Chapter 8

Conclusions

8.1 Achievements

This work was devoted to the analysis of high-speed multiuser communication systems suited to frequency-selective channels. The initially aimed application was the powerline outdoor access network, that is to say a strongly branched wired distribution network, intended to provide a simultaneous link with a network head-end to multiple subscribers physically distributed along the main cable. The results obtained in this work have a large scope, however, and are not restricted to the powerline scenario.

The starting point was the derivation of realistic models for the channel transfer functions. This task (and only this one) was performed in the specific powerline context. The multiconductor transmission line theory (MTL) has been applied to various cable structures which are commonly used in power distribution networks. Several modes of propagation, the so-called eigenmodes, have been identified : they correspond to fixed distributions of voltages and currents in the conductors, that propagate with their own propagation factor $e^{-\gamma z}$ along the multiconductor structure. The fundamental characteristics of these eigenmodes (voltage and current distribution, characteristic impedance, phase velocity, attenuation factor) have been analyzed in a wide frequency range (0.5 to 25 MHz) and related to the fundamental cable characteristics (geometry, size, materials). This made it possible to model accurately the transfer function of a complete access network including a high number of cable segments, derivations, and terminations. A specific multi-dimensional scattering matrix algebra was developed to achieve that goal. The obtained channel transfer functions were also analyzed in the light of a simple multipath model, which allowed an intuitive interpretation. As expected, the channel responses are highly frequency-selective, with deep notches at some frequencies. Furthermore, the channel attenuation increases dramatically, not only with the distance of the subscriber with respect to the head-end, but also and above all with the number of taps between transmitter and receiver. Finally, the different contributions to the end-to-end channel impulse responses have been identified.

The issue of multiuser channel capacity has then been addressed, with an original approach aiming at providing fair data rates to every subscriber. The concept of balanced capacity has been proposed as an efficient way to satisfy fairness constraints among K users with different channel qualities. Ranging through the K-dimensional capacity region is achieved by modifying the power allocation among the users, and the decoding order in a successive decoding strategy. The optimal power allocation with balanced rates constraints was shown to be obtained in two steps: a first power allocation is computed, that maximizes a linear combination of individual data rates, then the weights of the linear combination (the so-called 'relative priorities') are iteratively updated until the balanced rates constraints are satisfied. Closed-form solutions for the first step have been derived for a memoryless multiuser channel, as a function of the channel gains and the user relative priorities. Specific power allocations have been obtained for the downlink and the uplink. Then a Newton-Raphson based algorithm has been proposed for the iterative updating of the relative priorities. It was shown to converge within a few iterations. These results have been extended to the case of frequency-selective multiuser channels. Different types of power constraints have been considered (PSD-sum, power-sum, individual power). The critical scenario is that of an individual power constraint : in that case, both power and rate constraints have to be satisfied simultaneously by every user, which makes the convergence of the proposed algorithm very slow. An alternative method, based on the Iterative Multiuser Water-Filling algorithm, has been proposed for that scenario. Finally, the issue of the optimal FDMA balanced rates computation has been addressed, with a simple constraint on the PSD-sum. An efficient subchannel allocation algorithm has been proposed. The balanced capacities obtained with these algorithms represent useful bounds on the effective bit rates that can be expected from practical transmission systems. They provide guidelines about the appropriate way of shaping the spectral density of the different transmitted signals as a function of the channel frequency responses, and also about the optimal joint decoding strategy.

A general transmission scheme was called for, that was able to shape the signal power spectral density with a high degree of flexibility. The proposed solution is the implementation of a paraunitary filter bank in the transmitters. Every user is provided with the ability to modulate any subset of filters with mutually independent sequences of PAM symbols. Furthermore, adaptive modulation can be used, i.e. the size of every PAM constellation can be adapted to the subchannel conditions. The maximal power spectral density of the transmitted signals is easily controlled as the sum of the modulated signature waveforms represents a flat PSD in the whole bandwidth. The classical modulation methods proposed in the powerline community (single-carrier, OFDM, CDMA) are obtained by selecting the appropriate FB (unit matrix, DFT filters, Hadamard codes). A further improvement lies in the combination of FB transmission with the CAP (Carrierless Amplitude-Phase) technique, which provides a flexible passband transmission scheme that is required if the available bandwidth does not extend down to the zero frequency. For a given choice of the implemented FB, the optimization of the transmission scheme is performed by selecting the appropriate signature allocation among the users, the appropriate power allocation among the different signatures, and the appropriate constellation size in each subchannel. The potential performance of different FBs can be compared. It basically depends on the flexibility offered by the FB : this flexibility increases with the number of subchannels and with the frequency-selectivity of the FB. An alternative solution lies in the use of CDMA with periodic long codes. With this solution, the optimization of the transmitter is not required any more as the average PSD of the transmitted signals is flat. So, every user is ensured to get an average performance, whatever the transfer function of its channel. User inequalities can be compensated by using a simple power control. The overall system complexity is reduced, at the price of a reduced bit rate performance. The choice for this solution rather than another depends on the trade-off between performance and complexity. Actually another argument disqualifies the choice of the long-code CDMA technique : the need to update the coefficients of the joint detector at the symbol rate. The complexity of the receiver is indeed dramatically increased in the long-code scenario.

MMSE linear and decision-feedback joint detectors have been derived in the general context of FB-based multiuser transmission. Infinite detectors have been firstly derived, as their performance provide an upper bound on the performance that can be expected from their FIR counterparts. In particular, it has been shown that the sum-capacity of the frequency-selective multiuser channel could be achieved by means of an infinite DF-JD followed by ideal AWGN decoders. The DF-JD thus provides an efficient way, from an information-theoretical point of view, of transforming a frequency-selective multiple access channel into a set of independent subchannels. The choice of the implemented paraunitary FB does not affect the achievable capacity in a single-user system. In a multiuser system, however, the achievable bit rates strongly depend on the signature allocation, and the flexibility associated with this allocation is related to the choice of the FB. The complexity associated with the derivation of practical FIR MMSE joint detectors has been analyzed in detail, with a particular attention for time-varying JDs suited to CDMA with periodic long codes.

The various reasons for which the practical bit rates that can be achieved with the proposed transmission (FB-based modulation) and detection (MMSE DF joint detection) system are lower than those offered by the true capacity region are now summarized :

1. *The power spectral density of the transmitted signals is constrained by the selected FB.* Furthermore, in a practical system, every signature in the FB should be allocated to a single user, which reduces the power allocation process to an integer optimization problem.

2. *The IIR DF-JD can only remove the causal interference.* Successive decoding among the users is not possible with the proposed joint detection structure. This does not affect the sum-capacity of the multiuser channel, but the global capacity region is reduced.

3. *Practical implementations of the MMSE JD suffer from an excess MSE* due to :

    - The use of a finite size (FIR) JD rather than the optimal IIR version.
    - The residual timing offset and/or jitter that remains after non-ideal timing synchronization.
    - Imperfect channel knowledge in the receiver, resulting in the derivation of JD coefficients that are not perfectly matched to the true channel responses.

4. *A finite-complexity decoder is used in every subchannel.* This is modeled by the SNR-gap $\Gamma > 1$ used to compute the bit rate that can be expected for a given received SINR. With a perfect decoder, the SNR-gap would be equal to 1. Actually the concept of capacity (which

implies error-free transmission) is here replaced by that of maximum bit rate for a given error probability.

5. *Error propagation must be taken into account.* Decision errors reduce the performance of both the DF-JD and the decision-directed channel estimator and timing synchronizer, which results into an increased MSE.

6. *The transmitted symbols do not have a Gaussian distribution - The size of the PAM constellation associated with every subchannel must be an integer.*

All these performance degradations must be taken into account in the derivation of a fair signature allocation among the users.

The sensitivity of the multiuser FB-based transmission scheme to channel estimation errors and timing synchronization errors has been derived. Using first-order approximations, closed-forms expressions have been obtained.

Finally, the issue of decision-directed maximum-likelihood timing synchronization has been properly extended to the multiuser scenario, assuming perfect decisions. The modified Cramèr-Rao bound has been derived and has been shown to be a simple extension of the single-user bound. Both timing estimation based on channel output and symbol-rate timing estimation have been investigated, and the associated bounds have been compared. Popular timing error detector structures (Early-late, Mueller and Müller) have been extended to the multiuser FB-based transmission scheme.

8.2 Perspectives

This thesis covered a number of important aspects related to the design of an efficient multiuser communication system : channel modeling, power allocation, multiuser capacity, modulation and multiple access, joint detection, robustness against channel estimation errors, and timing synchronization. There remains several issues that can be used as starting points for future studies. Here is a non-exhaustive list of items that would deserve a specific treatment in the prolongation of the present work :

- Transmission over multiconductor cables can be modeled as a *Multi-Input Multi-Output (MIMO)* system if all conductors are available up to the customer premises. Several sources could be used to couple the signal onto the system, and several sensors could be used to recover it at the opposite end. This concept of 'multiconductor diversity' has the potential to increase the capacity of powerline access networks. It is closely related to the concept of antenna diversity in wireless communication systems.

- The issue of *optimal duplexing* can be addressed. Rather than considering the global system as the concatenation (in different time slots) of a broadcast channel (downlink) and a multiple access channel (uplink), the transmission in both directions could be simultaneous, and a global optimal power allocation could be derived, possibly with fairness constraints among the users and among both directions of transmission.

- Concerning the issue of multiuser capacity associated with frequency-selective channels, different *power constraints* have been considered separately : power-sum vs. individual power, power itself vs. power spectral density. In a practical system, the effective constraint could be mixed : a global power budget $\bar{P}$ would have to be allocated to all users, with a maximum individual power $P_k > \bar{P}/K$ for every user, a maximum individual PSD γ_k at every frequency, and a maximum PSD-sum $\bar{\gamma} > \bar{P}/B$. A generalized power allocation algorithm with balanced rates constraints could be derived in this context.

- The introduction of *repeaters* in the network has the potential to increase the global capacity of the PLC system. The number of repeaters, and their position along the distribution cable, have to be optimized according to the network configuration. The balanced capacity of the system can be selected as the optimization variable. The power re-transmitted by the repeaters has to be taken into account in the global power budget.

- *Filter Bank design* can be investigated to improve the global system performance. In this work, the flexibility was restricted to the signature allocation among the users for a fixed signature set.

- The issue of *channel coding* has been discarded in this work. The decoder has been considered as a black box offering a fixed coding gain that was incorporated in the expression of the SNR-gap. The effect of a simple coding scheme on the proposed system performance should be modeled more accurately. Furthermore, joint modulation and coding techniques can be investigated to improve the global system performance.

- Maximum likelihood *channel estimation* techniques have to be designed and analyzed properly in the proposed multiuser FB-based context.

- The *time-varying* characteristic of the channel has not been considered. It has been assumed that the channel responses were sufficiently stable within periods of several seconds or even minutes, which enables the use of fixed joint detectors that can be computed explicitly on the basis of the channel estimates. Adaptive structures must be investigated if the channel changes are faster.

- Finally, the *noise scenario* used in this work is not representative of the powerline channel. A complete system should be robust against narrowband and impulsive noise, and incorporate specific features aimed at mitigating these types of noises.