Analysis of Modulation Methods for Data Communications over the Low-voltage Grid

Petra Čunčić, Alen Bažant

Abstract-- **The electric power supply network is a large infrastructure covering most parts of the inhabited areas. Due to the recent increase of demands in communication area, the electric power supply system is evolving from a pure energy distribution network to a multi-purpose medium, delivering energy, voice and various data services [1]. The technologies for data communications over the electrical power supply network are covered by the frequent term "Power Line Communications" (PLC).**

The development of suitable PLC systems requires an analysis of communication properties that a powerline channel has to offer, such as the transfer function and the noise scenario. The channel characteristics have a direct influence on the choice of the appropriate modulation method, which transforms a data stream into a signal suitable for the transmission over a specific medium. The purpose of this paper is to analyze those mentioned topics. Simulations for various narrowband modulation schemes were made to present the final results in form of BER (Bit Error Ratio) curves. The influence of the Decision Feedback Equalizer (DFE) on suppression of Inter Symbol Interference (ISI) was considered as well.

Index Terms-- **powerline communications, powerline channel, transfer function, noise analysis, modulation methods**

I. INTRODUCTION

The market deregulation has forced many power utilities to find and explore new business opportunities, which has increased the research in PLC area in the last decade. Providing services related to power distribution was initially in the focus of research, such as automatic meter reading (AMR) or tariff control [2]. It is possible to implement those services with a low information bit rate, and a real-time performance is not required. The required frequency band corresponds to the European CENELEC Standard EN 50065 [3], which rules the use of the frequency range from 3 to 148.5 kHz, so we speak about "narrowband PLC". The low bit rate communications over the powerlines can find its application in home automation, which results whit projects such as "Smart Home" (www.smarthome.com). Since the bit rate theoretically possible to achieve grows up to 100 Mbit/s [4], other implementations of PLC are possible (broadband PLC). The standards considering frequency ranges end EMC (Electro Magnetic Compatibility) allowed for broadband PLC are not unified and completely specified. In the last few years the use of Internet is increasing, and using the powerlines as communication medium could also be cost-effective, compared to other systems because of the existing infrastructure usage. We can distinguish three voltage levels of the electric power supply system: the high-voltage level (110-380 kV), the medium-voltage level (10-30 kV) and the low-voltage level (230/400 V). The voltage levels are interconnected by transformers designed in such a way that the energy loss is as low as possible at the power frequency of 50 or 60 Hz. For the high carrier frequencies typically used for data communication, the transformers are "natural" obstacles, which cause a perfect separation. This suggests a corresponding hierarchical structure for planning the communication system [5]. The focus of this paper is to analyze the data communications over the low-voltage grid, from the sub station to the connected households (see Fig. 1).

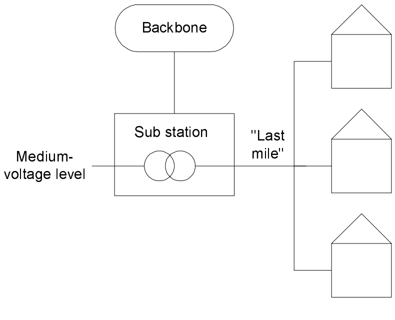

Fig. 1: Low-voltage grid

The low-voltage grid used as an access network which reaches to the end user, represents a "Last Mile" solution and can give opportunities to the power utilities in a rapidly growing market of communication providers. That was one of the main reasons of research and development of PLC in Europe. The existing indoor electrical infrastructure can be used to connect devices like PCs, printers, scanners in a home Local Area Network inside a building what encouraged the development in USA.

To use the potentials of powerlines and design appropriate PLC networks it is necessary to examine the characteristics of the powerline channel.

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II. TRANSFER FUNCTION

The general channel model shown in Fig. 2 is widely used in communication engineering. $s(t)$ is the signal on the output of the modulator, and $r(t)$ is the signal received on the input of the demodulator. $H(f)$, the transfer function of the channel, and the noise $n(t)$ will be discussed in following paragraphs.

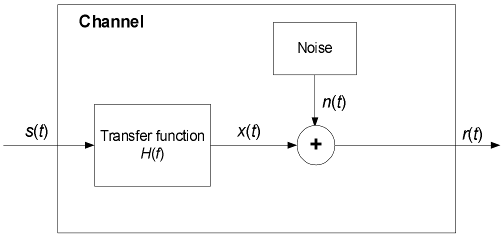

Fig. 2: General channel model

The transfer function is a complex variable expressed as:

$$H(f) = |H(f)|\, e^{-j\varphi_H(f)}$$

$|H(f)|$ is the frequency characteristic of the channel, $\varphi_H(f)$ the phase characteristic. The transfer function and the channel impulse response correlation is:

$$H(f) = FT\{h(t)\} = \int_{-\infty}^{\infty} h(t) e^{-2\pi f t} dt$$

$$h(t) = IFT\{H(f)\} = \int_{-\infty}^{\infty} H(f)\, e^{2\pi f t} df$$

where FT stands for Fourier transformation, and IFT for inverse Fourier transformation. The received signal is then:

$$r(t) = h(t) * s(t) + n(t) = \int_{-\infty}^{\infty} s(t-\tau) h(\tau) d\tau \; + n(t)$$

where * stands for convolution operator.

According to the multipath-propagation model [1], it is possible to mathematically determine the transfer function by knowing many physical parameters. It is actually more practical to measure the transfer function of the specific channel, what was done with help of a Hewlett-Packard spectrum analyzer (model HP 8753E). The measurements were done on three typical channels (channel Nr. 1 represents the best case, channel Nr. 2 represents average case and channel Nr. 3 represents the worst case), in frequency range of 0 to 35 MHz and the results are shown on following figures:

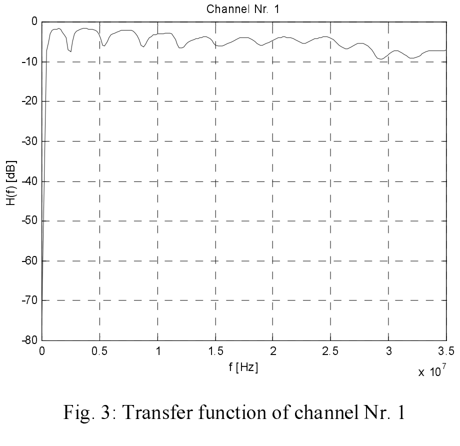

Fig. 3: Transfer function of channel Nr. 1

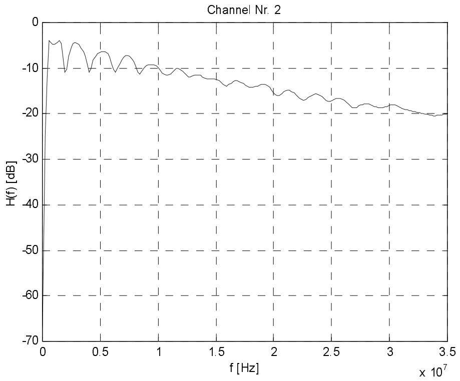

Fig. 4: Transfer function of channel Nr. 2

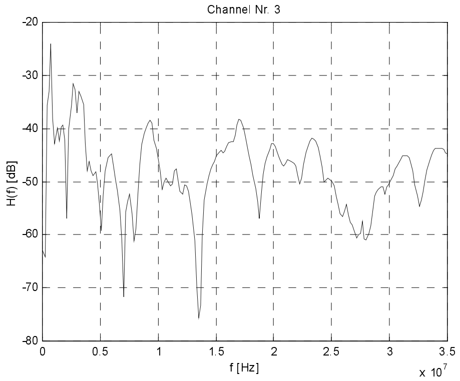

Fig. 5: Transfer function of channel Nr. 3

III. NOISE ANALYSIS

Besides signal distortion due to the cable losses and multi-path propagation, additive noise is the most crucial degrading factor influencing digital communications over powerline networks. A large part of interference is caused by electric machinery and devices during normal operation, various switching events causing different voltage or current peaks. Building installation networks are electromagneticly open structures and, as such, affected by radiation of various radio services, which may operate in close frequency ranges [5]. Unlike many other communication links, the powerline channel can not be represented by an additive white Gaussian noise (AWGN) environment. When analyzing the interference scenario, three different classes of noise can be identified: colored background noise, narrowband interference, and impulse noise [6].

A. Colored background noise

This kind of interference has a stochastic nature and can be described by a low power spectral density (PSD). It consists mainly of a sum of numerous low-power noise sources. Fig. 6 and Fig. 7 show the timeline and the power spectral density of background noise used in the simulation.

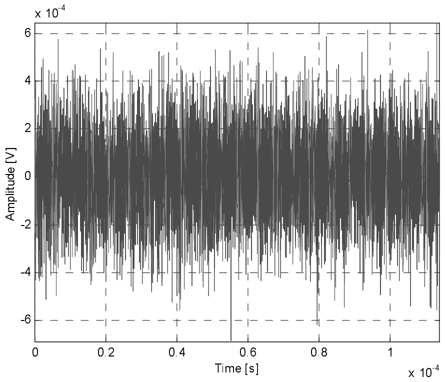

Fig. 6: Timeline of background noise

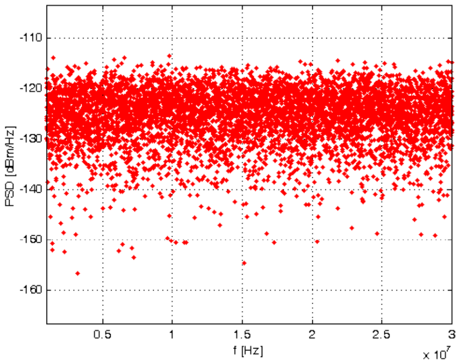

Fig. 7: Power spectral density of background noise

B. *Narrowband interference*

Narrowband interference is represented by occurrence of clear elevations in the spectrum, which occur only within a narrow and limited frequency range, but with high PSD [6]. At frequencies below 150 kHz, narrowband interference can originate from switching power supplies, frequency converters, fluorescent lamp, or television sets and computer screens. At higher frequencies, narrowband interference comes mainly from radio stations. Timeline and PSD of narrowband interference are given at Fig. 8 and Fig. 9.

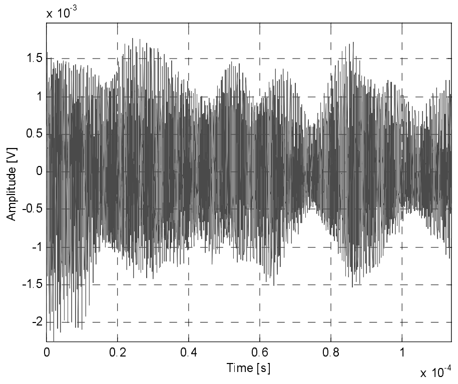

Fig. 8: Timeline of narrowband interference

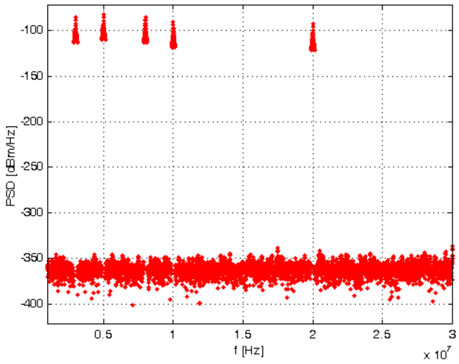

Fig. 9: Power spectral density of narrowband interference

C. *Impulse noise*

Impulse noise is characterized by short voltage peaks, which are rare single events caused mainly by on and off switching events [7]. 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, the variables describe impulses in form of an envelope that is shown on Fig. 10.

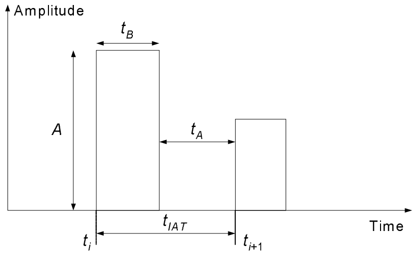

Fig. 10: Envelope model of impulses

A is the amplitude of the impulse and t_B is impulse width. Time parameters are t_i (i-th impulse arrival) and t_{IAT} (interarrival time) related as follows:

$$t_{IAT} = t_B + t_A = t_{i+1} - t_i$$

By introducing a generalized impulse imp(t/t_B) with unit amplitude and width t_B, the sequence of N impulses can be described as:

$$n_{imp}(t) = \sum_{i=1}^{N} A_i \operatorname{imp}\left(\frac{t-t_i}{t_{B,i}}\right)$$

Parameters A, t_B and t_{IAT} are random variables whose statistical properties may be investigated by measurements. The power spectral density of impulse noise is quite high compared to other interferences, up to 50 dBm/Hz. The Fig. 11 and Fig.12 represent the timeline example and PSD of impulse noise used in the simulation.

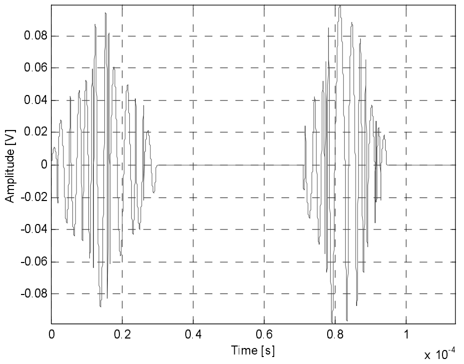

Fig. 11: Timeline of impulse noise

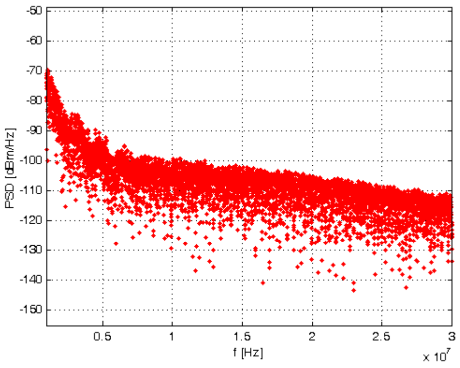

Fig. 12: Power spectral density of impulse noise

IV. MODULATION METHODS

The analysis of modulation methods simulated in program package Matlab® 5.3 considered narrowband modulation schemes such as Phase Shift Keying (PSK), Minimum Shift Keying (MSK), and Gaussian Minimum Shift Keying (GMSK) [8].

Fig. 13 presents the BER-curves simulated for different modulation methods (PSK, MSK, GMSK) in an AWGN environment. The curves for PSK and MSK match to the theoretical value for an AWGN channel [9]. Due to the Gaussian filter used in GMSK, this causes significant ISI, the correspondent BER-curve is positioned higher.

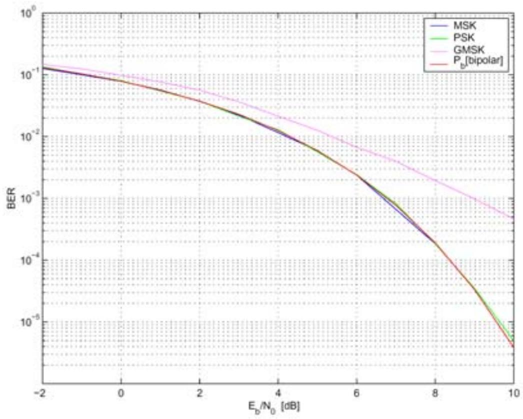

Fig. 13: PSK, MSK, GMSK BER-curves for AWGN

It is possible to see the advantage of GMSK on Fig. 13. In comparison to PSK or MSK, the spectrum of GMSK is narrower, so to choose the more convenient modulation method it is necessary to decide between the BER performance and the spectral width.

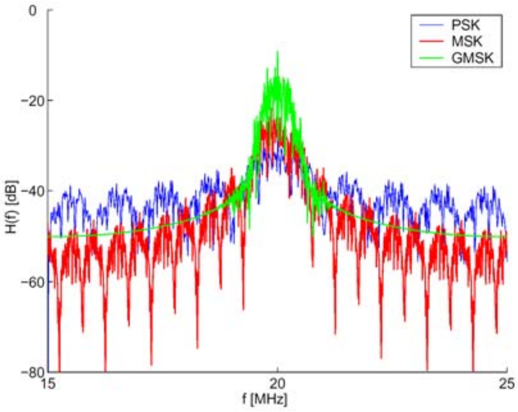

Fig. 14: Spectrum match of PSK, MSK and GMSK

The final results were BER-curves in relation to E_b/N_0, made for three different channels, various modulation methods and various types of noises. E_b is the energy per bit and N_0 stands for the noise-power density. Some examples are shown below.

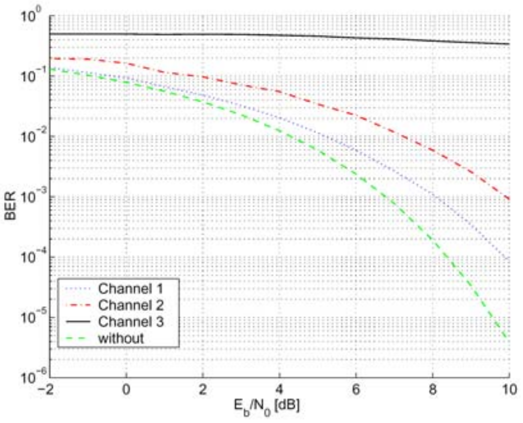

Fig. 15: MSK on different channels

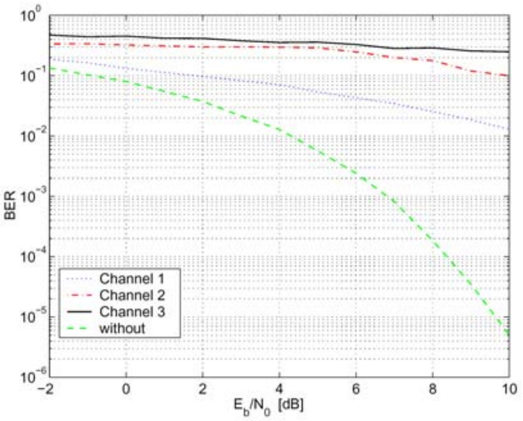

Fig. 16: PSK on different channels

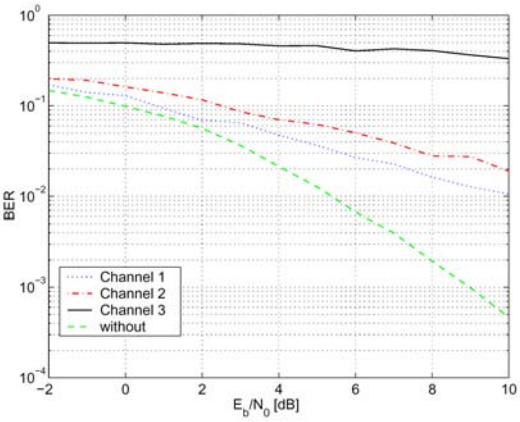

Fig. 17: GMSK on different channels

According to the measured transfer functions shown at Fig. 3, Fig. 4 and Fig. 5 the BER-curves for various channels match to the expectations. The best case is accomplished when the transfer function $H(f) = 1$ was used, the channel Nr.1 which represented the "best-case" transfer function has as well the best BER results, and the BER-curve for the channel Nr.3 is the highest.

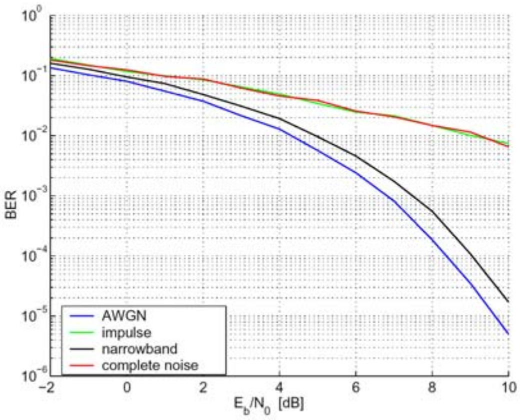

Fig. 18: Different types of noise

The Fig. 18 shows the impact of different types of noise on BER-curves when MSK was applied. The influence of impulse noise on data transmission over powerlines is very high that is clearly shown on Fig. 18.

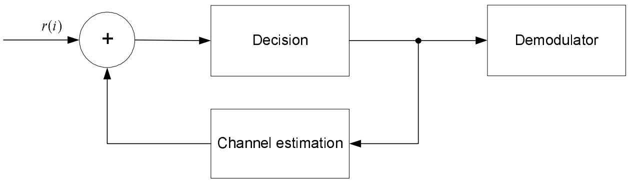

Fig. 19: Concept of DFE

By changing the variables of the simulation, it is possible to get other similar curves. To improve the performance of narrowband modulations, regarding the suppression of Inter Symbol Interference (ISI), channel equalization has been considered. The Decision Feedback Equalizer (DFE) by estimating the channel properties with help of a training sequence, can predict the ISI on the following symbol and compensate it [10], see Fig. 19.

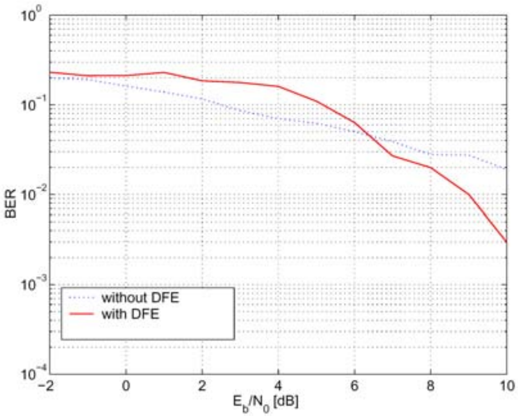

Fig. 20: Influence of DFE

Fig. 20 shows the influence of equalization on channel Nr.2 where the modulation method was GMSK. It is obvious that the DFE has a negative impact on the reliability of the transfer when the ratio E_b/N_0 is low. Single incorrect decisions may cause error propagation; the transfer of the training sequence can be disturbed by noise, so the channel estimation, predictions and compensations are not correct. As soon the ratio E_b/N_0 grows up to a certain value, the equalizer decreases the BER.

V. CONCLUSION

The narrowband modulation methods were used in the beginning of data communications over powerlines since the bit rates were low. Considering the required frequency band, those kinds of communication are called "narrowband PLC", and the regulative issues in this area are complete. The ISI could be suppressed by equalization. When no coding methods are used ARQ (Automatic Repeat Request) procedures ensure more reliable transfer with less error. The bit rates reasonable to achieve with narrowband modulation methods are not higher then some hundreds kbits/s. But due to the tendency of PLC systems to provide High-Speed services (broadband PLC), other modulation schemes have to be considered, such as spread-spectrum techniques (SST), resistant to all kind of narrowband interference, or OFDM (Orthogonal Frequency Division Multiplexing), resistant to frequency selective noise [5]. Regulatory issues considering the broadband PLC are not complete. Definition and unification of standards are still expected. Despite of that, commercial products are already present on the market: "Last Mile" solutions with rates to 4.5 Mbits/s (Ascom Powerlines, Main@net, etc.) and indoor communication systems with rates up to 14 Mbits/s (HomePlug Powerline Alliance[11]).

Acknowledgement
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