1. INTRODUCTION

Powerline communication (PLC) systems have many advantages and are good solution for communication networks. However, they are not designed to be a communication medium and hence exhibit a lot of peculiar features. PLC channels are characterized by a frequency selective transfer functions, attenuation increasing with length and frequency, severe narrowband interference and impulsive and coloured noise whose behaviour is different than that of stationary additive white Gaussian noise because it is time and frequency dependent (cyclo-stationary Gaussian model of noise). [1] [2]

Similar, asymmetric digital subscriber lines (ADSL) is a technology that enables high-speed data access over an existing telephone network. Many difficulties in the implementation of PLC are similar to problems in ADSL. Both, PLC and ADSL intend to use their respective transmission medium in a frequency range they were never originally designed for. That frequency range is comparable. The fact that a communication channel has to be established in an electromagnetic environment not intended for the chosen frequencies, makes many problems common to both technologies. Large power that is required when transmitting signals is also in common. Therefore, concepts of the ADSL technology can be adopted to suit PLC requirements. [3]

For many applications multi-carrier modulation schemes or multicarrier transmission techniques (MCM) are an attractive alternative to single-carrier systems. In Europe, orthogonal frequency division multiplexing (OFDM) like one of MCM schemes, is standardized for digital audio broadcasting. The American National Standardization Institute (ANSI) has selected OFDM transmission for ADSL. Investigations revealed that OFDM can also cope with the shortcomings of power line as communication media [1]. A reason for this success is the ability to deal with multi-path propagation (delay spread), peak power clipping and robustness to impulsive and narrow band channel noise that occurs in PLC systems.

In our previous papers we gave a brief overview of PLC systems. Standards as well as architecture of the system were presented [3]. The accent was on modulation techniques already used in PLC systems, especially MCM techniques and OFDM [4]. Here, we would like to introduce the newest idea of multi-carrier transmission, i.e., filter bank based MCM, which is already implemented in very similar systems, ADSL and VDSL. Hence, it can also be used in PLC systems. The main idea of the paper is to illustrate the filter bank based MCM, and show its advantages compared to DFT based MCM system. Further, we propose the filter bank based MCM technology as suitable for the PL environment.

The rest of the paper is organized as follows: In section 2, the comparison of traditional MCM and filter bank based MCM systems is given. In section 3, the basic theory of transmultiplexers is presented. Section 4 gives the explanation of one special class of filter bank systems - cosine modulated filter bank and one way of its implementation. Design example is shown in chapter 5 and conclusions follow in chapter 6.

2. ADVANTAGES AND DISADVANTAGES OF OFDM AND TRANSMULTIPLEXERS IN PLC

The main reason why OFDM modulation seems to be a good choice for PLC is because it is suitable for frequency selective channels. OFDM is MCM with carriers orthogonal to one another. It prevents interference between the closely spaced carriers. In order to eliminate ISI and multipath delay even more, the guard period is added. The guard interval length depends on the multipath channel delay spread and must be greater of the expected spread of multiple delays. Also, it is sensitive to frequency and phase errors between the transmitter and receiver [6]. The traditional MCM systems have been implemented using Discrete Fourier Transform (DFT) as the modulation technique. However, in systems based on the use of DFT, the sub-channel filters have poor stop band attenuation of approximately 13 dB. This is main drawback of DFT based system. Thus, narrow band interference in certain frequency band can make several sub-channels useless. Therefore, it is required to design sub-channel filters with desired stop band attenuation and degree of sub-bands overlapping, depending on the filter length and the transition bandwidth. This can be achieved using filter bank based multi-carrier system [7]. It employs two filter banks, a synthesis filter bank (SFB) at the transmitter side and an analysis filter bank (AFB) at the receiver side. This filter bank based system is known as transmultiplexer (TMUX). In such a system there is no need for guard times to separate consecutive symbols. That increases efficiency and robustness, synchronization is easier and the initialization sequence at the beginning of a connection is shorter [8].

3. FUNDAMENTALS OF TRANSMULTIPLEXERS

TMUX system can be considered as a multi-carrier system. It has certain advantages compared to existing DFT-based MCM and it is promising candidate for data transmission in frequency selective channels, such as PLC. The design and implementation of TMUX is based on filter banks [9]. The filter bank design is flexible; we can adjust the selectivity and thus tolerate stronger narrow-band interference.
than existing DFT-based systems. We can also adjust the sub-band overlapping.

In TMUX systems the transmission channel is divided into \( M \) sub-channels with frequency spacing \( 1/2M \) using the bank of \( M \) sub-filters as shown in Figure 1. The rate of symbols in sub-channel is \( 1/M \). The phase and amplitude distortions in the sub-channels and the interference between sub-channels can be controlled by properly designed sub-band filters. Phase distortion is eliminated if sub-band filters have certain properties. The amplitude distortion produces Inter-Symbol Interference (ISI) in the receiver. Nyquist criterion must be satisfied but if sub-channel equalizer is employed some flexibility can be introduced. The aliasing distortion of the filter bank corresponds to Inter-Carrier Interference (ICI) or crosstalk in TMUX. The prototype filter can be designed with the help of classical optimization techniques, but its computation of complexity is linearly related to the order of classical optimization techniques, but its length \( N \) can be several thousands and a direct technique also seems appropriate [8].

Key parameter in digital transmission is a delay. Overall delay budget allotted to the system is shared among functions in the transmitter and receiver. In single carrier transmission decoding and error correction uses most of the delay budget and the delay of sub-band filters should be minimized. Therefore, number of coefficients \( N \) is a trade-off between delay and filter performance (especially stop-band attenuation) [8]. Also, the computation of complexity is linearly related to the number of coefficients \( N \) and it should be decreased.

Filter banks can be designed with the perfect reconstruction (PR) or nearly PR property (NPR). NPR filter banks allow some amount of ISI and/or ICI. However, an analog channel between synthesis and analysis filters introduces distortion and noise and in such a case PR should imply perfect equalization in the receiver which is unrealistic. Therefore it is not necessary to examine PR filter banks [8]. However, it was shown in the literature that by allowing small amplitude and aliasing distortions, the resulting NPR filter bank possesses a significantly improved stop-band performance compared to the corresponding PR filter bank of the same delay. Also those distortions to the signal can be much smaller than distortions caused by other reasons. If filters are well derived, the maximum amplitude of the aliasing terms is guaranteed to be at most equal to the minimum stop-band attenuation of the channel filters [7].

In the following, we analyze the synthesis problem of TMUX. A maximally decimated \( M \)-channel TMUX is shown in Figure 2. It consists of synthesis filter bank that contains \( M \) filters \( F_m(z) \) and after the channel, in the receiver, is analysis filter bank of \( M \) filters \( H_m(z) \). There is a relationship between those two filter banks if they satisfy PR condition. In order to simplify analysis we assume that the channel response \( C(z) \) is equal to unity or to a pure delay.

The output signals in the frequency domain can be expressed as follows:

\[
y(z^M) = \frac{1}{M} T(z^M) \cdot x(z^M),
\]

where

\[
y(z) = \begin{bmatrix} Y_0(z), \ldots, Y_{M-1}(z) \end{bmatrix}^T,
\]

\[
x(z) = \begin{bmatrix} X_0(z), \ldots, X_{M-1}(z) \end{bmatrix}^T,
\]

and

\[
T(z^M) = \sum_{k=0}^{M-1} H_k(z e^{-j2\pi k/M}) F_k(z e^{-j2\pi k/M}).
\]

The matrix \( T(z^M) \) is so-called transfer matrix. Each element of this matrix represents the relation between certain input and corresponding output signal. The elements in the main diagonal are the transfer functions of \( M \) sub-channels of the system, and other elements describe the cross-talk between different channels. In the case when TMUX is based on PR filter bank, the transfer matrix is diagonal.

\[
T(z^M) = \text{diag}[S_0(z), \ldots, S_{M-1}(z)],
\]

where \( S_k(z), k=0, \ldots, M-1 \) are simple delays of the form \( z^{-kM} \) with \( k \) being an integer. The amplitude distortion in the analysis-synthesis configuration can be said to cause ISI in TMUX. Instead of aliasing distortion in other systems, the problem in TMUX is ICI. The values of ISI and ICI can be estimated from the matrix \( T \).

Because we expect to have big number of sub-channels, if we use TMUX in PLC systems, one convenient way to design and implement TMUX is using cosine modulated filter banks. We will explain this class of filter banks in the next chapter.

4. COSINE-MODULATED FILTER BANK, THEORY AND IMPLEMENTATION

Traditionally MCM can be implemented also using Discrete Wavelet MultiTone (DWMT) technique instead of DFT and it shows better performances. Hence, DWMT filter bank based system can be very frequency selective. Good way to
implement this type of filter bank is to use Cosine-modulated filter bank (CMFB). The basic idea of CMFB is that sub-channel filters can be derived from a single lowpass prototype filter, whose order is $N$ and transition band is centered on $f_c=1/4M$, using cosine modulation. The prototype filter controls the phase and amplitude distortions in the sub-channels and the interference between sub-channels. This is the most effective technique to construct the desired analysis and synthesis filters from design and implementation point of view. At the receiver, we need sine modulated filter bank (SMFB) [7].

First step in designing the CMFB is to optimize the prototype filter whose transfer function $H_p(Z)$ has the following form:

$$H_p(z) = \sum_{n=0}^{N} h_p(n) z^{-n}. \quad (6)$$

Phase distortion is eliminated if the prototype filter has linear phase. The linear phase is achieved if the impulse response of the prototype filter is symmetric [7]:

$$h_p(N-n) = h_p(n). \quad (7)$$

Also, -3dB point of the amplitude response is at about $\omega = \pi/(2M)$ and stopband edge is given by

$$\omega_S = \frac{(1+\rho)\pi}{2M}, \quad (8)$$

where $\rho > 0$ is the roll-off factor determining how much the adjacent channels are spectrally overlapped. In Figure 2 is shown that for $0 < \rho \leq 1$ only neighbouring channels on both sides overlap; for $1 < \rho \leq 2$: two neighbouring channels on both sides overlap; and it can be shown that for $\rho > 2$ at least three neighbouring channels on both sides overlap.

After the prototype filter is designed, the sub-channel filters for CMFB in general case can be expressed as:

$$h_k(n) = 2h_p(n) \cos((2k+1)\frac{\pi}{2M}(n-\frac{N}{2})+\phi_k), \quad (9)$$

and

$$f_k(n) = 2h_p(n) \cos((2k+1)\frac{\pi}{2M}(n-\frac{N}{2})-\phi_k), \quad (10)$$

where $\phi_k = (-1)^k\pi/4, k = 0,\ldots, M-1, M$ is the number of channels and $N$ is the length of the prototype filter. As can be seen, synthesis filters are time-reversed versions of the analysis filters, i.e. $f_k(n) = h_k(N-n)$ [7].

The idea is to design NPR filter bank with small amplitude distortions. In this case, prototype filter can be designed in the least mean square sense. Therefore we should find the coefficients of $H_p(z)$ to minimize

$$E_\delta = \int |H_p(e^{i\omega})| d\omega$$

subject to

$$1 - \delta_1 \leq |T_\delta(e^{i\omega})| \leq 1 + \delta_1, \omega \in [0,\pi]$$

and

$$|F(e^{i\omega})| \leq \delta_2, \omega \in [0,\pi]$$

for $i = 1, \ldots, M-1$. The parameters $\delta_1$ and $\delta_2$ are constraints that define the maximum allowable amplitude distortion and aliasing distortion of the filter bank, respectively. [7]

In filter banks with small amplitude distortion aliasing distortions are not considered in the optimization of prototype filter and the powers of the interference components can be estimated using formulas:

$$ISI = \max_k \left( \sum_n (\delta_1(n) - t_k(n))^2 \right)^{1/2}, \quad (14)$$

and

$$ICI = \max_k \left( \sum_{n \neq l} |F(e^{i\omega})|^2 \right)^{1/2}. \quad (15)$$

It has been shown that the attenuation of the highest stopband ripple comparing to PR case has been improved at the expense of small ISI and ICI. It was also noticed that for $1 < \rho$ the stopband attenuation can be well improved, but for $1 > \rho$ it can not be improved so much [7].

In more generalized NPR filter banks, both constraints $\delta_1$ and $\delta_2$ are specified. We can try to construct TMUX system with very low ICI levels, but if it is too small, the attenuation of the highest stop-band ripple decreases. [7]

These interference components of Error! Not a valid link. and Error! Not a valid link. are added to the channel noise and they form the total amount of distortions. Together they influence on the bit error rate (BER). In order to achieve desired BER we have to find the maximum value of number of sub-channels $M_{\text{max}}$, which also depends on channel conditions. This will be considered in our future work.

One way of CMFB implementation is parallel implementation [9] shown in Figure 3. It consists of

![Figure 3](image-url)
5. DESIGN EXAMPLES

In this section we illustrate the advantages of using TMUX instead of DFT in MCM and we give some numerical examples for the explained CMFB.

It is required to construct MCM of $M=8$ channels. First, we can use conventional DFT based system. The sub-channel frequency response for this case is given in Figure 4. It can be noticed that side-lobes in stop-band are rather high.

We can use also TMUX based MCM system described above. The prototype filter is designed using least square method (Kaiser window approach [10]) with maximum allowable stop-band ripple of $A_s=60$ dB. Sub-band overlapping factor $\rho$ is equal to unity. The length of the prototype filter $N=66$ and its frequency response is shown in Figure 5. In Figure 6 where is shown the frequency response of CMFB with $M=8$ channels, can be seen that attenuation in stop-band is at least 60 dB. The way of controlling stop-band attenuation in TMUX is obvious. We can estimate ISI and ICI using Equations (16) and (17).

6. CONCLUSION

As we have seen ADSL system encounters similar problems as PLC system, what is shown in this paper. Thus we show that NPR CMFB approach for highly selective maximally decimated TMUX systems is good solution for very frequency selective PLC system. We explained that filter bank characteristics can be improved by allowing small ISI and ICI and that stop-band ripples can be well and easy controled. We have also illustrated performance of NPR CMFB which will be used in our future research. Our aim is to show that TMUX based MCM is good option for PL systems.

REFERENCES

[1] Patrick J. Langfeld, Klaus Dostert, OFDM System Synchronization for Powerline Communications, Karlsruhe, Germany.

Abstract: In this paper we gave a basic theory and implementation of one, non-traditional approach to multicarrier systems. It was shown that filter bank based systems can be considered as multicarrier systems with far away better stop-band attenuation than multicarrier systems based on DFT. We presented cosine modulated filter bank and showed that stop-band attenuation can be well controled. That feature is very useful in frequency selective channels as it is medium in ADSL systems and in very similar PLC systems. The aim of our future work is to implement transmultiplexer systems in PLC system and prove its suitability for this case.

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