Power line modelling for creating PLC communication system

P. Mlynek, M. Koutny, and J. Misurec

***Abstract*—** The article presents a design of the power line communication model. This model is composed of communication model, model of power line and noise model. The communication model is realized as the OFDM system, power line are modelled from transfer function of two-port network or from transfer function of multipath signal environment. Noise model are modelled as white noise, which gets a spectral colouring by a filter. On the resulting PLC communication model was shown comparison of different modulation technique and coding scheme. The different levels of mapping the carrier frequencies in OFDM were simulated on the proposed model from the viewpoint of comparing symbol error with signal to noise ratio and the interference effect to symbols rearrange in the constellation diagram were simulated as well.

***Keywords*—**power line, OFDM, noise, modelling, modulation, coding

I. Introduction

THE PLC technology (Power Line Communication) uses a power lines for its data communication. PLC technology takes profits from the advantage of not requiring any additional wiring. There is a need to use distribution lines of electricity for the control signals, IP telephony transfer, and remote data acquisition [1],[2] and [3]. It comes up almost simultaneously with electrical power network developing. This technology becomes more and more important. It is primary given with growing need of data channels using for s communication with meter equipments and control systems in energy industries. Its expansion is expected with AMR (Automated Meter Reading) and AMM (Automated Meter Management) systems coming. They are part of new metering and controlling trend co-called Smart Metering. The PLC technology should be as an alternative to other existing data channels [4].

PLC systems fall into two areas: wideband PLC and narrow-band PLC. Wideband PLCs achieve the characteristics of wideband communication, enabling, for example, fast Internet access or implementation of small LAN networks. Narrow-band PLCs today seem to be a little in the background. This is, of course, given only by the area of applicability. Power networks can also be used for other applications, which would be hard to implement in practice through another type of communication. Specific services include central management of power consumption, tariffing, remote meter reading, commanding, etc.

There are a lot of failings for widely using of this technology. An interference of useful signal, smaller range of useful signal and equipments of energy network are the main. From the analysis of partial problems, there is a better to have a mathematical computer model of power line which it would enable a simulation of data transmission with power lines.

II. The using of PLC technology

The narrow-band PLC systems are used mainly in automation [3]. The automation systems based on this technology are implemented without an additional installation of communication networks. This means that high costs, which are necessary for the installation and realization of new networks within the existing buildings, are substantially reduced by the use of PLC technology.

The automation systems implemented by using the PLC can be used for various tasks:

- Control of various devices which are connected to internal wiring, for example: lighting, heating, air conditioning, etc.
- Central control of various home systems, such as: windows and control of doors.
- Security functions, sensor control, etc.

Wideband PLCs achieve the characteristics of wideband communication, enabling, for example, fast Internet access or implementation of small LAN networks.

III. PLC communication system

For a creating of the complete PLC communication system, there is necessary to create model of channels as well as noise model and a transmitter and a receiver models. The complete PLC model will be created from particular models. There will be possible to create analysis of a concrete power line based on the simulations of this system with various models of lines. The analysis will be possible to judge in term of possibility to using of various combinations of PLC technologies, security transfer, modulations, coding etc. So that there will be obtained to best

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parameters of data transfer in mentioned systems.

It is necessary to create the channel models for the PLC simulation. There are more possibilities of power line model creating. First of them is the power line model as environment with multipath signal propagation. The parameters of this line are obtained from a distribution network topology or based on metering.

Second of them is model, which applies chain parameter matrices to describing the relation between input and output voltage and current by two-port network.

In design of PLC system, it is necessary to bear in mind the character of transmission medium and interferences which the PLC communication is influenced. It is necessary to find useable guard coders, modulation technique and encryption to ensure of security and foolproof communication with smallest error rate between data source and receiver.

The PLC communication system is possible to divide to particular parts for purpose of modelling:

- PLC communication model,
- Models of power lines,
- Noise model.

IV. OFDM MODEL FOR PLC COMMUNICATION

The model of PLC communication is created by a transmitter, receiver and channel block. It serves for a creating of a source and destination of data communication for subsequent simulations of lines model which they are replaced by block of channel. The basic PLC communication model with OFDM system is shown in the Fig.1 [5], [6] and [7].

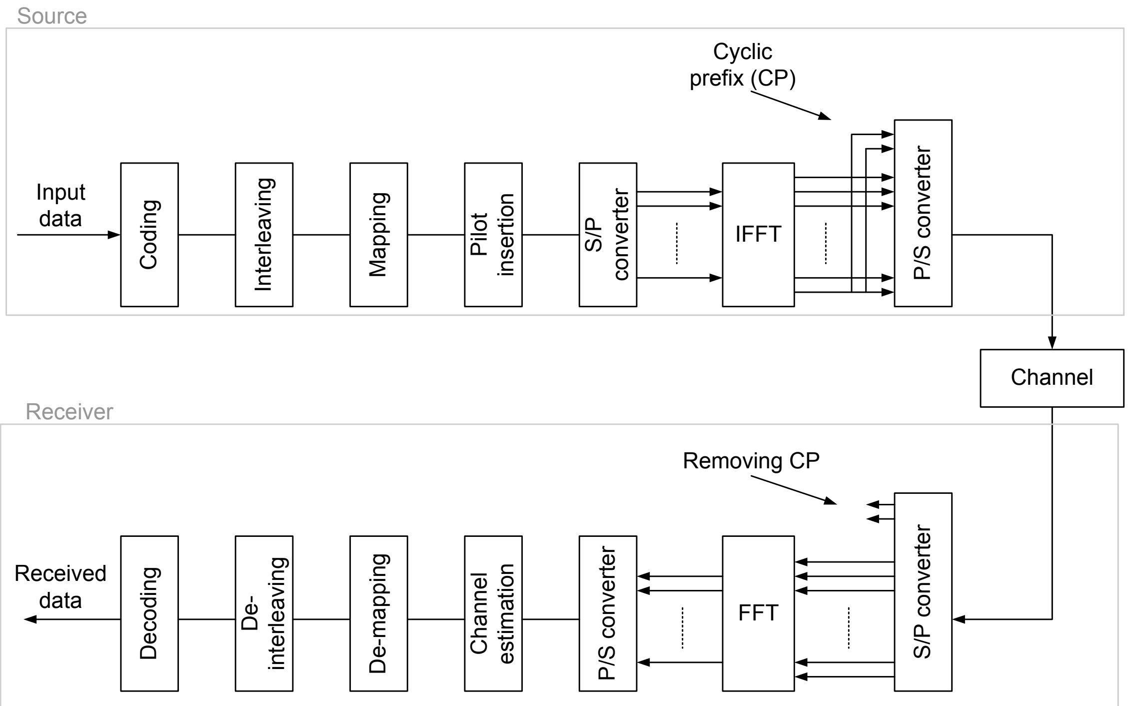

Fig. 1 The basic model of PLC communication with OFDM system

The coder adds the redundant information to the sequence of bits. If there is an error in bit chain the redundant information could be used for an error detection and correction by the help of detection and correction coders.

The scheme of coding is designed for detection and the correction independent errors. The scheme is not designed for the bulk of errors. The interleaving technologies are used for elimination of evolve of bulk errors during the transfer.

The serial data transfer is obtained from block of coding. This block is connected to a block of mapping. There is a transfer of bit sequence to a symbol sequence in block of mapping. A symbol distribution is a result of mapping. This distribution is shown in a constellation diagram and it is depended on chosen modulation.

The pilot signals are necessary to include to the transfer in case of continuous system detection. The estimation is important for determination of amplitude and phase of map's constellation each of subcarrier. The estimation of transfer channel in the OFDM system requests a inserting of known symbols or a pilot structure to the OFDM signal.

The useful data are transferred to the parallel stream in the S/P converter. The number of parallel streams matches to the number of carriers. These carriers will transfer useful data.

A protect interval is used in OFDM to prevent of ISI (inter symbol interference). A cyclic prefix (CP) is created by a few of last samples of OFDM symbols. CP creates a protect interval between adjacent transferred OFDM symbols in time area. This is a way how to keep orthogonally carries.

IFFT block transfers data from frequency to time area.

V. THE SOURCES OF INTERFERENCE

Besides simulation of transfer characteristic, it is necessary to identify possible sources of interference because the power line has a significant attenuation of signal and various interference and noise. Therefore the data transfer has a high error rate without any checking algorithm.

The fundamental influence on data transmission over power lines are mainly the negative characteristics of power networks. Can be summarized in a few points:

- Mismatched impedance
- Attenuation on the communication channel
- Interference (noise)
- Interference changing in time

Fig. 2 shows a simplified block model of the PLC communication channel, in which the described characteristics and parameters are included. The parameters of interference, except noise, are represented as a time variable linear filter described by the frequency parameters. Noise is depicted as additive random interference process.

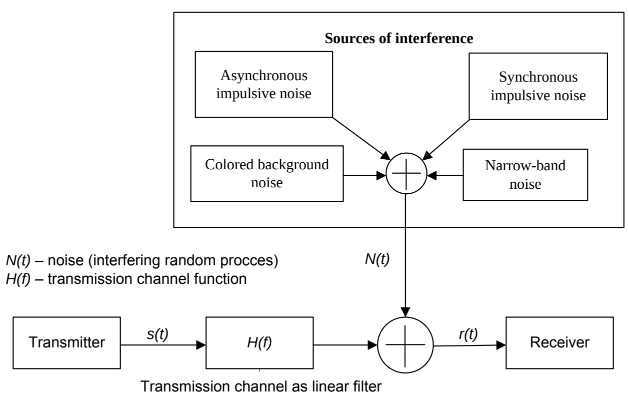

Fig.2 PLC channel model

This model captures the whole range of parameters which are necessary for a model of the communication system with corresponding characteristics, although this model is schematically simplified in the figure.

Transmission function and noise can be either estimated from the measurement or derived from the theoretical analysis.

In this paper, we deal with four different types of noise [6]*:*

Background noise: it is every time present in the network. It is caused by assembling of multiple sources of noise with low power. It can be described by a PSD (Power Spectral Density) that it declines with a growly frequency. The background power noise density can be described with equation:

$$A(f) = A_\infty + A_0 \cdot e^{\frac{-f}{f_0}} \qquad (1)$$

where A_∞ is power density for f $\rightarrow\infty$,and A_0 is a differences between A(∞) and A(0). This model enables modelling background noise as a white noise process, which gets a spectral colouring by a filter.

Narrow-band noise: this noise primary originates from the broadcasting stations that they transmit in a long, middle a short wave range. The amplitude can be changed in dependence on time and place. The narrow-band noise can be modelled as a sum of multiple sine noise with different amplitude:

$$n(t) = \sum_{i=1}^{N} A_i(t) \cdot \sin(2\pi f_i t + \varphi_i) \qquad (2)$$

where N is a number of waves of differencing frequencies f_i, amplitude $A_i(t)$ and phase φ_i. The amplitude $A_i(t)$ is a constant in simplest case but it can be established from broadcast transmission. The phase φ_i is randomly established from interval [0;2π].

Asynchronous impulsive noise: this type of noise is characterized by high and short spikes of voltage with length 10 – 100 μs. These spikes can reach up to 2kV level. This noise is the cause of the switching equipments in the distribution network. These kinds of noise are considered as a part of background noise.

Synchronous impulsive noise: is caused by thyristors in light dimmers and copiers. They are bursts of interference spikes with repeating of period. Synchronous impulse noise can be modelled by a source of white noise with a spectral colouring together with a periodical switching of rectangular wrap (Fig. 3).

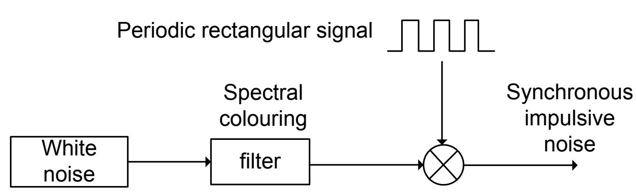

Fig. 3 Synchronous impulsive noise

VI. POWER LINE MODEL

A. Primary parameters of power line

The line can be described by using *R´, L´, C´, G´*parameters. These parameters denote a resistance, inductance, capacity and leakage relative to the length of the line.

Let's consider a single-phase signal distribution and management structure which is shown in Fig 4. The wire line includes phase, neutral and ground wires where each wire is inserted into the insulating sleeve and all wires are insulated with own sheath

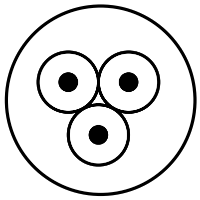

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Fig.4 The shape of power line

For the purpose of modeling, we consider the three-phase line as the two conductors and one transmission conductor, which they are a conductive core and they are surrounded by the same dielectric material. Then it is possible to determine the primary parameters with the equations [8]:

$$R' = \sqrt{\frac{\mu_r \mu_0 f}{\pi \sigma a^2}} \left[\frac{\frac{d}{2a}}{\sqrt{\left(\frac{d}{2a}\right)^2 - 1}} \right] , \qquad (3)$$

$$L' = \frac{\mu_r \mu_0}{\pi} \cosh^{-1}\left(\frac{d}{2a}\right) , \qquad (4)$$

$$C' = \frac{\pi \varepsilon_r \varepsilon_0}{\cosh^{-1}\left(\frac{d}{2a}\right)} , \qquad (5)$$

$$G' = 2\pi f C \tan\delta , \qquad (6)$$

where *d* is a distance between the centre of conductors, a is a radius of conductor, σ is a copper conductivity, ε_r indicates a relative permittivity of insulation, ε_0 is a permittivity of vacuum, *tan δ* is a factor variance a μ_r is a relative magnetic permittivity of the copper.

B. Substitute power line model

The signal propagation over a substitute model of the power line is shown in Fig. 5 [4] [6].

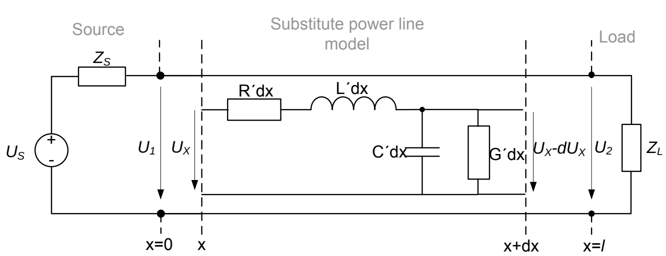


Fig. 5 Signal propagation over a power line

The voltage and current for the line are obtained from the theory of the elementary section of line.

$$U_x = A_1 e^{\gamma x} + A_2 e^{-\gamma x} , \qquad (7)$$

$$I_x = \sqrt{\frac{G + j\omega C}{R + j\omega L}} (-A_1 e^{\gamma x} + A_2 e^{-\gamma x}) . \qquad (8)$$

The parameters which describe the section of lines are the characteristic impedance and the specific transfer factor:

$$Z_C = \sqrt{\frac{R' + j\omega L'}{G' + j\omega C'}} , \qquad (9)$$

$$\gamma = \alpha + j\beta = \sqrt{(R' + j\omega L')(G' + j\omega C')} . \qquad (10)$$

If we consider the line, which it is equivalent to a wave propagating from the source to the drain, the transfer the function of the line with length *l* can be determined by:

$$H(f) = \frac{U(x=l)}{U(x=0)} = e^{-\gamma l} = e^{-\alpha(f)l} e^{-j\beta(f)l} . \qquad (11)$$

$$R'(f) << 2\pi f L'(f) \text{ a } G'(f) << 2\pi f C'(f) \qquad (12)$$

for

$$f = \langle 1{,}30 \rangle \ MHz . \qquad (13)$$

It was found that the L 'and C' dependence on the frequency is insignificant. Therefore the characteristic impedance and the specific transfer factor can be simplified:

$$Z_C = \sqrt{\frac{L'}{C'}} , \qquad (14)$$

$$\gamma = \frac{1}{2} \frac{R'(f)}{Z_c} + \frac{1}{2} G'(f) Z_c + j 2\pi f \sqrt{L'C'} . \qquad (15)$$

We replace $R'(f)$ with equation (17) to describe the real part of transmission factors as a function dependent on frequency.

$$R'(f) = \sqrt{\frac{\pi \mu_0}{\kappa r^2} f} \qquad (16)$$

where μ_0 and κ represent the constant permeability and conductivity and r is the radius of conductor.

It knows that $G'(f) \sim f$. It is possible to modify the formulation of the real part of transfer factor now:

$$\alpha(f) = \mathrm{Re}\{\gamma\} = \frac{1}{2Z_C}\sqrt{\frac{\pi\mu_0}{\kappa r^2} f} + \frac{Z_C}{2} f \quad . \qquad (17)$$

If we replace the parameters line (Z_C, r and other) by the constants k_1,k_2 a k_3, we can obtain the real and imaginary part of the transfer factor:

$$\alpha(f) = \mathrm{Re}\{\gamma\} = k_1\sqrt{f} + k_2 f \quad , \qquad (18)$$

$$\beta(f) = \mathrm{Im}\{\gamma\} = k_3 f \quad . \qquad (19)$$

The equation (18) was approximate by constants a_0, a_1 a k :

$$\alpha(f) = a_0 + a_1 f^k \quad . \qquad (20)$$

The transfer factor represents the loss on the line relate to the length of line in equation (18). Therefore the transfer factor is a function of the length l. It is possible to determine the attenuation of line as an amplitude of the transfer function of the channel defined in equation (22) by the appropriate choice of parameters a_0,a_1 and k.

$$A(f,l) = e^{-\alpha(f)l} = e^{(a_0 + a_1 f^k)l} \qquad (21)$$

C. Power line models

The power line model is required to simulate PLC communications. The power line model applies the methods used to model electricity distribution networks. The chain parameter matrices describing the relation between input and output voltage and current of two-port network can be applied for the modelling the transfer function of power line channel [9].

Modelling power line as cascaded elementary two-ports network enable working with elementary networks, two-ports, which can be described by cascade parameters. Cascade solution offers the possibility of choosing a certain degree of complexity and precision of the line being modelled. It is also possible to define individual blocks as macromodels describing a data channel. An example can be seen in the solution given in [10]. Fig. 6 shown a example of cascade connected two-port networks.

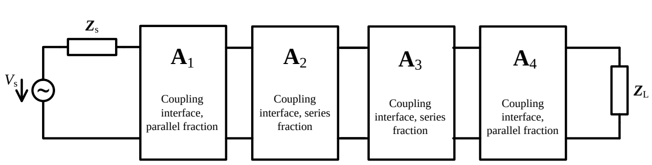


Fig.6 Cascade model of power line

Each part of the line is described by a separate cascade matrix $\mathbf{A}_1$ to $\mathbf{A}_4$. Internal series impedance $\mathbf{Z}_s$ of signal source V_s and parallel impedance of load $\mathbf{Z}_L$ can also be described by cascade parameters and included in the resultant transfer function. The resultant cascade matrix from the source to the load can be formed applying the chain rule:

$$A = \prod_{i=1}^{n} A_i \qquad (22)$$

The transfer function of appropriate two-port network is given by equation:

$$H = \frac{U_L}{U_S} \qquad (23)$$

The other alternative to modelling power line is a method, that the power line channel is assumed to be a multipath propagation environment. The parameters of the channel are acquired based on the topology of the distribution network and on the channel measurements.

The transmitted signal arrives in the receiver via the N signaling path. On path i the arriving signal is delayed by the time τ_i and attenuated by the complex attenuation factor C_i.

The impulse response of the channel $h(t)$ can be written as a sum of the delayed and attenuated Dirac pulses [3]:

$$h(t) = \sum_{i=1}^{N} C_i \cdot \delta(t - \tau_i) \Leftrightarrow H(f) = \sum_{i=1}^{N} C_i \cdot e^{-j2\pi f \tau_i} \qquad (24)$$

From the transfer function of power line model has been calculated the coefficient of filter and the power line channel has been modelled as a digital filter. The noises models have been modelled according to chapter B.

The power line model with noise model is shown in Fig.7. The particular noise has been made by a Simulink block's help.

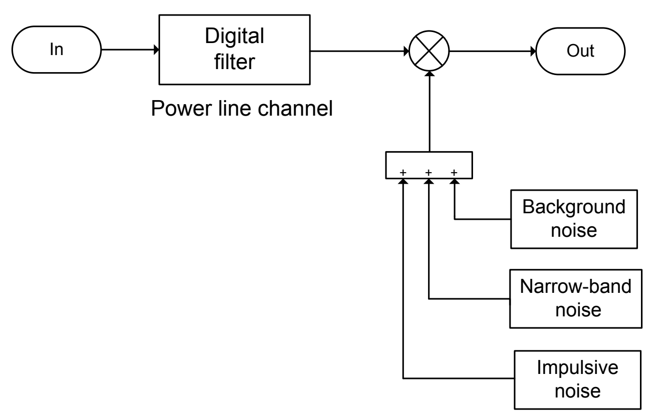


Fig. 7 Power line model

VII. Comparison of the different modulation using in OFDM system

The final model has been made from OFDM model and power lines model together with noises models in Matlab/Simulink [12], [13]. The testing of various types of modulations and coding for data communication over power line have been accomplished on created model. Fig. 8 shows a comparison of the BPSK, QPSK, 16-QAM, 64-QAM and 256-QAM modulations in OFDM system from the viewpoint of

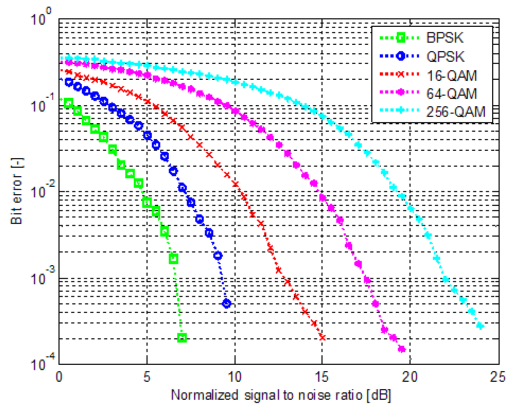


Fig. 8 BER dependence on Eb/N0 for particular modulation in OFDM system

comparing bit error (BER) with the normalized signal to noise ratio (E_b/N_0). If we set the desired value BER = 10^{-2}, i.e. less than one faulty bit per hundred of the total value, that the desired value of normalized signal to noise ratio (E_b/N_0) are shown in Tab. 1.

TABLE I
DESIRED VALUE OF NORMALIZED SIGNAL TO NOISE RATIO FOR BIT ERROR BER=10^{-2} FOR PARTICULAR MODULATION

Modulation	**BPSK**	**QPSK**	**16-QAM**	**64-QAM**	**256-QAM**
E_b/N_0[dB]	4,7	7,1	10,3	14,8	19,2

Fig. 9 shows the bit error rate (BER) dependence on the normalized signal to noise ratio (E_b/N_0) with using of various types of channels coding for 64QAM modulation. The best ability of correction achieves the convolution coder from used types of channel coding.

Fig. 10 shows how much time a particular modulation needs for the transmission of a fixed amount of data. We have chosen 1.10^5 symbols as the fixed amount of data. After the transmission of these data, the simulation stops and the time of data transmission date is shown. The QPSK modulation was the least susceptible to interference, but the transmission speed is the lowest whereas the 64-QAM modulation was the most susceptible to interference, but the transmission speed is the highest.

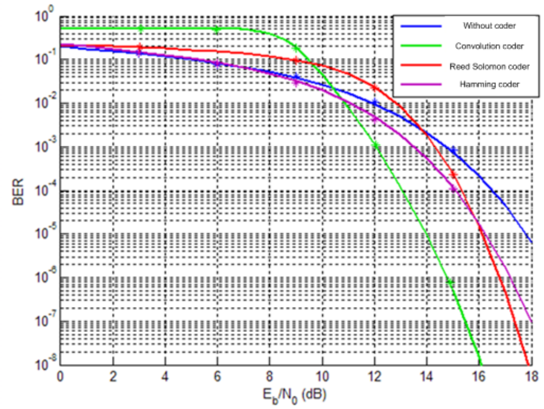


Fig. 9 BER dependence on E_b/N_0 for different coding scheme

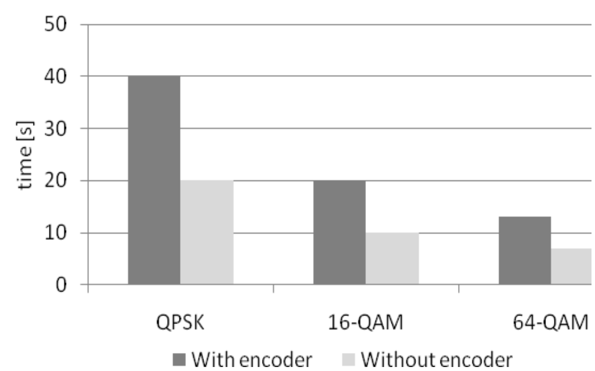


Fig. 10 Time for information transmission for different OFDM modulation

Fig. 11 shows how much time is needed for the transmission of a given amount of data for particular coding. From this graph it follows that the stronger the coding is, the more time is needed for the transmission of information.

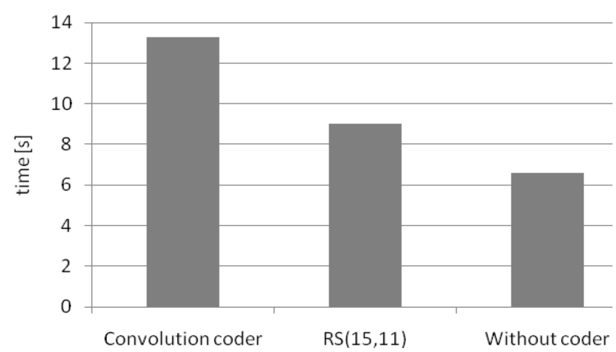
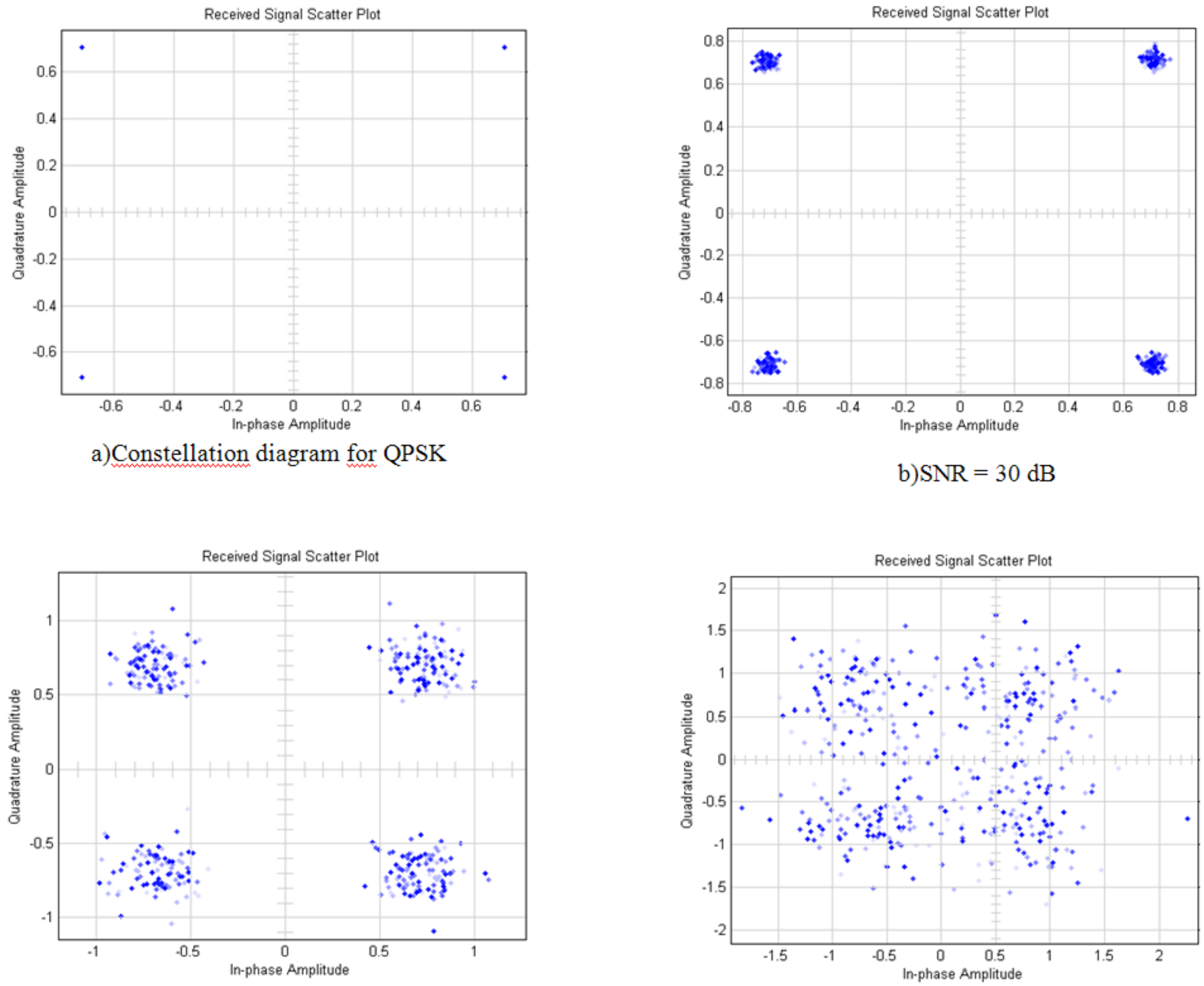


Fig. 11 Time for information transmission for 64-QAM



a)Constellation diagram for QPSK

b)SNR = 30 dB

c)SNR = 15 dB

b)SNR = 5 dB

Fig. 12 Effect of SNR on constellation diagram of OFDM modulation with QPSK

VIII. Simulation of the Interference Effect by QPSK and 64-QAM Using

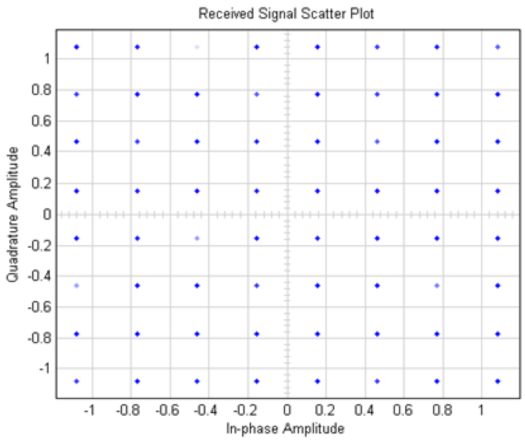
There is one of the possible ways to view the effect of interference. It is through constellation diagram. Therefore the effect of interference to the symbols is simulated in constellation diagram for different modulations. The other way to show possibilities OFDM is bit rate error showing as we can see in [10].

A. OFDM with QPSK

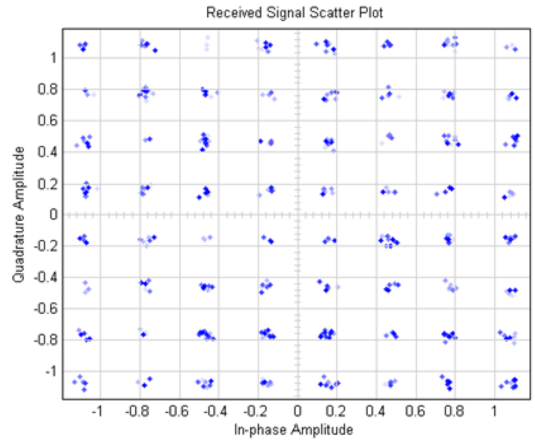
The basic symbol layout in constellation diagram and its behavior for the different levels of noise ratio (SNR) is shown in Fig. 12 for the OFDM with QPSK modulation. It can be seen that the more the distance of the signal/ noise ratio (SNR) is reduced the more the symbols are dispersed in the constellation diagram. It can be seen that the modulation is relatively resistant to interference from Fig. 12. It is due to using a smaller number of states which QPSK has.

B. OFDM with 64-QAM

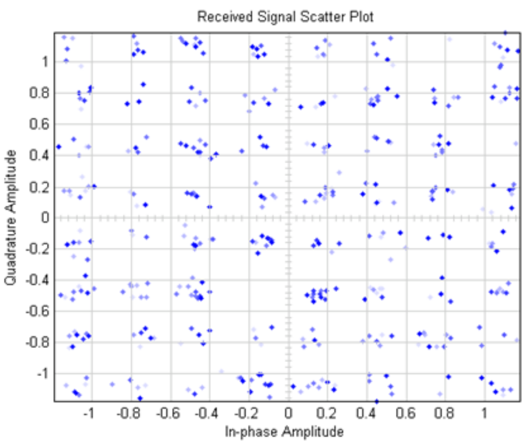
The basic symbol layout in constellation diagram and its behavior for the different levels of noise ratio (SNR) is shown in Fig. 13 for the OFDM with 64-QAM. It can be seen that the more the distance of the signal to noise ratio (SNR) is reduced the more the symbols are dispersed in the constellation diagram. It can be seen that the modulation 64-QAM is very



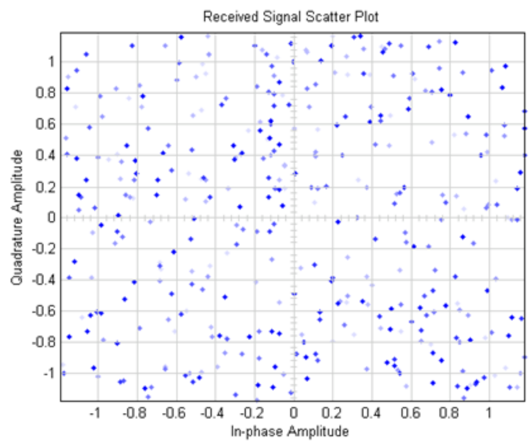
a)Constellation diagram for 64-QAM



b)SNR = 30 dB



c)SNR = 23 dB



b)SNR = 17 dB

Fig. 13 Effect of SNR on constellation diagram of OFDM modulation with 64-QAM

susceptible to interference from Fig. 13. It is due to using a large number of states which 64-QAM has.

IX. Conclusion

The progress in PLC technology has come about in the last decade. Remote data acquisition is now necessary because it is given by legal conditions. PLC technology is seem as an alternative data channel.

The article deals with design of the PLC communication system model. The model is composed of the OFDM communication model, the model of power lines and noise model.

The complex PLC communication model can be used for comparison of the performance of different modulation and coding schemes and for future standardization.

From the results of simulations it follows that an inappropriate choice of modulation and error correction coding can significantly affect the resulting signal.

The results of simulations based on the model will be compared with measurements in the future work.

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