Multi-Carrier Modulation and MIMO Principle Application on Subscriber Lines

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Abstract. *The multi-carrier modulation is used in many applications, primary for a wireless transmission, for example Wi-Fi and WiMAX networks or DVB-T. But the same physical principle can be used also for metallic lines in access or local networks, for example ADSL and VDSL. The multi-carrier modulation in these cases is called DMT. The dominant source of noise in multi-pair metallic cables is crosstalk when the information capacity is limited dramatically. However, information capacity of metallic lines can be increased, if the system is using MIMO principles, concrete VDMT modulation and line bounding concept. The methods for VDMT modulation and partial crosstalk cancellation are discussed and simulation results are presented.*

Keywords

Multi-carrier Modulation, Digital subscriber line, Twisted pair, Crosstalk cancellation, VDMT.

1. Applications of Multi-Carrier Modulation

The multi-carrier modulation (MCM) is used in many applications, primary for wireless transmission, for example in local networks (IEEE 802.11, Wi-Fi), metropolitan networks (IEEE 802.16, WiMAX) or video broadcast (DVB-T). The multi-carrier modulation in these cases is called orthogonal frequency multiplex (OFDM) or its variants. But the same physical principle can be used for metallic lines (twisted pairs) in access or local networks too, for example for asymmetric digital subscriber lines (ITU-T G.992, ADSL), very high speed digital subscriber lines (ITU-T G.993, VDSL). The multi-carrier modulation is then called discrete multi-tone (DMT).

The ADSL modems [5] use multi-carrier modulation in base-band with 256 sub-channels, sub-channel space 4.3125 kHz and adaptive SNR(f) dependence bit allocation from 0 to 15 bits for each sub-cannel. The total frequency band is from 4 (or 25, 138) to 1104 kHz. The VDSL2 [5] modems use multi-carrier modulation with maximum 4096 sub-channels and sub-channel space 4.3125 or 8.625 kHz. The total frequency band is from 4 (or 25, 138) kHz to maximal 30 MHz. The second generation digital subscriber lines ADSL2+ and VDSL2 gradually replace the first generation of ADSL systems in homes and small offices. Since there is a need to estimate the available bit rate, we have used MATLAB Web Server to design a simulator of xDSL lines that is available at our web pages [1].

2. Transmission Environment

Metallic lines in access networks begin at the main distribution frame in local exchange, then they run as a part of multi-pair cables to line distribution frames, from there they branch into smaller groups of subscriber lines or to individual lines leading to the subscribers' premises. In this network various types of cables with copper core (mostly 0.4 mm in diameter) and various numbers of pairs, basically arranged in quads, are commonly used.

The principal factors limiting the transmission of high-bit-rate signals are attenuation of the line and crosstalk between the pairs that is dominant source of noise in multi-pair metallic cables.

2.1 Simple Crosstalk Modeling

The dominant source of noise in multi-pair metallic cables is crosstalk representing the essential information capacity limit. However, the information capacity of metallic lines can be increased, if the system is using MIMO principles, concrete vectored DMT modulation (VDMT) and line bounding concept.

The described method for summarizing of contributive near-end and far-end crosstalk (NEXT and FEXT) has been recommended by the FSAN (Full Service Access Network) consortium [5]. The simplification of crosstalk computation is in crosstalk parameters (for NEXT and FEXT). These parameters are averaged over the total length of the subscriber line, not considering the real cascade structure. In addition, the position (in the same group, in different groups) of disturbing and disturbed pairs is ignored. The values of crosstalk constants are preventively calculated for the worst-case disturbance environment scenario. However, this worst case results in more pessimistic level of noise [9]. The typical attribute of crosstalk is very high variance of values [3]. It is clear that if we interleave the minimum attenuation values, we obtain the worst-case disturbance scenario, which is approximately 10 dB worse than average attenuation values. The maximum attenuation values are 12 or 15 dB (or more) higher than the worst-case scenario.

2.2 Dividing Pairs to Crosstalk Groups

The frequency dependence of crosstalk transmission function has a random character. With respect to the construction of standard cables used in access networks, it is possible to divide the symmetric pairs into several groups: **Neighboring pairs** – the pairs within a quad and those in the neighboring quads of the same subgroup; **Near pairs** – the pairs of the far quads in the same or neighboring subgroup; **Farther pairs** – the pairs in quads of the farther subgroups (separated by at least one subgroup); **Far pairs** – the pairs in other groups; **Pairs in other branch** of a cable tree. The knowledge of crosstalk transfer function between all pairs will be necessary for Dynamic Spectrum Management (DSM) purposes and for transmission using Vectored DMT modulation [7], [9].

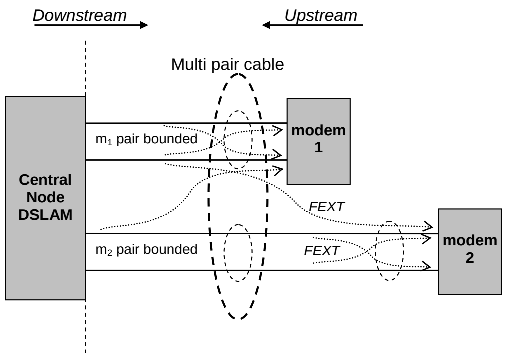

Fig. 1. The FEXT crosstalk for downstream direction in multi-pair cable with pair bounding between bounded pairs and between pairs from other bounding groups, too.

3. Using MIMO Concept for Crosstalk Cancellation

A simple method of crosstalk cancellation is used in the Gigabit Ethernet interface for cables of the 5E category for distances up to 100 m. For a longer distance it is suitable to dispose of crosstalk at the near-end using frequency division duplex technique (FDD) and then to deal with crosstalk cancellation at the far-end (see Fig. 1). The modems on provider side are usually concentrated in the central node in a device called digital subscriber line access multiplexer (DSLAM). The bit rate of metallic lines in access or local area can be increased, if the line bounding is used. DMT is very effective in canceling the crosstalk, particularly between sub-channels. This modulation is then called vectored DMT (VDMT) and can be classified as one from the group of MIMO systems (Multiple Input – Multiple Output) [8], [9]. The crosstalk can be cancelled out only in bounded multi-pair groups or bounded multi-pair groups and between its groups too for better performance.

3.1 DMT Modulation

The multi-carrier modulation (MCM) is selected for modern digital subscriber lines like ADSL/ADSL2+ and VDSL/VDSL2. It is the Discrete Multitone Modulation (DMT) in particular. The DMT can solve the problems of the poor characteristics of the transmission channel and unfavorable influence from other transmission systems.

The Inter-Channel Interference (ICI) is restricted by using weak and independent tones and by using the Discrete Fourier Transformation (DFT). The Inter-Symbol Interference (ISI) is restricted by using Cyclic Prefix (CP) and by using a FIR filter for shortening of the channel impulse respond. For example 512 samples of DMT symbol and 40 samples of CP are used for ADSL. The Decision Feedback equalizer (DFE) is also being used for received symbol adaptation. The DFE purpose is to reduce the ISI as well.

3.2 Vectored DMT Modulation

The Vectored DMT (VDMT) modulation is an extension of the classical DMT modulation. The crosstalk has main disturbing impact on DSL transmission performance in the metallic access network. It is possible to reduce NEXT by using frequency division duplex (FDD) principle for data transmission in the upstream (from user to network provider) and downstream (from network provider to user) direction. The VDMT is primarily designed to reduce the FEXT.

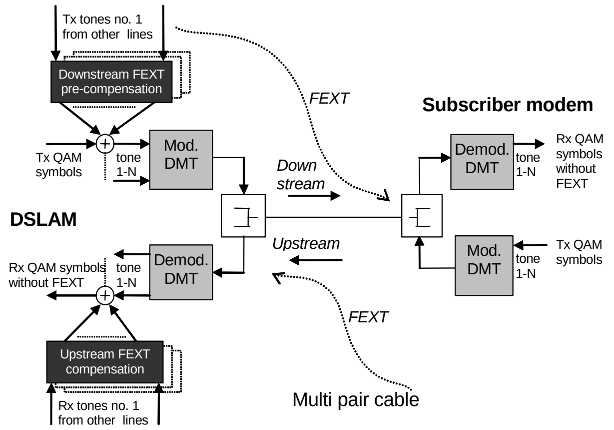

Fig. 2. The principle of VDMT – FEXT compensation on receiver side (Rx) for upstream and pre-compensation on transceiver side (Tx) for downstream.

The advantage of VDMT is a possibility to create multipoint networks, where the cancellation for both directions is done in a central network element. For the upstream direction there is compensation at the receiver side and for downstream the pre-compensation is used at the transmitter side (see Fig. 2). Generally, L user modems are connected to DSLAM by L twisted pairs. It is clear, that output DMT symbol (without CP) of the line i depends not only on input DMT symbol of the line i but also on past input DMT symbols. And even more, the output DMT symbol of the line i depends not only on input DMT symbols of the line i but also on the input DMT symbols of all L lines. For simplification it is useful to consider that the character of the channel noise is Gaussian and negative influence of the channel impulse response is reduced both by CP and synchronization of symbols being sent and received. For received symbol we can state:

$$y_i = H_{i,1} \cdot x_1 + \ldots + H_{i,i} \cdot x_i + \cdots + H_{i,L} \cdot x_L + z_i \quad (1)$$

where y_i is the vector of the output DMT symbol for the disturbed line i, x_i is the vector of the input DMT symbol for the disturbing line i, $H_{i,j}$ is the matrix of the channel transmission function (for $i = j$) or the crosstalk transmission function (for $i \neq j$ and $j = 1..L$) of the disturbing line i, z_i is the noise vector for the disturbing line i, including AWGN and crosstalk from other digital subscriber lines in the cable without VDMT. Equation (1) can be generalized for all L lines to MIMO system:

$$y = H \cdot x + z \quad (2)$$

where y is the matrix of the output DMT symbols of L lines, x is the matrix of the input DMT symbols of L lines, H is the matrix containing channel transmission functions and FEXT transmission functions, z is the noise matrix.

For correct VDMT operation it is necessary to know transmission path parameters, along with crosstalk from surrounding (neighboring) lines, which are placed in identical metallic cables. Transmission path parameters are identified during the process of establishing connection between subscriber modem and access DSLAM. The relatively stationary value of transmission parameters is one advantage of channels in metallic environment. To compensate the crosstalk completely it is required to send signals on all lines. They are present in DSLAM device, but not in subscriber's modem. Therefore, compensation has to be performed in both direction of transmission in DSLAM, or more precisely for the direction upstream the crosstalk is being compensated on the receiving side and for the direction downstream signal pre-compensation is applied on the transmitter side.

To carry out coordination of each DMT symbol in all cables is computationally very challenging. In order to decrease this demand, the factor QR method can be used. This method decomposes above derived matrix H into the unitary matrix and the upper triangular matrix. Significance of QR decomposition lies in decreasing computation complexity with crosstalk repression. Instead of taking into consideration disturbing lines L-1 for each line, after QR decomposition for line n-L no compensation signal will be used, for line L-1 only one and for the 1st line L-1 compensation signals must be used. Thereby the total number of operations will be decreased by half. The original symbols x can be estimated from received symbols y after QR decomposition [7] for tone k:

$$\hat{x}_i^k = dec\left[\frac{1}{r_{i,i}^k}\left(y_i^k - \sum_{j=i+1}^{L} r_{i,j}^k \cdot \hat{x}_j^k\right)\right] \quad (3)$$

where r^k are the elements of R matrix and dec denotes the decision operation.

3.3 Channel Capacity

For channels in metallic cable and VDSL2 lines the received signal is less then crosstalk. The approximation of the matrix elements can be used for tone k:

$$\left|r_{i,i}^k\right| \cong \left|h_{i,i}^k\right| \quad (4)$$

where h^k are the elements of H matrix (2). The bit-load for line i on tone k can be estimated:

$$b_i^k = \log_2\left(1 + \frac{s_i^k \cdot \left|r_{i,i}^k\right|^2}{\sigma_k^{\,2} \cdot \Gamma}\right) \quad (5)$$

where s^k is mean power of signal and σ_k is mean power of residual noise on tone k. The parameter Γ represents Shannon gap [5] and is a function of the target bit error rate (BER), code gain (CG) and noise margin (NM). The maximum achievable bit rate of the one twisted pair C_i and total bit rate of multi-pair channel C is calculated from (5):

$$C_i = \Delta_f \sum_{k=1}^{N} b_i^k \qquad C = \Delta_f \sum_{i=1}^{L}\sum_{k=1}^{N} b_i^k \quad (6)$$

where Δ_f is tone spacing, practically equal to the DMT symbol rate (for ADSL and VDSL 4 or 8 kBd).

3.4 Partial Crosstalk Cancellation

As was mentioned above, many of research works were concerned with principles, analysis and presumed results within the vector modulation VDMT application. The coordination of limited number of lines or more precisely of limited number of sub-channels should be performed with regard to the time-consuming calculation [7], [8]. The partial FEXT crosstalk cancellation in the upstream direction (compensation in the DSLAM on the receiving side) as well as in the downstream direction (pre-compensation in the DSLAM on the transmitting side) is realized by this approach. Thus, a frequency, space selection or both can be performed.

The selection can be performed on basis of the transmission functions analysis during the initialization process. The maximal available cancellation ratio of crosstalk specified by given technical resources (maximization of throughput) can be used as a starting point. On the other side the necessary reduction range of the crosstalk based on the bit rate requests is specified in accordance with provided nature of services. Certain uncoordinated number of lines (not integrated to the coordinated spectrum management and crosstalk cancellation system) should be nearly always allowed in practice. Primary presumptions resulting from the group cables structure that is used in the Czech Republic were following: **1.** The biggest source of crosstalk can be expected between the lines that are part of one quad; **2.** The most significant crosstalk is within the subgroup; therefore VDMT space selection will be used only within the given subgroup; **3.** The lowest crosstalk can be expected between the lines of the different subgroups that are separated by other subgroup in the cable profile; **4.** Results achieved with the full crosstalk cancellation can be approximated with the partial FEXT crosstalk cancellation (within less than 50 % of the profile).

3.5 Experimental Results

Analysis and measurements of the local cables were performed and following results were discovered: **1.** The first presumption was not confirmed – relatively low unbalances and crosstalk are achieved as a consequence of correct quad elements balancing; **2.** Just a part of the second presumption was correct. There are cables and group of cables for which the crosstalk cancellation within the subgroup reduces the most significant crosstalk sources. However, a high residual crosstalk remains in most cases; **3.** The third presumption was correct. Remote subgroups have very low influence on the disturbance compared to neighboring subgroups; **4.** The fourth presumption was not confirmed. The available throughput approximation within the full crosstalk cancellation is possible after crosstalk cancellation within given subgroup and neighboring subgroups (it corresponds to 3/5 of the profile); often also several dominant disturbance sources from the remote subgroups should be involved in cancellation.

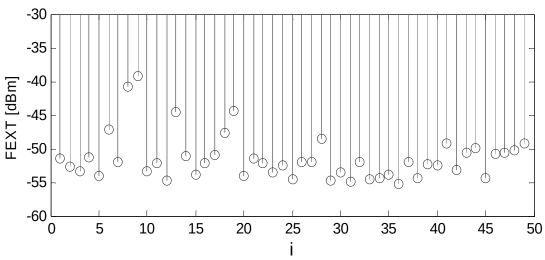

Fig. 3. Example of the total FEXT crosstalk power level from the single pairs of the cable – subgroup 2.

The mentioned findings can be demonstrated on measurement and simulation results. Firstly, a crosstalk influence in the cable group profile is presented. A total crosstalk performance is calculated up to the 30 MHz from line 1 to 49 into the reference line 0 that is a part of the subgroup 0 – 9. The neighboring subgroups are 10 – 19 and 40 – 49. Examples of the results are shown in Fig. 3. After further analysis and combination of the crosstalk performances data for this case it can be concluded that the FEXT cancellation from the line no. 8 and no. 9 makes 1.9 dB noise reduction of the total noise, the cancellation from the next four lines makes 3.5 dB total reduction and cancellation from other four lines (total cancellation from ten pairs) 4.2 dB total reduction only. Similar results were achieved from all over the measurement suite. Conclusion is that the partial coordination within the subgroup or more precisely within the 10 lines is deficient and does not lead to the required results in majority of cases.

4. Simulation Outputs

The available bit rate for systems without cancellation, with partial and complete crosstalk cancellation is calculated. Transmission functions and crosstalk of the line are the subjects of the measurements of the local cable (400 m length, 0.4 mm in diameter) in the frequency band from 138 kHz to 30 MHz (VDSL2 extended band). The choice of the transmission lines for cancellation is based on the limit determination (interval in dB) with regard to the worst case of the crosstalk. Tab. 1. shows the results for space selection for the different threshold of the crosstalk cancellation. Also the available bit rate that is calculated through a whole frequency band without transmission direction resolution and number of the lines that are above the given threshold and that should be added to the crosstalk cancellation systems are presented in Tab. 1.

Cancellation threshold [dB]	0	6	10	12	14	20
Number of selected lines [-]	0	4	8	16	32	49
Bit rate [Mb/s]	89	110	118	131	168	345

Tab. 1. Simulation results for space selection within partial FEXT cancellation.

Cancellation threshold [dB]	0	6	10	12	16	20
Number of selected tones [thousands]	0	3.8	10.4	19.7	56.1	103.2
Tones conversion to number of lines [-]	0	1.1	3	5.7	16.2	29.8
Bit rate [Mb/s]	89	100	109	117	146	198

Tab. 2. Simulation results for frequency selection within partial FEXT cancellation.

The bit rate gradual growth with increasing number of the coordinated lines is evident, but the approach to the full cancellation (in the last column) is very slow. Better results can be achieved by frequency selection (tone selection from all lines) as is shown in Tab. 2. The conversion is performed with regard to the total number of tones. The cancellation effect can be demonstrated through Fig. 4 and Fig. 5, where the bit rate distance dependence for upstream and downstream is showed for VDMT with full crosstalk cancellation and without crosstalk cancellation for 20% used lines in the cable profile and for additive Gaussian white noise (AWGN) level -136 dBm/Hz. Fig. 4 shows dependence for frequency plan 998, when optimal for asymmetric application (direction downstream is speedier them upstream) and Fig. 5 shows dependence for frequency plan 997, when optimal for symmetric application. The bit rate 100 Mb/s will be used for individual line with VDSL2 lines with VDMT on distance of hundreds meters in local and access network. Through line association (pair bounding with inverse multiplexing) the bit rate near 1 Gb/s can be achieved for example ten lines bundle.

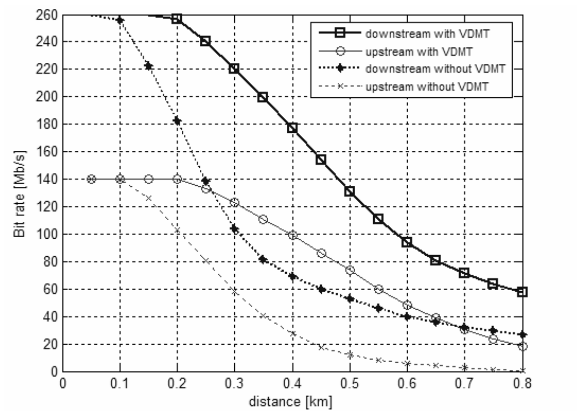

Fig. 4. Bit rate for frequency plan 998 (VDSL2) with full crosstalk cancellation (with VDMT) and without it.

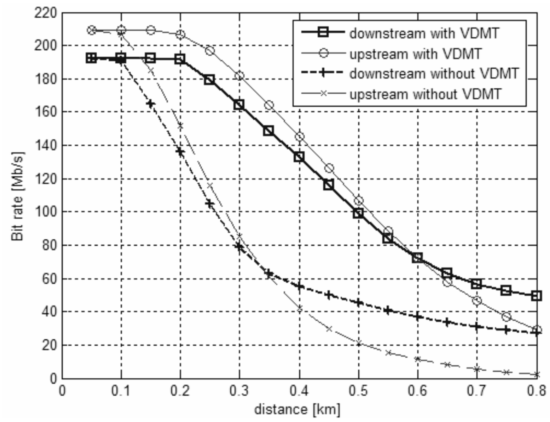

Fig. 5. Bit rate for frequency plan 997 (VDSL2) with full crosstalk cancellation (with VDMT) and without it.

5.Conclusions

The demands in the local and access networks for higher bit rates can be satisfied using VDSL2 lines, but the distance must not exceed 1 km. The ability of precise topology modeling and noise modeling of access networks is very important. With respect to the increasing number of systems in access networks, the implementation of new modulation and MIMO methods is necessary. Dynamic spectrum management (DSM) methods are also necessary to provide up-to-date information on the access network operational status and different transmission systems configurations making best of potentials of access networks. VDMT modulation utilization, alike the OFDM modulation for wireless systems, evokes the huge increase of the bit rate in the cables that are already engaged by subscriber lines compared with common transmission methods. It demands great calculation capacity from signal processors. The partial crosstalk cancellation with the most disturbing lines or DMT tones selection can be the solution. But this method of the solution is not the best for all cables that are used in the Czech Republic in accordance to performed experiments. However, bit rate 100 Mb/s can be achieved for individual line for middle-range lengths and with utilization of VDSL2 physical layer up to 30 MHz (band plan 997).

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