



Influence of Bridged Taps on Transmission Performance of VDSL2 Lines

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Abstract: The second generation of Very-High Speed Digital Subscriber Lines (VDSL2) represents a modern high-speed solution for present last-mile access networks. However, the transmission performance of VDSL2 lines is heavily dependent on the real conditions of symmetrical pairs and quads in local metallic lines and cables. One of the frequent elements in metallic access networks, which can negatively influence the transmission performance of modern digital systems, is bridged taps. This paper presents an analysis of the influence of bridged taps on transmission capacity of VDSL2 lines by using ABCD matrices. Thanks to that, the simulations can be performed for various scenarios and amounts of bridged taps and their parameters by simply cascading necessary matrices. The first part describes the models, while the second part is focused on simulations of VDSL2 digital subscriber lines for several examples with resulting conclusions.

Keywords: bridged taps; metallic lines; VDSL2; attenuation; FEXT

I. Introduction

The second generation of Very-High Speed Digital Subscriber Lines (VDSL2) belongs to xDSL digital systems, which are still often used in last-mile access networks to provide high-speed digital connections mainly for households and small companies [1]. These xDSL lines effectively exploit existing symmetrical pairs of local metallic cables and lines [2]. Thanks to that, they provide reliable and economically effective connections and can potentially offer transmission rate of tens of Mbps in both directions [2]. However, the transmission rate of VDSL2 lines is significantly dependent on real conditions and specific situations in metallic lines and cables in access networks [3]. Moreover, crosstalk, especially far-end crosstalk (FEXT) and other disturbances can limit the maximum achievable transmission capacity of VDSL2 lines [4]. Another potential problem, which can complexly affect the performance of these lines, is bridged taps, which are frequently located in present metallic cables in last-mile segment or in local networks [5]. The bridged taps can be easily caused and created in access networks due to various reasons, usually during the process of repairing the metallic cable or due to replacing the old cables with new lines, when old unused parts of old cables are not properly removed.

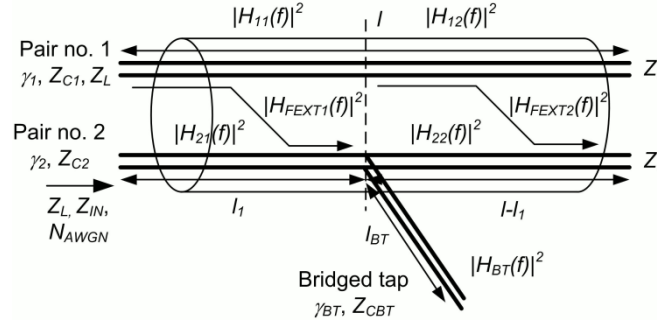
The problem of bridged taps in access networks was already studied and reported in several papers [6], [7], which introduced some basic conclusions. However, the methods presented in these papers can be used for simulations of only limited numbers of bridged taps. On the other hand, the technique used 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, which makes the resulting method more versatile. Moreover, the presence of bridged taps in transmission line can also negatively affect the input impedance and can cause impedance mismatches in case of load impedances on both sides of lines as well. Another potential problem represents the FEXT crosstalk. That is why the analyses of FEXT character for situations with bridged taps were performed as well.

The first part of this article is focused on mathematical derivation of presented model and method of calculations. The second part consists of simulations of VDSL2 for lines with bridged taps based on the presented models. Several examples with conclusions about the influence of bridged taps on the performance of VDSL2 lines are presented in the last section as well.

II. Modelling of Transmission Lines with Bridged Taps

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

Figure 1 The schematic illustration of a situation with bridged tap.



The propagation constants and characteristic impedances of both pairs are γ_1 , γ_2 and Z_{c1} , Z_{c2} respectively. The propagation constant of a bridged tap is γ_{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} .

According to the [3], the ABCD matrix of a transmission line (metallic pair), $ABCD_L(f)$, and ABCD matrix of bridged tap, $ABCD_{BT}(f)$, can be expressed as:

$$ABCD_L(f) = \begin{pmatrix} \cosh(l \cdot \gamma(f)) & Z_c(f) \cdot \sinh(l \cdot \gamma(f)) \\ \frac{\sinh(l \cdot \gamma(f))}{Z_c(f)} & \cosh(l \cdot \gamma(f)) \end{pmatrix} \quad ABCD_{BT}(f) = \begin{pmatrix} 1 & 0 \\ \frac{1}{Z_{CBT}(f) \cdot \coth(l_{BT} \cdot \gamma_{BT}(f))} & 1 \end{pmatrix} \quad (1)$$

where l is the length of a pair, $\gamma(f)$ its propagation constant and $Z_c(f)$ represents a characteristic impedance. Similarly, l_{BT} stands for the length of bridged tap, $Z_{CBT}(f)$ and $\gamma_{BT}(f)$ for its char. impedance and propagation constant respectively. The situation in Fig. 1 for the second line with one bridged tap can be described using ABCD matrices (1) as:

$$ABCD(f) = ABCD_{L1}(f) \cdot ABCD_{BT}(f) \cdot ABCD_{L2}(f); \quad ABCD(f) = \begin{pmatrix} a(f) & b(f) \\ c(f) & d(f) \end{pmatrix} \quad (2)$$

where $ABCD(f)$ represents the resulting matrix for cascaded situation, $ABCD_{L1}(f)$ and $ABCD_{L2}(f)$ are matrices of two sections of transmission lines with lengths l_1 and $l-l_1$ and $ABCD_{BT}(f)$ stands for the matrix of bridged tap. The input impedance of the second pair with a bridged tap can be expressed by [9] and previous matrices (1), (2) as:

$$Z_{IN}(f) = \frac{Z_L \cdot a(f) + b(f)}{Z_L \cdot c(f) + d(f)} \quad (3)$$

where $Z_{IN}(f)$ is an input impedance of pair with bridged tap, Z_L is a load impedance and $a(f)$, $b(f)$, $c(f)$ and $d(f)$ are elements of previous $ABCD(f)$ matrix (2). Generally, the power transfer function $|H(f)|^2$ can be calculated using ABCD matrices and formula provided by [9] as:

$$|H(f)|^2 = \frac{2 \cdot |Z_L| \cdot |Z_S + Z_{IN}|}{|Z_L \cdot a(f) + b(f) + Z_L \cdot Z_S \cdot c(f) + Z_S \cdot d(f)|} \cdot \frac{\cos \theta_L}{\cos \theta_{SIN}} \quad (4)$$

in which Z_L is a load impedance, Z_S is an impedance of a source of signal, θ_L represents a phase angle of Z_L and θ_{SIN} a phase angle of a term $Z_S + Z_{IN}$. Using the expression (4), power transfer functions of all sections of both pairs and also the transfer function of bridged tap in Fig. 1 can be calculated using proper ABCD matrices for each section. The attenuation for a situation described in Fig. 1 with a single bridged tap can be expressed using previous equations (2), (4) for pair no. 1 without a bridged tap $A_1(f)$ and pair no. 2 with bridged tap $A_2(f)$ as:

$$A_1(f) = -10 \cdot \log(|H_{11}(f)|^2 \cdot |H_{12}(f)|^2) [dB]; \quad A_2(f) = -10 \cdot \log(|H_{21}(f)|^2 \cdot |H_{BT}(f)|^2 \cdot |H_{22}(f)|^2) [dB] \quad (5)$$

The simulation of FEXT crosstalk is based on standard simple FEXT model presented in [8]:

$$|H_{FEXT}(f)|^2 = K_{FEXT} \cdot f^2 \cdot l \cdot |H(f)|^2 \quad (6)$$

where $|H_{FEXT}(f)|^2$ represents the FEXT power transfer function, f is a frequency, l is a length of transmission line, $|H(f)|^2$ stands for power transfer function of a line and K_{FEXT} is a crosstalk parameter. This crosstalk parameter represents the summary capacitive and inductive unbalance between each two symmetrical pairs in a cable and can be obtained through the integration of these unbalances along the entire of a cable. The resulting FEXT power transfer function for situation described in Fig. 1 can be expressed using multiple cascaded elements, as presented in [10]. 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] and according to that, the summary FEXT transfer function for situation in Fig. 1 can be expressed as:

$$|H_{FEXT}(f)|^2 = |H_{FEXT1}(f)|^2 \cdot |H_{BT}(f)|^2 \cdot |H_{22}(f)|^2 + |H_{11}(f)|^2 \cdot |H_{FEXT2}(f)|^2$$

$$A_{FEXT}(f) = -10 \cdot \log(|H_{FEXT}(f)|^2) \quad [dB] \quad (7)$$

where $A_{FEXT}(f)$ is resulting FEXT attenuation between both pairs.

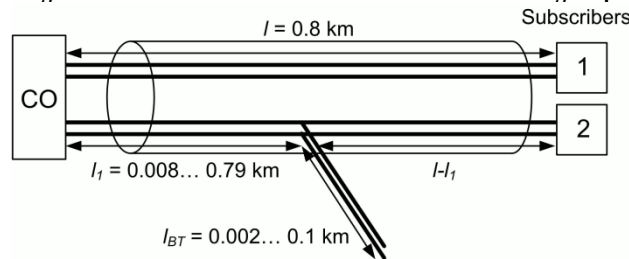
III. VDSL2 Performance over Lines with Bridged Taps

This chapter contains the description and results of performed simulations of VDSL2 over lines with bridged taps. All following calculations were performed for VDSL2 lines with frequency plan B8-12 for Europe up to 17 MHz (998ADE17), which are typically used in Czech Republic today. Downstream and upstream directions were analysed and separate graphs for both directions are always presented together with resulting maximum and minimum achieved transmission speed. 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 recommendation G.993.2 [11]. The metallic cable used for simulations has specification TCEPKPFLE 75x4x0.4. Generally, the simulations were performed for the situation with two symmetrical pairs in a cable, with both pairs running VDSL2 lines, while pair no. 2 contains one or more bridged tap(s) with either fixed or variable lengths or positions. The simulations were performed for three different scenarios.

A. The Results for a Scenario with Single Bridged Tap

In this scenario, pair no. 2 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. The situation is schematically illustrated in the following Fig. 2.

Figure 2 The schematic illustration of a situation with a single tap.



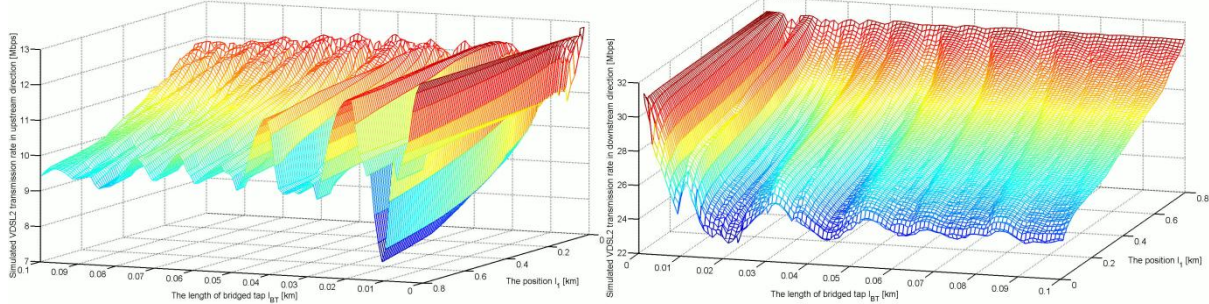
First, the values of upstream/downstream transmission rates of VDSL2 line without any bridged tap (pair no. 1) were calculated and are presented in Tab. 1.

Table I Calculated transmission rates for a VDSL2 line without any bridged tap.

	Upstream	Downstream
Transmission rate [Mbps]	12.904	31.152

Next, the simulation for the second pair with a bridged tap was performed. The following Fig. 3 contains the results of simulated transmission rates for both transmission directions.

Figure 3 The results of calculation of VDSL2 transmission rates in both directions for the first scenario with a single bridged tap.



The results in previous Fig. 3 illustrate the negative influence of bridged taps on transmission rates of VDSL2 lines. This influence depends on the length of bridged taps and also on their positions. It can be 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]. On the other hand, the impact of long bridged taps is noticeable in the entire frequency band, because their presence introduces flat attenuation character across wide frequency range. Due to that, both graphs in Fig. 3 do not contain any sharp peaks and dips in case of a long bridged taps with lengths above 0.05 km. Moreover, 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. These conclusions generally correspond with the results provided in [6], [7] and [9]. The maximum and minimum achieved transmission rates for both directions in this scenario are presented in the following Tab. 2.

Table II The maximum and minimum transmission rates in both directions for scenario with a single bridged tap.

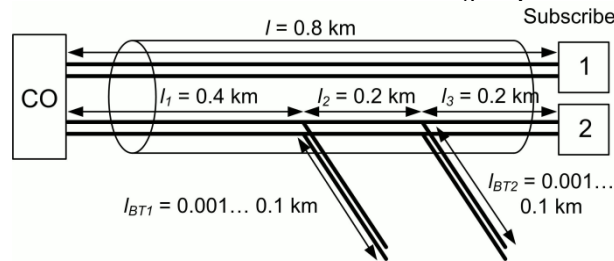
	Upstream	Downstream
Maximum trans. rate [Mbps]	12.816	31.130
Minimum trans. rate [Mbps]	7.954	22.820

B. The Simulations of VDSL2 Lines with Two Bridged Taps

1) Two Bridged Taps with Variable Lengths

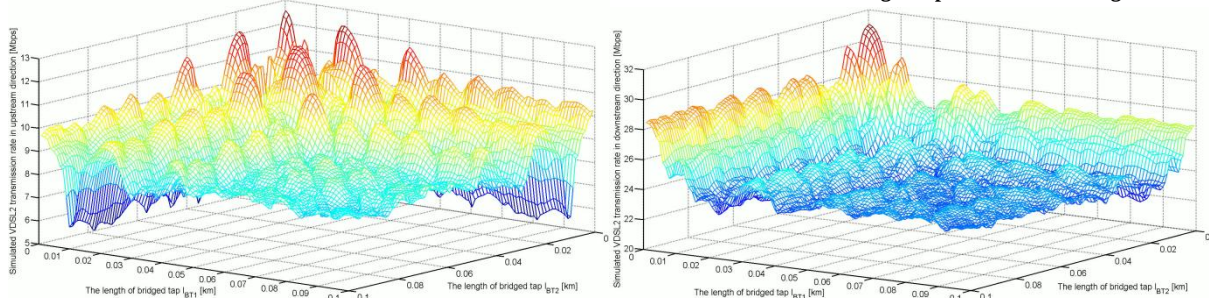
This scenario assumes the presence of two bridged taps connected to the pair no. 2 and is described in Fig. 4, in which the locations of both bridged taps are fixed and their lengths l_{BT1} , l_{BT2} vary from 0.001 to 0.1 km. The transmission rates for VDSL2 line for pair no. 1 are the same as in the previous scenario presented in Tab. 1.

Figure 4 The schematic illustration of a scenario with two bridged taps with variable lengths.



The calculation of transmission rate in both directions was performed and its result is presented in Fig. 5.

Figure 5 The simulation of VDSL2 transmission rates for both directions in case of two bridged taps with variable lengths.



The results of simulations for a scenario with two bridged taps with variable lengths verify previous conclusions. It is evident, that the length of a bridged tap, which is closer to the transmitter side in both transmission directions (l_{BT1} in case of downstream and l_{BT2} in case of upstream direction), affects the resulting transmission rate more compared to the second bridged tap. Generally, the maximum and minimum achieved transmission rates in both directions are lower compared to the first scenario with only one single bridged tap, because the presence of multiple bridged taps causes more frequency peaks and dips in characteristics of attenuation, FEXT and impedance. The upstream performance is evidently more influenced by the presence of two bridged taps and the Fig. 5 contains more peaks in the resulting simulation. Moreover, there are several critical lengths of both bridged taps, for which the resulting transmission performance steeply increases or decreases. This is given by the ratios between lengths of both taps and wavelengths for particular VDSL2 frequency upstream/downstream ranges in B8-12 profile. Tab. 3 contains values of minimum and maximum achievable trans. rates for both directions.

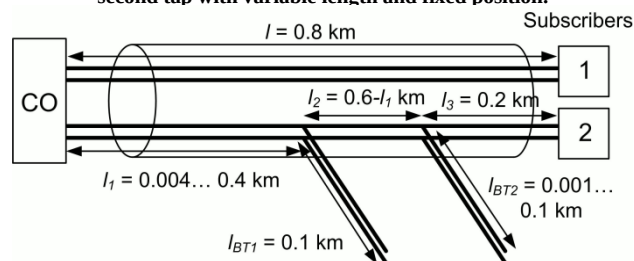
Table IIIThe maximum and minimum trans. rates in both directions for a scenario with two bridged taps with variable lengths.

	Upstream	Downstream
Maximum trans. rate [Mbps]	12.894	31.034
Minimum trans. rate [Mbps]	5.992	21.970

2) First Bridged Tap with Variable Position and Second Bridged Tap with Variable Length

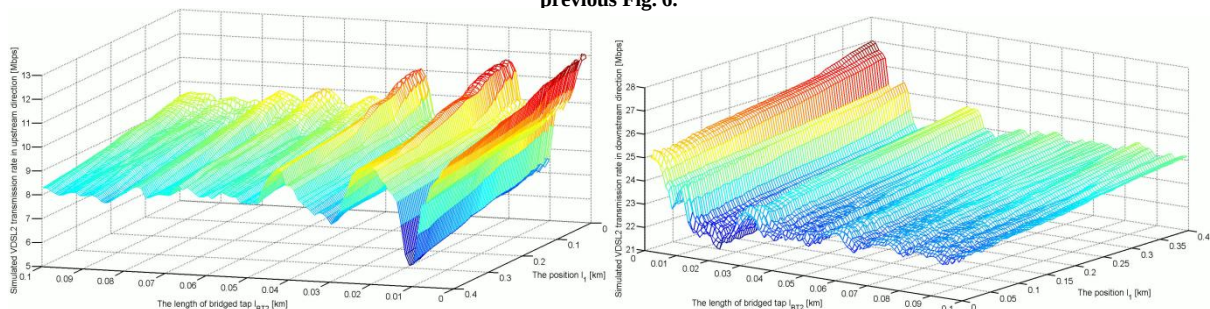
This situation is illustrated in next Fig. 6, in which the first bridged tap has fixed length $l_{BT1} = 0.1$ km while its position l_1 varies from 0.004 to 0.4 km from the beginning of the pair. The location of the second bridged tap is fixed at the distance of 0.2 km from the far-end, while its length l_{BT2} varies from 0.001 to 0.1 km.

Figure 6The schematic illustration of a situation with two bridged taps – first bridged tap with fixed length and variable position, second tap with variable length and fixed position.



The results of simulations of VDSL2 performance in both transmission directions for this situation are presented in following Fig. 7.

Figure 7The result of simulation performed for VDSL2 line in both directions for a situation with two bridged taps described in previous Fig. 6.



It is obvious, that the upstream performance of VDSL2 line is mostly affected by the second bridged tap and its varying length. The transmission rate in downstream direction increases with incrementing the position l_1 , while the varying length of the second bridged tap l_{BT2} results mainly in wavy character of transmission performance of VDL2 line. Tab. 4 contains the results of minimum and maximum achievable transmission rates in both directions for this situation.

Table IVThe maximum and minimum trans. rates in both directions for a scenario with two bridged taps described in Fig. 6.

	Upstream	Downstream
Maximum trans. rate [Mbps]	12.498	27.220
Minimum trans. rate [Mbps]	5.984	21.124

IV. Conclusions

This article is focused on the problem of bridged taps in metallic lines and cables and their influence on the transmission performance of modern high-speed VDSL2 system. The presented method of modeling the lines with bridged taps is based on the ABCD matrices and cascaded elements of lines. The calculations were performed for three different scenarios. First, the influence of a single bridge tap was analyzed. The previous Fig. 3 together with calculated transmission rates clearly illustrates, that the presence of a bridged tap primarily affect the transmitter side of a line. Moreover, the influence on attenuation characteristic depends on the length of a tap (especially on the rate between its length and the wavelength of propagating signal), while the rate of FEXT crosstalk depends on its length and also the position. These conclusions were further verified with the simulations performed for the second scenario, in which two bridged taps with either fixed positions and variable lengths or variable positions and fixed lengths were analyzed. However, all presented simulations and calculations were performed for simple bridged taps without any loading impedances. Therefore, in practice, the numerical results might differ if the taps were terminated. Still, the general conclusions presented in previous chapter are valid for any situation. The model presented in this article can be further extended for situations with multiple bridged taps or lines by simply cascading more ABCD matrices and elements of transmission lines.

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Acknowledgments

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