On the Performance of Filter Bank Based Multicarrier Systems in xDSL and WLAN Applications

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Abstract—In this paper, we consider filter bank based multicarrier systems which have been considered for fast digital subscriber line applications and possibly could be interesting also for broadband wireless LAN applications. In addition to being resistant to narrowband interference, these systems provide better spectral shaping than DFT-based OFDM and DMT systems for the subchannels, as well as for the overall signal. Furthermore, they provide better efficiency because the time-domain guard interval is not needed and the guard-band in frequency domain can be reduced. The channel equalization for such systems has been an open problem, but the paper demonstrates that it can be solved, at least in principle, even though effective adaptive equalization algorithms are still under development. Another open question is the performance when nonlinearities are included in the chain, especially in the transmitter power amplifiers. In the paper, it is demonstrated that the performance of filter bank based systems with nonlinear power amplifiers is only slightly worse than in the corresponding OFDM/DMT systems. When the number of channels is the same, no more than 1 dB higher input backoff is required.

I. INTRODUCTION

Filter bank based multicarrier techniques, such as the so-called Discrete Wavelet Multi Tone (DWMT) technique [1], [2] have received some attention in the area of high-speed data transmission in wireline access networks. In comparison to the standard DMT approach [3], the main advantage of these techniques is the good spectral shaping of the subchannel signals, making them highly tolerant against narrowband interference. A VDSL transmultiplexer based on cosine-modulated perfect-reconstruction filter banks has been presented in [4].

Such multicarrier systems have some good properties also when radio communication systems are concerned. We consider here especially the area of broadband wireless access networking, where DFT-based OFDM systems are in a strong position [5], [6]. One advantage of filter bank based multicarrier systems is that, due to better spectral shaping of the overall signal, the guardbands between different channels can be reduced while maintaining the adjacent channel interference at a low level without any additional filtering. In general, the overall bandwidth of each subchannel is controlled by the roll-off parameter $\rho$ of the filter bank design and it can be expressed as

$$W_{\text{sub}} = (1 + \rho)B,$$  \hspace{1cm} (1)

where $B$ is the subcarrier spacing. In a typical design, $\rho = 1$ and the subchannel signal is attenuated by $30\ldots60$ dB outside the subchannel bandwidth [4]. Thus, one subchannel spacing is, in theory, sufficient as a guardband between two multiplexes of subchannels. This could possibly also help to develop flexible ways to divide the frequency band for different users. However, the requirements for the analog transmitter and receiver front-ends and A/D converter have to be taken into account when considering the power levels of nearby multiplexes.

Another property, and potentially a benefit, is that the time-domain guard interval approach cannot, and need not to be applied to deal with the multipath channel. However, this is also a major difficulty, since adequate channel equalization techniques are not yet available for such filter bank based multicarrier systems. The earlier approaches [7], [8] have rather high implementation complexity. Some new ideas for channel equalization have been presented by the authors in [9] for the xDSL case and in [10] for the broadband wireless case.

Section II gives the basic idea of using filter banks as transmultiplexers. The equalization issue for the filter bank based multicarrier systems is discussed in Section III. Section IV gives simulation results for equalizer performance and for the effects of nonlinear transmitter power amplifier.

II. FILTER BANKS AS TRANSMULTIPLEXERS

OFDM and DMT can be considered as filter bank based transmultiplexer (TMUX) systems [11] (see Fig. 1). In general, in spectrally efficient multicarrier systems, the subchannels are partly overlapping in the frequency domain, while the orthogonality of the subcarriers is maintained. This means that, in ideal conditions, there is no crosstalk (intercarrier interference,ICI) between the subchannels and each subchannel is free of Intersymbol Interference (ISI). Different approaches for spectrally efficient TMUX design using partially overlapping subchannels have been considered in the literature since 1960’s [12]. In case of OFDM, the filter banks needed in the transmitter and receiver ends are implemented through Inverse Discrete Fourier Transform (IDFT) and Discrete Fourier Transform (DFT), respectively. However, it is well known that the selectivity of DFT as a filter bank is rather limited.

In a previous paper [4], we presented efficient solutions for VDSL systems based on the idea of cosine-modulated filter banks. This approach provides efficient synthesis and analysis filter banks for the transmitter and receiver, respectively, and the performance (stopband attenuation and the degree of overlapping of the subbands) can be well controlled. In ideal conditions (perfect reconstruction filter bank), the ICI and ISI powers are zero.
Fig. 1. Maximally decimated $M$-channel TMUX.

Real baseband signal model is used in the VDSL application, whereas in the WLAN application I/Q format is used. Correspondingly, cosine modulation or complex modulation is used to create the filter bank from a lowpass prototype filter design. Efficient implementations are based on DCT (αDSL, real bank) or DFT (WLAN, complex bank). In the case of complex bank, the channel filters for transmitter an receiver can be given as

$$f_k(n) = h_p(n) e^{j(2k-1)\pi n \left(\frac{n-M-1}{2}\right) - j\pi(n-1)^2}$$

and

$$h_k(n) = h_p(n) e^{j(2k-1)\pi n \left(\frac{n-M-1}{2}\right) + j\pi(n-1)^2},$$

where $k = 1, \ldots, 2M$ and $h_p(n)$ is the common prototype filter (linear phase FIR lowpass filter, whose 3 dB bandwidth is $\pi/(2M)$).

The stopband edge for the prototype filter has to be larger than $\pi/(2M)$ and is defined by

$$\omega_s = \frac{(1 + \rho)\pi}{2M}.$$  

When $0 < \rho \leq 1$, only adjacent channels on both sides overlap a given channel. The same prototype filter design and the filter optimization techniques presented in [4] can be used in both (DFT and DCT) cases for perfect reconstruction designs. Fig. 2 shows an example design. From the data modulation point of view, such filter banks implement offset QAM type of modulations [4].

III. EQUALIZATION

A. Guard Interval Based Approach

In OFDM and DMT systems, guard intervals are often used to combat intersymbol interference due to multipath channel [5, 6]. Guard interval is a cyclic extension of the actual symbol waveform, used as a prefix to absorb the delayed components of the previous OFDM symbol. If the guard interval is at least as long as the channel delay spread, the orthogonality of the subcarriers is preserved with arbitrary stationary channel responses (however, Doppler shift may destroy the orthogonality). Under these conditions, if reliable frequency-domain channel estimation can be carried out, the channel equalization itself is a simple task: each subchannel signal from the DFT block of the receiver is multiplied by a complex number, inverse of the sub-channel gain estimate.

B. Effects of Nonideal Channel in Filter Bank Based Systems

In filter bank based multi-carrier systems, the basic symbol waveform is, instead of a rectangular pulse of symbol duration, a Nyquist pulse overlapping with the previous and next symbols (see Fig. 2). In this case, the guard interval idea cannot be efficiently utilized. Furthermore, the orthogonality of the subcarriers is easily lost.

It is clear that arbitrary scaling of the amplitudes does not affect on the orthogonality. But effects of nonlinear phase response of the channel may be serious. This is because the perfect reconstruction property of filter banks relies partly on exact matching of the phases of the overlapping parts of sub-channel frequency responses.

If the phase response can be assumed to be a linear function of frequency within the frequency band of each subchannel, then each subchannel signal experiences a delay which is equal to the group delay of the subchannel. Furthermore, if the group delay (envelope delay) and phase delay (effecting the carrier phase offset) are different, then the waveform is distorted. These effects appear as crosstalk between subchannels and intersymbol interference within each subchannel.
C. Equalization Approaches for Filter Bank Based Systems

To eliminate the effect of nonlinear phase response after the receiver analysis bank, it would be necessary to be able to resample the subchannel waveforms at correct sampling instants. Also the carrier phase should be adjusted properly for each subchannel. This would eliminate ISI within each subchannel [9]. Furthermore, since neighboring subchannels would experience practically the same delays, also the crosstalk would be practically eliminated. However, to be able to implement resampling after the receiver filter bank, either the filter bank output has to be oversampled (which is the case in [7]), or the resampling should be incorporated in some clever way to the receiver (analysis) filter bank itself.

The alternative approach is to equalize the channel phase response before the receiver bank so that the overall phase response is linear [10]. Then the amplitudes of the subchannels can be equalized in the same manner as in OFDM systems using complex multipliers for each subchannel. In case of wired transmission systems utilizing the twisted pairs of the telephone network, this latter approach seems to be feasible [9], but in the case of broadband wireless access radio channel, the phase response is so irregularly behaving that the time-domain equalization approach seems to be impractical.

IV. PERFORMANCE EVALUATION BASED ON SIMULATIONS

We have tested the ideal performance of two proposed types of equalizers in the corresponding channel environments by computer simulations.

A. Time-Domain Phase Equalizer for xDSL

The time domain phase equalizer approach was tested for the VDSL application [9]. A 64 channel perfect reconstruction cosine modulated filter bank was considered. It has the roll-off factor parameter \( p = 1 \) and about 49 dB stopband attenuation. The channel model was obtained from measurements of actual subscriber lines (770 meters length of modern plastic-shielded cable). Fig. 3 shows the residual signal-to-interference ratio with optimized 2-, 3- and 4-tap FIR equalizers. Here the interference includes the ISI within the subcarrier and the ICI from the two neighboring subcarriers. It can be seen that rather short phase equalizers are able to provide good performance, since the channel phase response behaves rather smoothly as a function of frequency [9].

B. Oversampled Receiver Bank Approach for WLAN

The oversampled receiver bank approach with ideal symbol timing and carrier phase recovery for each subcarrier was tested in the WLAN case [10]. The filter bank parameters were similar as above, except that now a complex DFT-based filter bank is utilized. The channel model is now a stationary multipath channel with exponentially decaying power delay profile [6]. Fig. 4 shows the signal and interference components for every subcarrier, in a specific simulation with 108 ns delay spread.

Fig. 5 shows also the ideal capacity comparison [10] between the filter bank based system (with 32, 64, or 128 subcarriers), ideal equalized OFDM system [13], and ideal guard interval based OFDM system, assuming that 25% of the overall symbol interval is used as a guard interval. The effect of frequency domain guard band is not taken into consideration here.

C. Effects of Power Amplifier Nonlinearity

To test the performance with nonlinear power amplifier in the transmitter, the soft-limiting model of Fig. 6 was used.
The operating point of the amplifier is usually identified by the backoff. In this paper, the following definition for the input backoff (IBO) is adopted:

\[ IBO = 10 \log_{10} \frac{P_{O,IN}}{P_{IN}}, \quad \text{(in decibels)} \quad (5) \]

where \( P_{IN} \) is the mean power of the signal at the input of the amplifier and \( P_{O,IN} \) is the input power corresponding to the maximum output power (saturation power). Figs. 7 and 8 show the noise to signal-ratio and BER performance of OFDM and filter bank based systems as a function of input backoff in cases of 32, 64, or 128 subcarriers. About 49 dB stopband attenuation was achieved by using the design parameter \( p = 1 \). The results show slightly worse performance for the filter bank based system, but the difference is always clearly less than 1 dB.

To study the spectral characteristics of these systems, the power spectral densities at the amplifier output were evaluated.

Figs. 9(a) and 9(b) show the power spectra for the 64 subcarriers case with input backoffs of 5 dB and 8 dB, respectively. It can be seen that with sufficient backoff and stopband attenuation in the filter bank design, the filter bank based system provides much better spectral characteristics.

**V. Conclusions**

The experiments described above illustrate that the equalization problem in filter bank based multicarrier systems can be solved, at least in principle, and good performance for such systems can be achieved in the two considered applications.

The time-domain phase equalizer approach relies heavily on the smoothness of the channel phase response, which may be difficult to guarantee in extreme cases even in the VDSL application.
The results of the BER-simulations with nonlinear amplifier model show slightly worse performance for the filter bank based systems, but the difference is always clearly less than 1 dB. This drawback could possibly be more than compensated if lower number of subchannels is sufficient due to better spectral shaping of the subchannel signals.

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