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THE ANALYSIS OF FEATURES OF MODIFIED PRECODING AND CODING TECHNIQUES USED BY THE VDSL TECHNOLOGY

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For successfully analyzing the signal protection in the case of VDSL transmission on metallic homogeneous symmetric lines, it is necessary to know the basic features of the VDSL environment and the main properties of the techniques able to eliminate the negative influences on the transmitted signals. This article briefly discusses the proposed coding and precoding techniques and introduces a simulation model for the VDSL environment. The main part of the article is focused on analyzing various types of precoding techniques alone or in combination with the trellis code modulation and with the discrete multitone modulation. The results of our modelling can be used for approving the VDSL system performance.

Keywords: coding and precoding techniques, the VDSL environment, the VDSL simulation model, THP and FLP precoding, BCH, RS and Ungerboeck coding

1 INTRODUCTION

One of the most important features of the present data communication is its orientation on broadband services. Nowadays, a-speed Internet access seems to be the most popular service but also other services — such as Video on demand, Conferencing or Teleworking — are gradually expanding. From the technical viewpoint, the transmission capacity of the access network is the main condition of deployment. To fulfil this condition, one can choose from among several solutions —- installing optic fibres, using wireless technologies, utilizing the existing cable distributions or telephone lines.

Metallic homogeneous lines hide a great economic potential that can bring one of the most profitable, relatively easily and quickly realizable solution. The most prospective technologies are xDSL ("x" Digital Subscriber Line) technologies. Thanks to their high variability in transmission rates, they are able to adapt to a transmission capacity of the homogeneous metallic lines for customer requirements and to guarantee delivering high-quality broadband services to all customers. In comparison with the contemporary ADSL technology, the VDSL technology would be able to offer higher transmission rates together with shorter distances and a higher available frequency bandwidth. Naturally, these ambitious requirements imply a lot of problems linked with a distortion and noises occurring in a transmission channel. However, there are various possibilities to solve these problems. The most effective solutions are precoding and coding techniques.

This paper concerns with protection of information signals by means of precoding and coding techniques at the transmission in the VDSL environment. First, the analysis is focused on the field of precoding techniques, namely on the *Tomlinson-Harashima precoding* (THP) and the *Flexible precoding* (FLP), which are analyzed partly separately and partly in combination with selected coding and modulation techniques. Next, the analysis is focused on a combination of precoding and coding techniques. Furthermore, the paper concerns with a possible combination of precoding and modulation techniques. Various types of modulations are presented — single-carrier modulations (SCM), multi-carrier modulations (MCM) and codulations (TCM). Our analyses are based on simulation results that reflect the negative influences of the VDSL environment at the signal transmission. Therefore, a simulation model of the VDSL transmission system is also briefly presented.

2 THEORETICAL PART

2.1 Precoding and coding techniques used by the VDSL technology

For the VDSL technology, the following traffic parameters are considered [1]: the transmission rates range from 13 Mbit/s on a distance of 1500 m up to 52 Mbit/s on the maximum distance 300 m; the frequency bandwidth is situated between 300 kHz and 30 MHz. As for modulations, there are considered single-carrier modulations (SCM) — the Quadrature Amplitude Modulation (QAM), the Carrierless Amplitude Modulation (CAP), or multi-carrier modulations (MCM) — the Discrete Multitone Modulation (DMT), the Discrete Wavelet Multitone Modulation (DWMT), the Zipper DMT Modulation (ZDMT), the Synchronized DMT modulation (SDMT). The first

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type, the SCM has a great advantage of easy implementation, higher level of integration and thus a smaller size, while the second group, the MCM is more resistant to distortion and noises and can achieve more effective utilization of the available frequency bandwidth. The frequency bandwidth of VDSL signals, that is larger than for other xDSL ones, is responsible for extended negative influences of the transmission environment — such as the impulse noise, interference with AM radio broadcasting or with amateur radio communication — during signal transmission. Since these negative influences appear randomly and their impacts on signal performance are unpredictable, the only solution to this problem is to minimize these influences. We can achieve this relatively efficiently with multiple-error-correcting codes combined with interleaving techniques. These codes are realized by adding a systematic redundancy to useful information at the transmitter side. Thanks to this redundancy, the receiver side of the transmission channel can correct the occurring bit errors and recover the original information signals.

In the case of SCM modulation, another problem is distortion. This effect is manifested in imbalanced attenuation of the transmitted signal in the frequency area and in different rates of individual frequency components. The distortion problem is caused not only by the transmission channel but also by the transmitter and receiver. The distortion is expressed by deformation and overlapping of the channel symbols in the time domain. This phenomenon is known as the *intersymbol interference* (ISI) and results in ineffective utilizing of the available frequency band. This ISI problem is more significant at signal transmission by means of xDSL technologies on metallic homogeneous lines. Here, the ISI significantly decreases the utilized part of the frequency bandwidth and, moreover, the transmission rate. Nowadays, a lot of methods are known to solve this negative effect and get closer to the theoretical Nyquist values. One of the first and best-known methods is called duobinary signalling or partial response (PR) signalling in general. In the transmitter, the particular ISI is inserted into the useful information signal and the signal transmission is realized at the Nyquist rate. In the receiver, the detection process is modified in order to remove correlated ISI. More information can be found in [2, 3]. Interesting methods suppressing the ISI are based on multiple-error-correcting codes, especially on convolutional codes [3]. Another method is represented by linear correctors realized through finite impulse response (FIR) filters. However, they cause a worthless boost of the useful information signal and a colouring noise. Better results can be achieved using the minimum-mean-squared-error (MMSE) or zero forcing (ZF) decision feedback equalizations (DFE). However, real decision feedback equalization suffers from error propagation. Moreover, coded modulation cannot be applied in a straightforward manner since the DFE needs a zero delay decision that cannot be realized through the Viterbi algorithm (some complicated and algorithmically difficult solutions can be found in [4]). A practical solution to overcome these problems is the use of precoding techniques.

2.2 Possibilities of error-correcting codes

Thanks to the nature of errors occurring at signal transmission, it is necessary to use multiple-errors correcting codes with high efficiency. Therefore, we are focusing on the BCH and the RS codes from block codes and on the Ungerboeck codes applied as part of the TCM from trellis codes.

2.2.1. Bose-Chaudhury-Hocquenghem (BCH) codes

BCH codes [2, 4, 5] that are capable of correcting t errors over the field $GF(q)$ with the code length $n = q^m - 1$ are defined by the generator polynomial $g(x)$ in the form

$$g(x) = \mathrm{LCM}\left[m_{\alpha^j}(x), m_{\alpha^{j+1}}(x), \dots, m_{\alpha^{j+2t-1}}(x)\right] \quad (2.1)$$

where LCM represents the least common multiple, $m_{\alpha^j}(x)$ is the minimal polynomial for element α^j of the $GF(q^m)$. If α is the primitive element of the $GF(q^m)$, then we call this subclass of the BCH codes as primitive BCH codes, for which the generator polynomial is mostly a polynomial of the lowest degree. Parameter t determines the number of errors that can be corrected by this code. Sometimes the BCH code can correct more than t errors. For this reason, a value $2t + 1$ is called the designed code distance. The minimum code distance d^* may be larger.

Decoding of the BCH codes can be performed in different ways. One of them is through calculation of syndromes that consists of the following steps:

1. Syndrome calculation from a received sequence.
2. Finding the error locator polynomial.
3. Finding the roots of this polynomial that show a position of the errors.
4. Finding the symbol error values.

The BCH codes represent a big set of codes consisting of many code subsets with specific features and with special names. Golay and RS codes belong to them.

2.2.2. Reed-Solomon (RS) codes

Thanks to the ability of repairing burst errors, RS codes [3, 4, 5] are one of the most spread multiple-error-correcting block codes used in satellite and mobile communications, in digital television broadcasting and data storing on CD and DVD discs.

As a subclass of BCH codes, the RS codes are characterized by a special feature that coefficients of the generator polynomial belong to the same field $GF(q)$ as its roots. For the codeword length, the following equation can be written:

$$n = q^m - 1 = q - 1\,. \quad (2.2)$$

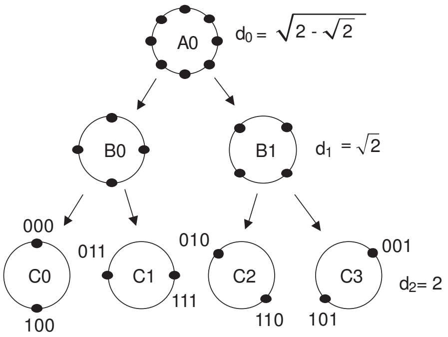

Fig. 1. Partitioning of the 8-PSK constellation

Then the minimal polynomial over the $GF(q)$ of the primitive element α in the same $GF(q)$ is

$$f_\alpha(x) = x - \alpha\,. \tag{2.3}$$

Using $j = 1$ from (2.1) and after substitution (2.3) into (2.1), we get the generator polynomial of RS codes in the following form:

$$g(x) = (x-\alpha)(x-\alpha^2)\dots(x-\alpha^{2t})\,. \tag{2.4}$$

The value t determines the number of s-ary symbols that can be corrected by this code type. Each symbol is regarded as corrupted, if it contains a single bit error or multiple bits error. The most often $q = 2^s$ is chosen. Then the code specification $RS(n,k)$ indicates the RS code with the code length $n \times s$ and information part length $k \times s$. The other characteristic feature of RS codes is that the designed code distance is the same as the minimum code distance and equals to:

$$d^* = d = 2t + 1 = n - k + 1\,. \tag{2.5}$$

From equation (2.5), we can see that RS codes are optimum codes in the sense of the Singleton bound (more information in [4, 5]) and they belong to a category of the maximum-distance codes. The RS codes have a relatively short block-length as compared to other cyclic codes over the same alphabet. That is the reason of their popularity and wide utilization.

Decoding of the RS codes is realized in the same way as for BCH codes.

2.2.3. Ungerboeck codes

Ungerboeck codes [6, 7, 8] belong to a class of convolutional codes. They are used in connection with the Trellis-coded modulation (TCM) and are able to achieve a coding gain from 3 dB up to 6 dB without extending the bandwidth in the AWGN channel.

The Ungerboeck codes are generated by a method called the mapping by set partitioning that can be specified in the following way:

1. All parallel branches in a trellis are separated by the maximum possible Euclidean distance (in Fig. 1, all constellation points are chosen from one of the subsets C0, C1, C2, C3). The existence of parallel branches is caused by the transmission of unencoded bits together with encoded ones.
2. All branches coming into the particular state or leaving it have been assigned the second-best Euclidean distance (in Fig. 1, channel symbols are chosen from subsets B0 or B1).

Practical realization can be performed by special types of convolutional coders. Their characteristic feature is that p incoming bits are separated into the two groups: The first group, k bits are encoded in the convolutional coder and after encoding are used to determine one of the 2^k possible subsets of channel symbols (constellation points). This is encoding through the convolutional code with the rate of $k/(k+1)$. Each of these subsets can be obtained through shifting the basic set $\mathbf{\Lambda}_c$. The second group of $p-k$ bits is left unencoded and selects one of the $2^{(p-k)}$ signal points in each subset.

For decoding the Ungerboeck codes, the Viterbi algorithm with a soft decision is used. A metric is the quantized Euclidean distance. Since this process is relatively complicated, there must be found a balance between the coding gain and the complexity of decoding.

2.3 Possibilities of precoding techniques

Under precoding techniques, we can distinguish three basic principles and then several modifications that improve the features of the basic ones. These basic precoding schemes are Tomlinson-Harashima, Flexible and Trellis precodings. Particular precoding schemes differ in the precoding loss, in combinations with signal shaping or with the TCM, and in stability or complexity of implementations.

2.3.1. Tomlinson-Harashima (THP) precoding

The THP precoding [9] represents a non-linear technique that employs a modulo arithmetic and is used to eliminate the ISI and to limit maximal and average output powers. The THP precoding block scheme is shown in Fig. 2.

Supposing the use of the M-point QAM modulation where symbols are selected from the set $A = \{\pm1,\dots,\pm(\sqrt{M}-1)\} \times \{\pm1,\dots,\pm(\sqrt{M}-1)\}$. For this constellation, the operation of the THP can be interpreted as follows: The unique sequence $\langle d[k]\rangle$, $d[k] \in 2\sqrt{M}\cdot\mathbf{Z}^2$ (the *precoding sequence*) is added to the data sequence $\langle a[k]\rangle$ in order to get the *effective data sequence* (EDS) $v[k] = a[k] + d[k]$. Values of the precoding sequence are chosen in such a way that the channel symbols fall into the half-open interval $R = \left(-\sqrt{M}, +\sqrt{M}\right)^2$. The values $d[k]$ can be selected by a simple memoryless modulo operation. Consequently, the EDS is filtered with

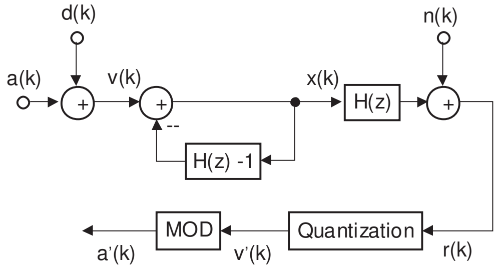

Fig. 2. The THP precoding block scheme

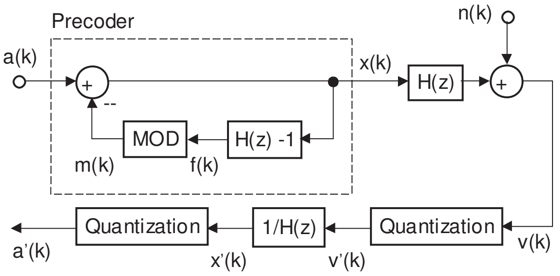

Fig. 3. The FLP (LTP) precoding block scheme

a formal inverse of the transmission function $H(z)$ resulting into the sequence entering the channel:

$$x[k] = a[k] + d[k] - \sum_{\kappa=1}^{p} h[\kappa] \cdot x[k-\kappa] = v[k] - f[k] \,, \quad (2.6)$$

In this way, the ISI produced by the $H(z)$ is eliminated and the signal $r[k]$ at the receiver input has the following form:

$$\begin{aligned} r[k] &= \sum_{\kappa=0}^{p} h[\kappa] \cdot x[k-\kappa] + n[k] \\ &= x[k] + \sum_{\kappa=1}^{p} h[\kappa] \cdot x[k-\kappa] + n[k] = x[k] + f[k] + n[k] \\ &= v[k] - f[k] + f[k] + n[k] = v[k] + n[k] \quad (2.7) \end{aligned}$$

where $n[k]$ represents the near white Gaussian noise sequence. A quantization slicer follows which produces estimates $v'[k]$ of the effective data symbols from which the estimated data symbols $a'[k]$ are produced by a modulo reduction into the interval R.

Precoding loss for the THP depends on an increasing number of constellation points. For moderate sizes of constellations, this precoding loss is negligible.

The THP can be directly combined with the TCM. The only restriction is that a periodic extension of the signal constellation must not reduce the intra subset distance. Since the TCM expands the signal set, the THP precoding loss is reduced by a small amount.

In the field of signal shaping, a straightforward combination of the THP and shaping techniques designed for the AWGN channel is not possible because of a non-linear device in the feedforward path of the THP precoder. A solution is to combine shaping and precoding techniques into one unit. With the THP, only one shaping technique works together — the *trellis shaping*. The combination of trellis shaping and of the THP is called the *trellis precoding* and represents a new precoding technique.

Since the THP reduces the transmitted signal into an exactly limited interval, spectral nulls in the transmission function have no influence on this type of precoding and, therefore, the THP is suitable for all types of channels transmission functions.

Although the implementation of the THP is relatively easy, problems can arise when the received symbols are reduced into the Voronoi area R. The solution can be found in the *dynamic shaping* [10] or in the *linear time varying precoding* [11].

2.3.2. Flexible (FLP) precoding

The FLP precoding was firstly presented in 1992 [12] and it is also known as the *Laroia-Treter-Farvardin precoding*. Its basic feature is the application of linear equalization at the receiver side. The FLP (LTP) precoding block scheme is shown in Fig. 3.

Likewise in the case of the THP, we consider the signal set $A \in 2\mathbf{Z}^2 + (1,1)$ taken from a translation of the signal lattice $\mathbf{\Lambda}_a = 2\mathbf{Z}^2$. Let $x[k] = a[k]$ be transmitted over the channel without precoding. Then the channel output is the information signal $a[k]$ enriched with the ISI expressed as:

$$f[k] = \sum_{k=1}^{p} h[k] \cdot x[k-\kappa] \,. \quad (2.8)$$

If we are supposing the $f[k] \in (_a$, then the channel output $v[k]$ belongs to the set $2\mathbf{Z}^2 + (1,1)$. Thus, a quantization slicer can eliminate the noise and the $1/H(z)$ recovers data without any noise enhancement. Unfortunately, $f[k] \notin \mathbf{\Lambda}_{a^*}$ in general. Hence, the $f[k]$ sequence is generated at the transmitter through the filter $H(z) - 1$. However, it is not subtracted completely from the data sequence but it is quantized to the nearest point $d[k] \in \mathbf{\Lambda}_a$ and only the quantization error $m[k] = f[k] - d[k]$ is subtracted. At the channel output, there is

$$\begin{aligned} v[k] = x[k] + f[k] + n[k] &= a[k] - m[k] + d[k] + m[k] + n[k] \\ &= a[k] + d[k] + n[k] \quad (2.9) \end{aligned}$$

where $v[k]$ is the element from the set $2\mathbf{Z}^2 + (1,1)$ and $n[k]$ represents the Gaussian noise. At the receiver, the estimation $v'[k]$ is generated by a threshold device. In order to recover the data, $v'[k]$ is filtered by the inverse channel filter with the transmission function $1/H(z)$ to get the estimation $x'[k]$ of the transmitted symbols. As the $m[k]$ is in the Voronoi region R of $\mathbf{\Lambda}_a$ and the $a[k]$ comes from a translation of the $2\mathbf{Z}^2$, the data can be recovered by quantizing the $x'[k]$ to the nearest point in A.

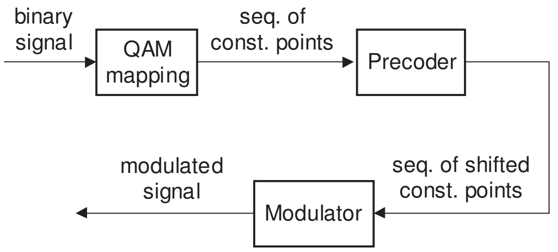

Fig. 4. The block scheme of the VDSL simulation model

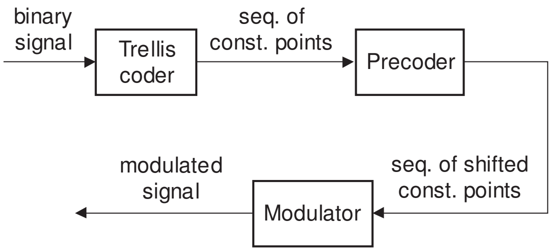

Fig. 6. The TCM encoder with the precoder and the QAM modulator

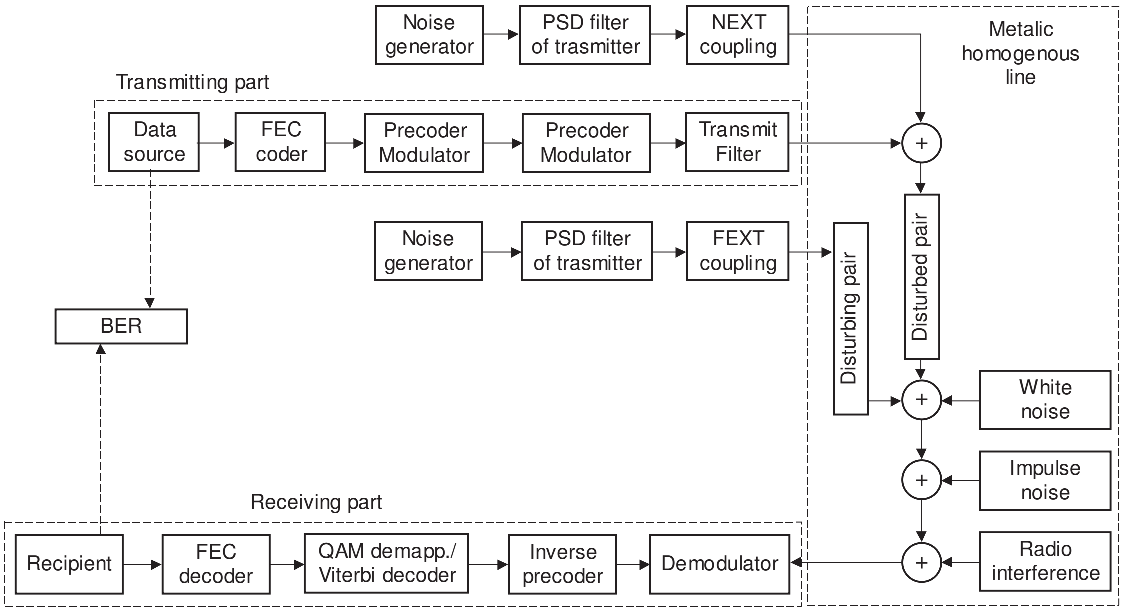

Fig. 5. The QAM modulator with the precoder

For M-QAM modulations, precoding loss with the FLP is the same as in the case of the THP precoding according to [9].

The FLP can also be combined with the TCM in a straightforward manner. The only difference is that the set $\mathbf{\Lambda}_a$ is divided into the subsets $\mathbf{\Lambda}_c$. Then the channel output sequence contains symbols of trellis code and not only valid signal points.

The FLP was initially introduced to support the constellation shaping on ISI channels. However, it is restricted to power shaping, *ie*, reduction of the average transmitted power that implies the generation of the average distribution. The FLP precoding has a disadvantage arising from using the inverse channel filter. If the transmission function of the channel filter contains zeros at the unit circle, *ie*, spectral nulls, then they lead to spectral poles in the $1/H(z)$ and the inverse channel filter is no longer stable. Therefore, the inverse precoder produces burst-errors. The solution of this problem can be found in [13].

In terms of implementation, the FLP decoder has to handle with a high dynamic range of incoming signals. This fact causes all problems mentioned above in the case of the THP. Moreover, implementation of the inverse channel filter behind the quantization block is problematic.

3 EXPERIMENTAL PART

3.1 The simulation environment and the basic model conception

Our analysis are based on computer simulations that cover the most important features and characteristics of the real transmission environment for the VDSL technology and result in searching for the best combination of coding and precoding techniques.

For our modelling of the VDSL transmission path, we used the software program Matlab v6.1 together with additional libraries like *Signal Processing Toolbox* 4.2 and *Communication Toolbox* 1.4. The realized model (Fig. 4) represents the signal transmission in the VDSL environment utilizing metallic homogenous lines for high-speed data signals in the downstream and upstream directions. Our VDSL environment model is the enhanced version of the ADSL environment model introduced in

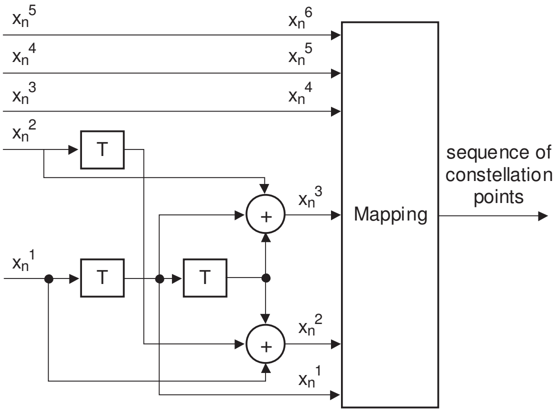

Fig. 7. The TCM encoder

[14], [15]. New features of this simulation model are VDSL transmission characteristics and applications of precoding techniques and trellis coded modulations.

Our simulation model (Fig. 4) can be divided into three main parts:

1. Transmitting part — it is responsible for encoding (because of using the FEC technique) and for modulation of signals into a form suitable for the transmission channel.
2. Transmission channel (the metallic homogenous lines) — this part of the model accounts for the negative influences on the transmitted signal. Above all, these are the propagation loss, signal distortion, crosstalk noises, white and impulse noises.
3. Receiving part — it is conceptually inverse in comparison with the transmitter. Its main functions are signal amplification, removing of the ISI, demodulation and correction of error information bits.

3.2 The transmitting part of the model

The transmitted message carried to the receiving part is generated as a random binary chain with a given length. This message is also saved (for the BER calculation), encoded by a particular type of the FEC codes (RS, BCH) and modulated. It can be chosen from two kinds of modulations — the first one is the classical QAM modulation (Fig. 5) and the second one is a combination of the QAM and the convolutional coding, *ie* the TCM (Fig. 6). In the following analysis, QAM modulation is chosen because of its compatibility with the considered precoding techniques, low distortion resistance and easy implementation in the Matlab program environment.

In the classical QAM (Fig. 5), the QAM mapping of a binary sequence to the constellation points is performed and then a precoding technique is applied. The output from the precoder is modulated in the QAM modulator.

In the QAM/TCM combination (Fig. 6), the trellis encoder is used to encode a binary sequence into the sequence of decimal numbers in the range from 0 to 31 and they are consequently mapped into the sequence of constellation points. The structure of the TCM encoder together with the used convolutional code (8-state code with the constraint length $K = 3$ and the rate $R = 2/3$) is shown in Fig. 7 [6]. According to results from [6] this type of TCM encoder can achieve an asymptotic coding gain 3.8 dB. Then the sequence of constellation points is processed by the precoder and modulated in the QAM modulator. Finally, the signal is filtered and sent into the transmission channel.

In this case, we receive the complex baseband signal instead of the passband real signal at the output of the QAM modulator. Because of mutual equivalence of the two signal representation types, this substitution can be made [17]. Naturally, all other blocks of the transmission path (filters, noise generators) must be implemented with respect to this complex signal representation.

3.3 The transmission line

Utilizing of local subscriber loops for the broadband access of subscribers by means of the VDSL technology assumes replacing a significant part of metallic lines by optical fibres. This will bring a subscriber distribution point (SDP) unit closer to subscribers, when metallic lines distribute signals to subscriber premises.

Although metallic lines form only a small part of the transmission path, their influences on the transmitted signals will not negligible.

The negative influences of the VDSL environment at signal transmission depend on the parameters of metallic homogeneous lines (core material, cable insulation, core diameter, the number of neighbouring lines in the cable binder, cable length). If we want to achieve exact results from simulations, all these factors must be accounted for. Of course, this leads to a complicated and complex simulation model. For modelling of all these influences, a theoretical description together with simulation methods is introduced in [14, 15].

Default values of parameters at signal transmission via homogenous metallic lines are the 50-pairs cable, core diameter 0.4 mm, line length 500 m and supposed presence of NEXT and FEXT crosstalk signals [16].

3.4 The receiving part of the model

At the receiver side, the distorted and attenuated signal is first amplified, next demodulated and then fed into the inverse precoder that removes constellation changes introduced by the precoder at the transmitter side. If the TCM is used, the TCM decoder follows and the Viterbi algorithm is searching for the most probable binary sequence. Otherwise, the QAM demapping block converts the constellation points sequence into a binary data sequence that is corrupted by transmission errors. They are consequently removed in the FEC decoder. Finally, the corrected sequence is compared with the original transmitted message and the bit error rate is calculated.

We should notice that individual precoding techniques suppose conceptually different manners of signal regeneration, therefore this process is not exactly described here.

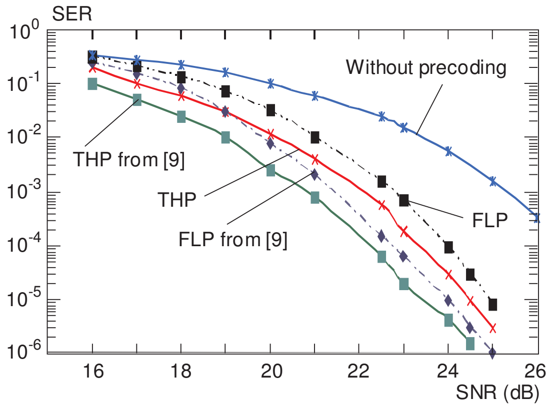

Fig. 8. The SER versus the SNR for various precoding techniques

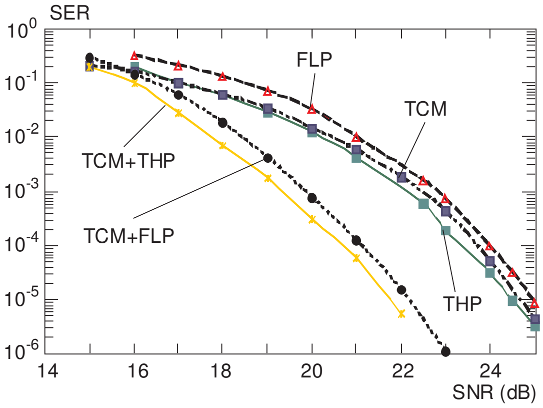

Fig. 9. The SER versus the SNR for a combination of precoding techniques with the TCM

For both methods, it is essential to know the transmission function of metallic lines. This information can be extracted from the signal transmission of predefined symbol sequences at the initialization process.

4 RESULTS OF THE ANALYSIS

Our simulation results are based on a comparison of the bit error rate (BER) and the symbol error rate (SER) in dependence on the signal-to-noise ratio (SNR) at the receiver input. Estimations of both error ratios are made by Monte Carlo simulation methods [17].

4.1 Comparison of precoding techniques

In this part, mutual comparison of precoding techniques is made. Parameters were chosen in order to agree with those defined in [9] to verify the modelling and simulation implementation of our precoding techniques. Therefore, the transmission bit rate is 2.048 Mbit/s and the 32-QAM modulation constellation is used. We consider both types of crosstalks and the background noise.

The results of simulations can be found in Fig. 8. The graphs represent the dependences of the symbol error rate on the signal-to-noise ratio for different precoding techniques (for the case of precoding absence, a linear equalizer is used). Furthermore, for verifying our precoding techniques, results from [9] are also contained.

As one can see, in our implementation of the precoding techniques, one can see a precoding gain about 3 dB and better results are achieved with the THP precoding that is about 0.5 dB better than the FLP at $SER = 10^{-6}$. This is caused by the inverse channel filter $1/H(z)$ at the receiver and its error propagation (as mentioned in 2.3.2). Different parameters of the transmission path can be the reason for the fact that our implementation of precoding techniques is about 1 dB worse than the one used in [9]. The authors considered a transmission environment for the ADSL technology.

4.2 Combination of precoding techniques with the TCM

Since this part of the analysis focuses on the meaning of precoding techniques in combination with the TCM, we first make simulations only with the TCM without any precoding. We used the TCM encoder described in part 3.2. The application of the TCM produces an expansion of constellation points from the initial 32 without coding to 64 with coding at the same transmission rate 2.048 Mbit/s. Parameters of the transmission channel are the same as in previous simulations. To remove attenuation and dispersion of the transmission path, a linear equalizer is used.

Precoding techniques in combination of with the TCM has to change properties of the precoder as they worked with the trellis containing 64 points.

Representations of the simulation results are based on the dependence of the symbol error rate on the signal-to-noise ratio. Graphical results are shown in Fig. 9.

As one can see, the combination of precoding techniques with the TCM significantly increases error protection of the signal. If we additionally use precoding, then we achieve a precoding gain (TCM+precoding versus TCM) 2.5 dB for application of the THP and 2 dB with FLP at $SER = 10^{-6}$. This analysis confirms the importance of combining the precoding techniques with the TCM, which is also important in comparison with individual precoding techniques. In this case, the coding gain (TCM + precoding versus precoding) equals to 3 dB at both precoding techniques. The extension of constellation points caused by the TCM modulation produces a lower precoding loss — precoding loss (TCM + precoding versus precoding) is 0.07 dB at THP and 0.57 dB at FLP. The higher value in the case of the FLP is caused by the error propagation at the receiver side (because of the inverse channel filter).

4.3 Combination of precoding techniques with DMT

The last part of the analysis focuses on stand-alone precoding techniques in combination with DMT modu-

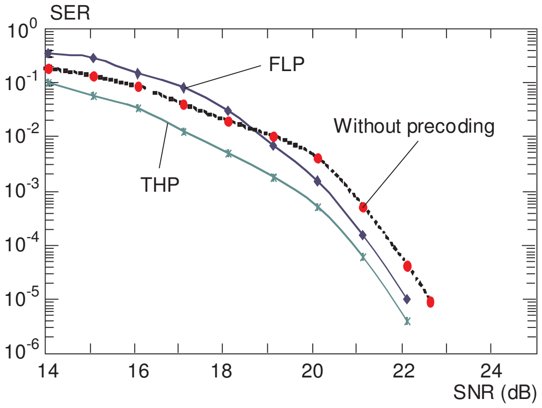

Fig. 10. The SER versus SNR for a combination of precoding techniques with the DMT

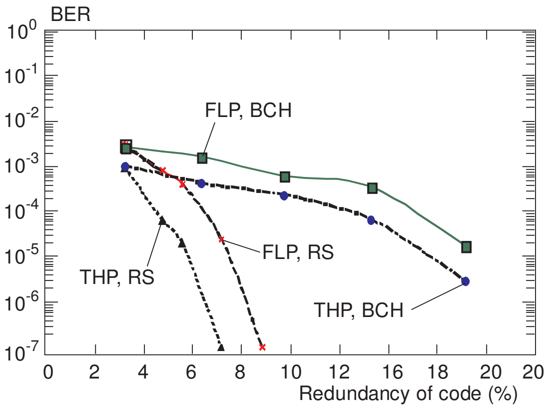

Fig. 11. The comparison of various coding and precoding techniques combinations

lation. The basic concept of DMT can be modified for using in the VDSL technology [1]. Our simulation model is based on the fact that the precoding process is performed for each channel individually and the results are evaluating in one channel. The data sequence is mapped on 32 constellation points.

In this case the results are not as positive as in the previous simulations. Precoding gain is 1 dB in the case of THP and 0.5 dB in the case of FLP at $SER = 10^{-5}$. These relatively low values are probably caused by small signal deformations in the transmission channel, since the signal modulated by the DMT in the subchannel takes only a narrow bandwidth (about 4 kHz).

Then, we can say that the combination of precoding techniques focused on ISI cancellation with DMT is of no significant importance. Maybe, this combination can be used to interchannel interference (ICI) cancellation.

4.4 Combination of coding and precoding techniques

Considering results from the previous parts, we can declare that errors occurring during signal transmission are grouped in bursts (mainly if the inverse channel filter is used). Thus, we selected coding techniques that can correct burst errors — RS and BCH codes with the code length $n = 255$ (based on the results from [15]).

Parameters of the signal transmission are corresponding to the real VDSL transmission environment. The data rate is 25.6 Mbit/s, the 32-ary QAM modulation is used and the line length is 500 m. Information bits are protected by a combination of one coding with one precoding technique.

Fig. 11 shows the differences in performance between different combinations of coding and precoding techniques. As can be predicted on the basis of the results from part 4.1, signal transmission with THP is better than with FLP and it is in combination with both coding techniques. From the coding techniques, the RS codes have a better performance, so we can declare that a combination of THP and RS techniques is the best solution.

5 CONCLUSIONS

This paper analyzes the problems of signal protection in a VDSL environment at signal transmission. We present a review of various characteristics and features of coding and precoding techniques applicable in VDSL modems. Furthermore, we briefly described the simulation model that is used to analyze various combinations of precoding, modulation and coding techniques used for high-speed data transmissions.

One of the procedures for solving the ISI problem is represented by precoding techniques. We focused on the Tomlinson-Harashima precoding and the Flexible precoding. They were analyzed partly separately and partly in combination with selected coding and modulation techniques. Both analyses confirmed better results of the THP precoding in comparison with the FLP precoding. Also, in practice, most manufacturers prefer THP.

The second analysis is oriented on a combination of precoding techniques with special modulation types — the TCM and the DMT modulations. It is obvious according to the simulation results that a coding gain of about 3 to 4 dB can be achieved by applying the TCM modulation and precoding versus only the precoding, and also that a precoding gain from 2 to 2.5 dB (it depends on the type of precoding, THP is better) can be achieved with this combination in comparison with only TCM. Somewhat different is the DMT modulation. If we used a precoding with the DMT, we achieved a precoding gain only about 0.5 to 1 dB (at both precoding techniques). This gain is relatively low in comparison with QAM or CAP modulations. The application of precoding techniques is attractive for the VDSL modems based on the QAM/CAP modulations or on the TCM modulation but it is of low importance for VDSL modems using the DMT modulation.

It is well-known that the FEC codes can increase the quality of services in the environment of metallic homogeneous lines. We are focused on Bose-Chaudhury-Hocquenghem and Reed-Solomon codes from block codes and on Ungerboeck codes from convolutional codes as a part of the TCM. We analyzed these codes in combination with precoding techniques. Our results show that

RS codes are the most effective for eliminating the errors caused by the impulse noise and by the crosstalks.

Better properties of RS codes are caused by their ability to correct burst errors that are more typical for signal transmission in the VDSL environment (influence of crosstalks, impulse noise). We can declare that the optimal signal protection ensured by block codes can be achieved by combination of the Tomlinson-Harashima precoding with the Reed-Solomon codes.

The combination of the Tomlinson-Harashima precoding and the Reed-Solomon codes with the code length of 255 symbols and the redundancy of 6 up to 10 % seems to be suitable for signal transmission by means of the VDSL technology. The THP precoding removes signal distortion alias the inter-symbol interference (mainly if the QAM or CAP modulations are used) and RS codes eliminate the effects of the impulse noise and crosstalks. In the environment with extremely negative influences upon signal transmission, the THP precoding can be supplemented by the TCM that increases the noise and ISI reduction at a cost of a small increase in complexity. Then these techniques should be able to provide a satisfactory protection of signal transmission by means of the VDSL technology in the environment of metallic homogeneous lines.

Appendix — Abbreviations

ADSL	Asymmetric Digital Subscriber Line
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BCH	Bose-Chaudury-Hocquenghem
CAP	Carrierless Amplitude Modulation
DFE	Decision FeedBack Equalizer
DMT	Discrete Multitone Modulation
DWMT	Discrete Wavelet Multitone Modulation
FEXT	Far-End Crosstalk
FIR	Finite Impulse Response
FLP	Flexible Precoding
GF	Galois Field
ICI	Interchannel Interference
ISI	Intersymbol Interference
NEXT	Near-End Crosstalk
PR	Partial Response
QAM	Quadrature Amplitude Modulation
RS	Reed-Solomon
SER	Symbol Error Rate
SDP	Subscriber Distribution Point
SNR	Signal-to-Noise Ratio
TCM	Trellis-Coded Modulation
THP	Tomlinson-Harashima Precoding
VDSL	Very high bit rate Digital Subscriber Line
xDSL	x Digital Subscriber Line

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