CHAPTER 1

Introduction

The communication flow of today is very high. Many applications are operating at high speed and a fixed connection is often preferred. If the power utilities could supply communication over the power-line to the costumers it could make a tremendous breakthrough in communications. Every household would be connected at any time and services being provided at real-time. Using the power-line as a communication medium could also be a cost-effective way compared to other systems because it uses an existing infrastructure, wires exists to every household connected to the power-line network.

The deregulated market has forced the power utilities to explore new markets to find new business opportunities, which have increased the research in power-line communications the last decade. The research has initially been focused on providing services related to power distribution such as load control, meter reading, tariff control, remote control and smart homes. These value-added services would open up new markets for the power utilities and hence increase the profit. The moderate demands of these applications make it easier to obtain reliable communication. Firstly, the information bit rate is low, secondly, they do not require real-time performance.

During the last years the use of Internet has increased. If it would be possible to supply this kind of network communication over the power-line, the utilities could also become communication providers, a rapidly growing market. On the contrary to power related applications, network communications require very high bit rates and in some cases real-time responses are needed (such as video and TV). This complicates the design of a communication system but has been the focus of many researchers during the last years. Systems under trial exist today that claim a bit rate of 1 Mb/s, but most commercially available systems use low bit rates, about 10-100 kb/s, and provides low-demanding services such as meter reading.

The power-line was initially designed to distribute power in an efficient way, hence it is not adapted for communication and advanced communication methods are needed.

Today's research is mainly focused on increasing the bit rate to support high-speed network applications.

This thesis is about communication on the power-line (on the low-voltage grid). Section 1.1 gives a general description of power-line communications. Section 1.2 explains some preliminaries needed in digital communications and Section 1.3 describes the power-line channel, its characteristics, problems and limitations, and also serves as a survey of current research. Finally Section 1.4 gives an outline of the rest of this thesis. Other introductory descriptions on power-line communications are given in [14], [20], and [36]. Reference [36] also studies new business opportunities for the power utilities and reports research on coming technology.

1.1 *Power-Line Communications*

The power-line network is a large infrastructure covering most parts of the inhabited areas. In Sweden the power is typically generated by, e.g., a power plant and then transported on high-voltage (e.g., 400kV) cables to a medium-voltage sub station, which transforms the voltage into, e.g., 10kV and distributes the power to a large number of *low-voltage grids*.

Figure 1-1 shows an example of a typical low-voltage grid.

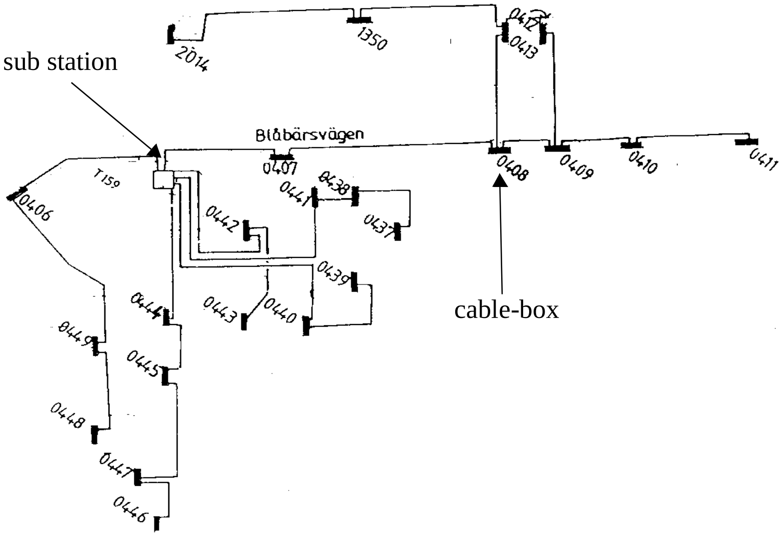

FIGURE 1-1 An example of a low-voltage grid.

Each low-voltage grid has one *sub station*, which transforms the voltage into 400 V and delivers it to the connected households, via low-voltage lines. Typically several *low-voltage lines* are connected to the sub station. Each low-voltage line consists of four wires, three phases and neutral. Coupled to the lines are *cable-boxes,* which are used to attach households to the grid.

This thesis is about communication on the low-voltage grid, communication between the sub station and the households. Related issues are how to communicate inside a household and how to communicate on the medium-voltage grid.

Many systems today use a topology with a central node (the sub station) communicating with clients (the households). All communication is between the sub station and the households and there is no communication between households. Because there is a physical connection between every two households it would also be possible to support this kind of communication. As an alternative, this communication could be routed through the sub station.

The configuration with a central node and a set of clients may be compared with systems for mobile telephony, e.g., GSM [33]. In GSM a base station (central node) is connected to all mobile phones (clients) within a restricted area. Thus the network topology is not unusual, but used in practice.

Power-line communication is based on electrical signals, carrying information, propagating over the power-line. A communication *channel* is defined as the physical path between two communication nodes on which the communication signal is propagated [1], [41]. In a low-voltage grid there is a lot of different channels, in fact the links between the sub station and each household are all different channels with different characteristics and *qualities*. If the communication system supports communication between households all these links are also different channels.

The quality is estimated from how good the communication is on a channel. The quality is mostly a parameter of the *noise level* at the receiver and the *attenuation* of the electrical signal at different frequencies. The higher the noise level the harder it is to detect the received signal. If the signal gets attenuated on its way to the receiver it could also make the decision harder because the signal gets more hidden by the noise.

On the power-line the noise is generated from all loads connected to the grid. Also broadcast radio interferes with the communication. The attenuation is a parameter of the physical length of the channel and impedance mismatches in the grid. The power-line is often considered a harsh environment because of the time-variant characteristics of the noise and the attenuation, but this is also the case in most communication systems and only limits the performance that can be achieved. Advanced communication systems exists today, designed to overcome the problems with such channels as, e.g., GSM. The characteristics of the power-line channel are further described in Section 1.3.

This thesis is focused on the research on the power-line as a communication channel. The objective is to come up with advanced digital communication methods to support higher bit rates and more reliable communication on the low-voltage grid. To understand the problem field some preliminaries are needed from digital communications. This is the subject of the next section.

1.2 *Digital Communications*

In this section we study some preliminaries from digital communications. A model of a digital communication system is given in the next section and the last two sections give a short introduction to *bandwidth* and *diversity*.

1.2.1 System Model

Figure 1-2 shows a simplified model of a digital communication system. Recommended textbooks on this subject are [1], [41] and [54]. The objective of the communication system is to communicate digital information (a sequence of binary information digits) over a noisy channel at as high bit rates as possible. The data to be transmitted could origin from any source of information. In case the information is an analog signal, such as speech, then an A/D converter must precede the transmitter.

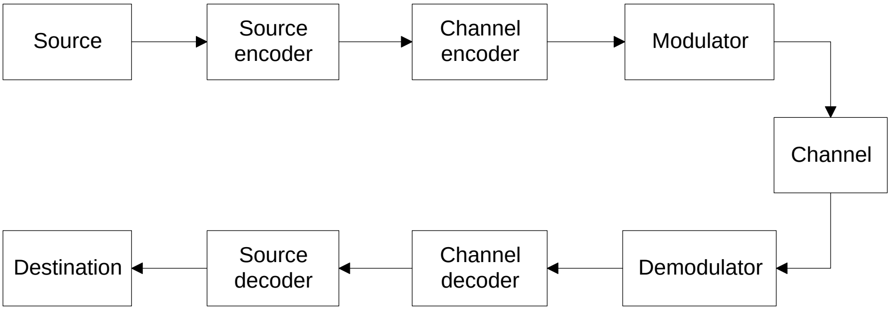

FIGURE 1-2 A model of a digital communication system.

The source encoder outputs data that are to be transmitted over the channel at a certain *information bit rate*, R_b. As a measure of performance we define the *bit error probability*, P_b, as the probability that a bit is incorrectly received at the destination. As we will see later, the channel may interfere with the communication, thus increasing the bit error probability.

Source Coding

Most data contains redundancy, which makes it possible to compress the data. This is done by the *source encoder* and minimizes the amount of bits transmitted over the channel. At the receiver the source decoder unpacks the data to either an exact replica of the source (lossless data compression) or a distorted version (lossy data compression). If the received sequence does not have to be an exact copy of the transmitted stream then the degree of compression can be increased.

Channel Coding

In order to reduce the bit error probability the *channel encoder* adds redundancy (extra control bits) to the bit sequence in a controlled way. When an error appears in the bit stream the extra information may be used by the channel decoder, to detect, and possibly correct, the error. The redundancy added is depending on the amount of correction needed but is also tuned to the characteristics of the channel.

Two coding techniques often used are *block codes* [41] and *convolutional codes* [27], [41].

Modulator

The *modulator* produces an information-carrying signal, propagating over the channel. At this stage the data is converted from a stream of bits into an analog signal that the channel can handle. The modulator has a set of analog waveforms at its disposal and maps a certain waveform to a binary digit or a sequence of digits. At the receiver, the demodulator tries to detect which waveform was transmitted, and convert the analog information back to a sequence of bits.

Several modulation techniques exists, e.g., spread-spectrum [41], OFDM (Orthogonal Frequency Division Multiplex) [18], GMSK (Gaussian Minimum Shift Keying) [33], FSK (Frequency Shift Keying) [41], PSK (Phase Shift Keying) [41] and QAM (Quadrature Amplitude Modulation) [41].

Channel

The channel might be any physical medium, such as coaxial cable, air, water or telephone wires. It is important to know the characteristics of the channel, such as the attenuation and the noise level, because these parameters directly affect the performance of the communication system.

1.2.2 Bandwidth

The frequency content of the information-carrying signal is of great importance. The frequency interval used by the communication system is called bandwidth, W [41]. For a specific communication method, the bandwidth needed is proportional to the bit rate. Thus a higher bit rate needs a larger bandwidth for a fixed method. If the bandwidth is doubled then the bit rate is also doubled.

In today’s environment bandwidth is a limited and precious resource and the bandwidth is often constrained to a certain small interval. This puts a restriction on the communication system to communicate within the assigned bandwidth.

To compare different communication systems the *bandwidth efficiency,* ρ, is defined as

$$\rho = \frac{R_b}{W} \tag{1-1}$$

and is a measure of how good the communication system is [41]. Today, an advanced telephone modem can achieve a bit rate of 56.6 kb/s using a bandwidth of 4 kHz and the bandwidth efficiency is 14.15 b/s/Hz. A meter reading system for the power-line channel that has a bit rate of 10 kb/s and communicates within the CENELEC A band has a bandwidth efficiency of 0.11 b/s/Hz, thus the performance of the telephone modem is much higher.

1.2.3 Diversity

To reduce the error probability of harsh channels, *diversity techniques* [41] may be used. Examples are *time diversity* and *frequency diversity.*

In time diversity the same information is transmitted more than once at several different time instants. If the channel is bad at some time instant the information might pass through at some other time when the channel is good (or better). This is especially useful on time-varying channels.

Frequency diversity transmits the same information at different locations in the frequency domain. It can be compared to having two antennas transmitting at different frequencies, if one of them fail the other might work.

1.3 The Power-Line as a Communication Channel

In this section we study the power-line as a communication channel and discuss the current research. In Section 1.1 we defined a channel as a physical path between a transmitter and a receiver. Note that a low-voltage grid consists of many channels each with its own characteristics and quality.

Figure 1-3 below shows a digital communication system using the power-line as a communication channel. The transmitter is shown to the left and the receiver to the right. Important parameters of the communication system are the output impedance, Z_t, of the transmitter and the input impedance, Z_l, of the receiver.

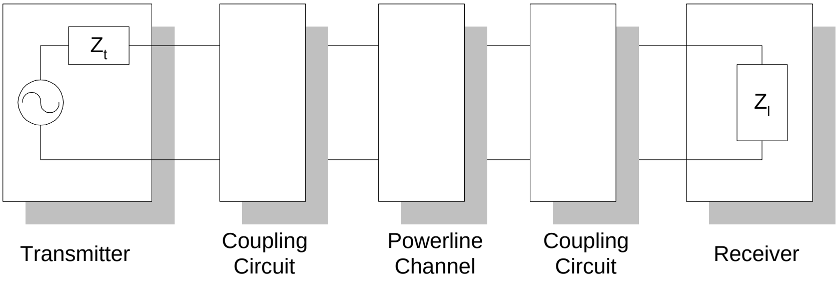

FIGURE 1-3 A digital communication system for the power-line channel.

A coupling circuit is used to connect the communication system to the power-line. The purpose of the coupling circuits is two-fold. Firstly, it prevents the damaging 50 Hz signal, used for power distribution, to enter the equipment. Secondly, it certifies that the major part of the received/transmitted signal is within the frequency band used for communication. This increases the dynamic range of the receiver and makes sure the transmitter introduces no interfering signals on the channel.

In the following sections we study different behaviors and properties of the power-line channel. In Section 1.3.6 we use a model of the power-line communication channel, incorporating these characteristics.

1.3.1 Bandwidth Limitations

As described above the bandwidth is proportional to the bit rate, thus a large bandwidth is needed in order to communicate with high bit rates.

In Europe the allowed bandwidth is regulated by the CENELEC standard, see [8]. The standard only allows frequencies between 3 kHz and 148.5 kHz. This puts a hard restriction on power-line communications and might not be enough to support high bit rate applications, such as real-time video, depending on the performance needed.

Figure 1-4 shows the bandwidth, as specified by the CENELEC standard. The frequency range is subdivided into five sub-bands. The first two bands (3-9 and 9-95 kHz) are limited to energy providers and the other three are limited to the customers of the energy providers. In addition to specifying the allowed bandwidth the standard also limits the power output at the transmitter.

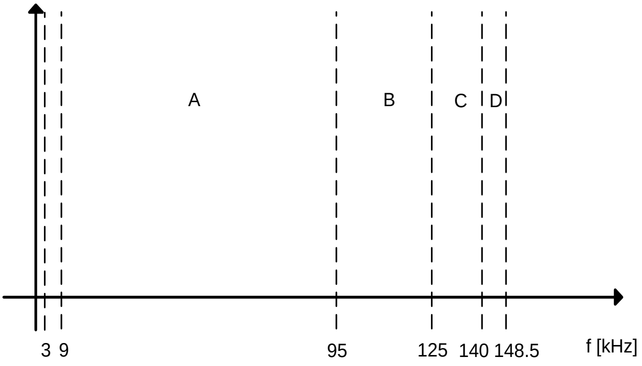

FIGURE 1-4 The frequency bands in the CENELEC standard.

In order to increase the bit rate, larger bandwidth may be needed. Recent research has suggested the use of frequencies in the interval between 1 and 20 MHz [4], [5], [20]. If this range could be used it would make an enormous increase in bandwidth and would perhaps allow high bit rate applications on the power-line. An important problem is that parts of this frequency band is assigned to other communication system and must not be disturbed. Other communication systems using these frequencies might also disturb the communication on the power-line. Examples of communication systems in this interval are broadcast radio, amateur radio and airplane navigating, see [20], [40].

1.3.2 Radiation of the Transmitted Signal

When transmitting a signal on the power-line the signal is radiated in the air. One can think of the power-line as a huge antenna, receiving signals and transmitting signals. It is important that the signal radiated from the power-line does not interfere with other communication systems.

When using the frequency interval 1-20 MHz for communication the radiation is extremely important because many other radio applications are assigned in this frequency interval. It is not appropriate for a system to interfere with, e.g., airplane navigation or broadcast systems. Recent research has studied this problem and tries to set up a maximum power level of transmission [28], [46], [55]. It is important that this work is finished in the near future since it limits the use of this bandwidth and the development of communication systems for the power-line channel.

When the cables are below ground the radiation is small. Instead it is the radiation from the households that makes the major contribution. Wires inside households are not shielded and thus radiate heavily. A solution might be to use filters to block the communication signal from entering the household [4], [35].

1.3.3 Impedance Mismatches

Normally, at conventional communication, impedance matching is attempted, such as the use of 50 ohm cables and 50 ohm transceivers. The power-line network is not matched. The input (and output) impedance varies in time, with different loads and location. It can be as low as milli Ohms and as high as several thousands of Ohms and is especially low at the sub station [2], [24], [31], [34], [38], [53].

Except the access impedance several other impedance mismatches might occur in the power-line channel. E.g., cable-boxes do not match the cables and hence the signal gets attenuated.

Recent research has suggested the use of filters stabilizing the network [35]. The cost of these filters might be high and they must be installed in every household and perhaps also in every cable-box.

1.3.4 Signal-to-Noise-Ratio

A key parameter when estimating the performance of a communication system, is the *signal-to-noise power ratio*, *SNR* [41]:

$$SNR = \frac{\text{Received power}}{\text{Noise power}} \tag{1-2}$$

This parameter is related to the performance of a communication system. The higher SNR the better communication.

The noise power on the power-line is a sum of many different disturbances. Loads connected to the grid, such as TV, computers and vacuum cleaners generate noise propagating over the power-line. Other communication systems might also disturb the communication, thus introducing noise at the receiver. Noise measurements are found in [2], [6], [15], [20], [24], [32], [38].

When the signal is propagating from the transmitter to the receiver the signal gets attenuated. If the attenuation is very high the received power gets very low and might not be detected. The attenuation on the power-line has shown to be very high (up to 100 dB) and puts a restriction on the distance from the transmitter to the receiver [2], [15], [20], [24]. An option might be to use repeaters in the cable-boxes, thus increasing the communication length.

The use of filters could improve the signal-to-noise ratio [35]. If a filter is placed at each household blocking the noise generated indoors from entering the grid, the noise level in the grid will decrease, but the cost is a higher complexity.

It is important to point out that although the power-line is considered a harsh environment when it comes to attenuation and disturbances, these parameters exists in any communication system used today.

1.3.5 The Time-variant Behavior of the Grid

A problem with the power-line channel is the time-variance of the impairments, see e.g., [2]. The noise level and the attenuation depend partly on the set of connected loads, which varies in time. A channel which is time-variant, complicates the design of a communication system. At some time instants the communication might work well but at other times a strong noise source could be inherent on the channel, thus blocking the communication.

To solve this a possible solution is to let the communication system adapt to the channel [41]. At any time the characteristics of the channel are estimated, e.g., through measurements, and the effect is evaluated to make a better decision. The cost of this is higher complexity.

1.3.6 A Channel Model of the Power-Line Communication Channel

In the previous section we have seen some impairments that reduce the performance of a power-line communication system:

- Impedance mismatches at the transmitter
- Channel attenuation
- Disturbances (noise)
- Impedance mismatches at the receiver
- Time-variations of the impairments

Figure 1-5 shows a model of the power-line channel with the parameters above. All impairments except the noise are shown as time-variant linear filters [41], [42] characterized by its frequency response. The disturbance is shown as an additive interfering random process.

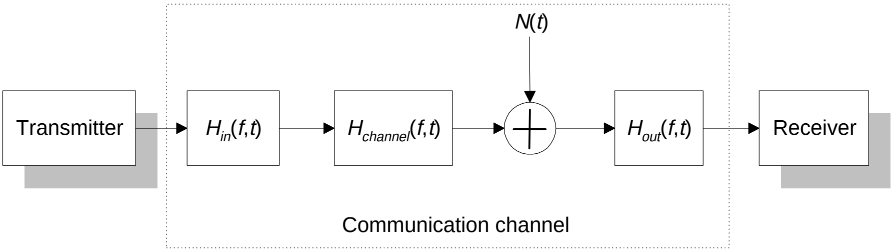

FIGURE 1-5 Impairments present on the power-line channel.

All the impairments above can be incorporated into a single filter model, shown in Figure 1-6, consisting of a time-variant filter and additive noise.

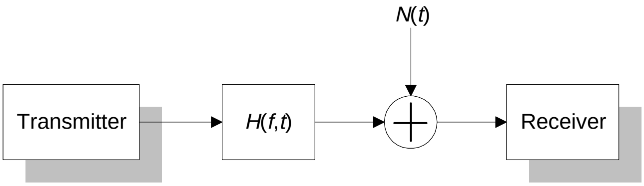

FIGURE 1-6 A simplified model of the power-line channel.

Despite of its simple form this model captures a whole range of properties essential to communication system design and to the corresponding performance [41].

The transfer function and the noise can either be estimated through measurements or derived by theoretical analysis. Measurements on the power-line channel are found in [2], [6], [15], [20], [24], [31], [32], [34] and theoretical models in [3], [10], [13], [16], [20], [39], [56]. Still a lot of measurements and modeling are needed to get a thorough understanding of the grid due to the variance of the characteristics.

1.3.7 Summary

In this section we summarize the references in the previous sections and also add some new references.

Current research is focused on the characteristics of the power-line as a communication channel and the development of effective communication methods.

The characteristics, such as attenuation, noise level and access impedance have been studied in different papers. The references [2], [24], [31] study frequencies up to 150 kHz and [6], [15], [20], [31], [34], [38] present measurements for higher frequencies. Especially recommended are [2], [15], [24] and [38], where the last one is focused on indoor communication. The outdoor grid and the indoor grid are two different environments and the behavior is not the same. Measurements have been done by several projects, but it is still hard to give a precise model of the power-line out of these measurements because of the variance in time, at location and with loads.

Instead of measuring the channel characteristics, one alternative is to theoretically derive specific channel characteristics. Different theoretical methods to do this analysis have been studied, see e.g., [3], [10], [13], [16], [20], [39], [56].

A recommended serie of papers is [24], [25], [26] and study frequencies up to 100 kHz. First the channel parameters are measured and statistically described, then bounds on the channel capacity are calculated. Reference [20] is a tutorial on power-line communications on the low-voltage grid. It contains market analysis, overviews, communication protocols, measurements, and descriptions and simulations of different types of cables and topologies.

The radiation problem is described in [28], [46], [55], which report measurements of the radiation and also try to set up a limit of the transmitter power.

Standardization of power-line communication in a regulatory perspective is found in [22] and a general discussion of different standards for power-line communication is given in [35].

Other papers dealing with most aspects of power-line communication can be found in Proceedings from the International Symposium on Power-line Communications conferences, see [43], [44] and [45].

Different modulation methods have been proposed to be used on the low-voltage grid. Methods often considered as candidates are OFDM (Orthogonal Frequency Division Multiplex), spread-spectrum and GMSK (Gaussian Minimum Shift Keying). These methods are described in [18], [41] and [33].

1.4 Thesis Outline

The remaining six chapters are concerned with different aspects of power-line communications.

Chapter 2 Communication Channel Properties of the Low-voltage Grid

In this chapter we study some basic properties of the power-line channel. By observing an existing system using the low-voltage grid as a communication medium it is possible to draw conclusions of how large-scale variations affect the communication, such as the variation in time and energy usage in the grid. Also the performance of individual channels are measured and related to the distance between the transmitter and the receiver and the location in the grid.

Chapter 3 On the Effect of Loads on Power-Line Communications

Loads change the condition of a grid. It is therefore interesting to study how this change of state affects the communication. By using a moveable load source consisting of a set of industrial machines we have been able to relate the effect of this load to the degradation of performance of a running communication system. It is also studied how the distance to the load is related to quality of the channels.

Chapter 4 Measurements of the Characteristics of the Low-voltage Grid

To further explore the characteristics of the power-line, measurements have been done in a specific low-voltage grid. We show measurements of the noise level and the attenuation of the power-line channel. Frequencies in the bandwidth regulated by the CENELEC standard [8] is studied, but also frequencies up to 16 MHz. The results are also related to the performance analysis in Chapter 2.

Chapter 5 Receiver Strategies for the Power-Line Communication Channel

From the measurements in Chapter 4 it is clear that the noise level can not be modeled as an additive white gaussian noise process (AWGN) [41], thus it is non-white. (An AWGN process is characterized by the power being evenly distributed over the whole frequency band). In this chapter we study the effect of this non-white noise on specific receiver structures. Two receiver structures are compared with respect to robustness and narrow-band disturbances.

Chapter 6 A Modulation Method for the Power-Line Communication Channel

The experiments in Chapter 2 and 3 and the measurements in Chapter 4 imply that a robust modulation method might be used, robust against phase changes and attenuation. In this chapter we introduce a modulation method designed to support robustness. The method is a combination of FSK and PSK [41]. The error probability and the bandwidth efficiency of the method are calculated and compared to other robust methods.

In this chapter we also summarize the key result from previous chapters and try to use this to design a communication system for the power-line. The outcome is a communication strategy designed to support robustness and ease of implementation. Modulation methods, coding and diversity are used.

Chapter 7 Conclusions

Here we conclude the thesis and report the key results.