Channel estimation in OFDM power line communication based on pilots and particle filtering

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Abstract: Aiming at the nonlinear, non Gaussian and time-varying characteristics of power line channel, a comb-type pilot arrangement channel estimation scheme combined PF algorithm and linear interpolation method is proposed. In the proposed scheme, firstly the indoor power line channel has measured using the pseudo-noise (PN) correlation method, and an autoregressive (AR) model has set up to describe the measured channel. Then, channel estimation for the measured channel at the pilot frequencies is exploited PF algorithm, while at the data frequencies is obtained by linear interpolation method. Furthermore, the performances of channel estimation schemes respectively based on least square (LS), kalman filtering (KF), unscented Kalman filtering (UKF) and PF algorithm have been compared. Simulations have shown that PF algorithm is particularly useful in dealing with nonlinear and non-Gaussian problems such as power line channel estimation, so the proposed scheme based on PF achieves higher estimation accuracy and better performance than the other schemes. Meanwhile, it is confirmed that PF algorithm has its own unique advantage in dealing with the power line channel estimation.

Key Words: Power Line Communication (PLC); Channel Estimation; Particle Filtering (PF); OFDM

1 INTRODUCTION

Power line communication (PLC) is a novel access technology which makes the use of the present power line resources efficiently. However, PLC also faces its own set of obstacles and technical challenges. Due to load fluctuations in the power system, PLC channels experience time-varying, frequency-selective fading in multipath propagation and represent a non-linear behavior [1, 2]. Moreover, transfer function of the power lines depend of location, topology network, connected loads, and is impaired by colored and impulsive noise [3]. Orthogonal frequency division multiplexing (OFDM) has been of major interest for PLC [4, 5] due to its high data rate transmission capability and its robustness to multi-paths delay spread. However, in order to ensure the good performance of OFDM systems, channel estimation is crucial for coherent detection in OFDM systems.

There are basically two ways to tackle the problem of channel estimation: pilot aided channel estimation schemes and blind channel estimation schemes. In the former case, some previous researches on channel estimation in OFDM have been widely investigated in the literature [6-9]. This method is the most popular channel estimation techniques, but it reduces band efficiency of the system significantly. In the term blind channel estimation schemes, there is some literature discussing channel estimation in OFDM based communications [10-15].The major advantage of this scheme is that the pilot symbols do not need to be transmitted, so the spectrum utilization of the system is improved. However, the method has large amount of calculation and slows down the convergence. For these reasons, it is not suitable to track the time-varying fading channels in the presence of fast channel variations.

Kalman filtering (KF), extended Kalman filtering (EKF), unscented Kalman filtering (UKF) and Particle filtering (PF) has been employed for channel estimation in OFDM systems [16-24]. However, such KF, EKF, UKF solution works reliably only if the underlying assumption on the Gaussianity of the noises and state hold. PF is one kind of sequential Monte Carlo simulation method based on the Bayesian principle, which is a powerful tool for dealing with difficult nonlinear and non-Gaussian problems [25]. The distinct advantage for PF solution is that it relaxes the assumptions on the distributions of noise and state. However, at the author acknowledges a minor effort has been carried out for exporting, analyzing, and optimizing channel estimation techniques based on PF algorithm in the PLC networks' environment. Power line channel is a class of nonlinear time varying system and its noise distribution is complex, PF algorithm has the obvious advantages for power line channel estimation. Furthermore, power line channel can be described by an autoregressive (AR) model [26]. Therefore, a comb-type pilot-aided channel estimation scheme for OFDM power line communication based on PF algorithm is proposed in this paper. In the

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proposed scheme, firstly the indoor power line channel impulse responses exploiting the pseudo-noise (PN) sequence's excellent periodic autocorrelation properties is measured, and an AR model to describe the measured channel is built; then the estimation of the measured channel at the pilot frequencies is based on PF method, and a simple linear interpolation method have been used to estimate the measured channel response at the data frequencies.

The rest of this paper is organized as follows. Section 2 introduces measurement method, principle and measurement results based on PN correlation method for power line channel. Section 3 describes OFDM system structures based on power line channel. The proposed PF algorithm for power line channel estimation is presented in more detail in Section 4. Simulations results are presented in Section 5 and the conclusions are given in Section 6.

2 Channel measurements for indoor power line communication

Fig.1 illustrates the channel sounding measurement system [27]. PN sequences are easily generated using linear feedback shift registers, and they possess excellent periodic autocorrelation properties. Therefore, let periodic PN sequence be the transmitting signals. PN sequence with the chip rate of 20MHz is realized by Agilent signal generator, and is injected into the power line by coupler. The received signal is over-sampled at the rate of 100MS/s by digital oscilloscope, and then is saved by PC. After completing measurement process, over sampled signals cross-correlated with the reference PN sequence on PC to give channel impulse responses. In the actual measurement system, receiver and transmitter realize measurement synchronization using the Agilent signal generator's synchronous port to trigger the digital oscilloscope. Therefore, the reliable amplitude and phase frequency response characteristics can be obtained.

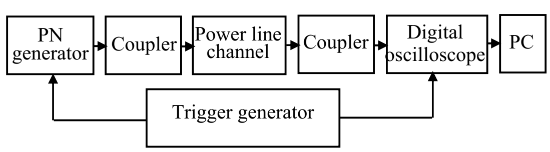
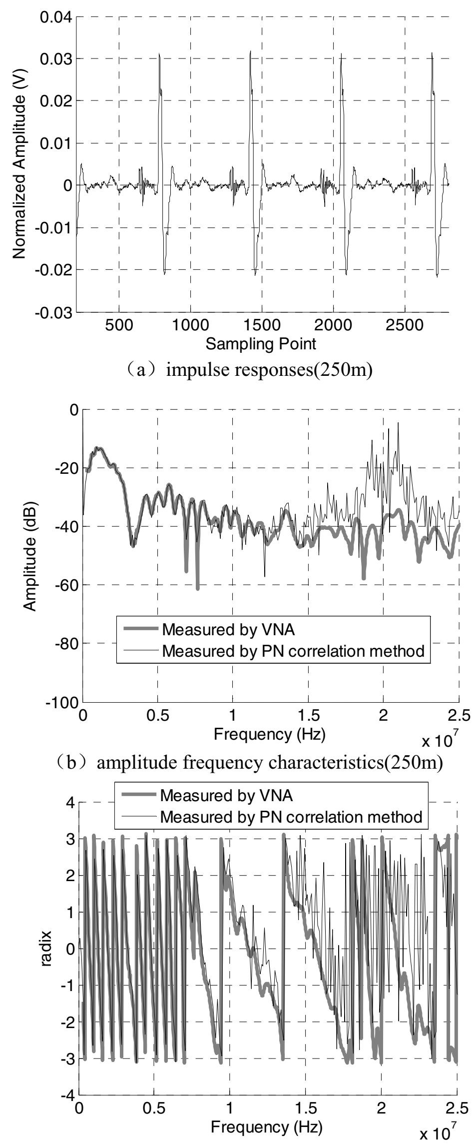


Fig. 1 Block diagram of the power line channel synchronous measurement system

The indoor PLC channel transmission characteristics are measured with length 250m in a laboratory. Sounding parameters are as follows: the chip rate of PN sequence is 20MHz, the number of the linear feedback shift registers is 7, and sampling rate of the digital oscilloscope is 100MS/s. In order to verify sounding method's correctness, the channel sounding in frequency domain is generally implemented by using the vector network analyzer (VNA) to compare the sounding results based on PN correlation method.

Fig. 2 is the synchronous measurement results for power line channel. Fig. 2(a) is the channel normalization impulse responses. Fig. 2 (b) shows the channel amplitude frequency response characteristics and its comparison with VNA's sounding results. Fig. 2 (c) is the channel phase frequency characteristics and its comparison with VNA's sounding results. Here, Fig. 2 (b) and Fig. 2 (c) show the measurement results by PN sequence as a black line. The measurement results by VNA are shown as the grey line. These sounding results are basically consistent with each other which have demonstrated the efficiency of the measurement method. Meanwhile, In Fig.2 (a), the significant delay-spread is shown. The reasons are power line does not have a well defined characteristic impedance. The reflections from terminations can cause the structure seen (deep nulls) in the transmission characteristic and "ringing" which increase the delay spread. Fig.2 (b) shows distinct frequency selective notches at certain frequency. These results indicate power line channels experience frequency-selective fading in multipath propagation and represent a non-linear behavior. Therefore, PF algorithm is proposed for power line channel estimation with its powerful capacity of dealing with nonlinear and non-Gaussian problems.



(a) impulse responses(250m)

(b) amplitude frequency characteristics(250m)

(c) phase frequency characteristics(250m)

Fig.2. synchronous measurement results for power line channel

3 OFDM System model based on power line channel and its channel state-space model

Consider an OFDM system model based on power line channel employing N subcarriers. The bits to be transmitted are first mapped onto constellation points $X(k)$. The quadrature phase shift keying (QPSK) is considered. The modulated data $X(k)$ are modulated in blocks of N, adopting an N-point inverse fast Fourier transform (IFFT). The comb-type pilot assignment, which the pilot signals are uniformly distributed within each OFDM block, has been exploited. It has a higher retransmission rate with the assumption that the payloads of pilot signals of the two arrangements are the same. Therefore, the comb-type pilot arrangement system provides better resistance to fast-fading channels.

Assuming the N_p pilot signals $\boldsymbol{X}^p(m), m=0,1,\cdots,N_p-1$, are uniformly inserted into $\boldsymbol{X}(k)$. Then the total N subcarriers are divided into N_p groups, each with $L=N/N_p$ adjacent subcarriers. In each group, the first subcarrier is used to transmit pilot signal. Therefore the OFDM signal modulated on the kth subcarrier can be expressed as

$$X(k)=X(mL+l)=\begin{cases} X^p(m) & l=0 \\ \text{information data} & l=1,2,\ldots,L\text{-}1 \end{cases} \quad (1)$$

In order to eliminate any interference between adjacent OFDM symbols, the guard interval is inserted. Paralleling-to-serial (P/S) conversion, the transmitted signal is sent to a frequency selective multipath fading channel. At the receiver, after removing the guard interval, the received samples are sent to a fast Fourier transform (FFT) block to demultiplex the multi-carrier signals.

Assume that the guard interval is longer than the length of channel impulse response. $Y(k)$ can be represented by

$$Y(k)=X(k)H(k)+W(k), k=0,1,\cdots,N\text{-}1 \quad (2)$$

where $W(k)$ is the Fourier transform of the channel additive Gaussian noise $w(n)$.

The received pilot signals $\boldsymbol{Y}_p(k)$ are extracted form $\boldsymbol{Y}(k)$, the channel transfer function $\boldsymbol{H}(k)$ can be obtained from the information carried by $\boldsymbol{H}_p(k)$. With the knowledge of the channel responses $\boldsymbol{H}(k)$, the transmitted data samples $\boldsymbol{X}(k)$ can be recovered by simply dividing the received signal by the channel response:

$$\hat{X}(k)=\frac{\boldsymbol{Y}(k)}{\hat{\boldsymbol{H}}(k)} \quad (3)$$

where $\hat{\boldsymbol{H}}(k)$ is an estimate of $\boldsymbol{H}(k)$. After signal demapping, the source binary information data are reconstructed at the receiver output.

Coherent OFDM detection requires channel estimation and tracking. A channel estimation scheme in OFDM power line communication based on PF algorithm is proposed. The basic idea of the proposed scheme is that AR model is set up for the power line channel namely the system state equation. At the receiver, the measurement equation is built, and then the real-time estimation for the current channel state is obtained through the current time of the observation information and the previous time channel state. Based on the idea mentioned above, the following state-space model is obtained.

$$\boldsymbol{Y}_n^p=\boldsymbol{X}_n^p\boldsymbol{H}_n^p+\boldsymbol{W}_n^p \quad (4)$$

$$\boldsymbol{H}_n^p=A\boldsymbol{H}_{n-1}^p+\boldsymbol{V}_n^p \quad (5)$$

where $\boldsymbol{Y}_n^p=[Y_n^p(0),\cdots,Y_n^p(N_p-1)]^{\mathrm{T}}$, $\boldsymbol{X}_n^p=\mathrm{diag}\{[X_n^p(0),\cdots,X_n^p(N_p-1)]\}$ $\boldsymbol{W}_n^p=[W_n^p(0),\cdots,W_n^p(N_p-1)]^{\mathrm{T}}$ denote the received signal, the transmitted signal and the system noise in pilot subcarriers, respectively for the nth OFDM symbol. $\boldsymbol{W}_n^p$ is the additive white Gaussian noise (AWGN) with variance σ_n^2 . $\boldsymbol{H}_n^p=[H_n^p(0),H_n^p(1),\cdots,H_n^p(N_p-1)]^{\mathrm{T}}$, $\boldsymbol{V}_n^p=[V_n^p(0),\cdots,V_n^p(N_p-1)]^{\mathrm{T}}$ ar e the channel response of pilot carries and the state noise at time n, respectively. $\boldsymbol{V}_n^p$ is the Gaussian noise process N(0,1). A is the parameters of the AR model. Its initial value can be obtained through the zeroth-order Bessel function of the first kind $J_0(2\pi f_{\mathrm{d}}\mathrm{T})$. Here, f_{d} is the maximum Doppler frequency spread, T is the OFDM symbol duration.

4 Particle filtering based channel estimation in OFDM power line communication

4.1 Particle filtering algorithm

Particle filtering algorithm using the non-parametric Monte Carlo simulation method can achieve recursive Bayesian filtering. Its basic idea includes the recursive computation of relevant probability distributions using the concepts of importance sampling and approximates the posteriori probability distribution with discrete random measures.

The problem is now to track $\boldsymbol{H}_n^p$, as the new observation vector $\boldsymbol{Y}_n^p$ is received. According to the theory of particle filtering, given the posteriori distribution is $p(h_{n-1}^p|y_{1:n-1}^p)$ at time n-1. Through prediction stage and update stage, a prior distribution $p(h_n^p|y_{1:n}^p)$ at time n can be obtained from formulation in (6) and (7).

$$p(h_n^p|y_{1:n-1}^p)=\int p(h_n^p|h_{n-1}^p)p(h_{n-1}^p|y_{1:n-1}^p)\mathrm{d}h_{n-1}^p \quad (6)$$

$$p(h_n^p|y_{1:n}^p)=\frac{p(y_n^p|h_n^p)p(h_n^p|y_{1:n-1}^p)}{p(y_n^p|y_{1:n-1}^p)} \quad (7)$$

where $p(y_n^p|y_{1:n-1}^p)=\int p(y_n^p|h_n^p)p(h_n^p|y_{1:n-1}^p)\mathrm{d}h_n^p$ .There is integral calculation in Eq. (6) which is computationally expensive. In generally, the SIR algorithm is exploited to approximate the a posteriori distribution. We draw N_s samples, $\{h_n^s\}_{s=1}^{N_s}$ (N_s is the total number of particles), from the importance density, that $h_n^s\sim q(h_n^p|h_{1:n-1}^s,y_{0:n}^p)$. Then, the posteriori distribution at time n can be approximate as Eq. (8).

$$p(h_{1:n}^p|y_{1:n}^p)\approx\sum_{s=1}^{Ns}\omega_n^s\delta(h_{1:n}^p-h_{1:n}^s) \quad (8)$$

Therefore, recursively computes the particle weights as

$$\omega_n^s \propto \omega_{n-1}^s \frac{p(y_n^p | h_n^s) p(h_n^s | h_{n-1}^s)}{q(h_n^s | h_{n-1}^s, y_n^p)} \quad (9)$$

In order to reduce the computational complexity, the transitional prior $p(h_n^p | h_{n-1}^p)$ is chosen for the importance density in the paper. Therefore, the particle weight updating formula can be simplified as

$$\omega_n^s \propto \omega_{n-1}^s p(y_n^p | h_n^s) \quad (10)$$

4.2 Channel estimation based on particle filtering and linear interpolation for OFDM systems

Based on the state-space model, the channel response at the pilot frequencies can be estimated using PF algorithm. Then, the channel response of data subcarriers will be estimated by linear interpolation. The detail steps to implement the PF algorithm in power line channel for estimation the channel response at the pilot frequencies are given as follows:

Step 1 Initiate a set of N_s particles $\{H_0^{(i)}, i = 1, 2, \cdots, N_s\}$ using the least square (LS) algorithm based on come-type pilot and the received signal $\boldsymbol{Y}_0^p$ .The weight of all particles is $1/N_s$. Here N_s is the total number of particles.

Step 2 Approximately obtain the channel frequency response $\bar{\boldsymbol{H}}_n^p$ at time n from Eq. (4) and get a new set of N_s particles $H_n^{(i)}$ from $H_{n-1}^{(i)}$ $(i = 1, 2, \cdots, N_s)$.

Step 3 Update the weights as Eq. (12) and normalize weight as Eq. (12).

$$\bar{\omega}_n^{(i)} = \omega_{n-1}^{(i)} p(\boldsymbol{Y}_n^p | \bar{\boldsymbol{H}}_n^p) = \omega_{n-1}^{(i)} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{|\boldsymbol{Y}_n^p - \boldsymbol{X}_n^p \bar{\boldsymbol{H}}_n^p|^2}{2\sigma^2}} \quad (11)$$

$$\omega_n^{(i)} = \bar{\omega}_n^{(i)} \Big/ \sum_{i=1}^{N_s} \bar{\omega}_n^i \quad (12)$$

Step 4 Calculate the effective particles size as

$$N_{\text{ef}} = 1 \Big/ \sum_{i=1}^{N_s} (\omega_n^{(i)})^2 \quad (13)$$

If $N_{\text{ef}} > N_{\text{th}}$ (N_{th} is the threshold of the effective number for particles, here $N_{\text{th}} = N_s / 4$), the program goes to step 5. Otherwise, resample and reset the weights $1/N_s$ for particles.

Step 5 calculate the more accurate estimation value for the channel response in pilot subcarriers at time n

$$\hat{\boldsymbol{H}}_n^p = \sum_{i=1}^{N_s} \omega_n^{(i)} H_n^{(i)} \quad (14)$$

Step 6 $n = n + 1$, then the program goes to step 2.

After obtaining the estimated channel $\hat{\boldsymbol{H}}_n^p$ at the pilot frequencies using PF algorithm, an efficient interpolation technique in comb-type pilot based channel estimation is necessary in order to estimate channel at the data frequency by using the channel information at the pilot frequencies. The simple linear interpolation method for power line channel estimation is shown to perform better than Gaussian interpolation, cubic interpolation and spline interpolation in [28]. Therefore, in this paper linear interpolation method is used to estimate the channel response at the data frequencies. Specifically, the channel estimation at the data subcarrier k, $mL < k < (m+1)L$, using linear interpolation is given by:

$$H_n(k) = H_n(mL + l) = (H_n^p(m+1) - H_n^p(m))\frac{l}{L} + H_n^p(m) \quad (15)$$

where $0 \le l < L$.

5 Simulation results

In this section, computer simulations are performed on to confirm the performance of the proposed scheme. In particular, the power line channel measurement results mentioned in Section 2 are utilized for channel estimation.

1) Description of simulation

The simulation environments are as follows. The FFT size is 1024. The subcarrier number N is 460, the pilot number is 30 and the interval between two pilots is 16 subcarriers. The number of sample of the CP is 256. Each frame data contains 36 OFDM symbol. For PF algorithm, the number of the particles is 100, and processing 500 times Monte Carlo. The threshold for SIR is 0.25. In order to verify PF algorithm is suit for power line channel estimation, three channel models are used in the simulations. The 1st channel model is the measured power line channel mentioned above. The 2nd channel model is the Gaussian channel and the 3rd channel model is the multi-path Rayleigh fading channel. The performance of the proposed channel estimation scheme based on PF algorithm over these channel models will be compared.

Assume that accurate timing and frequency synchronization are perfect at the receiver since the aim is to observe channel estimation performance. Furthermore, assume that choosing a cyclic prefix of time length to be greater than the maximum delay spread in order to preserve the orthogonality of the subcarriers and avoid inter-symbol interference among consecutive OFDM symbols. The comb-type pilot-aided channel estimation at pilot frequencies is performed by using LS, KF, UKF and PF scheme, and then linear interpolation is applied to all of schemes estimation result to compare overall estimation results. Simulations are carried out for different signal noise ratio (SNR) values and for different subcarrier modulation mode.

2) Simulation results and discussion

The results of computer simulations are shown from Fig.3 to Fig. 7. The legends "LS+linear interp., KF+linear interp., UKF+linear interp., PF+linear interp.," denote linear interpolation schemes of comb-type channel estimation respectively with the LS, the KF, the UKF and the PF estimate at the pilot frequencies.

Fig. 3-5 compare the bit error rate (BER) performance among PF, LS, KF and UKF channel estimation scheme over power line channel, multi-path Rayleigh fading channel and Gaussian channel, respectively. The simulation is performed with the QPSK modulation mode. Compared these figures, some simulation analysis results can be obtained as follows.

(1) The BER performance of LS algorithm combined with linear interpolation method is the worst compared with that

of other channel estimation schemes. This is because that, for LS algorithm, the influence of noise is ignored during channel estimation process.

(2) The performance respectively based on PF, KF and UKF scheme is better than LS scheme. The result is expected since the estimator error of PF, KF and UKF is calculated during the iterative process and descends with the increase of the number of iterations.

(3)The proposed channel estimation scheme based on PF algorithm achieves a better performance than KF, UKF estimation techniques especially for high SNR. This is reasonable since power line channel present a nonlinear behavior and PF algorithm has the advantages to cope with this problem. However, KF algorithm is suit to cope with linear and Gaussian problems. Although UKF algorithm through unscented transformation can used to solve the nonlinear problem, but the calculation precision for nonlinear distribution variables is limited.

(4) The BER gap for all estimation schemes among these channel models ranges from the maximum to the minimum as follows: Gaussian channel, power line channel and multi-path Rayleigh fading channel. The reason is the performance of Gaussian channel is much better than that of power line channel and Rayleigh fading channel, namely the improvement of the estimation precision based on the proposed scheme is the maximum among all the estimation schemes. It again verifies that the proposed scheme based on PF algorithm is more suited to deal with power line channel estimate.

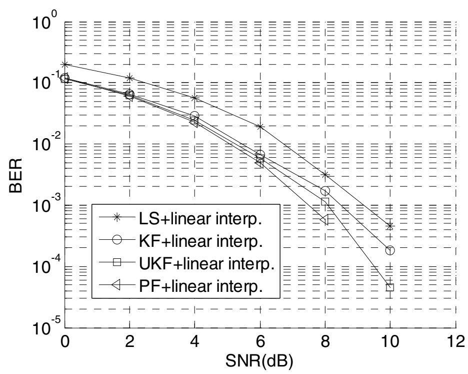


Fig. 3 BER performance for different estimation schemes over power line channel (QPSK)

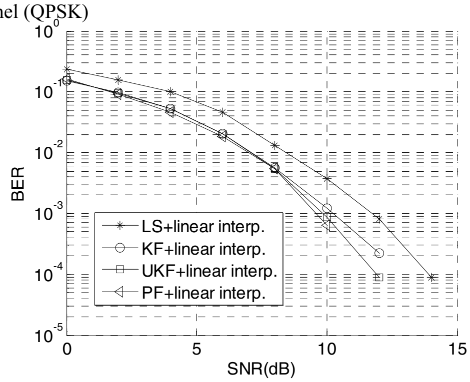


Fig. 4 BER performance for different estimation schemes over Rayleigh fading channel (QPSK)

Fig. 6 shows the BER performance of the PF scheme under different pilot spacing with QPSK modulation method. From the figure it can be seen that, when the pilot spacing is reduced, namely the number of pilot is increased, BER of system will reduce. However, with the increasing number of the pilot, the BER performance of the proposed schemes does not reduce significantly. It is indicated the advantages of linear interpolation namely that the interval between two pilots is increased meanwhile keeping the BER performance of the PF scheme unchanged.

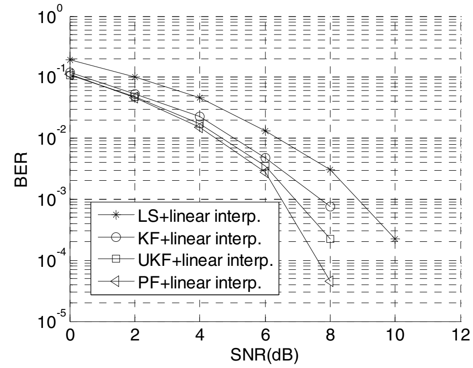


Fig.5 BER performance for different estimation schemes over Gaussian channel (QPSK)

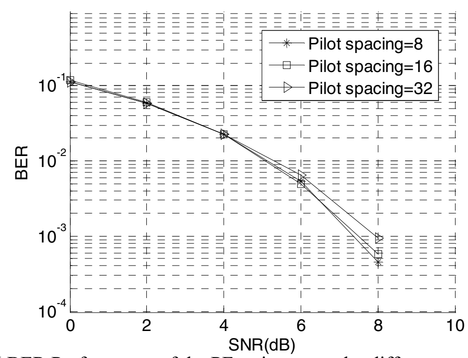


Fig. 6 BER Performance of the PF estimator under different number of pilot spacing (QPSK)

6 Conclusions

In this paper, a comb-type pilot arrangement channel estimation scheme combined PF algorithm and linear interpolation method is proposed for PLC channel. In the proposed scheme, the indoor power line channel transmission characteristic firstly is measured using PN correlation method. Then PF algorithm is exploited to track the measured channel response at the pilot frequencies and linear interpolation algorithm is used to obtain the measured channel response at the data frequencies. Comparisons have also been made with the channel estimation scheme based on LS, KF, UKF and PF algorithm, respectively. KF and UKF algorithm are lack of the capacity for dealing with the common nonlinear and non-Gaussian problems, while PF algorithm has the powerful capacity for these problems. Power line channel is a class of nonlinear time varying system and has complex noise distribution. Therefore, the performance of the proposed scheme based on PF algorithm for power line channel estimation will be much better than that of the other schemes. Simulations also have proved that the proposed scheme performs the best among all channel estimation schemes and its efficiency has validated. Moreover, it is confirmed that the proposed scheme can be used in PLC systems.

REFERENCES

[1] Banwell T C, Galli S. A novel approach to the modeling of the indoor power line channel-part 1: circuit analysis and companion model. IEEE Transactions on power delivery, 2005,20(2):655–663

[2] Dostert K. Multipath model for the powerline channel. IEEE Transactions on communications, 2000,50(2):553–559

[3] Cañete F J, Cortés J, Díez L, et al. Analysis of the cyclic short-term variation of indoor power line channel. IEEE Journal on Selected Areas in Communications, 2006, 24(7):1327–1338

[4] David Bueche, Patrick Corlay, Francois-Xavier Coudoux, et al. Recent developments in the standardization of power line communications within the IEEE. IEEE Transactions on Consumer Electronics, 2010, 56(3):1794–1800

[5] Antonino Musolino, Marco Raugi, Mauro Tucci. Cyclic short-time varying channel estimation in OFDM power-line communication. IEEE Transactions on Power Delivery, 2008,23(1):157–163

[6] David Bueche, Patrick Corlay, Marc Gazalet, et al. A method for analyzing the performance of comb-type pilot-aided channel estimation in power line communications. IEEE Transactions onConsumer Electronics, 2008, 54(3):1074–1081

[7] Degardin V, Lienard M, Degauque P. Optimizations of equalization algorithm for power line communication channel. Electronics Letters, 2003,39(5):483–485

[8] Muharrem A Tunc, Erik Perrins. Pilot based channel estimation and transform domain analysis in broadband PLC for smart grid. 2013 IEEE International Conference on Smart Grid Communications, Oct. 21-24, 2013, Vancouver, BC, 2013:283–288

[9] Tang T, Deng G, Jiang J. Estimation of time-varying channels for pilot-assisted OFDM systems. The Journal of China Universities of Posts and Telecommunications, 2007; 14(2):94–98

[10] Muquet B, Courville M D, Duhamel P, Subspace-based blind and semi-blind channel estimation for OFDM systems. IEEE Transactions on Signal Processing, 2002, 50(7):1699–1712

[11] Schafhuber D, Matz G. MMSE and adaptive prediction of time-varying channel for OFDM system. IEEE Transactions on Wireless Communications, 2005,4(2):593 –602

[12] Marco Raugi, Mauro Tucci. Power-line communications channel estimation and tracking by a competitive neural network. IEEE Transactions onConsumer Electronics, 2006, 52(4):1213–1219

[13] Liand C, Roy S. Subspace-based blind channel estimation for OFDM by exploiting virtual carriers. IEEE Transactions on Wireless Communications, 2003,2(1):141–150

[14] Ding X, Meng J, PetersenBR. Blind channel estimation for HomePlug power-line communications: a feasibility? IEEE Transactions on power delivery, 2011,26(2):754–763

[15] Yu Y H. Blind particle filtering detector over time-varying frequency-selective and nonlinear channels. Chinese Journal of Electronics, 2013, 22(2):377–381

[16] Karthik Muralidhar, Kwok Hung Li. A low-complexity kalman approach for channel estimation in doubly-selective OFDM system. IEEE Signal Processing Letters, 2009,16(7):632-635

[17] Yuanjin Z. A novel channel estimation and tracking method for wireless OFDM systems based on pilots and kalman filtering. IEEE Transactions on Consumer Electronics, 2003, 49(2):275–283

[18] Tareq Y. Al-Naffouri. An EM-based forward-backward kalman filter for the estimation of time-variant channel in OFDM. IEEE Transactions on Signal Processing, 2007,55(7):3924–3930

[19] Han K Y,Lee S W, Lim J S, et al. Channel estimation for OFDM with fast fading channels by modified kalman filter. IEEE Transactions on Consumer Electronics, 2004, 50(2):443–449

[20] Huang M, Chen X, Xiao L, et al. Kalman-filter-based channel estimation for orthogonal frequency-division multiplexing systems in time-varying channels, IET Communications, 2007,1(4):795-801

[21] Komninakis C, Fragouli C, Sayed A H, et al. Multi-input multi-output fading channel tracking and equalization using Kalman estimation. IEEE Transactions on Signal Processing, 2002,50(5):1065–1076

[22] Jaechan Lim, Hong Daehyoung. Frequency-selective and nonlinear channel estimation with unknown noise statistics. IEEE Communications Letters, 2010,14(3):245–247

[23] Frederic Lehmann. Blind estimation and detection of space-time trellis coded transmissions over the Rayleigh fading MIMO channel. IEEE Transactions on Communications, 2008,56(3):334–338

[24] Banani S A, Vaughan R G. Blind channel estimation and discrete speed tracking in wireless systems using independent component analysis with particle filtering. IET Communications, 2012,6(2):224–234

[25] Djurić P M, Kotecha Jayesh H, Zhang J Q, et al. Particle filtering. IEEE Signal Processing Magazine, 2003, 20(5):19-38

[26] Guo J B, Wang Z J, Lv H F, et al. Transmission characteristics of low-voltage distribution networks in China and its model. IEEE Transactions on power delivery, 2005,20(2):1341–1348

[27] Zhang P L, Zhang H X. Channel measurements and modelling for indoor power line communications. TELKOMNIKA, 2013,11(4):1940–1947

[28] David Bueche, Patrick Corlay, Marc Gazalet, et al. A method for analyzing the performance of comb-type pilot-aided channel estimation in power line communications. IEEE Transactions on Consumer Electronics, 2008, 54(3):1074–1081