Chapter 1

Introduction

1.1 Powerline communications

Digital communications over powerlines is an old idea that dates back to the early 1920s. For some decades, the omnipresent power grid has been used for low-speed data communications [1]. Many different standardized or proprietary systems have been used for the transmission of control and management signals (e.g. remote meter reading) by power supply companies. However, the powerline has largely been dismissed as being too noisy and unpredictable to be useful as a practical high-speed communication channel.

A significant change occurred when the last telecommunication monopolies were ended by 1998. In the same time, major advances in the fields of modulation, coding and detection enabled the design of efficient broadband communication systems over powerlines. The idea of exploiting the low-voltage (LV) power grid to provide broadband Internet access to residential customers has been proposed as an alternative to the other classical 'last-mile solutions' such as ADSL, cable modems, or wireless access systems. LV powerline communication (PLC) networks have a tree-like topology, with a PLC modem installed at the medium-voltage/low-voltage (MV/LV) transformer and providing connectivity to all premises in the neighbourhood. The architecture of the LV PLC network has to be optimized for the special characteristics of the distribution grid, which changes from one geographic area to another, considering the number of households per transformer and the distance from the transformer to the customer premises. When larger distances are involved, as it is the case in European topologies, intermediate repeaters are typically needed to regenerate the signal from the head-end and provide adequate coverage in every customer outlet.

There is also growing interest in the prospects of reusing in-building powerline cables to provide a broadband LAN within the home or office. The major advantage offered by powerline-based home networks is the availability of an existing infrastructure of wires and wall outlets, so new cable installation is not required. The user can employ home networking devices for connecting several computers, sharing printers, or sharing a broadband Internet connexion.

Another important field of research is the use of the MV network for communication purposes. It can be used as a backbone to connect the low-voltage transformer stations to the Internet if conventional backbone networks, like fiber optic cables, are missing. MV lines have their own characteristics for communication: they are typically less noisy, and have fewer branches and taps than LV lines, so the environment is less hostile for communications and longer distances can be achieved. The problem with MV lines is that special couplers are needed for injecting the signal in the line to ensure that the mains voltage does not damage the equipment.

1.1.1 The power distribution grid

The hierarchical structure of the power distribution grid is basically the same in every country :

- High voltage (HV, above 36 kV) powerlines, emanating from power plants, form a wide-meshed long-distance nationwide transportation network.
- Medium voltage (MV, ranging from 1 kV to 36 kV) powerlines, constituting a finer meshed network, bring electrical power into cities, towns, and villages.
- Low voltage (LV, below 1 kV) powerlines ensure the final distribution to customer premises. The LV grid represents a very fine-meshed network, precisely adapted to the density of consumer loads.

From an MV/LV transformer, power is distributed over buried or aerial multiconductor cables to the customer premises, where they end on a panel board, from which the indoor wiring to various appliances and wall sockets starts.

In the European power supply network, a given MV/LV transformer can provide power to several hundred households. Typically, between 3 and 10 service cables emerge from one transformer substation, forming a tree-like structure. Three phases are provided, with a voltage of 400 V from phase to phase and 230 V from phase to neutral. The neutral conductor is usually grounded. In most European countries, all three phases and the neutral are brought to the customer's panel board: thus, the service cables generally include 4 conductors. In some countries, however, only one phase and the neutral are supplied to the buildings.

The U.S. power supply network has a different structure. The MV distribution circuit consists of a three phase main trunk. Depending on the load, a two-phase or one-phase tap extends into load areas. In direct neighbourhood to buildings, single-phase transformers provide the LV, which is immediately passed to the buildings' panel board. As a consequence, the length of the LV segment is usually less than 300 m, with 1 to about 10 customers per transformer. The secondary side of the transformer provides 240 V with a grounded center tap, and the customer receives power over three wires with 2 x 120 V or 240 V. Standard loads are connected to the 120 feeds while large loads use the 240 V level.

1.1.2 The powerline channel

Adequate channel models (including various classes of channel frequency responses and a complete noise scenario) are required to assess the performance of a PLC system. Unfortunately, these models have not been standardized yet, so there is no widely accepted model similar to COST models for mobile radio channels or ANSI/ETSI models for DSL channels.

The PLC channel presents a number of technical challenges. Frequency-dependent attenuation is caused by conductor and dielectric losses. Signals do not propagate along a single path, but suffer from reflections caused by impedance mismatches at line discontinuities. Hence, the PLC channel can be considered as a multipath environment with frequency-selective attenuation. Roughly speaking the channel transfer function has a low-pass characteristic, with deep notches at some frequencies. The degree of branching is responsible for increasing attenuation as each tap absorbs a certain amount of the transmitted power. Multipath reflections result in dispersion of the time domain signal. This can be characterized by the delay spread, which is the total time interval during which signal reflections with significant energy arrive at destination from the origin. Time dispersion generates intersymbol interference, which has to be handled by adequate equalization structures in the receiver.

Furthermore, the channel frequency responses are slowly time varying, although at certain moments they can change abruptly due to changes in the load distribution on the line, typically when electric appliances are connected and disconnected. As a consequence, the channel response should be continuously monitored by the transmitter/receiver, and transmission and/or detection parameters should be adapted to the channel change.

The most widely used model for the channel transfer function $H(f)$ is the multipath model proposed by Philipps [2] and Zimmermann [3] :

$$H(f) = \sum_{i=1}^{N} g_i \; e^{-(a_0 + a_1 f^k)\, d_i} \; e^{-2\pi j f \tau_i}$$

where d_i and τ_i are the length and delay of the N relevant propagation paths, g_i is the weighting factor for path i, and $\{a_0, a_1, k\}$ are model parameters to be adjusted. The exponent k has typical values ranging from 0.5 to 1, while the number of paths N is generally in the range of 5-50. This model was validated in the frequency range of 500 kHz to 30 MHz. It is valid for both outdoor and indoor PLC channels. The indoor lines are shorter, but they suffer from strong branching : the number of relevant paths is then usually higher while the attenuation associated with each path is smaller. Actually, the proposed model is the result of a top-down approach : the various parameters need to be determined through measurements. As such, it is not suitable for the computation a priori of the actual transfer function of a given link. Alternative models, based on the multiconductor transmission line theory (MTL), have been proposed in the case of indoor [4] and outdoor [5] channels. With these bottom-up models, it is possible to compute a priori and deterministically the transfer function of any PLC link, on the basis of the network topology and the cable characteristics.

In contrast to most other "well designed" communication channels, powerlines do not represent additive white Gaussian noise (AWGN) channels. The interference scenario is rather complex. The noise sources can be divided into 3 classes :

- *Colored background noise* is caused by common household appliances. It has a fairly low power spectral density which, however , significantly increases towards lower frequencies. The average PSD varies in the range between -140 and -125 dBm/Hz and remains stationary over periods from minutes to hours. The resulting PSD is actually the sum of numerous low-power noise sources.

- *Narrowband noise* is made of continuous wave signals with amplitude modulation, mainly produced by ingress of broadcast stations operating in the medium and shortwave bands. The mean interference level varies with the time of the day.

- *Impulsive noise* can be subdivided into three classes. Firstly, periodic impulsive noise synchronous to the mains frequency are caused by some domestic appliances such as light dimmers. They have a repetition rate of 50 or 100 Hz (60 or 120 Hz in the U.S.) and are of short duration (10-100 μs). Secondly, periodic impulsive noise asynchronous to the mains frequency is caused by switching power supplies. The spectrum repetition rate is generally in the range from 50 to 200 kHz. Finally, aperiodic and asynchronous impulsive noise is caused by transients due to switching within the network. The impulse duration ranges from several microseconds to a few milliseconds with a power spectral density than can exceed by 50 dB the level of the background noise at some frequencies. This kind of noise may occur at irregular intervals and contains considerable energy. It considerably affects high-speed communication, in such a way that complete symbols or even bursts of symbols cannot be decoded by the receiver. This has to be taken into account in the design of a complete and effective PLC system. Asynchronous impulsive noise is characterized by three random variables : amplitude, impulse width, and interarrival time. The statistical distribution of these parameters has been established through measurement campaigns. This allowed the derivation of a mathematical model [6] for the synthesis of asynchronous impulsive noise in realistic powerline channel emulation systems. Fortunately, even in heavily disturbed environments, it was found that the occurrence of the asynchronous impulsive noise concerned less than 1 percent of the time.

1.1.3 Electromagnetic compatibility, standards and regulations

Electromagnetic compatibility with respect to existing wireless services (fixed radio services, broadcasting, amateur radio, nautical radio, mobile radio, etc.) is a major issue in the elaboration of a universal PLC standard. The problem is that power cables and networks have been designed for the purpose of efficient power distribution at frequencies of 50 or 60 Hz, and certainly not for for the transmission of communication signals at frequencies of up to 20 or 30 MHz.

The high-frequency PLC signals are injected in differential mode. Differential mode currents are equal in magnitude and flow in opposite directions on the conductors. Balanced lines are necessary to achieve signal propagation in the desired differential mode. A lack of network or cable symmetry (defined in terms of impedance between conductors and ground) leads to unwanted common mode conversion. Common mode currents flow in parallel on all conductors, while the return current flows into the ground. These common mode currents are responsible for electromagnetic radiation. Actually, the powerlines operate as more-or-less efficient antennas.

Two classes of solutions can be investigated to minimize signal radiation from PLC networks. Firstly, the symmetry of the lines used for HF signal transmission should be exploited as far as possible, or even improved by network conditioning. In the access segment (assuming the distribution of three phases to the customers), a better symmetry is generally obtained by injecting the signals between two phases rather than between a phase and neutral. This solution is not applicable to indoor networks (two wires plus ground protective) where the signal injection is necessarily between phase and neutral. HF filters have also been proposed to keep HF signals on the useful propagation paths and prevent them from entering unused portions of the power network. Secondly, the power spectral density (PSD) of transmitted PLC signals should be reduced. For a given total power, this means that the signal spectrum should be spread as much as possible in the available bandwidth. As the channel transfer function decreases rapidly with frequency, spectrum spreading lowers the transmission efficiency. Actually, the mandatory restriction of the transmitted signal PSD represents a fundamental limitation to the performance of practical PLC systems. Unintentional radiation may occur from several sources in parallel. For this reason, the specification of a radiation limit should not be restricted to a single PLC device.

As PLC systems can be considered as unintentional radiators, licensing (i.e. frequency assignment through an authority) is not required, but PLC signal emissions must be compliant with current EMC limits. On the international level, a PLC standard (IEC 61000-3-8) [7] exists for frequencies below 525 kHz. At higher frequencies, the CISPR 22 publication [8] specifies limits for information technology equipments, and distinguishes between power supply ports and telecommunication ports. The disturbance potential of the device under test is measured through an artificial network emulating real-world network conditions. An adaptation of this standard to the special case of PLCs is underway. On the European level, a frequency range from 3 to 148.5 kHz, the so-called 'CENELEC-band' [9], is available for low speed PLC (up to 100 kbits/s) according to standard EN50065. For higher frequencies, a CENELEC/ETSI joint working group has been set up [10] to develop EMC requirements for wired transmission networks, including PLCs. This standard covers emission limits and measurement methods for all types of communications networks to ensure that the various technologies are treated equally. Various limits of electrical field levels at a distance of 3 meter of the network are currently proposed by different European countries at frequencies of up to 30 MHz. In the U.S., the use of PLC is regulated by the FCC Part 15 [11], which distinguishes between frequencies below and above 490 kHz. Compared to the proposed European limits, the American standard is highly generous for high-speed PLC. In Japan, a national standard regulates the frequency range 10-450 kHz, while PLC is currently not allowed at higher frequencies.

The disturbance potential of the PLC system is measured through the impact of PLC signals on a standard AM broadcast receiver. For that purpose, the emitted electromagnetic field is measured within a bandwidth of 9 kHz, which represents the usual AM radio receiver bandwidth, by means of a standardized magnetic loop antenna placed at a specific distance of the PLC network. The whole frequency range (from some kHz up to 30 MHz) has to be investigated. In order to determine how PLC signals symmetrically fed into the power supply network are converted into unwanted radiation, the concept of decoupling factor $K(f, d)$ was proposed. It can be regarded as a transfer function between the communication signals on the lines as input and the inadvertently radiated field as output, summarizing the impact of all parameters that influence this transfer function. Typical values of $K(f, d) = 10^{-3}/m$ have been reported for a distance of $d = 3$ meter. According to [12], the maximum PSD of transmitted PLC signals can reasonably be assumed to be in the range of -65 to -40 dBm/Hz.

Another important issue is the EM compatibility of different PLC systems. The coexistence of both the PLC access systems and different indoor systems requires a clear frequency separation. The current proposition is to dedicate the frequency range below 10 MHz to the access domain, and to assign frequencies above 10 MHz with no upper limit to indoor use. The fundamental reason of this proposal is that frequencies above 10 MHz are not usable in the access domain due to the lowpass characteristic of the channel responses. As indoor channels are much shorter, there is sufficient bandwidth above 10 MHz for most of the high-speed applications.

The frequency bands available for outdoor PLC transmission are not yet standardized. Most probably they will be in the range of 500 kHz to 10 MHz. The lower frequencies are dedicated to existing low-speed services (such as applications working in the CENELEC-band) while the higher frequencies will be allocated to indoor PLC systems. A possible solution is the 'chimney approach', which consists of allocating several narrow and not-contiguous bands to PLC systems at frequencies that are not used intensively by wireless services. Another solution is to use the whole frequency range for PLC, but with a lower PSD. Within international bodies such as the PLCforum (www.plcforum.org), which is a leading international association that represents the interests of manufacturers, energy utilities, and research organizations active in the field of PLC, frequency band standards have been proposed [12]: band A (0.5-20 MHz), band B (0.5-10 MHz) and band C (equivalent to B but excluding major broadcast and amateur radio frequencies).

1.1.4 Coding and modulation

The selection of an adequate modulation scheme for PLC must account for four major factors :

- The frequency-selective (and slowly time-varying) nature of the channel
- The interference scenario including narrowband interference and strong impulsive noise
- The multiuser aspect of the system, with many customers that request an access to the same physical medium simultaneously
- Regulatory constraints with regard to EMC, that limit the transmitted PSD

Three classes of modulation techniques are usually cited in the context of broadband PLC :

- *Single-carrier modulation* is an attractive proposition from the complexity point of view. If PLC transmission is only allowed in a small number of non-contiguous frequency bands, single-carrier modulation can be used separately in each band. Powerful detection and equalization techniques are needed to combat intersymbol interference. The deep frequency notches present in the channel transfer function prevent the use of linear equalizers. On the other hand, optimal symbol (MAP) or sequence (Viterbi) detectors exhibit a computational complexity that increases exponentially with the length of the impulse response, which is considerable in the powerline channel. Reduced-complexity versions of these detectors can be investigated. Another solution is the MMSE decision-feedback equalizer. Measures should be taken to avoid catastrophic error propagation caused by impulsive noise, and to allow the tracking of channel parameters.

- *Spread-spectrum* techniques, in particular DS-CDMA, make use of a code sequence that spreads narrowband signals over a wider bandwidth. Spread-spectrum techniques are naturally robust to narrowband interference. Moreover, CDMA is well-suited to multiuser systems including several users possibly with different rate demands. Like for single-carrier techniques, a robust channel equalization is required.

- *Multicarrier modulation*, in particular OFDM, is particularly well-suited for PLC. The information symbols are transmitted in parallel on many orthogonal subcarriers occupying a narrow subband. Using a cyclic-prefix extension technique, the effect of the channel on each subcarrier is transformed into a simple complex gain which depends on the channel transfer function evaluated at the subcarrier frequency. Hence, a frequency-selective channel becomes equivalent to a set of multiple flat-fading subchannels, and equalization of the data simply amounts to a normalization by a complex scalar. Using multilevel modulations, the bit rates on each subcarrier can be matched to the specific channel conditions, by the so-called bit loading technique. This aspect is important in the PLC context as the channel transfer function presents deep notches and also because of the narrowband noise. Moreover, the PSD of the transmitted signal can be shaped by selecting an appropriate subset of carriers, which is important in order to comply with the EMC requirements. The main drawback of the OFDM system is the need for the cyclic prefix whose duration depends on the channel memory, which is quite long in PLC channels. Time domain equalizers (TEQ) are commonly used in single-user OFDM systems to shorten the length of the equivalent channel impulse response. A multiple access method based on OFDM, the so-called 'OFDMA', can be investigated, but it is not compatible with the TEQ technique.

The multiuser aspect is generally handled by the medium access control (MAC) layer. The channel is made available for a given customer in specific portions of the time. A better performance can be expected from advanced multiple access techniques like CDMA or OFDMA, by which several customers are allowed to use their channel simultaneously.

A choice should be made of either a robust solution providing a sufficient quality for a wide range of variations of the channel parameters, or an adaptive one. Obviously, since the characteristics of the powerline channel change over time (sometimes abruptly), a better performance can be expected when the transmission parameters can be adapted to the channel conditions. Furthermore, the nominal channel transfer function is also strongly dependent on the specific network topology and the position of the customer modem, which definitely requires an adaptive system able to provide a customized solution for a wide range of PLC configurations.

Finally, powerful coding techniques are required to ensure reliable communications in the extremely noisy PLC medium. A large range of coding and decoding techniques have been considered in a PLC context, a review can be found in [13].

1.1.5 The HomePlug standard

In 2001, an industrial standards organization called the HomePlug Powerline Alliance (www.homeplug.org), originally founded by 13 major companies, announced the completion of the HomePlug 1.0 specification [14] for a 14 Mbits/s in-home powerline networking technology based on OFDM. HomePlug compliant products are today available on a large scale in the consumer market. They appear as a competitive alternative to Ethernet and Wi-Fi (IEEE 802.11x) solutions. The HomePlug Powerline Alliance is now establishing a 100 Mbits/s class in-home powerline networking standard, called HomePlug AV, to provide distribution of data, video and audio signals throughout the home.

The HomePlug 1.0 standard specifies the physical (PHY) and medium access control (MAC) layers of the protocol stack. To overcome the hostile PLC environment, adaptive OFDM with a cyclic prefix (CP) extension and bit loading has been adopted. The frequency band is approximately 4.3 to 20.9 MHz, that is a bandwidth of roughly 17 MHz. Actually the band from 0 to 25 MHz is divided into 128 evenly spaced carriers, of which 84 fall within the band used. Some subcarriers are left unused in the amateur radio bands. The tone map can be adapted to support regulatory requirements of different countries. Compliance with radiated power requirements has resulted in -50 dBm/Hz of transmission PSD in the USA (FCC Part 15), and -80 dBm/Hz in the amateur radio bands. One OFDM symbol comprises 256 IFFT samples plus 172 samples for the cyclic prefix, and the sample rate is 50 MHz. Channel estimation is used by the transmitter to detect channel conditions and adapt the transmission parameters by avoiding poor subcarriers and by selecting an appropriate modulation method and coding rate for the remaining subcarriers. Active modems perform channel estimation at least once every 5 seconds. Three variants of phase shift keying (PSK) modulation are used: coherent binary PSK, differential BPSK, and differential quadrature PSK. Both turbo product codes and Reed-Solomon concatenated with convolutional codes are used for forward error correction (FEC), in conjunction with interleaving and automatic repeat request (ARQ) techniques. The bit rate can vary from 1 Mbit/s to 14 Mbits/s practically continuously according to the number of usable carriers, modulation methods, and coding rate. Burst transmission is used, i.e. short frames of 20 to 160 OFDM symbols are transmitted by the different modems. A preamble and frame control combination are used as delimiters that start and end the frames, for the purpose of synchronization and control. Only the payload portion of the frames is adapted to channel conditions. The MAC protocol is a modified multiple access with collision avoidance (CSMA/CA) protocol with priority signaling. The modems communicate with each other freely, without any centralized coordination. Encryption techniques are used to ensure the confidentiality of the transmission.

1.1.6 PLC systems in the access segment

The feasibility of powerline broadband transmission in the access segment has been demonstrated through many independent field trials. Proprietary technologies have been deployed up to now, with a vast range of modulations and system architectures. Moreover, the structure of the powerline network itself has a strong impact on the design of appropriate PLC systems. The proposed LV access systems are sometimes extended to the MV segment, or even into the indoor home network. Reports of specific PLC trials can be found in [15] (Europe) an [16] (United States), for example.

One of the leaders in the field of broadband access PLC systems is DS2 (Design of Systems on Silicon, www.ds2.es). Their products can currently achieve speeds up to 45 Mbits/s, and a next generation of 200 Mbits/s PLC chipsets is announced. A high-speed modem (Head End), containing the DS2 chipset, is installed in the MV/LV transformer. Each transformer contains either an Internet router or an ATM concentrator, enabling the link with a large broadband network. A telephone operator (PTT) supplies the broadband network. Each customer site requires a powerline modem (Customer Premises Equipment or CPE), again containing the DS2 chipset. The use of a gateway between the powerline modem and a LAN at the customer premises enables several users to connect and share the high-speed connection. The selected modulation is again adaptive OFDM with cyclic prefix extension. Multilevel quadrature amplitude modulation (QAM) is used on the more than 1000 subcarriers. The system continuously monitors the channel attenuation and noise level with a very high spectral resolution. Information from these measurements is used to adapt the modulation parameters per carrier in real time in order to keep the bit error rate to the desired level. If the signal quality falls beyond acceptable levels in a part of the spectrum, the affected carriers are not used to send information. The frequencies used by the system can be configured from 2 to 34 MHz, and are adapted according to channel conditions and to the evolving standards and regulations in place in different countries. The transmitted PSD can be shaped with deep notches of more than 30 dB at any frequency and with any bandwidth. Fast channel estimation and a robust timing and frequency synchronization scheme are implemented. Several interrelated and configurable FEC algorithms (including soft-decision decoding and Reed-Solomon decoding) are used to match the quality-of-service requirements.

1.2 Outline of the thesis and contributions

In this work, a simplified communication scenario is considered, that represents some of the key aspects of the global PLC scenario, but not all of them :

- **Multiuser** communications are considered. This implies that many users (up to 20 users in this work) wish to establish a communication with the head-end simultaneously. This aspect raises a number of questions regarding the optimal way of sharing the resources (power, time, frequency) among the active users, the impairment caused by the other-user signals to the quality of a given-user link, and the need for a fairness control mechanism in a scenario where the quality of the different user channels can be very heterogeneous. The head-end is located at the MV-LV transformer while the different user modems are physically distributed along the powerline. The uplink (communication from the user modems toward the common head-end) and the downlink (communication from the common head-end towards the user modems) are considered separately. A simple time-division duplex scheme is assumed. The network structure is illustrated in Figure 1.1.

- The channel transfer functions are **frequency-selective**. The frequency-selectivity is caused by cable losses, and mainly by the multipath effect in a strongly branched network. Intersymbol interference (ISI) results from the long impulse responses and calls for efficient equalization techniques. In a multiuser context, multiple-access interference (MAI) cannot be avoided and joint detection is required. Furthermore, the transmitted spectrum should be optimized according to the channel selectivity.

- Other important hypotheses are related to the assumption that the communication system is operated on **wired channels**:

  - Only the lower frequencies are available for efficient transmission, due to the lowpass characteristics of the cable responses. *Baseband transmission* is thus basically considered in this work. Actually, the available frequency spectrum does not extend down to the zero frequency, but rather in a range from F_0 to $F_0 + B$, where B is the effective bandwidth, and F_0 is much smaller than B. The system is thus 'quasi-baseband' and the use of a carrier is not required. *Carrierless* solutions are investigated, i.e. passband signals are directly produced in the digital domain before digital-to-analog conversion.
  - The power budget of the communication system is primarily dictated by *EMC restrictions*. As the signal bandwidth B is extremely large as compared to that of the wireless services that must be protected by the EMC requirements, the fundamental power limit is put on the *power spectral density* of the transmitted signal. As several transmitters can be active simultaneously,

the restriction can be applied on the signal-sum rather than on each individual signal.

- The channel transfer function is *slowly time-varying*. It is assumed that the channel responses remain approximately constant over periods of several thousands of symbols. Channel estimation is performed during the communication setup and channel tracking is performed periodically. Both transmitter and receiver are assumed to have a quasi-perfect knowledge of the channel responses. The resource allocation algorithm and the design of an efficient joint detection structure rely on this channel knowledge.
- Synchronization issues are restricted to the problem of *multiuser timing synchronization* as the communication system is of the carrierless type. Like for the channel estimation, the timing parameters are assumed to be estimated at the communication setup, and tracking is ensured during transmission with the appropriate structure.

The *noise scenario* considered in the sequel is the simple additive white Gaussian noise (AWGN) channel. The effects of narrowband noise and impulsive noise are discarded. Finally, the issue of channel coding is not considered in this work.

This thesis is structured as follows.

The first logical step is the characterization of the transmission environment, which includes the derivation of the channel transfer functions and the identification of the noise scenario. Tools for the computation of powerline channel responses are developed in **chapter 2**. This is actually the only chapter of this thesis that is specifically dedicated to the powerline scenario : the other chapters have a general scope and can be applied to a wide range of multiuser frequency-selective channels. For the first time, the powerline cables used in the LV access segment are modeled with the formalism of the *multiconductor transmission lines (MTL) equations*. Maxwell's equations are firstly solved in the cross-section of some typical powerline cables, which provides the distribution of the electromagnetic fields associated with the propagation of TEM waves in the cable structure. From these distributions, and considering lossy conductors and dielectrics, multidimensional lineic capacitance, lineic inductance, lineic resistance and lineic conductance parameters are derived. The MTL equations are then

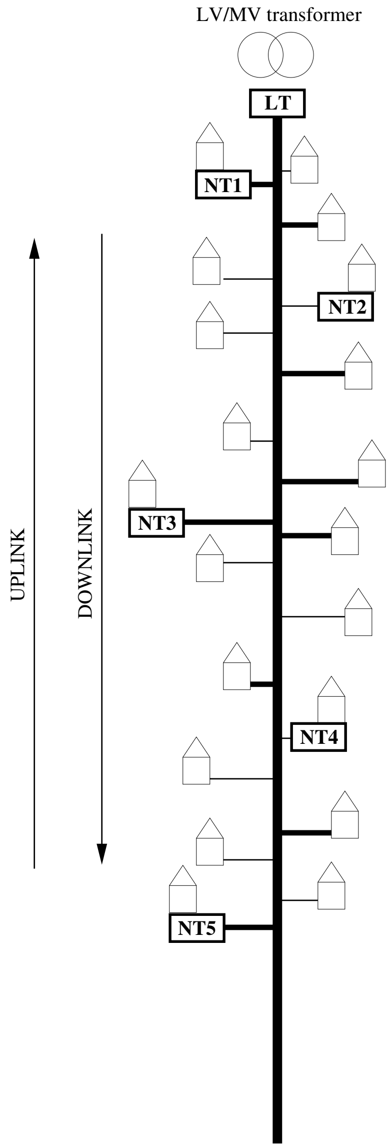

Figure 1.1: *The powerline access network: uplink and downlink transmission*

solved, and their solutions are shown to correspond to a number of propagation eigenmodes that are characterized by well defined distributions of voltages and currents on the conductors, with a common propagation factor $e^{-\gamma_n z}$. The lineic attenuation, phase velocity and characteristic impedance associated with the different eigenmodes are studied as a function of the conductor geometry and the material properties. The impulse response associated with a simple cable segment is derived. The analysis is then extended to the case of complex power distribution networks including a main distribution cable and a number of derivation cables, with specific terminations. Adequate mathematical methods, based on the multidimensional scattering matrix formalism, are derived to allow the computation of the end-to-end transfer function associated with a given communication link. A specific example of a 300 meter long network, with 20 derivations and three different types of cables, is analyzed in detail. Finally, a simple and intuitive multipath channel model is proposed. Results were published in [5, 17].

The next logical step is the derivation of the best performance that can be expected from the proposed channels, in terms of maximum throughput. This problem is analyzed in the light of multiuser information theory, which is the object of **Chapter 3**. The set of simultaneously achievable data rates is known to be the capacity region, which is a convex volume in the K-dimensional space, where K is the number of active users. An original concept, *balanced capacity*, is firstly introduced as a fair method for the distribution of individual data rates to the different users competing for the limited resources. The optimal power allocation problem is solved in the multiuser memoryless channel scenario. Explicit solutions for the optimal sharing of a total power between K users are derived for the downlink (broadcast channel) and the uplink (multiple access channel). An iterative algorithm for the computation of the maximum balanced rates is derived. The case of a multiuser frequency-selective channel is then addressed. Several types of power constraints are proposed and the associated capacity regions are compared. Explicit expressions of the optimal power allocations (among the users and among the frequency spectrum) are derived. Efficient algorithms are proposed for the computation of maximum balanced rates. The specific case of an individual power constraint is shown to be much more complex to handle, and an alternative suboptimal algorithm is proposed, based on the Iterative Multiuser Water-Filling algorithm. Then, the problem of FDMA capacity computation is addressed. It consists in distributing the power to the different users in mutually exclusive frequency bands. Results are finally presented for a 20-user powerline access network. This study has been partly presented in [18].

In **Chapter 4**, practical modulation schemes are proposed. The selected modulation has to be flexible enough in order to allow an efficient multiple access. Furthermore, a generic framework is called for, that allows the comparison of the classical modulation methods proposed in the context of PLC: single-carrier, CDMA and OFDM. The proposed general solution is based on the parallel modulation of a number of signature waveforms by mutually independent sequences of QAM symbols. The signature waveforms are assumed to be mutually orthogonal, and constitute a paraunitary filter bank (FB). Every user is provided with the ability to modulate any subset of waveforms. An adequate signature allocation algorithm implemented in the head-end computes the optimal signature allocation among the users. Single-carrier, CDMA and OFDM are obtained by selecting the appropriate FB. The effect of the frequency-selective channels on the transmitted signals is analyzed, and the received signal is assumed to be sampled at a fractional rate. IIR and FIR observation models, relating the received sequences of samples to the transmitted symbol sequences, are derived. The idea of CAP modulation (Carrierless Amplitude-Phase) is extended to CAP-FB, allowing the definition of a generic FB-based passband transmission scheme. Two variants are finally described. Firstly, CAP-CDMA with long codes is a multiple access scheme where each user is allocated a single time-varying binary signature code. With this method, the signature allocation algorithm is not needed any more, and every user is ensured to obtain an average performance level. Secondly, cyclic-prefixed block transmission, traditionally restricted to multicarrier (OFDM), is extended to the general FB-based transmission scheme.

Chapter 5 is dedicated to the derivation of practical joint detection structures. First of all, the effect of the selected modulation scheme on the multiuser capacity region is investigated. The matched filter bound (MFB) is derived as an alternative upper bound on the optimal performance that can be expected from real detectors. Infinite linear and decision-feedback (DF) minimum mean square error (MMSE) joint detectors are presented. Their performance is computed and compared to the multiuser capacity. Their FIR counterparts are derived, and the computational complexity associated with the coefficient computation is analyzed. The scenario of CAP-CDMA with long codes is analyzed separately, and reduced-complexity algorithms for the computation of MMSE joint detectors suited to long-code CDMA are proposed. Finally, cyclic-prefixed equalization structures are analyzed and performance is compared for different FBs. Original results related to multiple access and joint detection have been presented in [19, 20, 21, 22, 23, 24, 25, 26, 27].

The previous chapter assumed a perfect channel knowledge and a perfect timing synchronization. Actually, both parameters (channel coefficients and sampling time) are permanently estimated and tracked. In **Chapter 6**, the impact of non-ideal timing synchronization and non-ideal channel estimation on the signal-to-noise ratio at the output of the joint detectors is analyzed. The idea of timing sensitivity is introduced, and explicit methods for the computation of the timing sensitivity in a FB-based transmission system are proposed. Results on this topic can be found in [28].

Finally, **Chapter 7** addresses the problem of multiuser timing estimation. The average multiuser decision-directed (DD) Cramèr-Rao lower bound is derived. Both feedforward and feedback joint timing error tracking structures are introduced. Two practical timing error detectors are adapted to the multiuser FB-based transmission system: the early-late detector and the symbol rate (Mueller and Müller) detector. The associated results have been partly presented in [29].