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Frequency domain based LS channel estimation in OFDM based Power line communications

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Original scientific paper

This paper is focused on low voltage power line communication (PLC) realization with an emphasis on channel estimation techniques. The Orthogonal Frequency Division Multiplexing (OFDM) scheme is preferred technology in PLC systems because of its effective combat with frequency selective fading properties of PLC channel. As the channel estimation is one of the crucial problems in OFDM based PLC system because of a problematic area of PLC signal attenuation and interference, the improved LS estimation technique is proposed. We investigate and evaluate proposed frequency domain LS channel estimation method for OFDM based power line communication system. Also performance comparing with existing pilot based estimation algorithms towards proposed method in terms of their computational complexity, error correction, and suitability conditions is made.

Key words: Power Line Communication, OFDM, Channel Estimation, Least Squares estimation, Linear Minimum Mean-square Error estimation

LS estimacija kanala u frekvencijskoj domeni u OFDM baziranim komunikacijama preko strujnih vodova. Ovaj rad je fokusiran na realizaciju komunikacije preko vodova niskonaponske mreže s naglaskom na tehnike procjene prijenosnog kanala. OFDM schema je preferirana prijenosna tehnologija u PLC sustavima zbog svoje učinkovitosti u borbi s osobinom selektivnog frekvencijskog iščezavanja signala kod PLC kanala. Kako je procjena kanala jedan od najvažnijih problema u OFDM baziranom PLC sustavu zbog problematičnog područja gušenja i interferencije PLC signala, predstavljena je poboljšana tehnika LS procjene kanala. Istražili smo te evaluirali predstavljenu metodu LS procjene kanala u frekvencijskoj domeni za PLC sustave bazirane na OFDM modulacijskoj tehnici. Također je napravljena usporedba karakteristika predložene metode s poznatim algoritmima procjene kanala uz pomoć znanih simbola (pilota) u području njihove računalne složenosti, ispravljanja grešaka te uvjetima prilagođavanja.

Ključne riječi: komunikacija strujnim vodovima, OFDM, procjena prijenosnog kanala, procjena metodom najmanjih kvadrata, procjena metodom linearne srednje kvadratne pogreške

1 INTRODUCTION

The electric power supply network infrastructure is covering most parts of the inhabited areas. The growing telecommunication market provides the possibility of using electric power system for a possible pay out market solution for advanced information technology such as high speed data transmission, real-time video, voice connections, and High-definition television (HDTV). The PLC technology has advantages in accessibility and the existing infrastructure. On the other hand, the power line medium was not designed for high frequency data transmission. Frequency-dependent attenuation, changing impedance, fading and noise conditions varying in time are the negative properties of the PLC transmission channel. So, it is important to select adequately the modulation technique to achieve high speed data transmission in PLC channel.

Frequency selectivity of PLC channel is caused by multipath propagation, due to different impedances of terminations of power line [1, 2]. The OFDM has been receiving growing interest in recent years due to effective combat with frequency selective PLC channels. The majority of the researches in the literature recommend OFDM as a relevant solution because of its excellent bandwidth efficiency needed for high speed data transmission. OFDM is multi-carrier based system and it is originated on prorated transmission bandwidth into parallel sub-channels with orthogonal carriers, which is an adequate solution in the case of inter-symbol interference (ISI), signal fading, channel noise, etc.

Further, channel estimation plays important role in OFDM systems and it can be used for enhancement of the system performance in terms of bit error rate (BER) [3, 4]. For the purpose of estimation, insertion of known symbols or pilots in the OFDM signal is required and thereby channel frequency response can be estimated. The most used algorithms for channel estimation are based on the least squares (LS) supported by linear and cubic interpolation and the linear minimum mean-square error (LMMSE) approaches.

The rest of the paper is organized as follows. In Section 2, proposed model based on coded OFDM is presented. The proposed power line channel model and environmental noise are presented in Section 3. In Section 4, the basic comb-type LS and block-type LMMSE channel estimation algorithms is reviewed. The proposed comb-type LS estimation algorithm with its computational complexity is carried out in Section 5. Simulation results are presented and discussed in Section 6. The paper finishes with discussion and the conclusion in Section 7.

2 OFDM BASED PLC SYSTEM MODEL

Multi-carrier transmission techniques are based on the idea of dividing the overall bandwidth into many sub-channels with its own assigned carrier. With this solution it can be obtained almost ideal propagation properties for all data flows even if the overall channel is characterized by coloured noise and frequency selectivity. OFDM technique can be considered as an evolution of multi-carrier techniques: it is characterized by very high spectral efficiency thanks to orthogonal sub-carriers utilization; sub-carriers orthogonality condition is guaranteed if frequency spacing is equal to inverse of OFDM symbol duration. The orthogonality guaranties that streams do not interfere with one another and multi-channel transmission provide elimination of inter-symbol interference (ISI) and inter-carrier interference (ICI) phenomena.

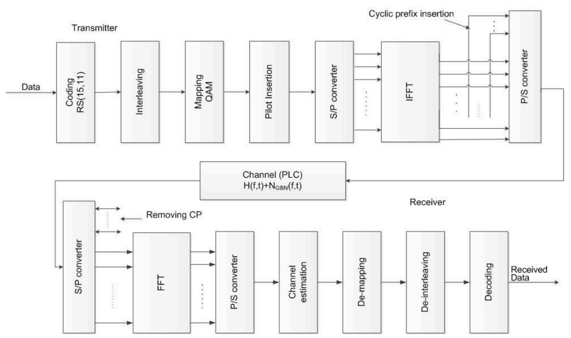

Figure 1. PLC OFDM model

OFDM modulation splits a high data stream into a number of lower rate streams and those streams are transmitted in parallel with lower bandwidth over a number of orthogonal sub-carriers which are distributed in a frequency spectrum. The selection of relevant number of sub-carriers ensures to have low-rate parallel data streams in each sub-channel such that all of them will be ISI free. To avoid ISI almost completely, a guard time interval needs to be added to each OFDM symbol. The guard time interval needs to be longer than the delay spread of the overall channel. Also, in the guard time, the OFDM symbol should be cyclically extended in order to avoid ICI.

Basic principle of coded OFDM with pilot channel estimation is following (Fig. 1). The high-speed binary data, at 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. The next step is insertion of known symbols (pilots) on the predetermined position in order to perform correct channel estimation. Further, transformation of modulated data X_k from frequency into time domain data is done by IFFT [5] using IDFT (Inverse Discrete Fourier Transform):

$$x_t(n) = \frac{1}{N} \sum_{k=-N/2+1}^{N/2} X_k \cdot e^{j2\pi nk/N}, n = -N_g, ..., N-1 \quad (1)$$

where N is the number of total sub-carriers and $x_t(n)$ is time-domain sample. At the end of the transmitter side, protective guard interval and cyclic prefix are added. Such created OFDM signal is sent over PLC multipath fading channel. At the receiver side, the propagated signal is given as:

$$y(n) = x_t(n) \otimes h(n) + w(n) \quad (2)$$

where $h(n)$ is the power line channel impulse response, $w(n)$ is noise and $\otimes$ stands for convolution operator. After the cyclic prefix is removed, received signal is sent to the FFT block to de-multiplex using DFT (Discrete Fourier Transform):

$$Y(k) = \frac{1}{N} \sum_{n=0}^{N-1} y(n) e^{-j2\pi kn/N}, k = 0, 1, 2, ..., N-1 \quad (3)$$

The pilots $H_p(k)$ are extracted from the de-multiplexed signal in order to obtain the channel transfer function $H(k)$. The transfer function $H(k)$ is further used for recovering of the distorted transmitted data.

$$X(k) = \frac{Y(k)}{H(k)}, k = 0, 1, 2, ..., N-1 \quad (4)$$

De-mapping of recovered OFDM signal into the adequate OFDM sub-channel is carried out. The two last operations are de-interleaving and decoding, realized in order to get, as much as possible error free, reconstructed source binary information at the receiver side.

3 POWER LINE CHANNEL CHARACTERISTICS

Creating suitable channel model is essential parameter for modeling any communication system. In the literature different power line channel models can be found. Several approaches are emphasizing as widely spread and rather developed so the focus is put on those two, further stated. The first one is based on methods for radio channel modeling and the power line channel is categorized as a multipath propagation environment [1]. The above mentioned method is applied as the mathematical description and the simulation model of power line channel. Second one is based on methods used to model long electricity distribution networks. This method models transfer function of power line channel using chain matrix theory (ABCD matrix theory) [6].

3.1 Multipath Signal Propagation Model

The power line medium is time varying and unstable transmission medium. It is considerably dependent on network topology, cable branches and impedance mismatch. Because of those physical properties, a multipath scenario with frequency selective fading is considered. Mathematical model of transfer function (known as *Zimmerman and Dostert model*) can be defined as [2, 7]:

$$\underline{H}(f) = \sum_{i=1}^{N} \underbrace{|g_i(f)|\, e^{\varphi_{g_i}(f)}}_{\substack{weighting\\ factor}} \cdot \underbrace{e^{-(a_0+a_1 f^k) d_i}}_{\substack{attenuation\\ portion}} \cdot \underbrace{e^{-j2\pi f \tau_i}}_{\substack{delay\\ portion}} \quad (5)$$

Equation (5) describes signal propagation with the low-pass characteristic and the delay portion. Each path is characterized by a weighting factor g_i which is the sum of transmission and reflection factors with path length d_i. The attenuation factor is modelled by the parameters a_0, a_1 and k obtained from measurements.

3.2 The generalized background noise

The important factor in the PLC model is environmental noise which can be categorized in following [7]:

1. coloured background noise
2. narrowband noise
3. periodic impulsive noise
4. non-periodic impulsive noise

In this work focus is put on generalized background noise W_{GBN} which is a superposition of the coloured background and narrowband noise (6). Those two noises are caused by a superposition of multiple sources of noise with low power and broadcasting in short, middle and long wave ranges, respectively [8]. Given results obtained from measurements in the office building in Osijek city center are statistically processed. The final result is a probability density function (PDF) for the noise power. It shows that measured data fits in between exponential and Rayleigh distribution [9]. Thus, such given statistical model is further used to create appropriate W_{GBN} model as a part of complete PLC simulation system.

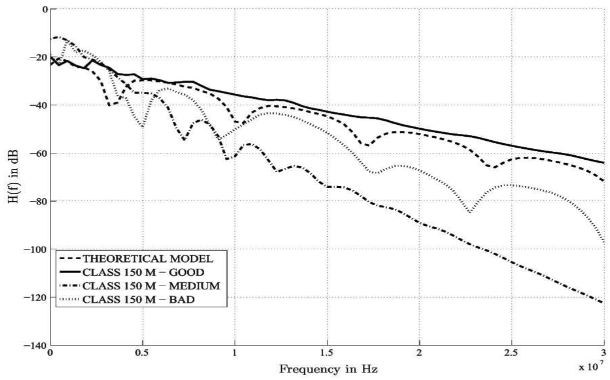

Figure 2. Frequency response of power line channel (parameters defined in [7])

$$\begin{aligned} W_{GBN}(f) &= W_{CBN}(f) + W_{NB}(f) \\ W_{CBN}(f) &= W_{\infty} + W_0 \cdot e^{-\frac{f}{f_0}} \\ W_{NB}(f) &= \textstyle\sum_{i=1}^{N} A_i(t)\sin(2\pi f_i t + \varphi) \end{aligned} \quad (6)$$

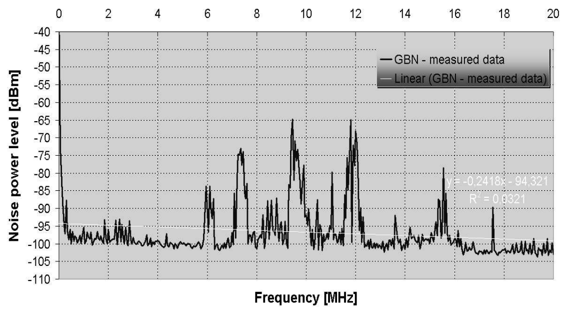

Figure 3. Measured PLC generalized background noise (0-20 MHz)

4 PILOT BASED CHANNEL ESTIMATION ALGORITHMS

Channel estimation has a great importance in power line communication system. As the PLC transmission channel is very hostile environment for data transmission, transmitted information suffers from amplitude scaling and phase rotation. Channel estimation can be obtained with help of inserted pilots into the OFDM symbols. There are two wide spread methods of inserting pilots into the signal [10]. First one dedicates entire OFDM symbol to carry pilot samples on the all the sub-carriers for channel estimation. This kind of pilot arrangement is called the block-type and it is suitable for slow-fading channels. Pilots are sent periodically in the time domain. As the training block contains all frequencies, channel interpolation is not required. Comb-type pilot arrangement is the second method of pilot insertion. In comb-type method pilot symbols are uniformly spread on selected 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.

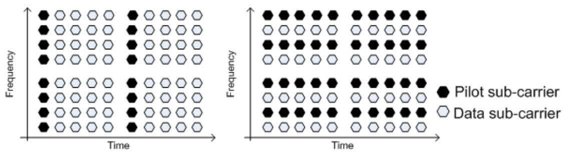

Figure 4. Block-type and Comb-type pilot arrangements

4.1 Comb-type LS Channel estimation

The relationship between transmitted signals X_k and received signal Y_k can be defined as:

$$Y^i(k) = H_k X_k^i + W_k, k \in (0, M-1) \quad (7)$$

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. Using known transmitted pilot symbols (X_p) and received symbols (Y_p) at predefined pilot sub-carriers, the raw channel estimate (H_{LS}) at pilot sub-carriers can be calculated as:

$$H_{LS} = \frac{Y_p}{X_p} \quad (8)$$

In order to estimate channel over all sub-carriers using channel information at the pilot-sub-carriers, the channel interpolation is needed. The following interpolation methods can be applied:

1. Linear Interpolation
2. Spline Interpolation
3. Cubic Interpolation
4. Low pass Interpolation

Phase errors caused by frame synchronization have high impact on channel estimation, particularly on interpolation methods. This error comes from a group delay of the received OFDM signal before de-multiplexing and consequently causes higher distortion at the estimated channel in comb-type systems. A simplified method of phase recovery can be applied to linear and polynomial interpolators and the change in phase $\tilde{\varphi}_p$ can be expressed as [11]:

$$\tilde{\varphi}_p = \angle \frac{1}{N_c - 1} \sum_{m=0}^{N_p-2} \tilde{H}_{LS}^*(m) \tilde{H}_{LS}(m+1) \quad (9)$$

where N_c and N_p are total number and number of pilot subcarries, respectively. The pre-compensation of the LS estimation can be performed as

$$\tilde{H}_{LS,pe}(m) = \tilde{H}_{LS}(m) \exp(j\tilde{\varphi}_p m) \quad (10)$$

where *pe* denotes phase estimation.

4.2 Block-type LMMSE channel estimation

This method of channel estimation uses second order statistic of the channel conditions to minimize mean square error. Relation between transmitted signal X_k and received signal Y_k is already stated in (7). LS estimator can be derived from the minimization of the square error of linear data model:

$$\left\|\varepsilon^2\right\| = (Y - XH)(Y - XH)^H \quad (11)$$

where superscript H stands for Hermitian transpose. The gradient is defined and equals zero:

$$\begin{aligned} &\tfrac{\partial}{\partial H}\varepsilon^2 = 2X^H Y - 2X^H X H = 0 \\ &\hat{H}_{LS} = (XX^H)^{-1} X^H Y \\ &\hat{H}_{LS} = X^{-1} Y \end{aligned} \quad (12)$$

Minimum Mean Square Error (MMSE) channel estimation has an excellent performance in suppression of noise and ICI, but it requires the high complexity of hardware implementation and information about channel and noise power level is needed [4]. Let us denote the error of channel estimation *e* as:

$$e = H - \hat{H} \quad (13)$$

where H is actual channel estimation and $\hat{H}$ is raw channel estimation, respectively. Minimum square error of channel is defined as:

$$\begin{aligned} E\left\{|e|^2\right\} &= E\left\{\left|H - \hat{H}\right|^2\right\} \\ &= E\left\{(H - \hat{H})(H - \hat{H})^H\right\} \end{aligned} \quad (14)$$

where *E{}* is the expectation. We can rewrite (14) as:

$$\hat{H}_{MMSE} = R_{HY} R_{YY}^{-1} Y \quad (15)$$

where R_{HH} and R_{YY} are the auto-covariance matrixes of *H* and *Y*, respectively. The cross covariance matrix between *H* and *Y* is defined as R_{HY}. Due to high complexity of MMSE estimation, Linear MMSE (LMMSE) channel estimator is widely used in communications [12, 13]. Using Singular Value Decomposition (SVD) is the core principle to find optimum low-level LMMSE estimator. The LMMSE estimation of channel response with σ_W^2 as variance of *W(k)* can be described as:

$$\hat{H}_{LMMSE} = R_{HH}(R_{HH}+\sigma_W^2(X^H X)^{-1})^{-1}\hat{H}_{LS} \quad (16)$$

As the defined channel estimator need to get matrix inversion every time the training data in *X* changes. Therefore we reduce the complexity by replace the $(X^H X)^{-1}$ by its expectation $E\left\{(X^H X)^{-1}\right\}$, which means the average power of all sub-carriers replace the instantaneous power of each sub-carrier in order to reduce the computation. Now the LMMSE channel estimator can be represented as [13]:

$$\hat{H}_{LMMSE} = R_{HH}(R_{HH} + \frac{\beta}{SNR} I)^{-1}\hat{H}_{LS} \quad (17)$$

where β is constant depending on the type of modulation, *SNR* is signal-to-noise ratio and *I* is the identity matrix. For example, when 64 QAM is used the β is 2.6854. After the estimation is performed and interpolated (in LS case), the phase should be restored (10) by multiplying the output by $\exp(-j\tilde{\varphi}_p m)$.

5 PROPOSED PLC CHANNEL ESTIMATION

LS estimator is the simplest estimator whose performance is quite general and LMMSE is more complex and it has been successfully applied in wireless communications. As the PLC channel has different properties from radio environment, the environmental noise and channel characteristics is time-variant through the day, a useful and simple channel estimation algorithm is important. The derived LMMSE estimator requires knowledge of the channel frequency correlation and the present *SNR*. In the case of fixed *SNR* and R_{HH}, the matrix inversion (17) can be calculated only once reducing complexity. This method causes significantly degradation of the estimator performance [10, 14] because of PLC channel *SNR* and R_{HH} are unknown in advance and time varying. Hence, the matrix inversion should be calculated for each estimation OFDM block and therefore increases estimator complexity and processing time. The proposed LS estimator is not based on statistical properties of the channel which reduces estimation complexity.

As we mentioned the comb-type LS estimate of transfer function *H* is susceptible to noise. Because the interpolation of channel is needed, we impose additional errors in channel transfer function. On the other side, block-type estimation gives whole channel transfer function at the given moment, but it needs all sub-carriers.

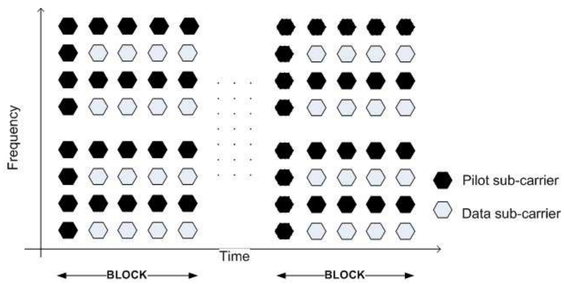

Figure 5. Proposed pilot arrangement

The main idea of proposed LS channel estimation algorithm is to combine features from comb-type and block-type channel estimation to get simple and effective estimator. The selected features should be suitable for combat with specific, especially time varying, PLC channel properties (Fig. 5). With the help of block-type estimation, the whole channel and noise condition at the desired OFDM symbol can be determined. It is performed by sending all pilot sub-carriers as the training sequence at first OFDM symbol (and further every L_B*-th* symbol). On this way the help transfer function is generated and the result of thus obtained channel transfer function H_{BT} will be stored in the receiver buffer. To avoid possibly storing a strongly distorted transfer function as a possible result of a noise effect, each following help function is adding to stored H_{BT} and the average value is stored into the buffer. After certain time interval buffer should contain the average channel condition for further utilizing.

After training sequence conventional comb-type LS estimator with interpolation is used (either spline cubic or linear) according to (8) and the result is H_{CT} transfer function that contours current state of the channel, especially noise condition. The proposed solution uses simple mean value between above defined two transfer functions to improve the stored H_{BT} by momentary obtained H_{CT}:

$$\hat{H}_{RES}(k) = \frac{\hat{H}_{BT} + \hat{H}_{CT}(k)}{2}, k = 1, 2, ..., M \quad (18)$$

where *M* represents a number of useful sub-carriers (DC, data, and pilot sub-carriers).

Concerning the increase of computational complexity of the proposed algorithm against conventional LS estimation, the complexity is increasing with two additional averaging of given transfer functions - H_{BT} on every L_B*-th*

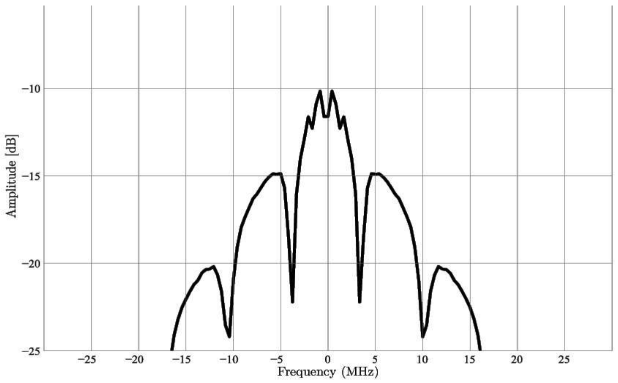

Figure 6. Theoretical channel transfer function at SNR=30dB

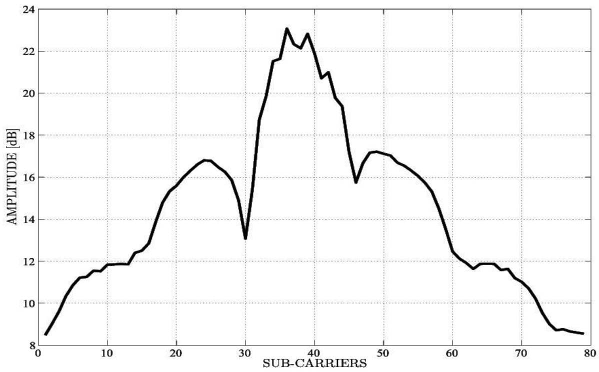

Figure 7. Proposed LS estimated channel transfer function at SNR=30dB

and H_{RES} on every symbol. Also hardware requirements at the receiver side rise as one additional *M* sized buffer is needed.

The bandwidth efficiency η of proposed LS estimation algorithm can be defined as number of pilot and number of data sub-carriers ratio in one estimation block (19). The L_B is the number of OFDM symbols, L_{pilots} is the number of pilots, L_{sc} is the number of sub-carriers and L_{data} is the number of useful data in one estimation block (Fig. 5). The estimation block is defined as a group of one training sequence and L_B*-1* conventional LS OFDM symbols.

$$\eta = \frac{L_{sc} + [L_{pilots} \cdot (L_B - 1)]}{L_{data}(L_B - 1)} \qquad (19)$$

As the proposed algorithm consumes additional bandwidth for channel estimation, the optimal size of one estimation block is needed to minimize the loss in total transmission capacity and to achieve the bandwidth efficiency of conventional LS estimator.

6 SIMULATION RESULTS

The simulation goal is to compare functional dependence of *BER* (bit error rate) towards *SNR* (Signal to Noise Ratio) for conventional comb-type LS estimator, block-type LMMSE, and proposed LS estimation algorithm. The influence of different channel characteristics (e.g., different channel topology, influence of environmental noise) on the proposed LS algorithm is investigated and performed. Also the bandwidth efficiency of proposed LS estimation algorithm against the conventional comb-type LS estimator is carried out. The introduced channel estimation method is evaluated using a framed-based Matlab and Simulink (ver.7.9.0) simulation with the total transmission bandwidth up to 30 MHz. The testing scenario of OFDM system model with 63 data and 15 pilot sub-carriers is applied. The transmission bandwidth is divided into 128 sub-channels by using 128 FFT. The size of one estimation block L_B is set on 350 OFDM symbols. Modulation is performed with 64 QAM modulation technique. Cyclic prefix length is 1/8 of the FFT length. The PLC channel is modelled as *Zimmerman and Dostert* model with various channel characteristics as depicted on Fig. 2. The channel is implemented as a digital filter and attenuates the input signal according to a transfer function. The filter coefficients are obtained from the transfer function (5) in the range from 0 to 30 MHz. The addition of environmental noise in the form of generalized background noise (Fig. 3) to attenuated input signal is performed.

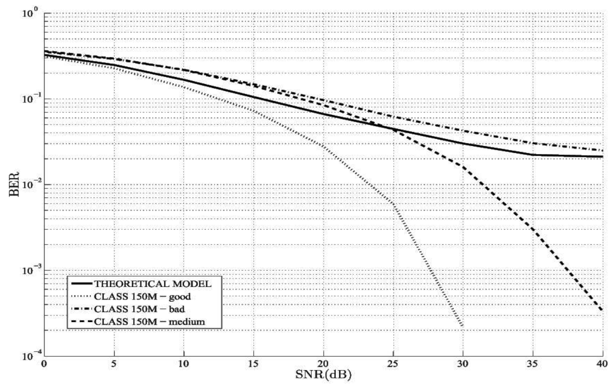

Figure 8. Proposed LS estimator for various channel topology (channel parameters defined in [7])

In first simulation set, the proposed LS estimation technique in various channel conditions defined through several channel topologies and additional environmental noise is performed. Simulation results depicted on Fig. 8 shows that proposed LS channel estimator performance strongly depends on channel condition and topology.

Further, the carried out simulation introduce performance of proposed LS estimator against conventional comb-type LS and block-type LMMSE channel estimators for the same set of the channel topologies. Comb-type estimators use linear interpolation, because foregoing research articles reference better performance linear over spline cubic interpolation.

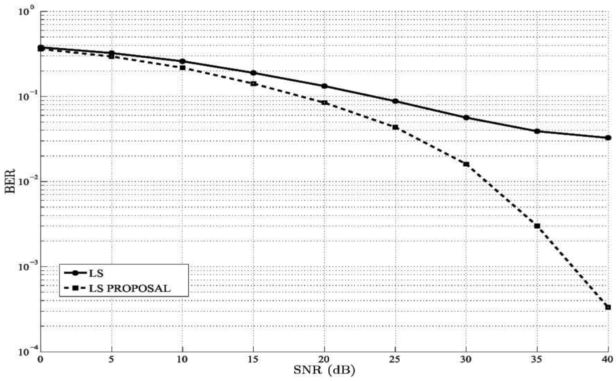

Figure 9. Comparison of conventional LS and proposed LS channel estimation for channel model class 150 medium (Fig. 2)

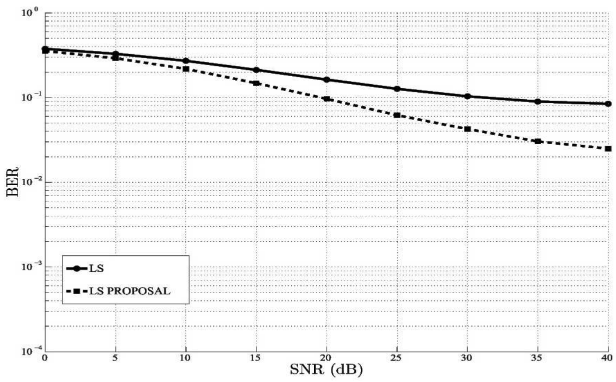

Figure 10. Comparison of conventional LS and proposed LS channel estimation for channel model class 150 bad (Fig. 2)

Figure 9, Fig. 10, and Fig. 11 show better performance of the proposed LS estimator against conventional LS estimator for all three cases of different channel properties. The enhancement of the proposed LS estimator against regular comb-type LS estimator rises proportional as the number and length of branches in channel decreases and the channel became less frequency-selective. At SNR=30dB the improvement of *BER* is $10^{-0.5}$ for *bad* channel properties and $10^{-1.5}$ for *good* channel properties. Moreover, for relatively simple channel complexity the performance of proposed LS estimator is good as LMMSE channel estimator performance (Fig. 11). Also in this case error free data transmission through PLC channel at SNR≥30dB can be achieved. The possible usage of proposed estimator is in PLC LAN systems for *in-home* or *small office* networking, where the internal electrical infrastructure is not as complicated as in *last-mile* solutions and can exist as an independent network.

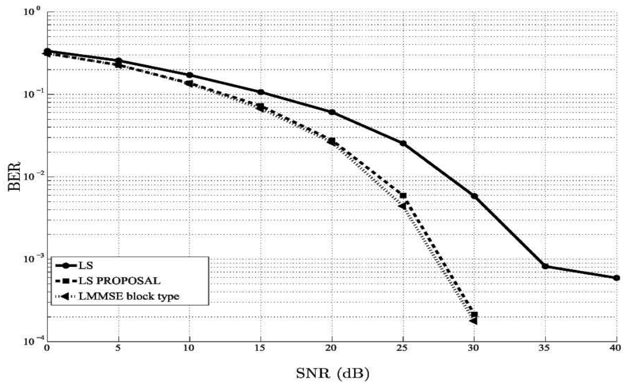

Figure 11. Comparison of conventional LS, proposed LS, and LMMSE channel estimation for channel model class 150 good (Fig. 2)

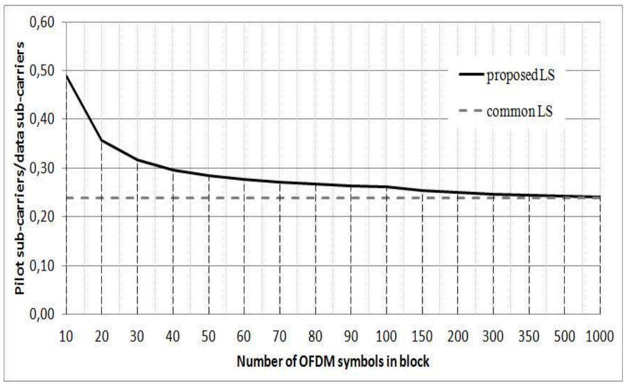

Figure 12. The bandwidth efficiency of proposed LS estimation algorithm

The bandwidth efficiency is investigated in correlation with the size of estimation block (Fig. 12). For the simulation properties the efficiency of conventional comb-type LS estimation is 15/63 ≈ 0.24. The efficiency of proposed estimation algorithm (19) is dependent on number of OFDM symbols in one estimation block. Fig. 12 outline that with L_B=40 the efficiency of proposed algorithm is below 0.3. The efficiency asymptotically approaches to 0.24 and reaches the value of conventional comb-type LS estimation with L_B=350.

7 CONCLUSION

The PLC channel denotes multipath propagation, strong channel selectivity, attenuation, and environmental noise. All those time-variant properties negatively affect the data transmission over power line communication channel. One of the methods to combat those negative properties is to develop adequately estimation algorithm to decrease data transmission errors.

In this paper, the effects of the channel estimation in PLC system using OFDM approach have been studied. One frequency (LS) and one time (LMMSE) domain channel estimation algorithm have been considered. Also one frequency domain based channel estimation algorithm is proposed. The proposed algorithm is combination of block- and comb-type pilot arrangement in LS channel estimation. It averages long time channel condition by block-type estimation and gets real time channel condition using comb-type estimation with associated interpolation method.

The simulation results bring that proposed LS estimation algorithm gives better performance in the form of BER from the conventional LS channel estimation algorithm. Also in the case of relatively simple channel complexity proposed algorithm shows almost same BER performance as more complex LMMSE algorithm and stands as good candidate to substitute complex LMMSE algorithm for PLC LAN systems for in-home and small office network solutions.

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