An Analysis of the Broadband Noise Scenario in Powerline Networks

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ABSTRACT
Opposite to many other communication channels the powerline channel does not represent an additive white Gaussian noise (AWGN) environment; in the frequency range from some hundred kilohertz up to 20 MHz it is mostly dominated by narrow-band interference and impulsive noise. After a basic classification of the different types of noise in the properties of background noise and narrow-band interference are discussed. Spectral analysis and time domain analysis of impulse noise gives some figures of the power spectral density as well as distributions of amplitude, impulse width and interarrival times. Furthermore a modular model of the noise scenario is presented. Besides coloured background noise and narrow-band interference the time behaviour of asynchronous impulsive noise is modelled by a partitioned Markov-chain.

Keywords: power line communications, noise analysis, noise model, impulse noise

1 Introduction
In order to establish high speed data communications with data rates in the range of Mbit/s over power line networks dedicated communication systems considering the hostile channel properties are required. For the design of appropriate modulation and coding schemes, detailed knowledge of the channel properties in the frequency range up to 20 MHz is essential. Besides signal distortion, due to cable losses and multi-path propagation, noise is the most crucial factor influencing digital communications over powerline networks. Opposite to many other communication channels the powerline channel does not represent an additive white Gaussian noise (AWGN) environment.

A lot of research was done in the last years investigating the channel properties up to 20 or 30 MHz. Numerous papers were published describing the channel properties of building installations [Plet87], [Phil98], [Hens99], [Hens00] or in the field of local loop access power line networks [Brow97], [Brow98], [Burr98], [Zimm98]. Models for the transfer function were published in [Phil99a] and [Zimm99]. Although the frequency response of the channel has been intensively investigated only little is known about the noise scenario. Investigations into noise in the HF-range are all restricted to, static spectral analysis of the background noise. Impulsive noise is not addressed at all. Statistics of impulsive noise are only investigated in [Chan89], but restricted to the frequency range below 200 kHz.

The goal of this paper is to provide basic knowledge about the broadband noise scenario by an analysis and modelling of the properties of the noise in the frequency range from some hundred kilohertz up to 20 MHz with a focus on impulsive noise.

The paper is organised as follows: Section 2 provides a classification of the noise scenario into five types of noise. A quantitative characterisation of the major types of noise is subject of section 3. Besides an analysis of the background noise spectral analysis and time domain analysis of impulse noise gives some figures of the power spectral density as well as distributions of amplitude, impulse width and interarrival times. A modular model for the noise is the focus of the last part of the paper, i.e. section 4. Besides background noise and narrow-band interference especially the time behaviour of the impulsive noise is addressed and modelled by a partitioned Markov-chain.

2 Classification of the Noise
Extending the basic classification provided by [Hooi98] for the frequency range below 100 kHz, the
additive noise in broadband powerline communication channels can be separated into five classes according to Figure 1:

1. coloured background noise: has a relatively low power spectral density (psd), varying with frequency. This type of noise is mainly caused by summation of numerous noise sources with low power. Its psd varies over time in terms of minutes or even hours.

2. narrow band noise: mostly sinusoidal signals, with modulated amplitudes. This type of noise is mainly caused by ingress of broadcast stations in the medium and short wave broadcast bands. The received level is generally varying with daytime.

3. periodic impulsive noise, asynchronous to the mains frequency: these impulses have in most cases a repetition rate between 50kHz to 200 kHz, which results in a spectrum with discrete lines with a frequency spacing according to the repetition rate. This type of noise is mostly caused by switching power supplies.

4. periodic impulsive noise, synchronous to the mains frequency: these impulses have a repetition rate of 50Hz or 100 Hz and are synchronous to the mains cycle. They are of short duration (some microseconds) and have a psd decreasing with frequency. This type of noise is caused by power supplies operating synchronously with the mains cycle.

5. asynchronous impulsive noise: is caused by switching transients in the network. The impulses have durations of some microseconds up to a few milliseconds with random arrival times. The psd of this type of noise can reach values of more than 50 dB above the background noise.

The noise types 1..3 usually remain stationary over periods of seconds and minutes or sometimes even for hours, and may be summarised as background noise. The noise types four and five, however, are time variant in terms of microseconds and milliseconds. During the occurrence of such impulses the psd of the noise is perceptibly higher and may cause bit or burst errors in data transmission. In the following section some noise measurements are presented and discussed.

3 Quantitative Description by Measurements

3.1 Measurement Set-up

The noise measurements were recorded with a set-up shown in Figure 2. The signal is captured from the powerline by a high impedance voltage probe. The capacitive coupling leads to a high-pass cut off frequency of about 200 kHz. A digital storage oscilloscope (DSO) capable of recording 1 million samples with a resolution of 8 bits was employed as receiver. For analysis of the spectral properties of the noise the bandwidth was limited to 20 MHz and a sample rate of 50 megasamples per second (MSPS) was chosen. For analysis of pulse amplitudes, widths and interarrival times, a peak detector with a sampling interval of 80 μs was used.

![Powerline Diagram](image)

Figure 2: Set-up for noise measurements

3.2 Spectral Analysis of Background Noise

As stated above, the background noise comprises coloured noise, narrow band noise and periodic impulsive noise with repetition rates much higher than the mains frequency. A high resolution spectral analysis of recorded background noise is shown in Figure 3. The record has a length of 20 ms, and the spectral estimation was performed using Welch's method [Mar87]. The obtained spectral resolution is about 750 Hz and the amplitude values are scaled indicating the rms value of harmonic waves in order to characterise the dominant type of noise, the narrow-band-noise caused by ingress of broadcast stations. Especially the 49m (5.95 – 6.2 MHz), 41m (7.2 – 7.5 MHz), 31m (9.4 – 10.1 MHz) and 25m (11.8 – 12.1 MHz) broadcast bands are quite obvious. But even in the frequency range below 5 MHz most interference can be characterised as narrow-band noise. The ingress from broadcast stations usually has the highest amplitudes in the evening hours, when propagation conditions for short wave radio are good. During daylight, this type of noise is usually much lower. In the range around and below 2 MHz some coloured noise can be seen, which is above the nearly white quantisation noise. Between 10 to 15 MHz equally spaced lines with varying amplitudes can be...
detected. A more detailed analysis of these lines reveals a spacing of 100 kHz corresponding to periodic impulse noise with a repetition time of 10 μs, which can also be detected in the time domain signal.

3.3 Time and Frequency Domain Analysis of Impulsive Noise

The classification of the types of noise in section 2 differentiates basically between background noise and impulsive noise. While background noise is stationary over seconds, minutes or even hours, the short time variance in the powerline environment is mostly introduced by impulsive noise caused by switching transients. This subsection investigates the impact of such impulse events on data communications.

**Example 1**

![Figure 4: Time domain signal of two impulse events](image)

Typical asynchronous impulse events are caused by switching transients anywhere in the powerline network. They often have a shape similar to damped sinusoids or overlaid damped sinusoids. The time domain signals of two examples are shown in Figure 4. Impulse 1 has a shape with a sharp rising edge followed by a damped oscillation. Its overall duration is about 50μs. Impulse 2 does not show such an clear structure. Its amplitude is only about 0.1 V and its overall duration is about 90 μs with an abrupt ending.

For characterisation of the impact of impulses on data communications the impulse energy and the impulse power are considered. With the arrivaltime $t_{ar}$ and the width $t_w$ of an impulse event, the impulse energy $E_{imp}$ can be calculated from the time signal $n(t)$:

$$E_{imp} = \int_{t_{ar}}^{t_{ar} + t_w} n(t)^2 \, dt$$  \hspace{1cm} (1)

The impulse energy is influenced by the form of the signal course as well as by the width of the impulse. In order to compare the impulse event with the background noise, the mean power of the impulse is more suitable. The impulse power $P_{imp}$ can be determined by:

$$P_{imp} = \frac{1}{t_w} \int_{t_{ar}}^{t_{ar} + t_w} n(t)^2 \, dt$$  \hspace{1cm} (2)

The mean power $P_N$ of a sample of a background noise signal $n(t)$ over the observation time $T_B$ leads to:

$$P_N = \frac{1}{T_B} \int_0^{T_B} n(t)^2 \, dt$$  \hspace{1cm} (3)

The impulse energy and the impulse power may serve as a measure for the impact of an impulse on a receiver. The relation between the mean power of the background noise $P_N$ and the impulse power $P_{imp}$ gives a measure for the dynamic change of the noise scenario during an impulse event.

**Table 1: Characteristic Parameters of the impulses from Figure 4.**

<table>
<thead>
<tr>
<th>Impulse</th>
<th>Impulse Width $t_w$</th>
<th>Impulse Amplitude $A$</th>
<th>Impulse Power $P_{imp}$</th>
<th>Impulse Energy $E_{imp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impulse 1</td>
<td>46.1 μs</td>
<td>1.77 V</td>
<td>-11.1 dBV²</td>
<td>5.54 dBV²</td>
</tr>
<tr>
<td>Impulse 2</td>
<td>90.6 μs</td>
<td>0.1 V</td>
<td>-31.3 dBV²</td>
<td>-11.7 dBV²</td>
</tr>
<tr>
<td>Background noise</td>
<td>Signal Power $P_{n,Background}$ = -52.5 dBV²</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The characteristic parameters of the two impulse examples from Figure 4 are listed in Table 1. While the power of impulse 2 is 21 dB above the background noise, impulse 1 worsens the signal to noise ratio during its occurrence even by more than 40 dB.

The characteristic parameters (1) - (3) are all determined from the time domain signal depending on the bandwidth of the measurement set-up from 0.2 to 20 MHz. For a more precise assessment of the impact on a communication system with limited bandwidth, the distribution of the noise power over the spectrum is a better approach. Therefore additionally the medium power spectral density $S_{nn,imp}(f)$ of the impulse event is considered for characterisation of impulse events.

The medium power spectral density of the two impulse examples is shown in Figure 5. It was determined with a parametric spectral estimator based on an AR-process [Marp87]. Both impulses exceed in the whole frequency range the psd of the background noise for at least 10-15 dB. In certain frequency bands impulse 1 exceeds the background noise for more than 50 dB.
and impulse 2 up to 30 dB. The spectral power is concentrated in certain frequency ranges. The maximum value is below 1 MHz. A statement which has general validity. The broadband portion of the psd is caused by the sharp rising edges of the impulses whereas the concentration in certain frequency bands is due to oscillations.

Figure 5: PSD of the impulse events from Figure 4.

The values of the characteristic parameters of the impulse examples indicate a high likelihood of bit or even burst errors for digital communications over powerlines, caused by impulse events.

3.4 Amplitude, Impulse Width and Interarrival Times of Impulsive Noise

Due to the high impact of impulse noise on data transmission it is essential to gain statistical information about the probability of impulse width, impulse amplitude and interarrival time.

One approach to model the impulses is a pulse train with a generalised impulse \( \text{imp}(t) \) with unit amplitude and unit width. The train of impulses \( n_{\text{imp}}(t) \) with pulse width \( t_w \), pulse amplitude \( A \) and arrival time \( t_{\text{arr}} \) can be described as

\[
n_{\text{imp}}(t) = \sum_{i} A_i \text{imp} \left( \frac{t - t_{w,i}}{t_{w,i}} \right).
\]

The parameters \( A, t_w \) and \( t_{\text{arr}} \) are random variables, whose statistical properties may be investigated by measurements. Therefore the statistical analysis of a measurement of these properties in a substation is presented and discussed in this subsection.

In order to achieve trade-offs between time resolution and span of a single measurement a peak detector with a sampling interval of 80 \( \mu \)s was used, allowing a measurement span of 20s for a single measurement. These settings limit the detectable impulse width to multiples of 80 \( \mu \)s and the maximum detectable interarrival time to 20 s. With that set-up nearly 1000 consecutive measurements were carried out covering an overall observation time of 333 minutes. By off-line post processing of the measurements about 70 000 impulses with a peak amplitude exceeding 100 mV were detected.

The statistics of the measured impulse amplitudes can be seen in Figure 6. About 90% of the detected impulses have an amplitude between 100 mV and 200mV. Only less than 1 % exceeds a maximum amplitude of 2 Volts.

In Figure 7 the measured frequency of the impulse width \( t_w \) is shown. It is obvious that during that measurement only about 1% of the impulses had a width exceeding 500 \( \mu \)s and only 0.2% exceeded 1 ms. The largest detected impulse width is about 5.7 ms.

Figure 6: Measured frequency of impulse amplitudes

Figure 7: Measured frequency of impulse width
The interarrival time \( t_{\text{IAT}} \) indicates the time span between two impulse and is calculated from the arrivaltime of two impulses:

\[
 t_{\text{IAT}} = t_{\text{arr,j}} - t_{\text{arr,j-1}}. \tag{5}
\]

The frequency of the measured interarrival times (IAT) is shown in Figure 8. More than 90 % of the recorded interarrival times were below 200 ms. More detailed investigation revealed, that about 30% of the detected impulses had an interarrival time of 10 ms or 20 ms pointing to periodic impulses synchronous to the mains frequency. Besides that, many recorded interarrival times were below 5 ms due to burst-like impulsive events. Above 200 ms the measured interarrival times seem to follow an exponential distribution.

![Figure 8: Measured frequency of Interarrivaltimes (IAT)](image)

### 4 Noise Model

For evaluation of appropriate transmission schemes by means of simulation, a model describing the noise scenario by some characteristic parameters is of great value. Hence the last section of this paper presents a modular approach to a model of the noise scenario, which is suitable for simulations.

The model is oriented on the basic classification of the noise in Figure 1. Each type of noise is represented by a block generating this type of noise. With this approach the sensitivity of a transmission scheme for the different types of noise can be examined. A complex noise scenario can also be generated by the model by additive superposition of the output of different blocks.

In the following subsections approaches for a model of the background noise, the narrowband interference and the timing behaviour of asynchronous impulsive events are presented.

### 4.1 Background Noise

![Figure 9: A model for the generation of background noise](image)

The coloured background noise signal \( n_{\text{back}}(t) \) can by easily synthesised by filtering of a white noise source according to Figure 9. The noise shaping filter is described by its transfer function \( H_{\text{Mod}}(z) \) in the \( z \)-plane:

\[
 H_{\text{Mod}}(z) = \frac{B(z)}{A(z)} = \frac{1 + \sum_{i=1}^{m} b_i \cdot z^{-i}}{1 + \sum_{i=1}^{n} a_i \cdot z^{-i}} \tag{6}
\]

The transfer function consists of an moving average (MA) portion in the numerator \( B(z) \) and an autoregressive (AR) portion in the denominator \( A(z) \). The parameters of the model are the variance \( \sigma^2 \) of the noise source and the coefficients of the filter. By use of an AR-process model, which means \( B(z) = 1 \), the parameters can be determined from a measured noise signal with an AR-spectral estimator [Marp87]. Due to the fact that the psd of the background noise changes only slowly over time, the model parameters have only to be changed for the simulation of a new state of the noise scenario.

### 4.2 Narrow-Band Interference

For simulation of narrow band interference a deterministic model seems to be suitable. The narrowband noise portion \( n_{\text{narrow}}(t) \) is described by an superposition of \( N \) independent sinusoids:

\[
 n_{\text{narrow}}(t) = \sum_{i=1}^{N} A_i(t) \cdot \sin(2 \pi f_i t + \varphi_i) \tag{7}
\]

Each carrier is described by its frequency \( f_i \), amplitude \( A_i(t) \) and phase \( \varphi_i \). The amplitude \( A_i(t) \) may be either constant over time or amplitude modulated for better approximation of AM-broadcast signals. The phase of the carriers may be chosen arbitrary out of the interval \( [0, 2\pi] \) and is not depending on time. The carrier may either separately synthesised in the time domain or jointly in the frequency-domain with help of an Inverse Fast Fourier Transform.

Neglecting the amplitude modulation, the received amplitudes of the narrow-band interference change only slowly with time, which means the parameters have only to be changed for a new noise scenario.
4.3 Partitioned Markov Chain for Impulse Noise

As stated above the short time time-variance of the noise scenario is introduced by the impulsive noise events, which can cause numerous bit and burst errors. Due to the fact, that the impulses are random events the properties are described by stochastic variables and must be represented by a stochastic model. In this subsection an approach for the description of the impulse width and the interarrival times with a partitioned Markov-chain is discussed.

4.3.1 Some Basics about Markov-chains

Random processes, whose future behaviour depends only on their present state or a limited period in the past may described by Markov-chains. In the following only discrete time instants \( k = 0, 1, 2, ... \) are considered. For simplicity time is only represented by \( k \). The course of the process is described by \( n \) states \( z_i \) \((i=1, 2, ... , n)\) and the output function \( \Phi(k) \) at time \( k \) depends only on the present state:

\[
\Phi(k) = \Phi(z(k) = z_i)
\]  

(8)

For clear illustration Markov-chains are visualised by graphs with the nodes representing the states and weighted arcs expressing the transition probabilities \( p_{ij} \) from state \( i \) to state \( j \) \((i,j=1,2,...,n)\) (Figure 11).

**Figure 11: Representation of a Markov-chain with two states by a state-graph.**

All statistic properties of the Markov-chain are described by its transition probability matrix \( P \):

\[
P = \begin{bmatrix}
P_{1,1} & P_{1,2} & \cdots & P_{1,n}
P_{2,1} & P_{2,2} & \cdots & P_{2,n}
\vdots & \vdots & \ddots & \vdots
P_{n,1} & P_{n,2} & \cdots & P_{n,n}
\end{bmatrix}
\]  

(9)

4.3.2 Partitioned Markov-chain

For representation of the occurrence of asynchronous impulsive noise events, a special form of the Markov-chain, a partitioned Markov-chain is well suited. In [Frit67] partitioned Markov-chains are proposed for the representation of bit and burst errors in binary communication channels.

The \( n \) states \( z_i \) \((i=1, 2, ..., n)\) representing the noise states are partitioned into two groups \( A \) \((i=1, 2, ..., v)\) and \( B \) \((i=v+1, v+2, ..., n)\). With the Output function \( \Phi(k) \) \( \Phi(k) = \Phi(z(k) = z_i) \) \((i=1, 2, ..., n)\) the \( v \) states in \( A \) represent the case where no impulse event occurs, and the \( w = n - v \) states in \( B \) represent the occurrence of an impulse event.

In addition to [Frit67] transition states are introduced which summarise the transitions from states in \( A \) to states in \( B \) and vice versa. With this representation the two cases can be described by independent transition probability matrices \( U \) for the impulse free states and \( G \) for the impulse states:

\[
U = \begin{bmatrix}
u_{1,1} & 0 & \cdots & 0 & 0
0 & u_{2,2} & \cdots & u_{2,v_1} & 0
\vdots & \vdots & \ddots & \vdots & \vdots
0 & \cdots & 0 & u_{v_1,v_1} & 0
0 & \cdots & 0 & u_{v_1,v_1} & 0
\end{bmatrix}
\]  

(11)

\[
G = \begin{bmatrix}
u_{v+1,1} & \cdots & u_{v_1,v_1}
0 & \cdots & u_{v_1,v_1}
\vdots & \vdots & \ddots & \vdots
0 & \cdots & 0 & u_{v_1,v_1}
0 & \cdots & 0 & u_{v_1,v_1}
\end{bmatrix}
\]
Table 2: Transition probability matrices of the example with $v=5$ impulse free states and $w=2$ impulse states.

<table>
<thead>
<tr>
<th>U</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0,9999775$</td>
<td>$0,0000225$</td>
</tr>
<tr>
<td>$0,8173416$</td>
<td>$0,1826584$</td>
</tr>
<tr>
<td>$0,9992129$</td>
<td>$0,0007871$</td>
</tr>
<tr>
<td>$0,9900302$</td>
<td>$0,0098965$</td>
</tr>
<tr>
<td>$0,9900302$</td>
<td>$0,2797342$</td>
</tr>
</tbody>
</table>

With the complementary probability distribution function ($cpf$), denoting the probability $P$ of a random variable $X$ exceeding a value $x$:

$$ cpf(x) = P(X > x) \quad (13) $$

the probability $cpf_w$ of the width of an impulse event exceeding a certain width $t_w$:

$$ cpf_w(k) = 1 \quad \text{for } k = 0 $$

$$ cpf_w(k) = \sum_{j=0}^{w} g_{w,j} \cdot g_{w,w}^k \quad \text{for } k = 1, 2, ... \quad (14) $$

and the probability $cpf_d$ of the impulse free time span between two impulses exceeding a certain time span $t_d$:

$$ cpf_d(k) = 1 \quad \text{for } k = 0 $$

$$ cpf_d(k) = \sum_{i=0}^{v} u_{v,i} \cdot u_{v,v}^k \quad \text{for } k = 1, 2, ... \quad (15) $$

can be expressed by elements of the matrices $U$ and $G$.

Both $cpf$s consist of a sum of weighted exponentials. Hence the elements of the matrices $U$ and $G$ can be determined from measured distributions of impulse width and impulse free time spans between two impulses by curve fitting techniques. In the following subsection this is demonstrated by an example.

### 4.3.3 Example

For the demonstration of the ability of the partitioned Markov-chain model to cover the statistics of real impulse events an example is discussed.

In the example the order of the model was chosen to $v=5$ and $w=2$. The function $\Gamma(k) = \sum_{i=1}^{n} a_i \cdot b_i^k \quad (16)$ was fitted to measured data with a modified Nelder-Mead-Simplex algorithm [Neld65] and from the fitted coefficients $a_i$ and $b_i$ the elements of the matrices $U$ and $G$ were determined (Table 2).

The result of the $cpf_d$ according to (15) is plotted into Figure 12 together with the measured distribution and the result of a simulation. The simulation was carried out for $10^6$ steps with a sampling time of $t_s = 80 \mu s$. The upper plot shows the overall result up to $10$ s whereas the lower one shows details in the range below $50$ ms. It is quite obvious, that the model fits the measured data pretty good. The small difference in the range below $50$ ms is of minor importance.

The $cpf_w$ of the impulse widths is plotted in the same way in Figure 13. The overall fitting of the model according to (14) with only two states is fairly good, especially in the range below $3$ ms.
5 Summary and Conclusions

From the measurements presented in this paper it can be concluded, that the noise scenario in powerline networks is definitely not of the AWGN-type; it is mostly dominated by narrow-band interference and impulsive noise and can considerably influence the quality and reliability of digital communication links.

The width, interarrival time and the power of impulse events typically reaches values which will very likely cause numerous bit or even burst errors in communication links with data rates of some Mbit/s. In order to overcome these obstacles sophisticated coding schemes must be considered.

Furthermore a statistical model of the timing behaviour of asynchronous impulse noise events, based on a partitioned Markov-chain, has been presented and validated with measured data. This model can be a valuable tool for performance evaluations of coding schemes.

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6 References


