IMPROVED LEAST SQUARE CHANNEL ESTIMATION ALGORITHM FOR OFDM BASED COMMUNICATION OVER POWER LINES

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ABSTRACT

As the low power electrical distribution network may be utilized for data transfer, it should be considered as a good candidate for "last mile solution". However, the power line medium strongly depends on its own characteristics (frequency selectivity, multi-path, and non-linearity) and on the environment (noise). The realization of a power line communication (PLC) system is performed with the coded Orthogonal Frequency Division Multiplexing (OFDM) modulation technique, because of its properties in adverse environment for signal transmission. To combat these harsh properties of power line medium (attenuation, phase errors and noise) and its impact on data transmission, improved Least Square (LS) channel estimation technique is typically used. The introduced channel estimation algorithm is based on the combination of comb- and block-type pilot sub-carrier arrangement, while the channel interpolation is done using linear and cubic spline interpolation. Further, the computer based simulation of PLC OFDM model is introduced and used to verify proposed channel estimation technique.

Keywords

Power Line Communication, Orthogonal Frequency Division Multiplexing, Channel Estimation, Channel Interpolation

1 INTRODUCTION

Broadband Power Line Communication (BPLC) has proved as a possible and cost-effective solution for miscellaneous broadband information technology such as high speed Internet access and broadband multimedia services. BPLC is the communication technology in evolution and it is still lagging behind in comparison with current leading access methods (digital subscriber line, cable television). On the other hand, the BPLC technology has the advantage of its accessibility, availability and existence of indoor electrical infrastructure; each wall outlet can be connection access point for Local Area Network (LAN).

The power line medium was not designed for data transmission. The negative properties of the channel are frequency-dependent attenuation, fading due to inadequate impedances of termination, and time-variant noise conditions. BPLC systems work in a frequency range up to 30 MHz to provide high data rate and can induce significant electromagnetic radiation [1], [2].

Orthogonal Frequency Division Multiplexing (OFDM) modulation technique is adopted in BPLC applications by most researchers. It is based on a form of multi-carrier systems. The transmission bandwidth is subdivided into parallel sub-channels and each sub-channel conveys the OFDM modulation orthogonal carrier. As the power line medium is characterized by multi-path properties and non-stationary behavior, it is possible that sub-carriers lose their orthogonality. In this case, the signal is distorted in the way that sub-carriers interfere with one another and result is known as Inter-Carrier Interference (ICI). In the case that the symbol duration is less than or equal to the maximum delay spread, Inter-Symbol Interference (ISI) phenomenon is introduced. To eliminate ISI and ICI phenomena, the guard time interval (GI) needs to be added and cyclically extended to each OFDM symbol.

Due to time-variant and frequency selective channel characteristic, the channel response has to be estimated correctly in order to get as much as possible error free data transmission at the receiver side. It requires the insertion of known symbols or pilot structure into the OFDM signal. The most popular and simplest technique for channel estimation is Least Square (LS). As the LS estimation can be realized both with block- and comb-type pilot arrangement [3]-[8], in this paper we introduce a combination of those two estimation techniques in order to combat erroneous data transmission over power line medium caused by noise, multi-path propagation, strong channel selectivity, and attenuation.

The rest of the paper is organized as follows. In Section 1, OFDM PLC system is described with the basic principles of OFDM. Section 2 presents basics of the broadband power line communications and the detailed description of power line channel. Low-complexity LS estimator and associated interpolation techniques are then presented. Also, the proposed LS channel estimation is introduced in Section 3. Simulation results are presented and discussed in Section 4. Section 5 concludes the paper.

2 OFDM PLC SYSTEM DESCRIPTION

In literature, coded OFDM with pilot channel estimation is highlighted as the most appropriate modulation technique for BPLC systems (Figure 1). The high-speed binary data, at the first step at the transmitter side, has been coded and interleaved. Afterwards, data is distributed in several parallel channels and mapped into adequate multi-amplitude-multi-phase signals.

4-QAM and 64-QAM modulations are considered in this paper. After modulation, the pilot symbols are inserted. Inverse Fast

Fourier Transform (IFFT) is performed on the modulated data in order to transform frequency-domain data, *X(k)*, on the *k-th* sub-carrier into time domain samples *x(n)* [8]:

$$x(n) = IDFT\{X(k)\} = \sum_{k=0}^{N-1} X(k) e^{j(2\pi kn/N)} \qquad n = 0,1,2,..,N-1 \tag{1}$$

where *N* is the Discrete Fourier transform (DFT) length.

At the end on the transmitter side, a protective guard interval and cyclic prefix are added in order to eliminate ISI and ICI in a linear dispersive channel. The resultant OFDM samples $x_t(n)$ can be expressed as follows:

$$x_t(n) = \begin{cases} x(N+n), & n = -N_g, -N_g+1, ..., -1 \\ x(n), & n = 0,1,2,...,N-1 \end{cases} \tag{2}$$

where N_g is the number of samples in the guard interval.

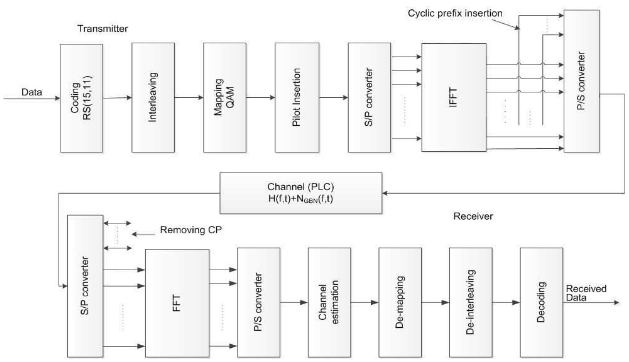

Figure 1. Model of pilot-based coded OFDM BPLC system

Further, the created OFDM signal is sent over BPLC multi-path fading channel and the propagated signal at the receiver side enters, given by:

$$y_r(n) = x_t(n) * h(n) + w(n) \tag{3}$$

where *h(n)* is the channel impulse response, *w(n)* is noise and * stands for the convolution operator. On the receiver side, guard interval should be removed from received signal $y_r(n)$ and signal *y(n)* should be de-multiplex with FFT using DFT processing:

$$Y(k) = DFT\{y(n)\} = \frac{1}{N}\sum_{n=0}^{N-1} y(n) e^{-j(2\pi kn/N)}, \qquad k = 0,1,2,..,N-1 \tag{4}$$

Next, we perform extraction of the received pilots $H_p(k)$ from *Y(k)* in order to obtain the channel transfer function *H(k)*. Using given channel transfer function, the transmitted data *X(k)* can be recovered by dividing the signal received *Y(k)* by the estimated channel transfer function:

$$X(k) = \frac{Y(k)}{H(k)}, \qquad k = 0,1,2,...,N-1 \tag{5}$$

The next step, before de-interleaving and decoding, is to de-map the recovered OFDM signal into the adequate OFDM time slot and sub-channel. The source binary information is reconstructed at the receiver side, as much as possible error free, after de-interleaving and decoding.

3 BROADBAND POWER LINE COMMUNICATION PROPERTIES

In the previous section, we described the mathematical specification of an OFDM system that is proposed as the most suitable for BPLC communication system. The system depicted on Figure 1 is composed of OFDM system, power line channel, and environmental noise [9]. For the mathematical description of the power line channel, there are several usable methods to specify the complex transfer function of power line channel that can be detected in literature. In this work, the two approaches are presented. The first one consists of considering the power line channel medium as a multi-path propagation environment [2], [9]-[11]. The second approach is based on modeling the transfer function of PLC by using the cascaded two-port networks model, also called ABCD matrix theory. This method represents the PLC channel by means of transmission matrices [12][13]. As the first approach is computational high cost at the high number of paths, the ABCD matrix theory of power line channel model is elaborated.

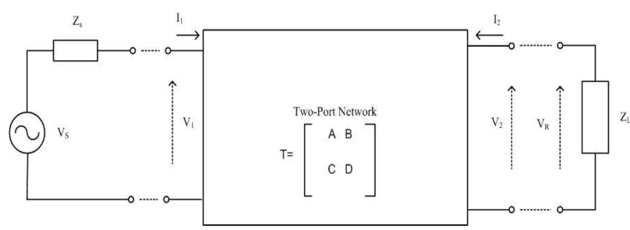

Figure 2. Two port network model

The most of the wired transmission structures can be described with Additive White Gaussian Noise (AWGN), in PLC systems the AWGN is just one component of the complex environmental noise. Generally, the noise in PLC systems can be sectionalized on three major classes: colored background noise, narrow band noise, and impulse noises [9],[14][15].

3.1 Power line channel model

The chain matrix theory (ABCD matrix theory) is used to model the power line channel. It is based on the two-port network model of a two-conductor transmission line [12][13]. A basic schematic representation is depicted on Figure 2. The relationship between the sending and receiving end of the two-port network, with the *A*, *B*, *C* and *D* as frequency dependent components, shown in Figure 2, can be written as:

$$\begin{vmatrix} V_1 \\ I_1 \end{vmatrix} = \begin{vmatrix} A & B \\ C & D \end{vmatrix} \begin{vmatrix} V_2 \\ I_2 \end{vmatrix} \tag{6}$$

For the transmission line with length *l* the transfer function, *H(f)*, can be defined as the output input signal ratio:

$$H(f) = \frac{V_R}{V_S} = \frac{Z_L}{A \cdot Z_L + B + C \cdot Z_S \cdot Z_L + D \cdot Z_S} \tag{7}$$

where $V_R=V_2=I_2Z_L$, $V_S= V_1+I_1Z_S$, Z_L, and Z_S are output signal, input signal, the receiver and transmitter impedances, respectively.

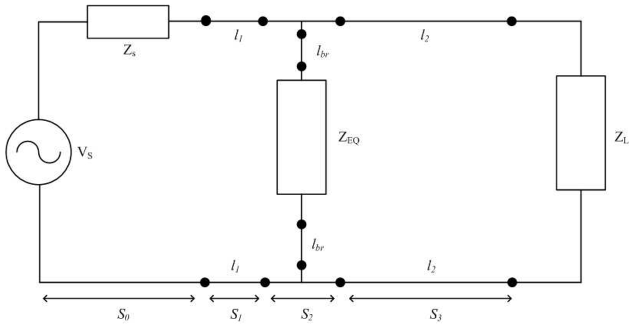

Figure 3. One bridge tap network model

Each additional tap with the equivalent impedance Z_{EQ} represent additional branch added in the network, as in Figure 3. The model is now divided in four serial network segments, defined as segments S_0, S_1, S_2 and S_3. For each segment the ABCD matrix can be calculated and the product of all calculated matrices defines the total system ABCD matrix.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \prod_{i=0}^{3} S_i = S_0 S_1 S_2 S_3 \tag{8}$$

The adding of each additional tap cause that the calculation of total system ABCD matrix becomes more complex as the number of taps increases. For the simulation purposes the following cable parameters are used: R=1.9884 Ω/m, G = 0.01686 nS/m, C= 0.13394 nF/m, L = 362.81 nH/m [12].

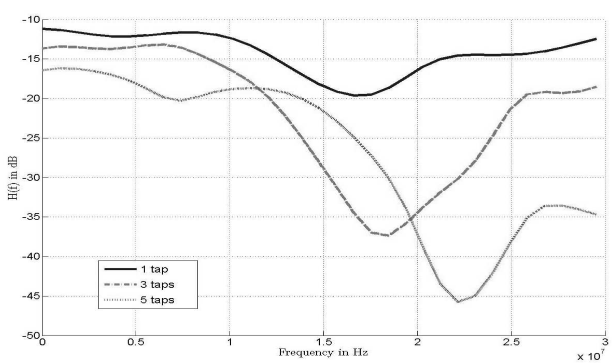

Figure 4. Transfer functions of the channel with different channel parameters and bridge tap length (parameters defined in [12])

3.2 Environmental Noise

PLC channels, in general, can be categorized as a hostile environment for data transmission. One of the crucial factors that cause signal distortions is additive environmental noise. The power-line noise can be described as a summation of miscellaneous classes of noises. First portion of the power-line noise is periodic impulse noise. It is generated by harmonics synchronous to the main network frequency of 50 Hz. The second portion is impulses generated by switching transients in the network, named asynchronous impulsive noise. The last entries are colored background and narrowband noise. Colored background noise can be defined as a superposition of noise with low power from multiple sources (9).

$$N_{CBN} = N_\infty + N_0 \cdot e^{-\frac{f}{f_0}} \tag{9}$$

Narrowband noise causes broadcast stations by broadcasting in short, middle and long wave broadcast bands (10).

$$N_{NB} = \sum_{i=1}^{N} A_i(t) \cdot \sin(2\pi f_i t + \varphi) \tag{10}$$

The power of colored background and narrowband noise, depending on signal propagation properties, is slowly varying in time. Additionally, the colored background noise shows a strong frequency dependency. For the simulation purposes, the colored background N_{CBN} and the narrowband noises N_{BN} were in focus in this work. The superposition of above mentioned noises can be introduced as Generalized Background Noise (GBN) (11) [9], [14]. The mathematical presentation of the generalized background noise can be defined through the power spectral density (PSD) function as summation of PSD functions N_{CBN} (9) and N_{BN} (10):

$$N_{GBN}(f) = N_{CBN}(f) + N_{NB}(f) \tag{11}$$

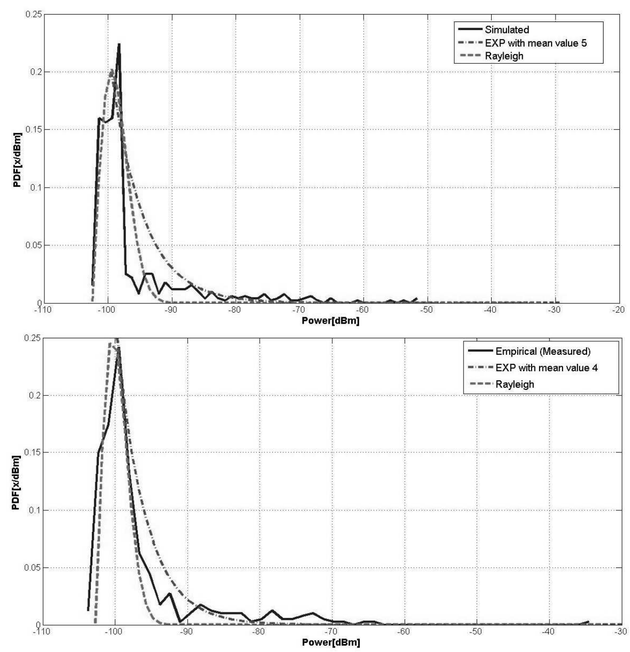

Figure 5. The generalized background noise – power spectral density of simulated and measured values [14]

Figure 5 shows the basic statistical analysis of measured and simulated data of the generalized background noise. In order to validate simulation given data the statistical analysis was obtained. The parallel statistical analysis of simulated and measurement data provide simulation usable GBN computer model.

4 PILOT ASSISTED CHANNEL ESTIMATION

Since the transmitted PLC signal is distorted on the input of receiver, a dynamic estimation of the channel is needed before de-modulation. Channel estimation can be performed by inserting known symbols (pilots) into the OFDM symbols [4]. There are two ways of inserting pilots into the signal. In the first one, the entire OFDM symbol is dedicated to carry pilot samples on all the sub-carriers for channel estimation, and it is sent periodically in the time-domain. Because the training block comprehend all sub-carrier frequencies, channel interpolation is not required. This method is known as block-type pilot arrangement and it is suitable for slow-fading channels. The second method of pilot insertion is comb-type pilot arrangement. In comb-type method pilot symbols are uniformly allocated in advanced defined sub-carriers in each OFDM block and repeated over multiple symbols. Channel estimation is performed at each symbol and interpolation is required to infer the channel frequency values of the non-pilot sub-carriers. When compared, comb- and block-type pilot arrangement, the comb-type method shows sensitivity to frequency selectivity and block-type is relatively insensitive to frequency selectivity [8].

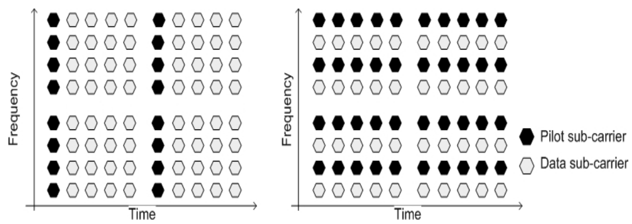

Figure 6. Block-type and Comb-type pilot arrangement

5 COMB-TYPE LS CHANNEL ESTIMATION AND INTERPOLATION TECHNIQUES

The signal at the input of the receiver side is given in (3). After removing CP, the data is serialized and FFT is performed. Now the signal can be written as:

$$Y(k) = X(k) \cdot H(k) + W(k) \tag{12}$$

where Y is the vector containing received pilots, X is a vector of original data from transmitter, H is a matrix of channel response of pilot sub-carriers and W is the vector of environmental noise. The procedure of the minimization of the square error of linear data model (12) and such given gradient equating with zero is resulting with the expression for LS estimator (13).

$$\begin{aligned} \left\|\varepsilon^2\right\| &= (Y - XH)(Y - XH)^H \\ \frac{\partial}{\partial H}\varepsilon^2 &= 2X^H Y - 2X^H XH = 0 \\ \hat{H}_{LS} &= (XX^H)^{-1} X^H Y \\ \hat{H}_{LS} &= X^{-1} Y \end{aligned} \tag{13}$$

where superscript H stands for the Hermitian transpose.
The next step is the interpolation in order to estimate the channel over all sub-carriers using channel information at the pilot-sub-carriers. Two varieties of interpolation will be presented: linear and spline cubic. Linear interpolation algorithm uses two consecutive sub-carrier pilots to determinate data sub-carriers situated between those sub-carrier pilots. Estimation of *k-th* data carrier, where $mL<k<(m+1)L$ is given by [8]:

$$\begin{aligned} \hat{H}(k) &= \hat{H}(mL+l) = \left(1-\frac{l}{L}\right)\hat{H}_p(m) + \frac{l}{L}\hat{H}_p(m+1) \\ &= \hat{H}_p(m) + \frac{l}{L}\left(\hat{H}_p(m+1) - \hat{H}_p(m)\right) \end{aligned} \tag{14}$$

for $0 \le l \le L$.
Spline cubic interpolation is based on the idea of fitting a series of unique cubic polynomials between each of the data points with the stipulation that the curve obtained be continuous and appear smooth. Approximation of each data sub-carrier is performed by using a third order polynomial on four adjacent pilot signals and their second order derivatives $z(m)$. The interpolation algorithm is given by [5]:

$$\hat{H}(k) = A\left(\frac{l}{L}\right)H_r(m) + B\left(\frac{l}{L}\right)H_r(m+1) + C\left(\frac{l}{L}\right)z(m) + D\left(\frac{l}{L}\right)z(m+1) \tag{15}$$

where $A(l/L)$, $B(l/L)$, $C(l/L)$ and $D(l/L)$ are constants determined by l/L.

6 PROPOSED PLC CHANNEL ESTIMATION

As the comb-type LS estimate of H is susceptible to noise, and the interpolation of channel is needed, we impose additional errors in channel transfer function. Those errors can influence the reconstruction of the source binary information at the receiver side. On the other side, block-type estimation gives whole channel transfer function, but it needs all sub-carriers. The main idea of proposed channel estimation algorithm is to combine comb-type and block-type channel estimation.

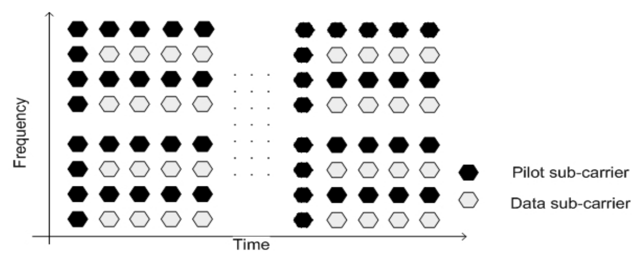

Figure 7. Proposed combined pilot arrangement

The algorithm presented in this work is realized by following. First, the block type pilot arrangement is sending, as the training sequence, first OFDM symbol (and further every *N-th* symbol), in such a manner the whole channel and noise conditions are captured at the desired OFDM symbol. Such given transfer function is proclaimed to be the help transfer function. The result of thus obtained channel transfer function H_{BT} will be stored in the additional receiver buffer. After every *N-th* symbol given help function is adding to stored H_{BT} and the average value is stored into the buffer. We avoid, in this way, possibly storing a strongly distorted transfer function and after some time interval we have the average channel condition. For that reason, receiver side requires additional M size buffer. After training sequence the conventional comb-type LS estimator with interpolation (either spline cubic or linear) according to (13) is used. H_{CB} is the result transfer function. The resulting comb-type estimation given transfer function, H_{CB} contours current state of the channel. The current noise condition can significantly distort pilot sub-carriers at a particular moment therefore the whole transfer function may take distorted values. Furthermore, the used interpolation technique also enters certain errors by interpolating the transfer function data. Our proposed solution for this possible estimation issue is that the stored H_{BT} improves a momentary obtained H_{CB} by the simple mean value between those two transfer functions for all OFDM symbols:

$$\hat{H}_{RES}(k) = \frac{\hat{H}_{BT}(k) + \hat{H}_{CB}(k)}{2}, k = 1,2,...,M \qquad (16)$$

where M represents a number of useful sub-carriers (DC, data, and pilot sub-carriers). The computational complexity of the proposed algorithm increases against conventional LS estimation by adding two averaging of given transfer functions - H_{BT} on every *N-th* and H_{RES} on every OFDM symbol. The hardware requirements rise as one additional M sized memory buffer is needed on the receiver side.

7 SIMULATION AND PERFORMANCE ANALISYS

The simulation goal is to compare the receiver Bit Error Rate (BER) performance towards Signal to Noise Ratio (SNR) for a conventional comb-type LS estimator and the proposed LS estimation algorithm. The influence of channel interpolation techniques and different channel characteristics (e.g., different channel topology, influence of environmental noise) on the proposed LS algorithm is investigated. Also, the correlation between interpolation technique and the number of pilot sub-carriers is explored. To evaluate the proposed channel estimation method, a framed-based Matlab and Simulink (ver.7.9.0) simulation is used [17]. The total transmission bandwidth simulation parameter is defined and its reach up to 30 MHz.

In the first simulation iteration, the correlation between the number of pilot sub-carriers and the interpolation method used in the LS estimation is investigated. As PLC channel simulation parameters, the 3 tap channel model with added environmental noise is used. Two cases are considered:

- The first one uses 4 pilot sub-carriers. FFT size is 64. Modulation is performed with the 4 QAM modulation techniques.
- The second one uses 6 pilot sub-carriers. FFT size is 128. Modulation is performed with the 64 QAM modulation techniques.

The linear and spline cubic interpolation techniques are simulated and compared on both models. The simulation that carried out the linear interpolation has slightly better performance results regardless of the number of pilots. Hence, using linear instead of spline cubic interpolation is more effective, because of its relatively simple implementation and better performance results in comparison with spline cubic interpolation method in this special case.

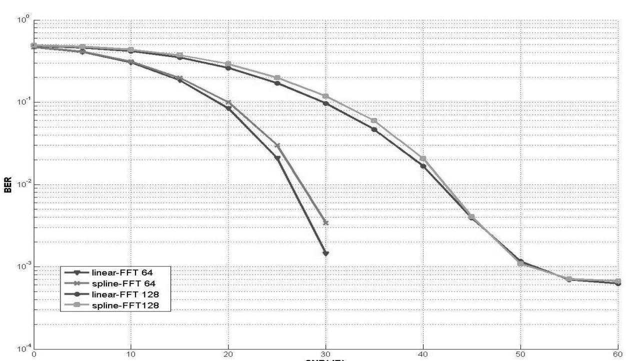

Figure 8. Interpolation methods comparison

Further, conventional LS estimation with proposed LS estimation algorithm are compared. Two possible scenarios are provided:

- The first one uses 30 data and 8 pilot sub-carriers. FFT size is 64. Modulation is performed with the 4 QAM modulation techniques.
- The second one uses 63 data and 15 pilot sub-carriers. FFT size is 128. Modulation is performed with the 64 QAM modulation techniques.

In both scenarios a cyclic prefix length of 1/8 of the FFT length is used. The PLC channel is modeled with 1, 3, and 5 bridge tap model (the model with 3 bridge taps is the default model). The channel attenuation is implemented as a digital filter. The filter coefficients are obtained from the transfer function (7) of the two port network (Figure 4). The next step is the addition of the environmental noise to the channel model in the form of generalized background noise (Figure 5) on the attenuated input signal. Simulations have carried out to show performance of conventional LS and proposed LS estimators in relation to channel conditions – channel attenuation caused by channel transfer function and additional environmental noise. Both interpolation methods were included in comparison in order to confirm results from first iteration of simulation. The benefits of the proposed channel estimation method with linear interpolation can be noticed in the decrease of the BER dependence of SNR for both models.

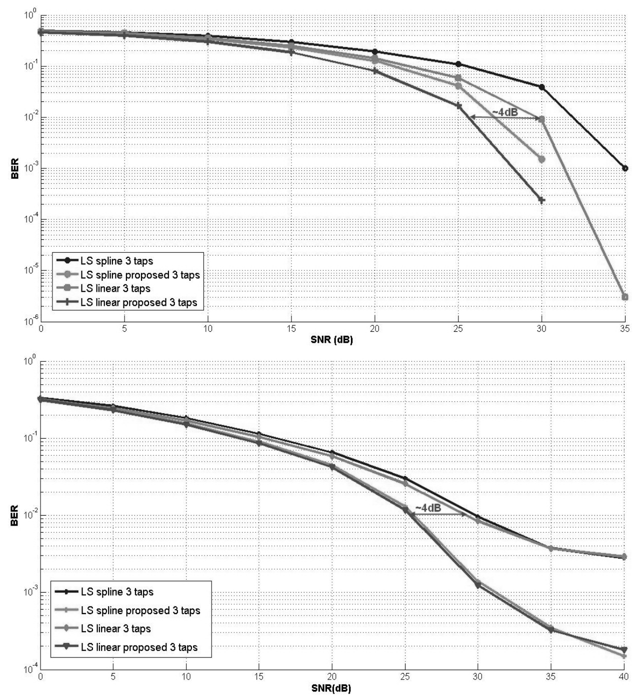

Figure 9. Comparison of interpolation methods for conventional and proposed LS estimator for 3 tap channel model: a) FFT 64, 4QAM; b) FFT 128, 64QAM

Simulation results depicted in Figure 9.a and Figure 9.b validate a better performance of linear over spline cubic interpolation for both models. Furthermore, if the desired BER is set to 10^{-2}, the SNR for proposed estimation technique with linear interpolation is about 4 dB lower in comparison with a conventional LS estimation. For the second model (FFT 128, 64 QAM) at the higher SNR environment this difference significantly increases, as can been seen in Figure 9.b.

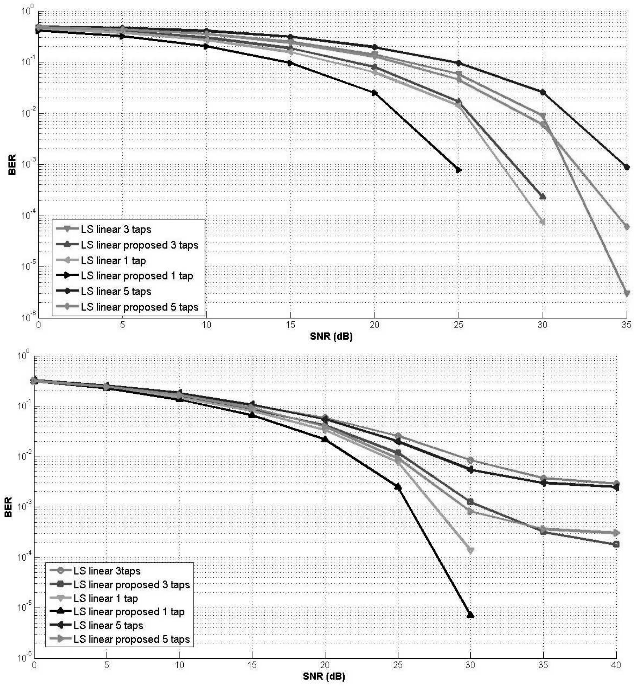

Figure 10. Comparison of conventional and proposed LS estimator for different channel models: a) FFT 64, 4QAM b) FFT 128, 64QAM

It has also been observed the influence of channel topology on the proposed estimation technique. Figure 10.a and Figure 10.b show the simulation results for different channel topologies. These results indicate better performance of the proposed against conventional LS estimation for all specified channel topologies. At SNR=30dB the improvement of BER is between 10^{-1} and $10^{-1.5}$, depending on the complexity of the channel topology. Moreover, for relatively simple channel complexities (1 and 3 tap for 64 FFT and 1 tap for 128 FFT) error free data transmission through PLC channel at SNR≥30dB can be achieved.

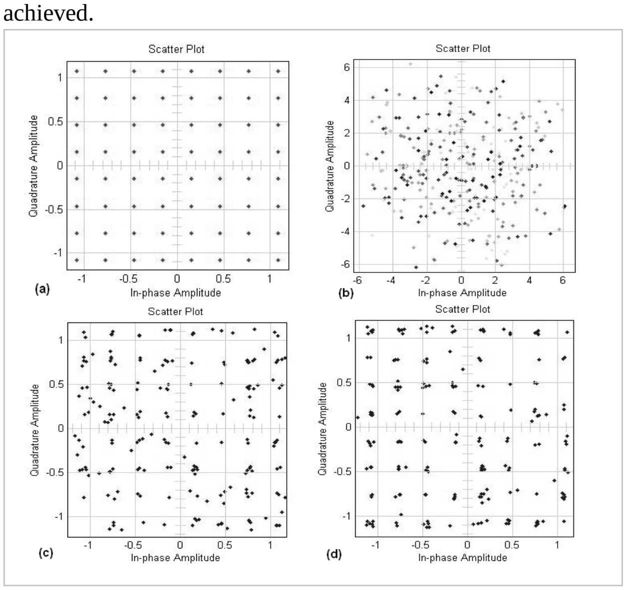

Figure 11. The comparison of constellations: a) Signal constellation at transmitter side; b) Constellation without channel estimation at receiver side; c) Constellation after conventional LS at receiver side; d) Constellation after proposed LS at receiver side

The proposed channel estimation algorithm can be applied in PLC LAN systems where the internal electrical infrastructure is not as complicated as in last-mile solutions. Those systems can build local PLC networks within houses or small offices. It can exist as a small independent network with possibility of connection to the outdoor area through the base station that controls whole in-home PLC network.

8 CONCLUSION

As the power-line communication channel is known as the harsh environment for data transmission, the conventional LS estimation algorithm in order to improve error correction on receiver side has been investigated. The main contribution of this paper is an improved LS estimation algorithm that decreases data transmission errors caused by amplitude and phase distortions in PLC channels. The proposed algorithm is based on the synergy of block- and comb-type pilot arrangement in LS channel estimation. It is a low-complexity algorithm that averages training block-type stored transfer function, known as a help transfer function, and a comb-type transfer function. In order to get a comb-type LS transfer function, linear and spline cubic interpolations are considered. Simulations show that the proposed LS channel estimation algorithm gives better performance in the form of BER and OFDM symbol constellation diagrams from the conventional LS channel estimation algorithm. Moreover, the comparison of linear and spline cubic interpolation shows that the linear interpolation is a slightly better choice for the interpolation technique in the presented PLC environment.

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Biographies

Mario Bogdanović was born in Osijek, Croatia, in 1978. In 2004 he received the B.Sc. in Electrical Engineering (Telecommunications) from the Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia. From 2004 he has been working at Siemens Convergence Creators (former Siemens) in Zagreb and Osijek as Senior Software Developer. He is now a PhD Candidate in the Faculty of Electrical Engineering and Computing, University of Zagreb. His main research interest includes broadband PLC systems and OFDM channel estimation techniques.

Alen Bažant received B.Sc., M.Sc. and Ph.D. in Electrical Engineering in 1985, 1990 and 1998 respectively from the Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia. Mr. Bažant was first employed at the Faculty of Electrical Engineering and Computing (FER) (January 1987) as the assistant, Department of Telecommunications. In 1989 joined Nikola Tesla (presently Ericsson Nikola Tesla) in Zagreb. Upon receiving masters degree stayed shortly with the Croatian Telecomm (former HPT) and then returned to FER as a teaching and research assistant. In 1993 he was employed with two companies in Zagreb, Optima O.S.N. and TIS d.d. His job in both companies was related to software engineering. In 1994 returned to FER and started working on his Ph.D. During 1995 and 1996 spent six months in Ericsson New Zealand (Wellington) working on the mobile telephony. In May 1996 returned to FER. Since 2005 he has been an associate professor. He is a co-author of one textbook. Mr. Bažant's research interests are in transmission media characteristics and analyses, modulations and line coding, in multiple access technologies used in access and local area networks and in technologies related to the lowest two layers of OSI reference model.