CHAPTER 4

Measurements of the Characteristics of the Low-voltage Grid

The performance of a communication system is directly related to the noise level at the receiver and the attenuation of the channel. If the noise level or the attenuation is too high then any communication system will have problems. In order to design a communication system, it is useful to have as much knowledge as possible of these parameters. If, e.g., the attenuation is known then a proper combination of coding, diversity and choice of modulation method can increase the performance of the communication system [41].

In this chapter we study the characteristics of some channels in a specific low-voltage grid. Measurements have been done at several locations in the grid, corresponding to these channels, to estimate the noise level and the attenuation of the power-line channel. The measurements have been carried out in the same area as the studies in Chapter 2 and Chapter 3. For a description of this grid see Section 2.2.1.

The disposition of this chapter is as follows

- Section 4.1 describes the measurement setup.
- Section 4.2 explains how the measurements have been performed.
- Measurements at frequencies up to 16 MHz are shown in Section 4.3.
- Measurements in the 20-450 kHz frequency band are shown in Section 4.4.
- Section 4.5 concludes this chapter.

4.1 Measurement Setup

The measurements have been carried out with an oscilloscope and a function generator. To protect the sensitive equipment from the damaging 220 V / 50 Hz signal used for power distribution, passive coupling circuits have been used. A schematic of the setup is shown in Figure 4-1 (compare with Figure 1-3).

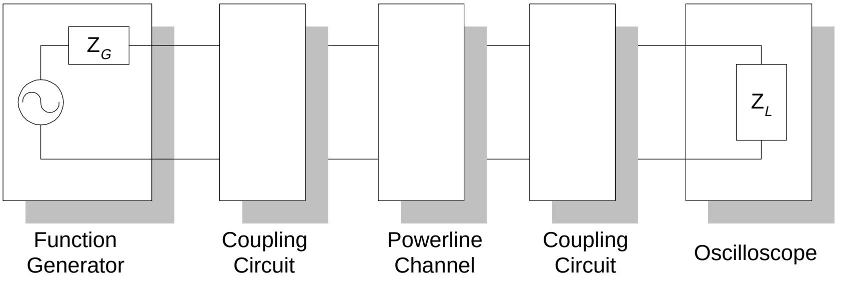

FIGURE 4-1 A schematic of the measurement setup.

Z_G is the output impedance of the function generator and Z_L the input impedance of the oscilloscope. These impedances have been set to 50 Ohm, which is supported by most measurement devices and also used in many communication applications.

In the next two sections we describe the measurement devices and the coupling circuits.

4.1.1 Measurement Devices

The oscilloscope that has been used is a Lecroy 9310CL Oscilloscope [29] with the following specifications

- 100 MS/s sample rate
- 1 MB memory per channel
- 2 channels
- 120 MB PCMCIA hard disk

The function generator is a Wavetek Model 193 with a bandwidth of 20 MHz and an option to generate a chirp signal over the entire frequency band.

The power to the devices has been taken from the same cable-boxes used for transmitting and receiving, but not at the same phase that has been used for communication.

4.1.2 Coupling Circuits

As coupling circuits, passive filters have been used. Figure 4-2 shows a schematic of the filter.

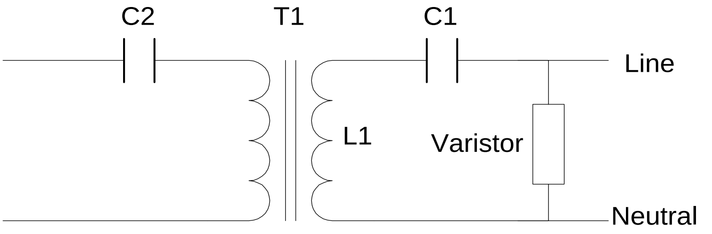

FIGURE 4-2 The coupling filter used to connect the measurement devices to the power-line.

The filter is a transformer isolated, differential mode, coupling circuit, and isolates the connected device from the power-line. The capacitor C1 and the self-inductance, L1, of the transformer, T1, form a series resonance circuit, a high pass filter to effectively remove the 50 Hz signal and its harmonics, but also other spectral components with low frequencies. The varistor serves as a surge protection unit, minimizing the effect of transients. Capacitor C2 prevents the transformer from shorting out the DC offset of the transmitter and has not been mounted when the filter has been used as a receiver. A description of how to design filters for the power-line is given in [17].

Two variations of this filter have been used, Filter A and Filter B, see Table 4-1. The cut-off frequency, specified in Table 4-1, is the frequency for which the transfer function magnitude is -3dB.

	Filter A	**Filter B**
C1	0.68 µF	0.1 µF
C2	10 µF	10 µF
L1	3.9 mH	1 mH
Cutoff frequency	3 kHz	25 kHz

TABLE 4-1 Component specification for Filter A and Filter B.

The squared magnitude of the frequency response of Filter A and Filter B is shown in Figure 4-3.

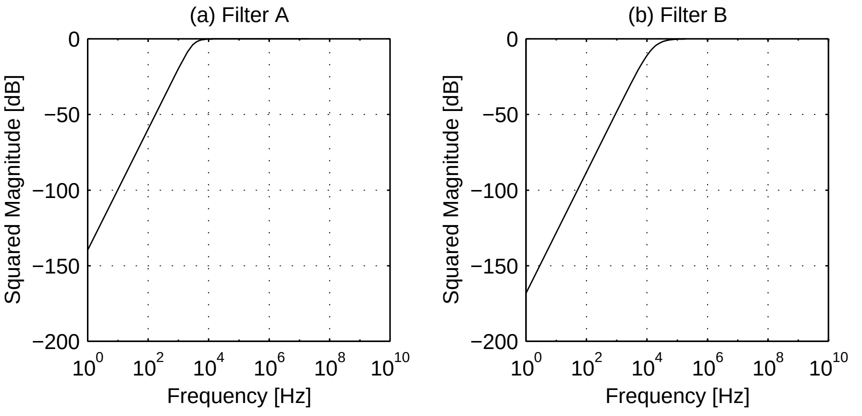

FIGURE 4-3 The squared magnitude of the frequency response of the filters called Filter A (a) and Filter B (b).

As the figure shows, both filters attenuate low frequencies, thus the 50 Hz signal and its harmonics are effectively removed (to a certain degree). Filter A has a flat frequency response above 10 kHz and is very well suited for the CENELEC A band (9-95 kHz) [8].

Filter B, to a greater extent, attenuates low frequencies to further increase the dynamic range of the receiver and is especially suited for frequencies above 100 kHz, e.g., the CENELEC B and C bands. Because the filter has a non-flat frequency response below 100 kHz the input impedance of the filter is affected in this region (the absolute value of the impedance increases). Test measurements have shown that the reduction in power of the noise and the signal on the power-line is small above 25 kHz. Below that frequency, the noise and the signal is scaled by a factor, which is the combination of the attenuation of the filter and the impedance mismatch between the filter and the power-line.

In all cases Filter B has been used to receive the signal and to measure the noise level. Filter A has been used to transmit signals with frequencies up to 450 kHz, while Filter B has been used to transmit higher frequencies.

The effect of aliasing has shown to be low when sampling at high rates (100 MS/s), since the noise level is low at high frequencies. Measurements in the frequency band up to 450 kHz have been done with a lower sample rate and in order to prevent aliasing, a high-pass filter attenuating frequencies above half the sample rate had to be used.

4.2 Measurement Techniques

4.2.1 Noise Measurements

As a measure of the noise level we have chosen to estimate the power spectrum, $R(f)$. The power spectrum describes how the power of a signal is distributed in the frequency domain [41], [42].

To estimate the power spectrum of a signal, N samples have been taken in the time-domain, at a sample rate of F_s samples (S) /second (s) during N/F_s seconds. By calculating the discrete fourier transform [42] on the samples it is possible to obtain an estimate of the power spectrum. Section 4.2.3 explains this procedure.

In all cases the number of samples have been set to 1 MB (the limit of the oscilloscope) and the sample rate and the window length have been set depending on the frequency band of interest.

4.2.2 Attenuation Measurements

The attenuation has been measured using a function generator, transmitting a chirp signal with constant amplitude (into a fixed impedance) at the sub station. A chirp signal is a signal that starts at a given frequency and continuously increase (or decrease) the frequency until it reaches the end frequency. The function generator has been set to generate this signal periodically with a sweep time of two minutes.

When the chirp signal arrives at the receiver it has been affected by the channel and has been attenuated. Because the attenuation vary in frequency, different parts of the chirp signal are attenuated differently and the received signal is a measure of the frequency response of the channel.

To estimate the attenuation, blocks of length N samples has been taken repeatedly of the received signal (at a much higher rate than the sweep rate of the function generator) at a sample rate of F_s samples/second. The power spectrum of each block has then been estimated with the technique described in Section 4.2.3. By taking the maximum of all blocks (for each frequency), we get an estimate of the attenuation for each frequency (assuming the power in the received signal is greater than the power of the noise). Because the blocks are much shorter (in time) than the length of the sweep time we get a fine-grain resolution of the frequency response. This process is the same method as transmitting a pure sinusoidal tone, calculating the power spectrum of this tone, changing the frequency to another tone, and so on until the frequency response for an arbitrary number of blocks has been measured. A similar method is used in [20].

The amplitude of the transmitted signal has been set to 2.5 V (into 50 Ohm) and the range of the chirp has been tuned to the frequency band of interest.

4.2.3 Theory of Power Spectrum Estimation

The power spectrum has been obtained by means of the discrete fourier transform. This section studies the theory behind this calculation, and follows [42] and [52]. In this section f is the normalized frequency, i.e., the original frequency divided by the sample rate. Assume that we have a sequence of N samples, $x(n)$, from a stationary random process, $x_a(t)$, with true power spectrum $R_{xx}(f)$. The discrete fourier transform, $X(f)$, of this sequence is calculated as

$$X(f) = \sum_{n=0}^{N-1} x(n)e^{-j2\pi nf} \tag{4-1}$$

The power spectrum of the stochastic process is estimated as

$$\tilde{R}_{xx}(f) = \frac{1}{N}\left|\sum_{n=0}^{N-1} x(n)e^{-j2\pi nf}\right|^2 \tag{4-2}$$

and is called a periodogram [42].

The variance of this estimation when N goes to infinity and the data sequence is a Gaussian random process is [42]

$$\lim_{N \to \infty} var[\tilde{R}_{xx}(f)] = R_{xx}^2(f) \tag{4-3}$$

Thus, the estimation is not a consistent estimate (the variance does not converge to zero) of the true power spectrum. To reduce the variance, various methods are used. A well-known technique is Welchs method [42], [52]. In Welchs method several periodograms are averaged to reduce the variance. The cost of this scheme is a reduction in frequency resolution.

Assume that we have a sequence of N samples, $x(n)$, from a stationary stochastic process. The N samples may be subdivided into L segments of M samples. Thus, the segments are represented as

$$x_i(n) = x(n + iD) \qquad i = 0, 1, ..., L-1,\ \ n = 0, 1, ..., M-1 \tag{4-4}$$

The segments are allowed to overlap and therefore D is not necessarily equal to M.

Before computing the periodogram each segment is windowed with a function $w(n)$ (e.g., a Hamming window) to get the modified periodogram of each sequence i.

$$\tilde{R}^i_{xx}(f) = \frac{1}{MU}\left|\sum_{n=0}^{N-1} x(n)w(n)e^{-j2\pi nf}\right|^2,\ i = 0, 1, ..., L-1 \tag{4-5}$$

where U is

$$U = \frac{1}{M}\sum_{n=0}^{M-1} w^2(n) \tag{4-6}$$

The power spectrum estimate, $R_{xx}^{W}(f)$, in Welchs method is the average of the L modified periodograms:

$$R_{xx}^{W}(f) = \frac{1}{L}\sum_{n=0}^{L-1} \tilde{R}_{xx}^{i}(f) \tag{4-7}$$

The expectation and the variance (no overlap) of this estimation is [42]:

$$var[R_{xx}^{W}(f)] = \frac{1}{L}R_{xx}^{2}(f) \tag{4-8}$$

$$E[R_{xx}^{W}(f)] = \int_{-1/2}^{1/2} R_{xx}(\theta)W(f-\theta)d\theta \tag{4-9}$$

where

$$W(f) = \frac{1}{MU}\left|\sum_{n=0}^{M-1} w(n)e^{-j2\pi fn}\right|^2 \tag{4-10}$$

As $N \to \infty$ and $M \to \infty$ the mean converges to the true power spectrum, $R_{xx}(f)$, and the variance converges to zero, which makes the estimate consistent.

The expectation of the estimation, (4-9), for a finite sequence contains a bias. This is seen if $W(f)$ and U are substituted into the expectation.

$$E[R_{xx}^{W}(f)] = \frac{1}{\sum_{n=0}^{M-1} w^2(n)}\int_{-1/2}^{1/2} R_{xx}(\theta)\left|\sum_{n=0}^{M-1} w(n)e^{-j2\pi(f-\theta)n}\right|^2 d\theta = R_{xx}(f)*W(f) \tag{4-11}$$

The result shows that the true power spectrum is convoluted with the fourier transform of the window function and the scaling factor is

$$\frac{\left|\sum_{n=0}^{M-1} w(n)\right|^2}{\sum_{n=0}^{M-1} w^2(n)} \qquad (4\text{-}12)$$

if the window is narrow compared to the distance, in frequency, to surrounding spectral peaks [52].

In this thesis we have used Welchs method to estimate the power spectrum and the scaling factor has been compensated for on all data.

4.3 Outdoor Measurements in the 1-16 MHz Frequency Band

In this section we study the characteristics of the power-line channel in the 1-16 MHz frequency band. The interest in this frequency interval has increased because of the assumed lower and more stable noise level in this frequency band. Another reason is the demand for higher bit rates, which suggests a wide bandwidth.

Chapter 2 showed that the quality of the channels in this grid varies depending on the location in the grid (among other factors). In this section we study one low-voltage line with some low-quality channels and one with only high-quality channels. Note that the quality of the channels was estimated from the PLC-P system, which uses the CENELEC A band. The measurements in this section are located at much higher frequencies and the results in chapter 2 do not necessarily imply the same relative quality at these frequencies.

We have chosen to study cable-boxes 444, 447 (these are connected to the same low-voltage line) and 443, see Figure 2-2. 444 and 443 can (out of the results in Chapter 2) be considered as high-quality channels and 447 represents a low-quality channel.

4.3.1 The Noise Level

Figure 4-4 to 4-6 show examples of measurements of the power spectrum of the noise in the considered cable-boxes. Measurements are shown at two different phases, phase one and phase three. The number of samples is 1 MS, the window length 8192 S and the sample rate 100 MS/s.

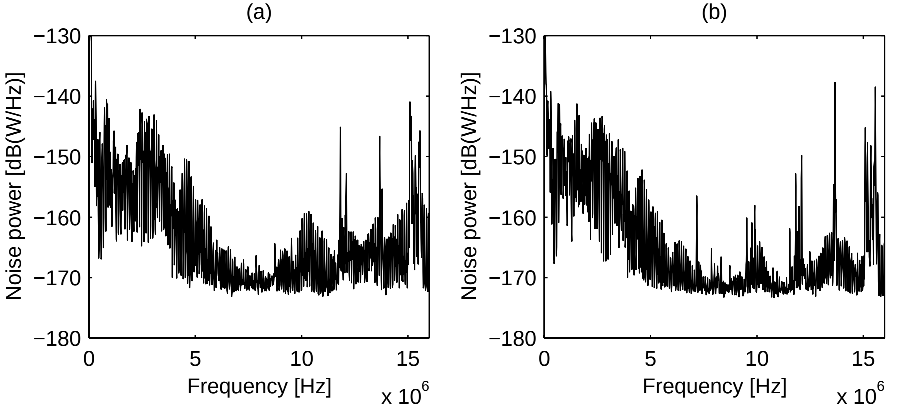

FIGURE 4-4 The power spectrum of the noise in cable-box 443 at phase 1 (a) and 3 (b).

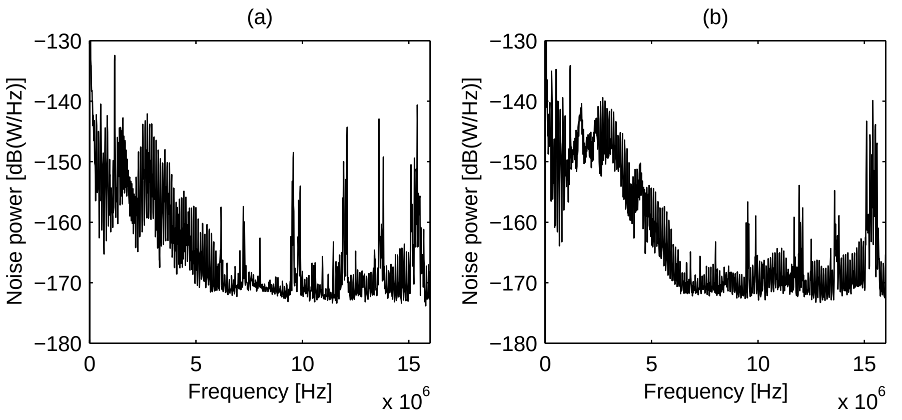

FIGURE 4-5 The power spectrum of the noise in cable-box 444 at phase 1 (a) and 3 (b).

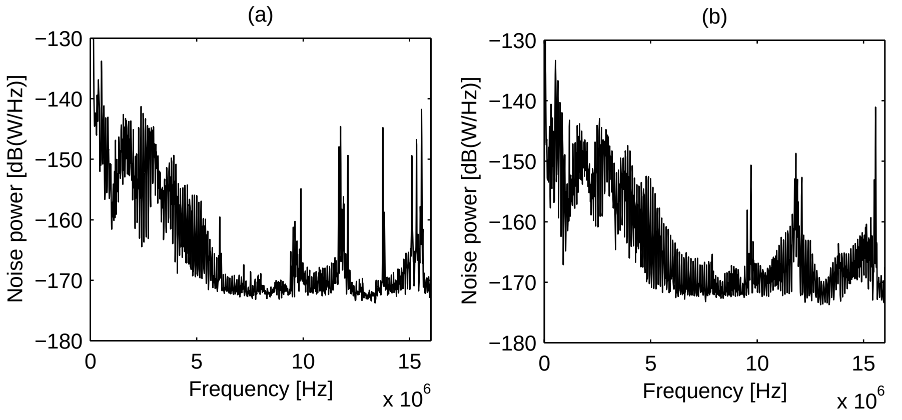

FIGURE 4-6 The power spectrum of the noise in cable-box 447 at phase 1 (a) and 3 (b).

The figures show that the noise level is rather similar in different cable-boxes although the actual levels differs. At 1 MHz the background noise is roughly -150 dB(W/Hz), it decays with frequency and at 7 MHz it is close to (and at some frequencies is) being out of dynamic range of the oscilloscope.

At higher frequencies, such as around 12 and 15 MHz, narrow-band frequencies may be found, probably corresponding to the frequencies used in broadcast radio. The location and strength of these disturbances varies depending on the actual cable-box.

Measurements in [15] and [20] show about the same behavior and levels as the measurements presented in this section, non-white noise that decays with frequency and narrow-band disturbances.

4.3.2 The Attenuation

To measure the attenuation of the power-line channel, the function generator has been connected to the sub station, transmitting a chirp signal in the range of 1 to 16 MHz with a magnitude of 2.5 V (into 50 ohm). The signal was then decoupled at each cable-box and the power spectrum of the received signal and the noise have been estimated with the technique described in Section 4.2.

Figure 4-7 - 4-9 show the power spectrum of the received signal and the noise in the selected cable-boxes. The bottom trace in each figure shows the average noise level measured at the receiver (as measured in the previous section), the trace in the middle is the maximum noise (calculated with the samples in the previous section) and the upper trace is the received signal. The transmitted signal has a power of -62 dB(W/Hz), the window length is 2002 S, the number of samples 1 MS, and the sample rate 100 MS/s. The figures show that the signal strength decays (the attenuation increases) with frequency and above 10 MHz it is in some cases hard to distinguish the received signal from the background noise.

The *SNR* in cable-boxes 443 and 444 are rather good, below 10 MHz it is above 20 dB. These two cable-boxes are located about 100 m from the sub station. Cable-box 447 is located on the same low-voltage line as cable-box 444, at a distance of 220 m from the sub station. This cable-box has a *SNR* up to roughly 25 dB lower than cable-box 444. This is reasonable since a longer physical channel imply a higher attenuation. Figure 4-7 - 4-9 also show that the actual *SNR* varies with frequency.

It is also clear that a lot of power is wasted in the sub station. When the signal reaches the first cable-box at least 25 dB (for high frequencies much more) has been lost. This might be, e.g., due to impedance mismatches between the transmitter and the power-line and other impedance mismatches within the sub station.

Measurements in [15] and [20] show a similar transfer function as we have measured, a frequency-selective channel, decaying with frequency.

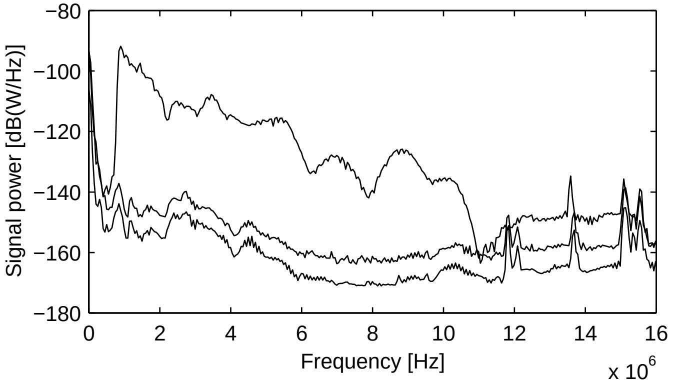

FIGURE 4-7 The received signal and the power spectrum of the noise in cable-box 443. The upper trace shows the received signal, the middle trace the maximum noise and the bottom trace the average noise level.

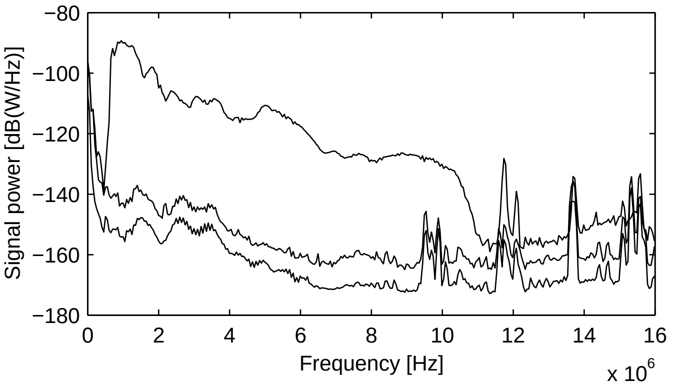

FIGURE 4-8 The received signal and the power spectrum of the noise in cable-box 444. The upper trace shows the received signal, the middle trace the maximum noise and the bottom trace the average noise level.

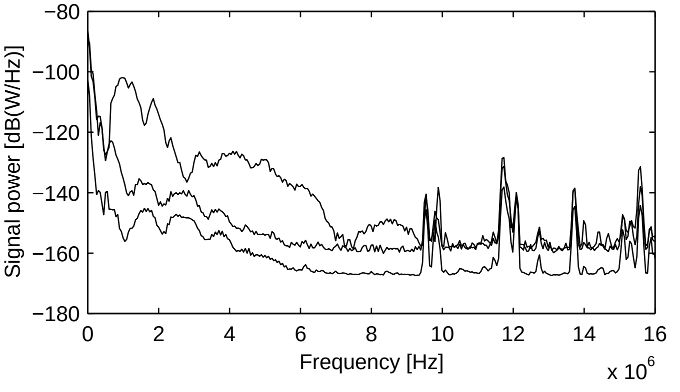

FIGURE 4-9 The received signal and the power spectrum of the noise in cable-box 447. The upper trace shows the received signal, the middle trace the maximum noise and the bottom trace the average noise level.

4.4 Outdoor Measurements in the 20-450 kHz Frequency Band

The frequency band up to 450 kHz is of particular interest because it enclose the allowed bandwidth in Europe [8] and also includes the bandwidth normally used in the United States and Japan. In this section we study the noise level and the attenuation of these frequencies for the same cable-boxes as in the previous section, cable-box 443, 444 and 447.

The results in Chapter 2 show that 443 and 444 can be considered as having relatively high-quality channels, on the contrary 447 is considered a low-quality channel. The PLC-P system, which is the system observed in that chapter, uses frequencies in the CENELEC A band (9-95 kHz), which is within the frequency band considered here. An objective with these measurements has also been to try to point out which parameters reduce the quality of some channels in the PLC-P system. Note that we do not evaluate PLC-P, but the quality of the channels that is used in the system.

4.4.1 The Noise Level

Figure 4-10 - 4-12 show the noise level in each cable-box considered. Measurements are shown for a weekday and a weekend. The number of samples is 1 MS, the window length 32768 S and the sample rate 10 MS/s. The measurements show that the noise level decays with frequency and is especially high in the frequency band up to 95 kHz, the CENELEC A band. At 25 kHz the noise level is about -110 dB(W/Hz). It is also seen that several narrow-band signals exist on the channel, with varying location and strength, depending on the actual cable-box. The measurements show that the noise level tends to be higher during the weekend, which might imply a time-varying effect of the channel.

Measurements up to 100 kHz are done in [24] and shows about the same noise level as presented here.

Cable-box 447 is considered a low-quality channel and Figure 4-10 - 4-12 show that the noise in the CENELEC A band seems to be higher for this cable-box than the other two, which could explain some of the problems with this channel experienced by the PLC-P system.

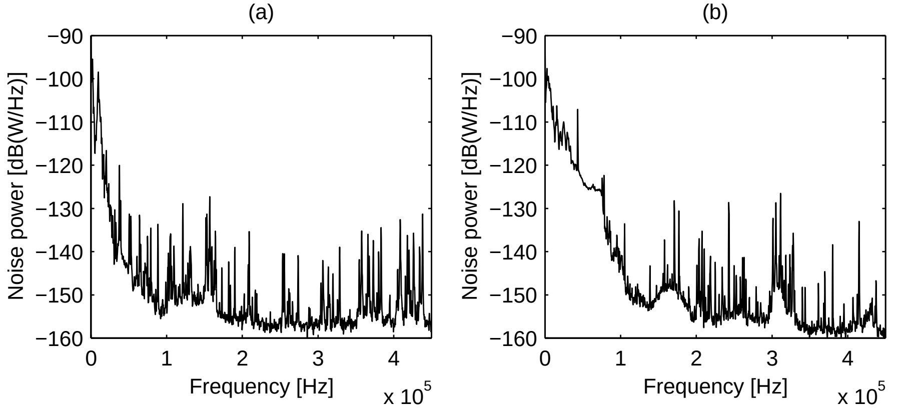

FIGURE 4-10 Examples of the power spectrum of the noise in cable-box 443 for a weekday (a) and a weekend (b).

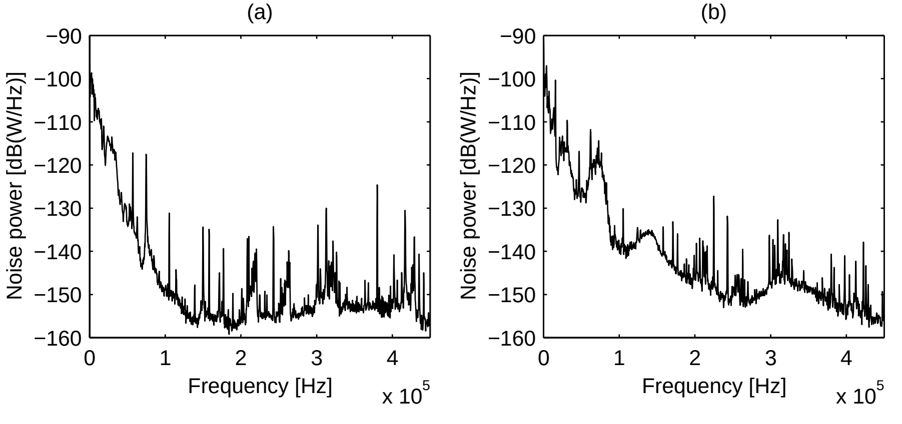

FIGURE 4-11 Examples of the power spectrum of the noise in cable-box 444 for a weekday (a) and a weekend (b).

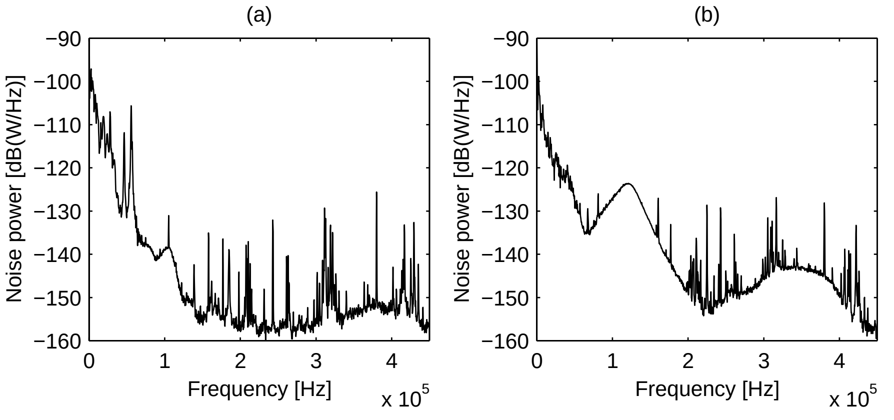

FIGURE 4-12 Examples of the power spectrum of the noise in cable-box 447 for a weekday (a) and a weekend (b).

4.4.2 The Attenuation

The attenuation of the power-line in this frequency band has been measured with the technique described in Section 4.2.2. A chirp signal from 20 kHz (this frequency has been chosen because of a limitation in the function generator) to 450 kHz with a magnitude of 2.5 V (into 50 Ohm) has been transmitted at the sub station and the signal has been received in each cable-box considered. The power of the transmitted signal is -45 dB(W/Hz). The window length used, is 10002 S, the number of samples 1 MS and the sample rate is 10 MS/s.

Figure 4-13 - 4-15 show the power spectrum of the noise and the received signal for the cases considered. The figures do not show the large variation in attenuation as in higher frequency bands, instead the transfer function is rather flat and without many notches. However, the transfer function in the frequency band up to 100 kHz varies with frequency and the *SNR* in this region is also lower. This could depend on the lower impedance in this region, which limits the input signal. Also here a lot of power is lost at the transmitter. Cable-box 443, which is located closest to the sub station, has lost about 30-60 dB of the power. This is more than the loss between cable-boxes 444 and 447 (the distance between these two is the same as between 443 and the sub station) and is probably due to impedance mismatches within the sub station.

The measurements also show that the low-quality channel in cable-box 447 has a higher attenuation than the other cable-boxes, which is reasonable due to the longer communication distance.

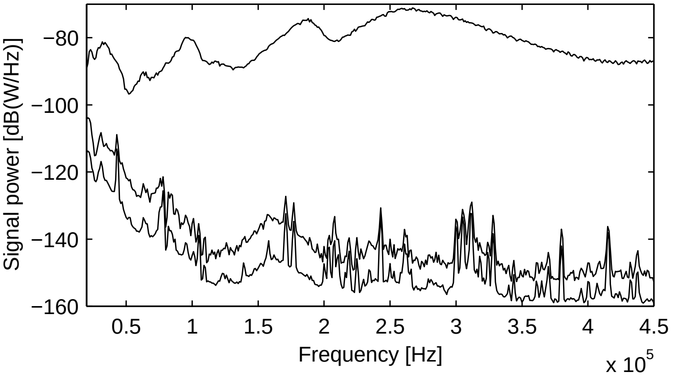

FIGURE 4-13 The power spectrum of the received signal and the noise in cable-box 443. The upper trace shows the received signal, the middle trace the maximum noise and the bottom trace the average noise level.

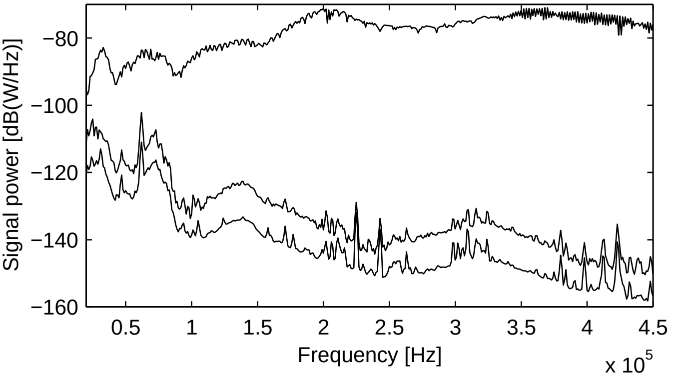

FIGURE 4-14 The power spectrum of the received signal and the noise in cable-box 444. The upper trace shows the received signal, the middle trace the maximum noise and the bottom trace the average noise level.

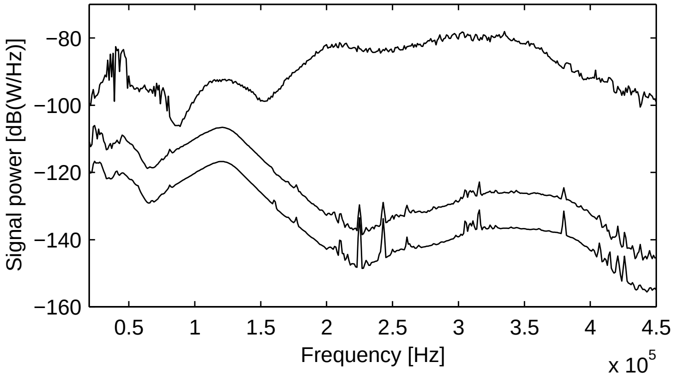

FIGURE 4-15 The power spectrum of the received signal and the noise in cable-box 447. The upper trace shows the received signal, the middle trace the maximum noise and the bottom trace the average noise level.

4.5 Conclusions

In this chapter we have seen several examples of the noise level and the attenuation of the power-line in a specific low-voltage grid. Although the number of measurements are limited it is clear that these parameters have to be taken into account when designing a communication system for the power-line channel.

Measurements of the noise level in the 20-450 kHz and 1-16 MHz frequency bands are presented. The measurements show that the noise is roughly -110 dB(W/Hz) at 25 kHz, is non-white, and decays with increasing frequency. Also several narrow-band disturbances have been found. This complicates the receiver and the effect of this noise on different receiver structures is studied in the next chapter.

The attenuation has been found to increase with frequency. Above 10 MHz it is hard to distinguish the received signal from the background noise, which limits the communication distance. The magnitude of the frequency response of the channel is not flat, except from decaying with increasing frequency, degradation in certain frequency bands occur, thus the channel is frequency-selective.

It has also been shown that a lot of power is wasted at the transmitter, probably due to impedance mismatches. This means that impedance matching should be attempted. To lower the output impedance of the transmitter could improve the performance because the input impedance at the sub station is often low.

Results from Chapter 2 has also been compared with the measured channel characteristics and it is found that a considered low-quality cable-box, at the time of measurements, was exposed to a higher noise level and higher attenuation than the others.

The measurements have also been compared to other measurements, which show similar behavior and levels. It is important to do measurements at several locations and in different countries, to increase the understanding of the power-line as a communication channel.