Chapter 6

Conclusions

In this chapter, the thesis is summarized (section 6.1), the original contributions are listed (section 6.2), and finally suggestions for future research are given in section 6.3.

6.1. Summary of the thesis

First, the main research questions are repeated in subsection 6.1.1. Following that, a per-chapter summary is given.

6.1.1. Main research questions

Copper channels suffer from attenuation and dispersion, caused by the skin effect and dielectric loss. Furthermore, they suffer from reflections, caused by impedance discontinuities. As a consequence, the achievable bit rate is limited by intersymbol interference: neighboring symbols interfere with each other.

The aim of this research was to find new equalization and modulation techniques that can be used to increase the data rate over copper interconnects while maintaining an acceptable bit error rate. These techniques must be compatible with future CMOS generations.

6.1.2. Chapter 2

Chapter two describes a practical model for copper cables and PCBs, for use in transient simulations. The model, incorporating both the skin effect and dielectric loss, gives a causal impulse response because the complex skin and dielectric impedances both comply with the Kramers-Kronig relations.

The model is fitted to coaxial and twisted pair cables and to a PCB. Model parameters for these channels are given.

6.1.3. Chapter 3

An analog OFDM system – based on analog mixers and integrate-and-dump blocks – is presented and analyzed. The impact of timing non-idealities such as jitter and duty-cycle deviations is analyzed.

The main findings were as follows.

- Jitter causes crosstalk between the in-phase and quadrature channels. Given a certain RMS jitter variance, low frequency tones can carry more bits than higher frequency tones for the same error rate, because the same time shift gives a different phase error at different frequencies.
- Duty-cycle deviations cause crosstalk between carriers at different frequencies because the OFDM orthogonality is lost.

- Harmonics from the switching mixers hinder the use of a large number of subcarriers, because of spectral overlap.

It is concluded that, because of the high sensitivity to timing errors, this analog OFDM system is currently infeasible and traditional PAM systems are more feasible (and more straightforward to implement) for copper channels with monotonously decreasing transfer functions. For copper channels with nulls in the transfer function and for copper channels that suffer from ingress noise, OFDM offers important advantages (for example in ADSL).

6.1.4. Chapter 4

A transmit equalizer for copper cables and PCBs can be made by having a transmitter switch between only two voltages. During the time length of one bit, if a ‘1’ bit needs to be transmitted, first a positive voltage is transmitted and then a negative voltage, and vice versa if a ‘0’ bit needs to be transmitted. By adjusting the ratio of the duration of these two voltages (the duty-cycle), the filter can be adjusted to the channel. This PWM filter thus has only one ‘knob’ (adjustment parameter).

This technique provides an alternative to the usual symbol-spaced FIR (SSF) pre-emphasis filters. The technique relies on timing resolution instead of on amplitude resolution, as the FIR filters do. This can be advantageous in the light of CMOS scaling – with ever increasing switching speeds and decreasing voltage headroom.

The transfer function of the PWM filter happens to fit very well to copper channels. The PWM filter more closely matches copper channels than both a 2-tap SSF filter and a 2-tap half-symbol spaced FIR filter. At the Nyquist frequency, the calculated magnitude of the PWM filter transfer function has a value of one while its derivative is non-zero, unlike with the 2-tap SSF filter. The PWM filter transfer function can be seen as a higher order filter with only one adjustment parameter. Time domain simulations with a skin-effect-only channel show that approximately twice the bit rate can be achieved compared to a 2-tap SSF for the same peak distortion.

A normal pulse amplitude modulated (PAM) signal is received at the end of the channel. Analysis shows that the eye opening at the receiver is unchanged compared to a 2-tap symbol-spaced FIR (SSF) filter (assuming that they both have the same voltage headroom). Therefore, the receiver circuits can remain unchanged.

Two 0.13μm CMOS chips and one 90nm CMOS chip were made as a proof-of-concept.

Measurements with these prototype chips show successful reception of data transmitted over coaxial and twisted pair copper cables, with up to 30dB loss at the Nyquist frequency, with BER 10^{-12}, compared to 20dB for a 2-tap SSF filter (and 30dB for more complex equalizers with more adaptation parameters). A bit rate of 5Gb/s was achieved over all channels. The cable loss consisted of different combinations of skin effect and dielectric loss. On an FR4 microstrip PCB trace, 25dB loss compensation was measured.

6.1.5. Chapter 5

We can extend the PWM pre-emphasis technique to a multitap version. The duty-cycle of this multitap PWM filter is a function of multiple bits instead of a function of only the current bit, as in Chapter 4. In this way, more complex filter transfer functions can be constructed, as with multitap FIR filters. The transmitter needs to switch between only two voltages, again allowing a transmitter implementation that is based on timing accuracy instead of on amplitude accuracy. The correct switch timing needs to be found as a function of multiple bits, in order to create the desired (effective) filter transfer function. This can be done by deriving the pulse-widths from the SSF filter taps by using a ‘same-area’ approach. Time domain simulations show eye openings nearly equal to those of the equivalent 3-tap SSF filter.

The power spectral density functions of the 3-tap PWM filters are calculated using their autocorrelation functions. At frequencies around the Nyquist frequency, these filters have a higher power spectral density than the SSF filter due to harmonic signals, inherent to PWM. A system designer should weigh up this side-effect of PWM against the abovementioned advantage of using a transmission equalizer that needs to switch between only two voltages. As long as the channel has a low-pass transfer function, the high-frequency part of the spectrum will be filtered out by the channel.

6.2. Original contributions

- The discovery that by applying pulse-width modulation (PWM) pre-emphasis to wireline equalization, 30dB of channel loss at the Nyquist frequency f_N can be overcome (with BER $<10^{-12}$), versus only 20dB with the commonly used 2-tap symbol-spaced FIR (SSF) pre-emphasis filter.

- The discovery that 30dB loss compensation can be achieved using a PWM equalizer with only a single adjustment parameter, namely the duty-cycle.

- Time-domain simulations which show that the PWM filter achieves approximately twice the bit rate of a 2-tap SSF for the same peak distortion on a theoretical skin-effect-only channel.

- Calculations which show that the eye height at the receiver is the same, whether PWM pre-emphasis or 2-tap SSF is used, because both filters have a transfer function of one at f_N.

- A comparison of the transfer functions of the PWM pre-emphasis filter and of the 2-tap SSF filter. At the Nyquist frequency, the calculated magnitude of the PWM filter transfer function has a value of 1 while its derivative is non-zero, unlike with the 2-tap SSF filter.

- Realizations of the PWM pre-emphasis transmitter in both 0.13µm and 90nm CMOS chips.

- Several multitap PWM schemes – especially one scheme with a reduced number of transitions – for a 3-tap PWM filter. Such multitap PWM filters can provide more complex transfer functions, as with a multitap FIR filter.

- Calculations which show that in an ‘analog’ OFDM system, jitter and duty-cycle variations cause crosstalk between the in-phase and quadrature channels at a given frequency, and between subcarriers at different frequencies, both of which limit the achievable bit rate.

6.3. Recommendations for future research

- A more generalized mathematical analysis should be made of the multitap PWM filter. More links should be made to existing PWM theory and schemes.

- Using a multitap PWM filter, it is possible to construct complex filter transfer functions. We should think of applications such as canceling reflections on PCBs. The multitap PWM filters should be implemented and tested.

- Low jitter is essential to achieve high loss compensation with PWM pre-emphasis. Therefore, it is important to further explore low-jitter PWM circuits, as this directly impacts on the performance of the PWM pre-emphasis transmitter.

- It is possible to combine PWM pre-emphasis with multilevel PAM systems to improve the spectral efficiency (if the SNR is sufficiently high).