ABSTRACT

In this paper we consider filter bank based multicarrier systems, which provide better spectral shaping than DFT-based Orthogonal Frequency Division Multiplexing (OFDM) or Discrete MultiTone (DMT) systems for the subchannels, as well as for the overall signal. Due to their better performance in case of narrowband interference, such techniques have received attention especially in the context of Very high-speed Digital Subscriber Line (VDSL) system development. However, the channel equalization for such systems is still an open problem. In this paper, it is demonstrated that filter bank based multicarrier systems are very sensitive to the nonlinear phase response of the channel. Alternative ways to perform the channel equalization are discussed. Also measurement results from real subscriber lines are presented and, based on these results, a two-step equalization approach is proposed.

1. INTRODUCTION

Multicarrier modulation techniques have received wide attention in the context of digital subscriber line system development. In multicarrier modulation, the available channel bandwidth is subdivided into a number of narrow subchannels, which are partly overlapping in spectrally efficient systems. The order of utilized modulation for each subchannel depends on the Signal-to-Noise Ratio (SNR) of the corresponding subchannel. In this way the transmission capacity of the transmission medium, twisted pair, can be utilized efficiently. In practice, multicarrier modulation has been implemented using Discrete Fourier Transform (DFT).

A conventional DFT-based multicarrier system, DMT, has been adopted for Asymmetric Digital Subscriber Line (ADSL) standards [1]. However, DMT is rather sensitive to narrowband interferences due to the large sidelobes of the DFT. Therefore, so-called Discrete Wavelet MultiTone (DWMT) technique has been proposed for VDSL standardization [2]. Both the DMT and DWMT can be considered as filter bank based transmultiplexer (TMUX) system. In DWMT, the idea is to make the filter bank more selective in order to limit the effect of narrowband interference to the subchannels which are in the frequency range of the interference.

In a previous paper [3], we presented efficient solutions for VDSL systems based on the idea of Perfect-Reconstruction (PR) Cosine-Modulated Filter Banks (CMFBs). In this paper, we analyze the differences between CMFB-based multicarrier systems and DFT-based multicarrier systems (OFDM, DMT) from the channel equalization point of view. A scheme based on phase equalization of the received signal before the receiver (analysis) filter bank is proposed.

2. MULTICARRIER SYSTEMS BASED ON COSINE-MODULATED FILTER BANKS

2.1 Cosine-Modulated Transmultiplexer Systems

Conventional filter bank based TMUX system is described more detailed in these proceedings [4]. Moreover, cosine-modulated TMUX approach together with further references are presented in [4]. As an example, Fig. 1 shows the amplitude responses of the subchannel filters for a 4-channel CMFB, as well as the overall impulse responses for the subchannels.

2.2 Data Modulation and Transmultiplexers

When CMFBs are used for data transmission in the TMUX configuration, each subchannel in the transmitter end takes $f_s/M$ real symbols per second resulting in the total symbol rate of $f_s$. In the modulation domain, each subchannel has a bandwidth of $(1 + \rho)f_s/(2M)$ and the subchannel spacing is $f_s/(2M)$.

In [3] we have shown that the subchannel signals can be considered to be offset-QAM type of signals.
This means that the underlying modulation is linear I/Q-modulation, and various equalization concepts applicable to this general modulation type can be utilized.

3. EQUALIZATION IN MULTICARRIER SYSTEMS

3.1 Guard Interval Approach

In OFDM systems, guard intervals are often used to combat InterSymbol Interference (ISI) due to multipath channel [5]. Guard interval is a cyclic extension of the actual symbol waveform, used as a prefix to avoid overlapping of consecutive symbols [6]. Consequently, the undesired effect of delayed components of the previous OFDM symbol can be removed. If the guard interval is at least as long as the maximum channel delay spread, the orthogonality of the subcarriers is preserved in stationary channels with arbitrary impulse response. 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 estimate.

Also time-domain equalization has been proposed for DMT systems in [7]. In this approach, the time-domain equalizer is designed to minimize the delay spread and, consequently, reduce the required length for the guard interval. However, the guard interval cannot be completely eliminated in this approach, and therefore it is not suitable for filter bank based systems.

3.2 Equalization Problems in Filter Bank Based Systems

In filter bank based multicarrier systems, the basic symbol waveform is, instead of a rectangular pulse of symbol duration, a Nyquist pulse overlapping with the previous and next symbols. In this case, the guard interval idea cannot be efficiently utilized. Furthermore, the orthogonality of the subchannels is easily lost. The equalization problem in DWMT systems has been discussed also in [8] where it was found to cause significant degradation in performance.

Let us consider the basic pulse shapes of different subchannels, as visualized in Fig. 1. It is clear that arbitrary scaling of the amplitudes does not have an effect on the orthogonality. But effects of nonlinear phase response of the channel may be serious. 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 InterCarrier Interference (ICI) between subchannels and ISI between consecutive symbols of each subchannel.

The basic difference between DFT-based multicarrier systems and filter bank based multicarrier systems is that in case of DFT, the basis functions are pieces of sine-waves which are orthogonal after arbitrary relative phase shifts (assuming that the guard interval is long enough), whereas the basis functions of filter bank based systems are pulse-shaped sine-waves whose orthogonality is lost more easily. On the other hand, if the stopband attenuation in the filter bank based system is sufficiently high, it is sufficient to consider the equalization for each subcarrier only in a narrow band in frequency-domain. If the bandwidth of subcarriers is sufficiently low (i.e., the number of subchannels is sufficiently high), linear channel phase response can be assumed in the overlapping parts of the subcarriers, and ISI and ICI (crosstalk) elimination can be based on the simple concepts described below.

3.3 Frequency-Domain Equalization Based on Oversampled Analysis Bank

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, using different sampling clock phases for subcarriers which are not close to each other in frequency. Also the carrier phase should be adjusted properly for each subchannel. This would eliminate ISI within each subchannel. Furthermore, since neighboring subchannels would experience practically the same delays, also the crosstalk would be practically eliminated. This means that, if the subchannel bandwidth is narrow in comparison to the coherence bandwidth of the channel, then the channel equalization problem can be converted to individual carrier phase and symbol timing recovery problem for the different subcarriers. 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 [9]), or the resampling should be incorporated in some clever way to the analysis filter bank itself. These approaches seem to increase the computational burden of the receiver bank considerably.

3.4 Time-Domain Phase Equalization

The alternative approach is to equalize the channel phase response before the receiver bank so that the overall phase response is linear and all subchannel delays are multiples of the subchannel symbol period \( M/ f_s \). Then the amplitudes can be equalized in the same manner as in OFDM and DMT systems using multipliers for each subchannel, as shown in Fig. 2.

We can have two alternative approaches to think about the phase equalizer.

Channel Matched Filter Approach

If the equalizer has impulse response which is matched to the channel impulse response (complex conjugate mirror image), then the cascade of the channel and equalizer has zero-phase response. This is actually a generalization to the multicarrier case of...
the general theory that after matched filtering, the signal can be sampled at the symbol rate without loosing any information from the received signal [10].

Phase Equalizer Approach

If the phase response of the channel is known or can be estimated, then we can design a filter (e.g., a FIR filter or allpass IIR filter) which equalizes the overall phase response to become approximately linear phase. This approach might be interesting from the implementation point of view, if this equalizer design can be carried out adaptively with reasonable implementation complexity, and if we can achieve lower implementation complexity for the equalizer filter itself than in the matched filtering approach.

As we shall see later, the phase response of a typical telephone subscriber line is rather smooth and rather predictable. In this case, approximative phase equalization could possibly be implemented with a low-order filter.

4. MEASUREMENT AND SIMULATION RESULTS

In Fig. 3 we can see measured phase responses and group-delay responses from some subscriber lines. Cable 1 and cable 2 are typical new plastic shielded access cables, cable 3 includes parts of both paper and plastic cables and cable 4 is typical paper shielded cable. Cable lengths are 380 m, 770 m, 610 m, and 750 m, respectively. In the worst case from a limited number of measurements, group-delay variation of 0.6 μs has been observed in the frequency band of 300 kHz . . . 20 MHz. The worst-case group-delay variation can be assumed to be in the order of 1 μs. For example, with 40 MHz channel sampling rate this corresponds to 40 sample intervals.

We have tested the phase equalization approach using these measured channel frequency responses. The results for cable 2 are described in the following. The signal bandwidth is assumed to be 20 MHz and the channel sampling rate is 40 MHz. The results were similar also for the other three cables, except that 8.5 MHz bandwidth was used for cable 3 and 15 MHz bandwidth for cable 4 due to high attenuation and noisy measured phase response at the higher frequencies. In this preliminary experiment, a 64-channel perfect-reconstruction CMFB with \( K = 5 \) and \( \rho = 1.0 \) was utilized. The stop-band attenuation of the channel filters is roughly 49 dB.

Simple FIR equalizers with 2, 3, or 4 taps (with channel sample interval spacing) have been considered. In addition, the possibility to adjust the sampling phase optimally was modeled by a freely adjustable delay in cascade with the FIR filter. The equalizer tap coefficients and the delay were optimized to minimize the mean squared phase error after the equalizer. The remaining overall phase responses are shown in Fig. 4.

The effect of the remaining phase error on the performance of the system was evaluated. We used a channel impulse response which corresponds to the equalized phase response and constant amplitude response. Here we take use of the property that the amplitude equalization can be carried out in frequency-domain after the analysis bank if the amplitude response is close to constant within the frequency band of each subchannel. In our application, this requirement is satisfied well because the amplitude response of the twisted pair is a rather smooth function of frequency, as can be seen in Fig. 3.

We evaluated the ISI and ICI (crosstalk) between neighbouring subchannels due to the channel impulse response. Fig. 5 shows the Signal-to-Interference Ratio (SIR) for each subchannel (except for the first and last ones) with the three equalizer lengths. Here the interference includes the ISI within the subchannel and the ICI from both adjacent channels. The powers of the interference components have been summed. The results are shown in Fig. 5. It can be seen that the 3-tap and 4-tap
FIR phase equalizers provide rather good performance in this cable. It was noticed, that in most cases the ISI part of the interference was stronger than the ICI part.

As an example, we assume that $10^{-4}$ raw bit-error-rate (before error control decoder) is required. Then about 18 dB or 24 dB SNR is needed with 16-QAM and 64-QAM modulations, respectively. The SIR due to nonideal equalization should be 6 dB or more below the required SNR in order not to degrade the performance greatly. In addition, we should take into account the fact that high-order modulation (like 64-QAM) is used in the lower frequencies only, whereas only lower-order modulation (like 16-QAM or QPSK) is used in the higher frequencies due to higher signal attenuation and high level of crosstalk between different twisted pairs in the cable. Taking into account these aspects, it can be concluded that the performance of the 4-tap equalizer is good-enough in the higher frequencies, whereas in the lower frequencies (below 3 MHz) there is need for some improvement.

There are several possible ways to improve the performance of phase equalization in the lower frequencies:

- using filter banks with more channels improves the performance clearly
- using somewhat higher equalizer length
- designing the equalizer to provide lower phase error in the low frequencies while allowing somewhat higher error in high frequencies

5. CONCLUSION

Different ways to perform the channel equalization were discussed. It was observed that the phase response linearity of the equalized channel is the essential requirement in such systems, if critically sampled receiver bank is utilized. The amplitude equalization can be done in frequency-domain in the same way as in OFDM or DMT systems.

In case of xDSL systems, the channel response is rather smoothly behaving, and a low-order time-domain equalizer was shown to provide promising results. However, the quality of phase equalization still has to be improved in lower frequencies to be able to use high-order modulations, like 64-QAM. In the future work, slightly higher orders for the equalizer will be examined, and also the idea of giving higher weight in the lower frequencies in the phase equalizer design will be tested.

Another big challenge in the future work is to device efficient and practical adaptive algorithms for the phase equalizer.

ACKNOWLEDGEMENTS

This work was carried out in the project “Fast DSL Technologies in Broadband Transmission” funded by the Technology Development Centre of Finland.

REFERENCES


