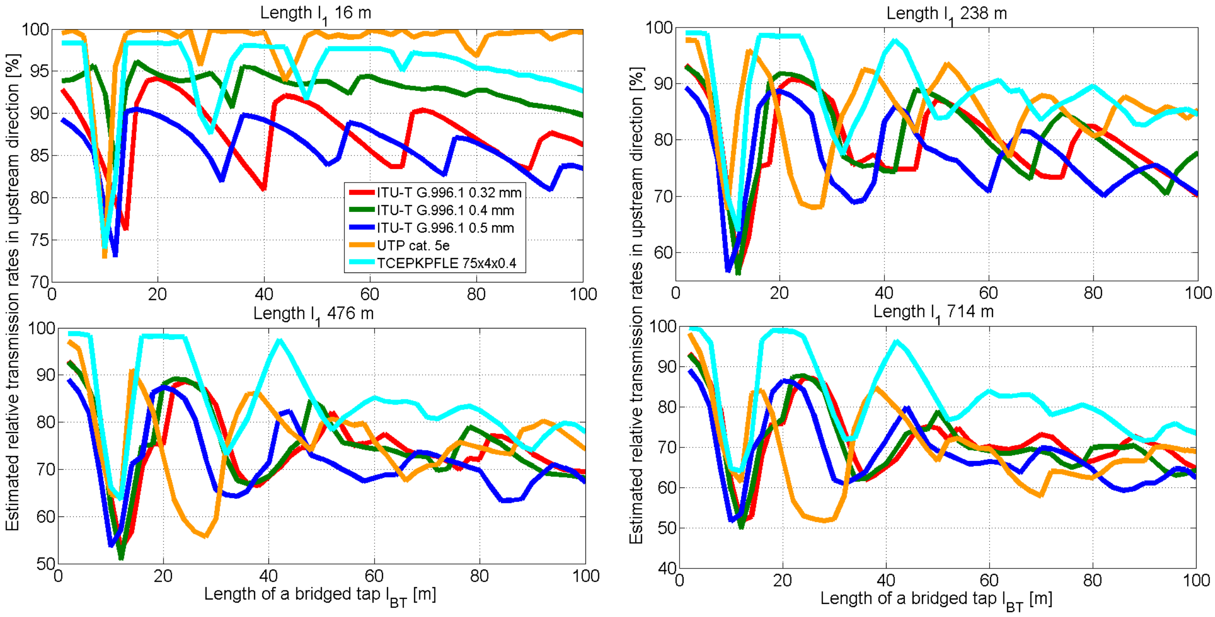

**Fig. 14:** Results of simulation performed for a scenario with 50 disturbing VDSL2 lines for selected positions of a tap $l_1$ in upstream direction.

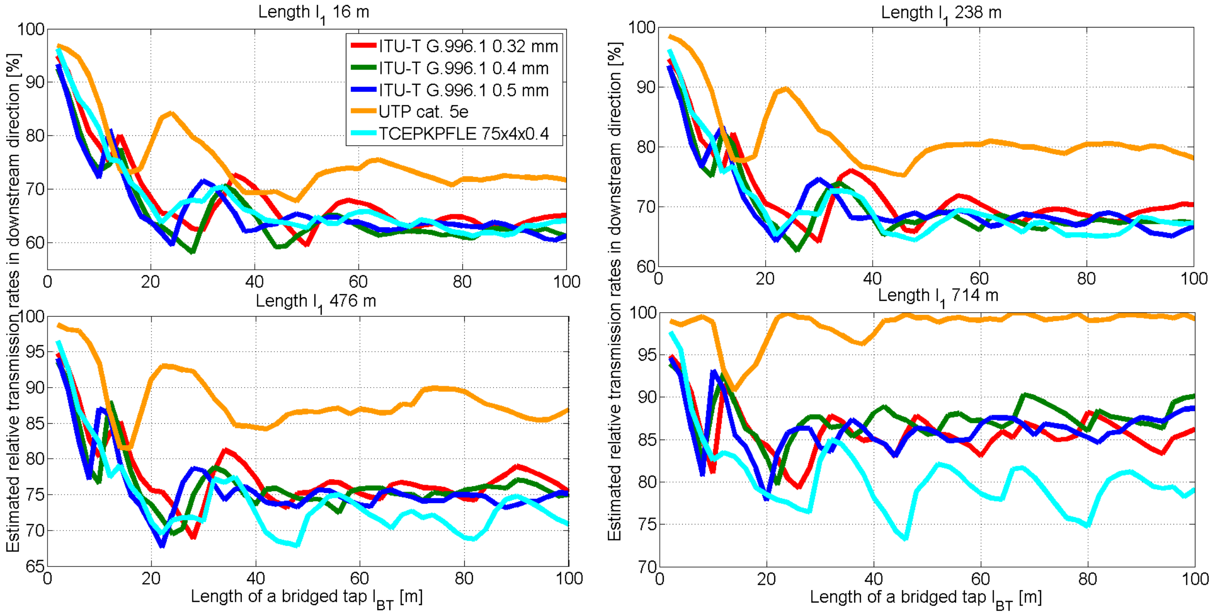

**Fig. 15:** Results of simulation performed for a scenario with 50 disturbing VDSL2 lines for selected positions of a tap $l_1$ in downstream direction.

which is also evident for downstream direction. The average degradation in this direction is usually between 10–35 % depending on the position of a tap, its length and type of a cable.

## 4. Conclusion

This paper analyzed the influence of bridged taps on the transmission performance of modern VDSL2 lines. The simulations were focused on two different sources of noises and disturbances in metallic cables - AWGN and FEXT and the estimations of transmission rates were also performed for 5 different types of metallic cables mostly used in access and local networks.

The results of simulations verified that the attenuation characteristics of metallic lines are influenced only by the length of a tap, however, the FEXT crosstalk depends both on the length of a tap and also its position. Due to that, the results for AWGN environment do not depend on the position of a tap, while the VDSL2 performance in FEXT dominated scenarios is based on both of its parameters. The simulations for FEXT scenario also verified that the location of a tap heavily influences mainly the transmitter side of a VDSL2 line, therefore the tap located close to the CO side effects mainly the transmission rate in downstream direction, while the tap in subscriber premise degrades mostly the upstream performance.

The comparisons for 5 different types of cables illustrate different sensitivity of each cable on the presence of a tap in AWGN or FEXT dominated situations. Thanks to the highest FEXT attenuation, the relative transmission rates of VDSL2 lines using UTP cat. 5e cable were the highest and were not influenced by the presence of bridged tap that much. On the other hand, since the UTP cables are not typically used for access networks, the ITU-T G.996.1 0.32 cable also represents a potential solution. However, the differences between standard telecommunication cables used in the simulations here, ITU-T G.996.1 0.32, 0.4, 0.5, and real TCEPKPFLE cable are usually not very critical.

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