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Transmission Capacity of Local Copper Cables

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Introduction

The local cable network (cable plant) is a part of public switched telephone network (PSTN) which connects local telephone exchanges with customer's premises equipment (CPE). It is built up of multipair twisted cables. Cable pairs are twisted to avoid mutual influence (crosstalks) among the pairs. Cable construction is developed for transmission of voice frequencies and it remains almost the same for some decades. This cable plant works well for telephone transmission even if all cable pairs are active. In the eightees ISDN technology appeared which transmitted signals up to 60 kHz and soon it became clear that only 70 % to 80 % of cable pairs met technical requirements for this technology. The main obstacle was mutual influence among pairs (crosstalks) which increases with frequency. Next came another transmission technologies as HDSL, ADSL, SHDSL, which were designed to connect PBX exchsnges to the PSTN and to deliver Internet to the customer's home. All these technologies are called xDSL. Nowadays some new technologies appear, but the principles and line codes are the same (2B 1Q, PAM-16, DMT). In general, transmission of signals with frequencies up to 1 MHz over local telephone lines is quite common now. Technologies up to 2 MHz or even 8 MHz (over short lines) are coming soon. Most widespread is the ADSL service, so it is important for operator company to make evaluation of practically achievable penetration of ADSL service over existing local cable plant [1].

This problem is not new. Theoretical evaluation of ADSL transmission speed under different conditions was made by developers of this technology [2]. It was done more than eight years ago. A lot of new products and technical standards have been developed during this time and that is why this investigation was made.

Investigation was done in following steps:

Two local cables were investigated. Losses, crosstalks and noise of 137 pairs was measured. Measured data were processed, analysed and compared with ITU-T model.

Signals of different xDSL systems were recorded and their power spectra found. Mutual dependence (or independence) of signals were evaluated. ADSL transmission speed for each frequency bin was measured using line simulator and noise generator. Expected bit mapping matrix was found from results of these measurements. Using these data, model was developed in MatLab environment. Two cases are analysed using developed model and results compared.

Models for cables with 0,5 mm and 0,4 mm wires

Model should give the following characteristics for frequency band 10 kHz to 1 Mhz: losses, near end crosstalk (NEXT), far end crosstalk (FEXT), external noise spectrum. Cable losses were calculated from the measurements and compared with specifications. Both data were close to each other, in 1 dB range. All measurements and calculations were made for active 100 Ω load. Difference between characteristic loss and loss of cable loaded with 100 Ω were calculated. For 2 km long cable with 0.5 mm wire this difference was about 3 dB at 10 kHz frequency. At frequencies higher than 29 kHz this difference is less than 1 dB. For this reason characteristic losses are used for our model.

Cable loss is value which could be measured or calculated with high degree of accuracy (error less than 1 dB). This value depends mainly on technological precision of wires and insulation. Crosstalks (NEXT and FEXT), on the opposite, depend on cable twisting pattern and there more uncertainties are involved. There are some deep theoretical investigations in this area. [2]. They give useful expressions for understanding the processes in general, but there is little use for practical calculation. Almost only way to gather results is to measure NEXT and FEXT for several hundreds of combinations of pairs, process results and derive their statistical characteristics. We followed this way. [4] contains useful information about NEXT and FEXT, but this information is too general for us. According to this Recommendation expected values of NEXT and FEXT could be calculated as:

$$\mathrm{NEXT}=140.69-15\lg(f), \qquad (1)$$

$$\mathrm{FEXT}=195.96+a(f)-20\lg(f)-10\lg(l), \qquad (2)$$

where f – frequency, Hz, a – loss of loop, dB, l – Cable length, m.

We made detailed measurements of two new cables VMOHBU 200 x 2 x 0.5. Both cables were new, just installed and spliced. One of them was 1.34 km long, the second – 2.52 km long. Loop resistance, losses, impedance, external noise, NEXT and FEXT for 137 combinations of pairs was measured. Instruments SLK-22 (*W&G*) and ELQ-2 (*Elektronika*) were used. Results were processed, analysed and approximated for convenience of further use. Fig. 1. shows measured values of NEXT. Here and later graphs are marked as follows: *next_1*- both measured pairs are inside the same ten pair group, *next_10*- pairs are taken from different ten pair groups, but in the same 50-pair group, *next_50* – pairs are in different 50 – pair groups.

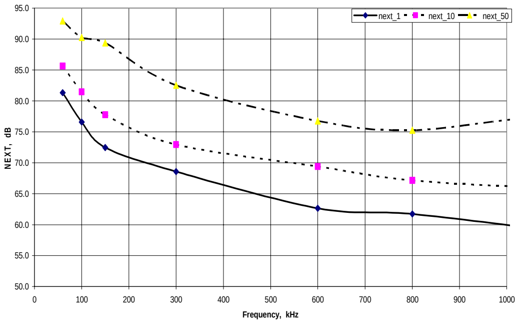

Fig. 1. Measured NEXT values

Fig.1. clearly shows how average values of NEXT depend on location of pairs. As it may be expected, maximal influence (minimal NEXT) is found between pairs of the same 10 – group. This *next_1* is taken for further calculations. Measured NEXT may be fitted with linear equation:

$$\mathrm{NEXT\_1}=162{,}8-17{,}18\ \lg(f). \tag{3}$$

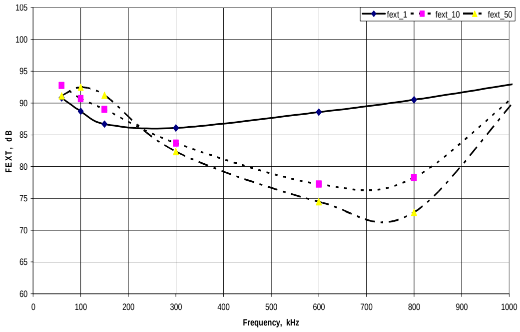

Fig.2. Measured FEXT values

Far end crosstalk (FEXT) depends on length and losses of the cable as it follows from (2). Measured values of FEXT are shown in Fig. 2. The meanings of variables and legend are the same as for Fig. 1.

To compare measured results with ITU model, new variable FEXTR (reduced FEXT) is introduced:

$$\mathrm{FEXTR}=\mathrm{FEXT}+10\lg(l)-a(f). \tag{4}$$

This value does not depend on cable length.

Measured values may be approximated by linear equation:

$$\mathrm{FEXTR\_1}=212{,}9-21{,}3\log(f) \tag{5}$$

and for further calculations FEXT values were taken according to:

$$\mathrm{FEXT}=212{,}9-21{,}3\lg(f)+a(f)-10\log(l). \tag{6}$$

Spectra of xDSL signals

Signals of ISDN, HDSL (over one pair), SHDSL (over one pair) and ADSL systems were recorded and their power spectra calculated. Measurements were made using instrument ELQ-2 and our own designed signal recorder. Measurements were made using line simulator LS 10.02. Attention has been paid to avoid interference of opposite transmission direction for ISDN, HDSL and SHDSL. Power spectral density (psd) was calculated according to Welch method. All psd vectors were interpolated for ADSL carrier frequencies: n 4312.5 Hz, where n is number of ADSL frequency bin 1< n > 256. Values of psd are saved and kept as m – files for further use. Approximation was made as close as possible to ETSI spectral masks.

Approximated spectra are saved as vectors in m – files with following names: psdI – ISDN psd, dBm/Hz, psdS – SHDSL psd, dBm/Hz, psdH – HDSL psd, dBm/Hz; psdAPd – ADSL downstream psd, dBm/Hz, psdAPu – ADSL upstream psd, dBm/Hz.

Mutual dependence of xDSL signals

To evaluate the signal/noise ratio, influence of all disturbing systems should be found and expressed in terms of noise power per ADSL frequency bin. For such calculation one need to know how xDSL signals influence each other or degree of mutual dependency of those signals. Records of ADSL signals were made with our own designed recorder. This four channel recorder was designed and built because such instruments were not available on the market. General purpose oscilloscopes did not meet our requirements such as high impedance balanced separated inputs, 0.5 mV sensitivity, record length not less than 0.5 megasamples with 12 bit resolution [3]. By now, ADSL signals from four ports of the same DSLAM were analysed. It was found that ADSL transmitted signals were stationary processes, at least in wide sense, and they were distributed according to Gaussian distribution law. Hypothesis test showed that it was reasonable to assume (with confidence level of 95 %) normal distribution of signals. If two processes are normally distributed and uncorrelated, then they can be considered as independent processes. Correlation coefficients were calculated for signals of symbol length. Their values were close to zero. In simple words, it means that power of sum of signals equals to sum of power of its components. To be more confident, cross power spectra of signals were calculated and they proved practical independence of ADSL signals as well. This investigation was reported in the conference *Electronics'2006* in Kaunas. Assumption about independency of signals is of vital importance for our model, because it dramatically simplifies the process of calculations of total noise power from different disturbers. The total power of noise could be calculated by adding up components of noise power caused by each disturber. This result is important as it indicates the progress of signal processing achieved in practical transmission systems as well. Transmitted signals close fit to the AWGN and it improves achievable transmission speed. It was not so with early 2Mbit/s systems which operated using line codes AMI and HDB-3. Spectra of such signals had evident maximum at a half of symbol frequency. In the case of synchronisation of number of such systems, their signals were not independent and it caused additional problems.

Bit mapping as a function of S/N ratio

Model should use information about practically achievable transmission performance of ADSL technology in terms of bit mapping. It may be expressed as a:

$$B(n) = f(Q), \tag{7}$$

where B(n) – bits per symbol (number of bits transmitted by one symbol in the one frequency bin), n – number of frequency bin, Q(n) – signal/noise ratio expressed in dB for respective frequency bin.

This relationship hardly depends on chipsets used in DSLAM and ADSL modem and software running the both of them. In some cases interoperatibility problems arises and transmission speed falls. For our measurements we used two ADSL testers made by *Aethra*. One of them D2061-CO simulates DSLAM with one port. Other D2061 simulates ADSL modem used at customer premises (CPE). We began with measurements on the real lines, but it was found soon that due to irregular noise sources bit mapping was too chaotic and ambiguous for analysis. Then measurements were made using line simulator LS 10.02.

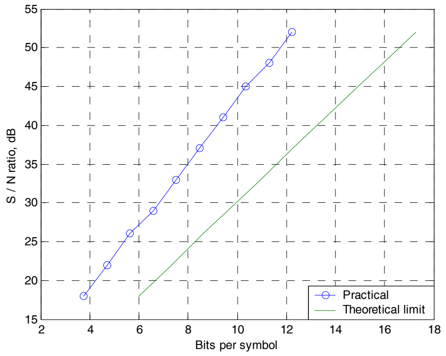

Fig. 3. Practical bit-per-symbol values and theoretical limit

Noise generator from the instrument ALT-200 was used at the receiver end of the line simulator. The best results were achieved with equivalent line length of 2.5 km 0.4 mm cable simulated. Measurements were made at the different noise levels applied. Noise signals were recorded and their psd calculated. For each experimental ADSL connection bit mapping was recorded. Ten test connections have been made (five for downstream and five for upstream). Spectra of transmitted signals and line attenuation were measured as well. From these results bit mapping relationship (matrix) was derived. It was found that upstream occupies bin No. 7 to bin No. 29, downstream occupies bin No. 38 up to bin No. 255. It corresponds to frequency bands from 30.2 kHz to 125 kHz and from 163.9 kHz to 1104 kHz respectively. Approximation was made from four such plots. Fig. 3. shows this relationship, that is, how many bits per symbol ADSL technology is capable to carry at different S/N ratios. For illustration, Shannon's limit is shown as well.

Mapping matrix. Upper row contains S/N (or Q) values in dB. Lower row shows corresponding values of bits per symbol.

$$\left|\begin{array}{cccccccccc} 18 & 22 & 26 & 29 & 33 & 37 & 41 & 45 & 48 & 52 \\ 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 \end{array}\right| \tag{8}$$

Practical implementation of model

Models are developed in MatLab environment. It was chosen for its good performance at the engineering calculations and availability. For simplicity it is considered transmission over one peace of cable.

Input data: cable type (0.4 mm or 0.5 mm) and its length; number of disturbing ADSL systems – nA; number of disturbing ISDN systems – nI; number of disturbing HDSL systems – nH; number of disturbing SHDSL systems – nS; vectors of signal spectra and cable losses (dB/km) are input from m–files. External noise is assumed with psdne – 121.5 dB/Hz. ADSL transmitted signal is assumed -40 dBm/Hz (for received signal calculations).

For calculation of influence among systems where transmission directions are separated by using different frequency bands, influence due to FEXT is taken into account. This is the case where signals with different levels do not coincide at the same frequency band. ADSL – ADSL influence is example of such case. In the case of systems where transmission directions are separated by using echo cancellation, transmitted signal with high level and received signal with low level is presented at the same place, at the same time, in the same frequency band. Influence due to NEXT is taken into account for such cases. Common examples are influence between two HDSL systems or influence between HDSL and ADSL.Calculations are made for the frequencies f=n·4312.5 Hz, where n is the number of ADSL frequency bin; 1<n<256. It allows us to plot graphs as a function of n; a(f) – loss of line, dB:

$$a(f)=a0(n)\ (l\ /\ 1000), \tag{9}$$

where a0(f) – loss of cable, dB/km, l – length of cable, m.

psdAr(f) – psd of received ADSL signal (desired signal): psdAr(f) = psdA(f)-a(f), dBm/Hz; Dne – psd of external noise, mW/Hz: Dne=10^(0,1 (psdne)); DnAd (f) – psd of all disturbing ADSL systems caused by FEXT, mW/Hz: DnAd(f) = [10^(0,1 (psdA(f)–FEXT))] nA; DnAd(f)=[10^(0,1(psdA(f)–212,9+21,3lg(f)–a(f)+ 10lg(l)))] nA; DnS(f) – psd of all disturbing SHDSL systems caused by NEXT, mW/Hz: DnS(f)=[10^(0,1 (psdS(f)–NEXT))] nS, after insertion (3) DnS(f) = [10^(0,1 (psdS(f)–162,8 + 17,18 lg(f)))] nS; DnI(f) – psd of all disturbing ISDN systems caused by NEXT, mW/Hz: DnI(f) = [10^(0,1 (psdI(f)–162,8+17,18 lg(f)))] nI; DnH(f) – psd of all disturbing HDSL systems caused by NEXT, mW/Hz: DnH(f)=[10^(0,1 (psdH(f)–162,8+17,18 lg(f)))] nH; Dnt – total psd of noise (from all disturbers), mW/Hz: Dnt(f)=Dne+DnAd(f)+DnS(f)+DnI(f)+DnH(f); psdnt(f) – total psd of noise (from all disturbers), dBm/Hz: psdnt(f)=10 lg(Dnt).

Q(f) or Q(n) – S/N ratio expressed in dB is

$$Q(f)= psdAr(f)–psdnt(f) \tag{10}$$

Distribution histogram of Q(n) is calculated for the same edges as used in bit mapping matrix (8). Number of bits per one ADSL symbol (all frequency bins) is calculated as a product of mapping vector by transposed Q distribution vector. ADSL transmission speed is found by multiplying Number of bits per symbol by symbol rate 4000 symbols per s.

Simplified model for demonstration

For demonstration simplified model is taken with ADSL downstream transmission only. Two cases are compared. Common data for both cases: line length: 3 km; disturbing systems: 10ADSL, 1 ISDN, 1 HDSL, 1 SHDSL.

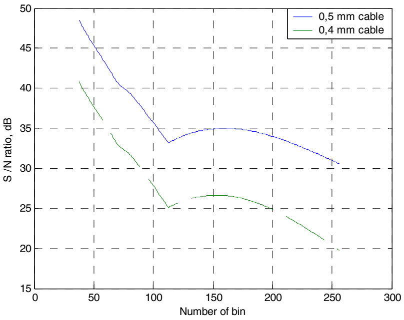

Fig. 4. S/N ratio for both cases

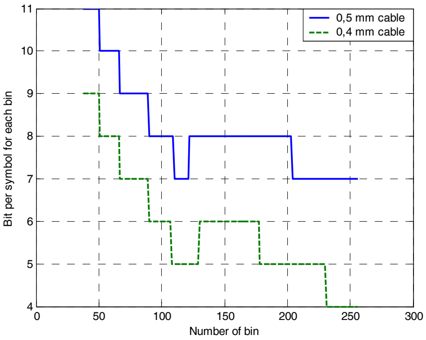

Fig. 5. Mapping chart for both cases

Cases differ from each other by cable type: 0.5 mm wire for the first case and 0.4 mm wire for the second one.

Fig. 4 shows S/N ratio (assigned as Q) for both cases.

Finally, Fig. 5 shows the mapping charts for both cases. Transmission speed, calculated according to the model is: 8100 kbit/s for 3 km 0.5 line and 5908 kbit/s – for 3 km 0.4 line. Results are better as they were calculated according to ITU cable model.

Conclusion

Model for calculation of ADSL transmission speed developed makes it possible to evaluate expected transmission speed over the copper cables. This model fits for different combinations of disturbing systems. It may be used for network planning or for prediction of transmission capacity of existing and planned networks. Model may be simply extended for using with two or more cascaded cables. Similar models are applicable for another xDSL systems as well.

References

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3. **Parts R.** Common mode voltage on telephone lines and its influence on measurements // Scientific Proceedings of RTU, Telecommunications and Electronics. – 2004.
4. **ITU–T G.991.2** Single-pair high speed digital subscriber line (SHDSL) transceivers.

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R. Parts. Transmission Capacity of Local Copper Cables // Electronics and Electrical Engineering. – Kaunas: Technologija, 2007. – No. 5(77). – P. 77–80.

Local network planners encounter with problem how to evaluate and predict the transmission speed of ADSL systems operating at copper cables where another xDSL systems operate as well. Model for such analysis is developed and presented. Model is based on measurements of real values of crosstalks among the cable pairs, spectra of transmitted signals and achievable transmission speed of ADSL systems. Model could be extended for the ADSL 2+ as well. Ill. 5, bibl. 4 (In English; summaries in English, Russian and Lithuanian).

Р. Партс. Пропускная способность местных медных кабелей // Электроника и электротехника. – Каунас: Технология, 2007. – № 5(77). – С. 77–80.

Местные планировщики сетей сталкиваются с проблемой, как оценить и предсказать скорость передачи систем ADSL, работающих на основе медных кабелей, где также работают другие xDSL системы. Развита и представлена модель для такого анализа. Модель основана на размерах реальных измерений перекрестных связей среди кабельных пар, спектров переданных сигналов и достижимой скорости передачи систем ADSL. Модель также может быть применена для ADSL 2+. Ил. 5, библ. 4 (на английском языке; рефераты на английском, русском и литовском яз.).

R. Parts. Vietinių varinių kabelių duomenų pralaidumas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2007. – Nr. 5(77). – P. 77–80.

Vietinių tinklų planuotojai susiduria su problema, kaip įvertinti ir prognozuoti ADSL sistemų, veikiančių tinkluose su variniais kabeliais, duomenų perdavimo greitį, kai tuose pačiuose tinkluose dirba ir kitos xDSL sistemos. Tokiai analizei sukurtas ir pristatytas modelis, paremtas realių matavimų rezultatais. Matuoti tokie parametrai: parazitinis ryšys tarp kabelio gijų porų, perduotų signalų spektras ir duomenų perdavimo ADSL sistemose sparta. Modelį būtų galima pritaikyti ir ADSL 2+. Il. 5, bibl. 4 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).