CROSSTALK MODELING FOR CALCULATION OF ADSL2+ DOWNSTREAM BIT RATES

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Abstract

Crosstalk is the main limiting factor in DSL (Digital Subscriber Line) transmission services; especially in cases when number of DSL transmission systems in a cable binder increases. Successful methods for decreasing crosstalk will improve reach, and bit rate of DSL systems. As well, from the spectrum management point of view, it is very important to have convenient positions of transmission systems in a cable binder, because of the way they generate crosstalk on a given DSL transmission system.

In this paper we provide calculation of downstream bit rate on ADSL2+ local loops limited by crosstalk noise. Two parameters are crucial for our calculation method: number of active ADSL2+ systems in a cable binder, and their positions inside the binder.

In order to calculate bit rate on ADSL2+ loops we have provided an in-depth analysis of a local telecom operator's cable infrastructure in terms of crosstalk. On the basis of measurements carried out on twisted quad cables in the frequency range from 20 kHz up to 2.2 MHz, and on twisted pair lengths between 300 m and 1700 m, we have derived theoretical models of far-end crosstalk (FEXT) and insertion gain. The measurements were performed on cables that are part of operating infrastructure, not on cables on a reel, thus providing a true insight into the situation telecoms worldwide are facing today.

Simulation results indicate that number and selection of active loops in a cable binder have a great impact on a bit rate. Presented bit rate calculation method and crosstalk models are a useful tool for planning of access network and ADSL-based services.

Keywords: ADSL2+, star quads, FEXT, insertion gain, spectrum management.

Presenting Author's biography

Vedran Mikac received the B.Sc.degree in electrical engineering in 2006 from the Faculty of Electrical Engineering and Computing, University of Zagreb at Zagreb, Croatia. Currently, he is working as a Ph.D. student and research assistant at the Department of Telecommunications, Faculty of Electrical Engineering and Computing. His interests include signal processing in communications, information theory and access telecommunication networks.

1 Introduction

DSL (Digital Subscriber Line) systems are widespread transmission systems in copper access networks. Today, among all ADSL standards, ADSL2+ (Asymmetric DSL version 2 Plus) guarantees highest bit rates in a downstream direction. Using frequencies up to 2.2 MHz, ADSL2+ is capable of supporting download transmission rates up to 25 Mbit/s on short loops, what makes it a technology that is appropriate for transport of bandwidth demanding services, such as multimedia and video. There are a lot of barriers which limit achievable bit rates of these systems. The major barrier is capacitive and inductive coupling between signals transmitted on different subscribers loops, known as crosstalk, [1] [5] [6].

This paper describes the method of downstream bit rate calculation of ADSL2+ systems limited by far-end crosstalk (FEXT). We have obtained insertion gain and crosstalk measurements from a local telecom operator. The measurements were performed on a deployed cable infrastructure, on loops between 300 m and 1700 m in length, in the frequency range from 20 kHz up to 2.2 MHz. Based on measurements, we have presented and analyzed crosstalk and insertion gain 1% worst-case models. The 1% worst-case models are commonly used crosstalk statistical models that correspond to 1% worst-case value. This means that in a given cable not more than 1% of its pairs will experience crosstalk that is worse than crosstalk predicted by the model [5] [6]. The models can be used in any access network built up with twisted quad cables. Finally, bit rate calculation was done taking into account several important parameters: positions of the transmission systems inside a cable binder, bit loading table and crosstalk.

There are three main contributions of this paper. First, we have presented a method for an empirical ADSL2+ loop bit rate calculation. Second, crosstalk models used in this paper were developed on the basis of measurements performed by a local telecom operator, thus providing an insight into the real situation in a cable infrastructure. Finally, the methods for bit rate calculation could be used for planning of access network and ADSL-based services, especially in networks where local loop unbundling process has begun.

The paper is organized as follows. Section 2 describes prerequisites needed for the crosstalk and insertion gain models, such as cable description and cable filling strategy. Section 3 explains how to normalize crosstalk to a specified length. In section 4 we describe the insertion gain and the crosstalk models based on measurements. Results of downstream bit rate calculation are elaborated in section 5. Finally, some concluding remarks are offered in section 6.

2 Crosstalk and insertion gain modelling prerequisites

2.1 Cable description

Measurements used as a basis for local loop analyses in this paper were performed on cables with polyethylene insulation and laminated polyethylene sheath. Such cable consists of arbitrary number of basic groups (30, 60 or 100), but we do not differentiate cables with different number of basic groups, because we do not focus on the interference between pairs in different basic groups. Each basic group consists of five star quads. Basic groups are combined into a main group that consists of 50 quads.

In Fig. 1 a cross section of a basic group is shown. Numbering system shown in this figure will be used throughout the paper.

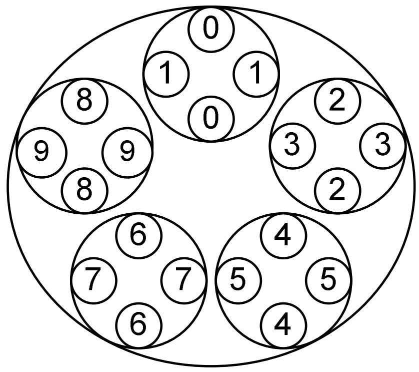

Fig. 1 Basic group cross section with pair numbering

2.2 Cable filling strategy

Conclusion derived from the Fig. 1 is that the crosstalk from the pair 0 to the pair 1 is not the same as the crosstalk from the pair 0 to the pair 4. Consequently, it is not the same whether two ADSL2+ systems are applied in the same quad, in adjacent quads or in quads that are separated by another quad. To determine which of these cable filling scenarios is the best, and which one is the worst, we have proposed a method described in the following paragraph.

A victim pair is a pair on which other pairs in a basic group generate highest level of crosstalk. In our case we will assume that the victim pair is pair 0. Number of ADSL2+ systems assigned to pairs in a basic group is called filling ratio (Tab. 1). For a given filling ratio, the algorithm, using simple recursion, tests all the possible combinations. As there are not many possible combinations, proposed method was sufficient for the task. If the algorithm finds several combinations that generate the same level of crosstalk on the victim pair, only the first one will be considered. From the models we have assumed that the majority of crosstalk power transfer occurs between pairs in a same quad. When interfering pairs are in quads that are separated by another quad the influence of one pair to another is minimal. Using the proposed method, the best and the worst basic group filling strategies are presented in the Tab. 1.

Tab. 1 The best and the worst filling strategies, the victim pair is pair 0

Filling ratio, [%]	Best case	Worst case
20	4	1
30	2 6	1 2
40	8 2 4	1 2 3
50	2 4 6 8	8 9 1 2
60	1 2 4 6 7	8 9 1 2 3
70	1 2 4 5 6 8	8 9 1 2 3 4
80	1 2 3 4 6 7 8	8 9 1 2 3 4 5

3 Far-end crosstalk measurements and conversion

In this section we present methodology of FEXT measuring and procedures we have used to normalize crosstalk on a given reference length. We have chosen that the reference loop length is 1000 m.

3.1 FEXT measurements

Our FEXT measurements were carried out with a line analyzer Trend Communications ALT2000 used at both ends of a line, in the frequency range from 20 kHz up to 2.2. MHz. Frequency samples were equally spaced (every 9,046 kHz).

3.2 FEXT conversion

FEXT is the major limiting factor when several ADSL2+ systems are applied in a same basic group in a cable binder. FEXT is very dependant on a loop length. To correctly calculate crosstalk for different loop lengths we recommend the procedure based on the ETSI FEXT model, [1], i.e.:

$$\left|H_F(f,l,N)\right|^2 = N^{0.6} K_F f^2 l \left|H_c(f,l)\right|^2, \quad (1)$$

where N is the number of disturbers in a cable, K_F is constant (for European cables, FEXT constant is typically considered to be $10^{-16.5}$ $Hz^{-2}km^{-1}$ [1]), f is frequency in Hz, l is loop length in km, and $\left|H_c(f,l)\right|$ is magnitude of channel transfer function.

Quality of the crosstalk model greatly depends on the number of performed measurements. We have assumed that the majority of measurements are usually carried out on an average loop length. Therefore our model has a characteristic of a reference model, wherein the average loop length is the reference length. To convert crosstalk to different length, we suggest following method:

$$\frac{\left|H_F(f,l)\right|^2}{\left|H_F(f,l_0)\right|^2} = \frac{K_F}{K_F}\frac{l}{l_0}\frac{f^2}{f^2}\frac{\left|H_c(f,l)\right|^2}{\left|H_c(f,l_0)\right|^2}, \quad (2)$$

$$\frac{\left|H_F(f,l)\right|^2}{\left|H_F(f,l_0)\right|^2} = \frac{l}{l_0}\frac{\left|H_c(f,l)\right|^2}{\left|H_c(f,l_0)\right|^2}, \quad (3)$$

$$\left|H_F(f,l)\right|^2 = \left|H_F(f,l_0)\right|^2 \frac{l}{l_0}\frac{\left|H_c(f,l)\right|^2}{\left|H_c(f,l_0)\right|^2}. \quad (4)$$

We have assumed that the magnitude squared of channel transfer function is [2]:

$$\left|H_c(f,l)\right|^2 = e^{-2\alpha(f)l}, \quad (5)$$

where f is frequency in Hz, l is loop length in km, and $\alpha(f)$ is local loop's attenuation constant in Np/km.

Applying Eq. (5) to the Eq. (4) gives a following result:

$$\left|H_F(f,l)\right|^2 = \left|H_F(f,l_0)\right|^2 \frac{l}{l_0} e^{-2\alpha(f)(l-l_0)}. \quad (6)$$

Evaluation of the Eq. (6) requires local loop attenuation model and FEXT models on the reference loop length (1000 m). These models are presented in subsections 4.1 and 4.2, respectively.

4 Reference model description

In this section we describe the local loop attenuation and crosstalk models used to calculate maximum achievable downlink bit rates. We also present the assumptions used in these calculations.

4.1 Attenuation model on the reference loop length

By applying previously described method on the data supplied by the local telecom operator, we have created graphs showing average value (Fig. 2) and standard deviation (Fig. 3) of local loop insertion gain.

For frequencies lower than 0.4 MHz, fitted average value (*avg*) of the insertion gain can be described by

$$G(f)_{avg} = -7.58163 - 1.77301\cdot 10^{-5} f \text{ [dB/km]}, \quad (7)$$

where f is frequency in Hz. The appropriate model for frequencies between 0.4 MHz and 2.2 MHz is

$$G(f)_{avg} = -0.0226959\sqrt{f} \text{ [dB/km]}, \quad (8)$$

where f is frequency in Hz.

Fitted standard deviation (*std*) of the insertion gain can be modelled using the following equation:

$$G(f)_{std} = 0.621285 + 3.89672\cdot 10^{-7} f \text{ [dB/km]}, \quad (9)$$

where f is frequency in Hz.

Fitted 1% worst-case model of the insertion gain can be expressed by the following equation:

$$G(f)_{1\%} = -0.0251356\sqrt{f} \text{ [dB/km]}, \quad (10)$$

where f is frequency in Hz. Fig. 4 shows 1% worst-case model of the insertion gain.

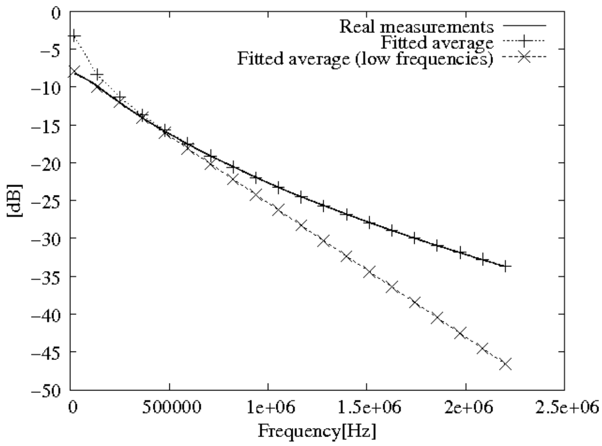

Fig. 2 The average insertion gain

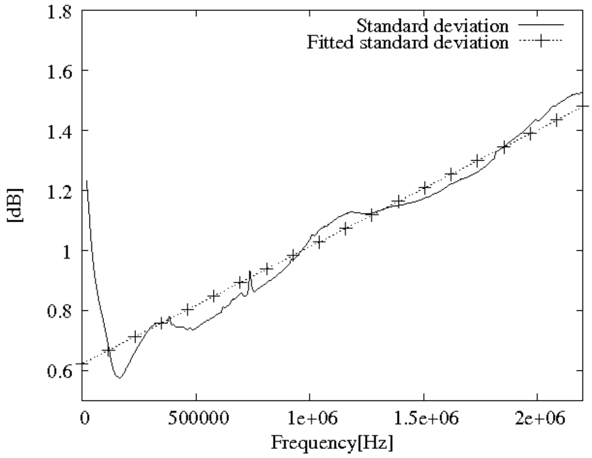

Fig. 3 Standard deviation of the insertion gain

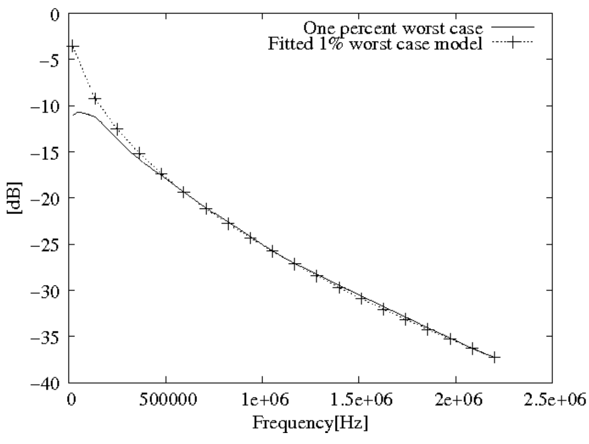

Fig. 4 The 1% worst-case model of the insertion gain

Finally, the relationship between local loop attenuation constant (α) and local loop insertion gain (*G*) on a loop that is 1 km long is the following [3]:

$$\alpha(f) = -G(f) \text{ [dB/km]}. \quad (11).$$

It is important to notice that the Eq. (11) returns values in dB/km. This value of α cannot be used directly in Eq. (6), because it has to be converted to Np/km. This can be done by dividing the result from Eq. (11) by 8.686.

4.2 Crosstalk models on the reference loop length

As it was mentioned earlier, there are three different crosstalk types in a basic cable group. To easily reference them in the figures and further in the paper, we use the naming convention described in Tab. 2.

Tab. 2 Crosstalk naming convention

Name	Description
FEXT-I	crosstalk between pairs in the same quad
FEXT-N	crosstalk between pairs in the neighbouring quads
FEXT-A	crosstalk between pairs in quads mutually separated by third quad

Fig. 5 and Fig. 6 show average value and fitted standard deviation of these three crosstalk types.

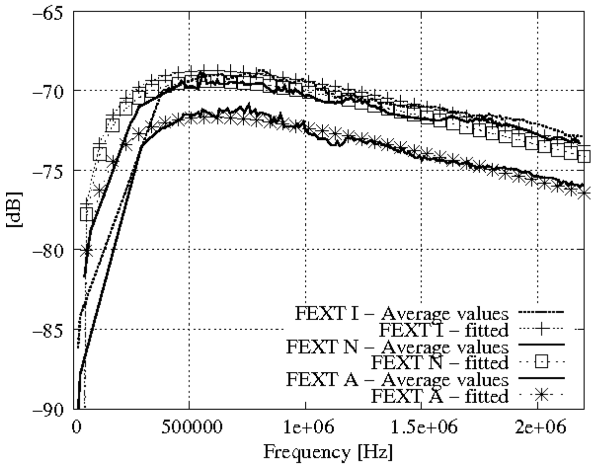

Fig. 5 Average crosstalk values

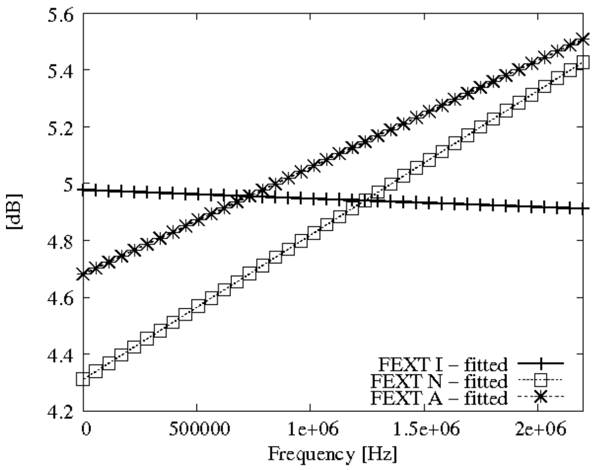

Fig. 6 Standard deviation of crosstalk

Average FEXT-I, FEXT-N and FEXT-A are fitted using the following equation:

$$H_{F-avg}(f) = A + 20\log(f) + G(f) \text{ [dB]},(12)$$

where *f* is frequency in Hz, and values of parameter *A* are defined in Tab. 3.

Standard deviation (std) of FEXT-I, FEXT-N and FEXT-A is fitted using the following equation:

$$H_{F-std}(f) = A + B \cdot f \text{ [dB]}, \quad (13)$$

where f is frequency in Hz, and values of parameters A, B are defined in Tab. 4. Column "Var. res." represents variance of residuals and shows how good the fit is.

Tab. 3 Constants used in Eq. (12) – average values

FEXT Type	A	Var. res.
FEXT-I	-166.78	0.15441
FEXT-N	-167.434	0.251875
FEXT-A	-169.716	0.114676

Tab. 4 Constants used in Eq. (13)

FEXT Type	A	$B \cdot 10^{-8}$	Var. res.
FEXT-I	4.97806	-3.02109	0.086704
FEXT-N	4.31021	50.8271	0.056165
FEXT-A	4.68093	37.6218	0.0313

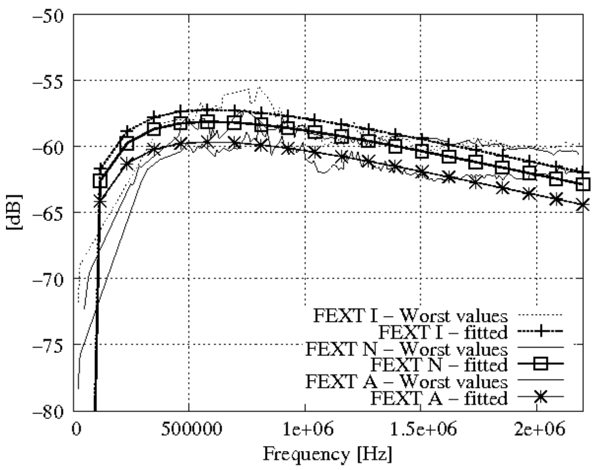

Fig. 7 The 1% worst-case model of crosstalk

By closer examination of the Fig. 5, one can notice that FEXT-I and FEXT-N values are close to each other. This result can be explained as the result of the pair twisting inside a quad. Our model is based on cables wherein all four wires in each quad are twisted together forming so called star quads [7]. Further on by detailed examination of the figure Fig. 7 one can notice that, at the higher frequencies, our model, based on the ETSI model does not fit data well. This can be explained with the peak in the standard deviation (similar to the peak for the FEXT-I at the frequency of 0.7 MHz). Worst case data is fitted using the equation Eq. (13). Calculated constants for 1% worst case are presented in Tab. 5.

Tab. 5 Constants used in Eq. (12) – worst case values

FEXT Type	A	Var. res.
FEXT-I	-155.275	0.755976
FEXT-N	-156.172	0.08538
FEXT-A	-157.706	0.5079

4.3 Other assumptions

As described in the subsection 4.2, we make a distinction between three different crosstalk types. We have determined bit loading using the Tab. 6, supplied by the local telecom operator, in order to calculate downstream bit rate of ADSL2+. Tab. 6 shows that each additional bit results in an SNR increase of 3 dB.

Tab. 6 SNR to bit loading convention

SNR, [dB]	bit loading
SNR < 21	0
$21 \le SNR < 24$	1
$24 \le SNR < 27$	2
$27 \le SNR < 30$	3
$30 \le SNR < 33$	4
$33 \le SNR < 36$	5
$36 \le SNR < 39$	6
$39 \le SNR < 42$	7
$42 \le SNR < 45$	8
$45 \le SNR < 48$	9
$48 \le SNR < 51$	10
$51 \le SNR < 54$	11
$54 \le SNR < 57$	12
$57 \le SNR < 60$	13
$60 \le SNR < 63$	14
$SNR \ge 63$	15

In our application, value of power used on each subchannel (tone) and on each pair is stored in an array. Each ADSL2+ system uses maximum allowed power on each tone and complies with the [4]. Fig. 8 shows the allocated power across all frequencies.

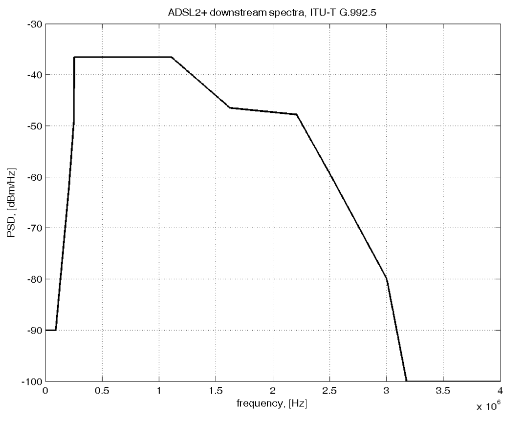

Fig. 8 ADSL2+ downstream allocated power

The crosstalk type is determined using the lookup table that stores all possible crosstalk combinations. As there are ten pairs, there are hundred different combinations. The crosstalk is summed using the FSAN method [5].

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5 Results of Downstream Bit Rate Calculation

We have performed calculation of the filling ratio versus the lowest bit rate per pair in a basic cable group. Furthermore, we have performed calculations of the worst achievable bit rate for different loop lengths and for different filling configurations. The worst achievable bit rate is a bit rate on the victim pair, which is defined in subsection 2.1. The results are shown in Fig. 9 and Fig. 10. Both figures were generated under the assumption that every system uses maximum allowed power.

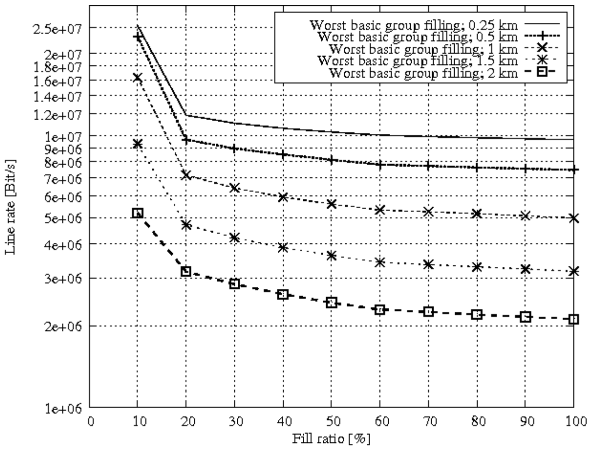

Fig. 9 The worst cable filling

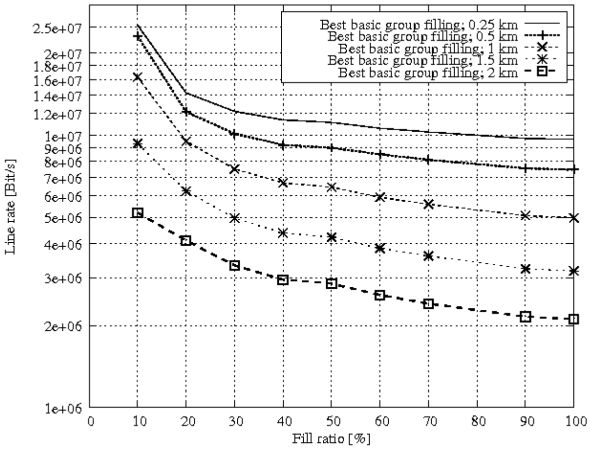

Fig. 10 The best cable filling

It can be noticed that allocation of DSL systems in a basic group has the major impact on the achievable bit rates. For example, when a loop is 1 km long, and the filling ratio is 30%, the difference between the best and the worst allocation of systems causes the bit rate at the victim pair to decrease for more than 1 Mbit/s. Furthermore, by observing the achievable bit rate at the 10% filling ratio and the 20% filling ratio, it can be noticed that for the deployment of services with adequate quality of service (QoS) it is crucial to use at least static spectrum management (SSM). By using the maximum allowed powers, bit loading per tone at higher frequencies is below acceptable values. This effect is due to a crosstalk increase as a function of frequency squared.

6 Conclusion

Crosstalk, as a major impairment of all DSL transmission systems, significantly reduces bit rate and reach of these systems. In this paper, we have presented bit rate calculation method based on parametric crosstalk models. The method is very suitable for copper quad cables, and it is a useful tool for design of access networks and services.

The importance of our insertion gain and FEXT models is their applicability to static and dynamic spectrum management in relation to the process of local loop unbundling (LLU) which becomes a necessity and lawful obligation for many operators in the world. This brings up the issue whether or not number of transmission systems and their layout inside a cable binder has great impact on a bit rate of each loop. An extensive measurements campaign has been carried out by the local telecom operator in order to address this question. We have concluded, from the conveyed analysis, the following: 1) cable filling ratio and the allocation of the ADSL2+ systems inside the cable binder have a major impact on the achievable bit rate on each subscriber loop; 2) in order to be effective, LLU must be based on empirical crosstalk models reflecting actual situation in twisted quad cable infrastructure. Hence, our analysis indicates that the implementation of capacity demanding services like IPTV necessitates spectrum management.

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