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직교주파수분할다중화기반 전력선통신에서 대역 효율적인 전송기법[†]

(A spectral efficient transmission method for ofdm-based power line communications)

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요 약 전력선통신은 스마트그리드 기반의 서비스가 제공될 수 있는 네트워크를 위한 미래 지향적 기술이다. 전력선통신 채널의 주파수 선택적 페이딩이 있는 환경에서, 직교주파수분할다중화 기술은 신뢰성 있는 통신을 제공한다. 본 논문에서는 직교주파수분할다중화 기반의 전력선통신 시스템에서 은닉학습신호를 이용한 주파수사용효율이 높은 기법을 제안한다. 은닉학습신호를 사용하면 채널 추정용 주파수를 따로 소모하지 않고도 채널 추정이 가능하고, 이는 데이터와의 간섭을 줄일 수 있는 학습신호에 할당된 파워를 이용해서 해결할 수 있다. 컴퓨터 시뮬레이션을 통해 제안한 기법이 기존의 기법들에 비해 저전압 및 중전압 송전 라인에서 높은 성취 가능한 데이터 율을 보여준다.

핵심주제어 : 전력선통신, 전부호화기, 은닉학습신호, 대역 효율성

Abstract Powerline communications (PLC) is a promising medium for network access technology where smart grid aided network services can be provided. In the presence of frequency selective fading in the PLC channel, orthogonal frequency division multiplexing (OFDM) is a technique for reliable communications. This paper presents a spectral efficient method using a superimposed hidden pilot for OFDM-based PLC systems. Based on the scheme using a hidden pilot, it is possible to estimate the channel with no consumption of bandwidth, but with utilization of power allocated to the hidden pilot. Computer simulations showed that the proposed scheme provides higher achievable data rate than that of the conventional schemes in low voltage and medium voltage transmission lines.

Key Words : Power Line Communication, Precoding, Hidden Pilot, Spectral Efficiency

1. Introduction

Recently, there has been a growing interest towards the possibility of using existing power lines as effective transmission mediums. Power line communication (PLC) is an attractive alternative technology for traditional networks due to its ability to offer broadband internet access, cable television, telephone service and home networking. The greatest advantage PLC is that there is no need for additional infrastructure, which is important in

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terms of cost in the implementation [1-5]. Recently, the PLC specifications G3-PLC, PRIME, HomePlug Green PHY, and HomePlug AV2, and the PLC standards IEEE 1901/1901.2 and ITU-T G.hn/G.hnem are discussed.

Due to the inherent property of PLC, data transmission is affected from many problems such as interference, multipath noise, attenuation delays, presence of echoes, frequency selective fading due to multipath, etc [1]. Hence, it is necessary to employ a suitable modulation scheme such as orthogonal frequency division multiplexing (OFDM) to remove its unwanted effects on signal transmission [6-8]. OFDM is a subcarrier modulation method for high speed data transmission over multipath fading channels. It distributes data over a large number of subcarriers spaced apart at precise frequencies to make them orthogonal to each other and reduces inter symbol interference.

In OFDM-based systems, a pilot-symbol-aided modulation (PSAM) scheme can be used to track channel state information (CSI) at the receiving end using pilot symbols that are previously known at the receiver [9]. Although accurate channel estimates can be obtained if the pilots are judiciously placed [10], this method reduces spectral efficiency, which is precious in wireless communications. Blind channel estimation [11] offers a spectral efficient method using statistical and other properties of the data. However, this method also has inherent shortcomings, such as slow convergence and phase ambiguity. Although the superimposed training (ST) scheme [12- 15], where pilot symbols are added to the data symbols, is an alternative method, the effect of unknown data degrades the performance of channel estimation. To solve this problem, a hidden pilot-aided precoding (HP) scheme [16], which uses a precoder to successively remove the inevitable unknown data interference without loss of bandwidth, was proposed. In addition, due to the spreading effect of the information data over the total available bandwidth using a precoder, it is possible to provide high frequency diversity.

This paper discusses the effect of using a HP scheme to provide a spectral efficient communication method in PLC. For the low-voltage (LV) and medium-voltage (MV) power line cases, a HP scheme outperformed the conventional schemes in terms of achievable rate, and thus, it is an adequate method for PLC with high data rate .

The rest of this paper is organized as follows. Section 2 presents a system model of a OFDM-based PLC and the design of a HP method. Then, Sections 3 are dedicated to channel estimation and the symbol detection scheme. The results of computer simulations are presented in Section 4. Conclusions are presented in Section 5.

2. System Model

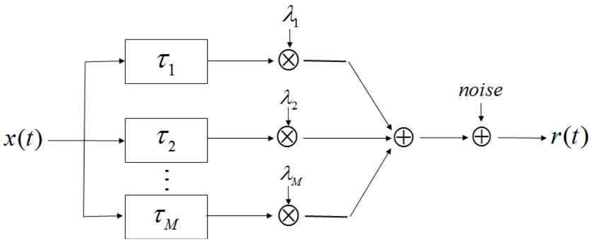
2.1 PLC Model

In the PLC system model, the most important factor to consider is power line channel model. Several techniques to model channel transfer characteristic of PLC networks have been presented in various literatures [2 - 4]. The most widely known model for the PLC channel is the multipath model, which is proposed by Zimmermann and Dostert [17]. It states the variety of loads connected to the network terminals and the presence of several cable branches which cause impedance mismatches. Due to these impedance mismatches, many reflections of signal appear during its transfer along the cable. This is called multipath fading or frequency selective fading.

In this channel model, the frequency response of the PLC channel may be expressed, in the frequency range from 500 kHz to 20 MHz, as

$$(q) = \;_{i}\; g_i e^{-(a\ + a_1 q^k) d_i} e^{-j2\pi q \frac{d_i}{v_p}} \tag{1}$$

where is the number of relevant propagation paths, a_o and a_1 are link attenuation parameters, k is an exponent with typical values ranging from 0.5 to 1, g_i is the weighting factor for path i, d_i is the length of the th path, and v is the phase velocity. If we let $\tau_i = d_i / v_p$ and $\lambda_i = g_i e^{-(a_o + a_1 q^k) d_i}$, the PLC channel model can be depicted as <Fig. 1>.



<Fig. 1> PLC channel model

Among the power lines, the medium voltage (MV) lines are used for power distribution between cities and large industrial companies. Since they can be directly connected to intelligent electronic devices (IEDs) such as reclosers, sectionalizers and phasor measurement units, PLC on MV lines can offer the functions of IED monitoring and control tasks. Low-voltage (LV) lines are connected to the MV lines via secondary transformer substations. PLC data on MV lines can pass through the secondary transformers onto the LV lines. Since it causes serious signal attenuation, a special coupling device or a PLC repeater is required for a high data rate PLC capability. Since a secondary transformer can service several houses, PLC on LV lines offer the data communication services containing the end customers' needs.

In the wide frequency bands in the power line, low-voltage (LV) and medium voltage (MV) power lines, below 1 kV and from 1 to 36 kV, respectively, are more advantageous than high-voltage (HV) power lines because they are a potentially convenient and inexpensive communication medium for control signaling and data communication. Note that the length of the multipath d_i for LV is shorter than that for MV power lines.

2.2 Design of HP Scheme

Here, the OFDM-based PLC system with N subcarriers was considered. The channel is assumed to be time-invariant over a single symbol block, but it could vary across blocks. The length of the cyclic prefix M was set to be equal to the number of taps of the channel impulse response.

To reduce inherent data interference for accurate channel estimation in a HP scheme, a precoding method based on polyphase sequences [16] is exploited. It is known that polyphase sequences are orthogonal codes and have good periodic autocorrelation and cross-correlation properties. Therefore, the reduction in the mutual interference between the data and pilot symbols can be done by these properties, while guaranteeing almost no decrease in the data rate. It is known that the length of a polyphase sequence was set to p^{r-1}, where p is a prime and r is an integer. If N is assumed to be the power of 2, the $N-1$ numbers of the polyphase sequence sets $= [\ _0, \boldsymbol{c}_1, \ldots, \boldsymbol{c}_{N-2}]$ can be generated. Then, a precoder matrix $\boldsymbol{P}$ and a pilot vector $\boldsymbol{t}$ can be derived by the following:

$$\begin{aligned} \boldsymbol{P} &= \boldsymbol{F}\ \boldsymbol{c}'\ \ , \boldsymbol{c}'_1, \ldots, \boldsymbol{c}'\ \ _{-3}], \\ \boldsymbol{t} &= \boldsymbol{F}\boldsymbol{c}'_{N-2}, \end{aligned} \tag{2}$$

where $\boldsymbol{c}' = \ \boldsymbol{c}^T, 0]^T$ is an $N \times 1$ vector.

At the transmit end, the transmit symbol block is set to $\boldsymbol{x} = \boldsymbol{P}\boldsymbol{s} + \boldsymbol{t}$, where $\boldsymbol{s}$ is an $(N-2) \times 1$ information data vector. Then, the modulation based on the inverse discrete Fourier transform (DFT), i.e., , is carried out and a cyclic prefix is inserted into each OFDM symbol vector. Before taking the DFT at the receive end, an 1 vector can be expressed as

$$\begin{aligned} y &= HF^{H}x + n \\ &= HAs + Hb + \overline{n}, \end{aligned} \tag{3}$$

where $A = F \ \ P$, $b = F^{H}t$. H is the circulant channel matrix with the first column $\ h^{T},0,\ldots,0]^{T}$, where h is the power delay profile of the time-domain channel with length L. It is assumed that $\overline{n}$ is additive white Gaussian noise with a covariance matrix $E[\overline{n}\overline{n}^{H}] = \sigma \ /N)I$, where I denotes an $N \times N$ identity matrix. A cyclic prefix is then removed and demodulation of the OFDM symbol block is performed by using F. The $N \times 1$ demodulated symbol vector r can be expressed as

$$\begin{aligned} & HF \ \ x + n \\ &= D(h \ \ )(Ps + t) + n, \end{aligned} \tag{4}$$

where $D(h_f)$ is an $\ \times N$ diagonal channel matrix with principal diagonal components that are the elements of h_f, which is the frequency response of the time-domain channel h. And $n = F\overline{n}$ with $\sigma_{\overline{n}}^{2} = \sigma_{n}^{2}$.

3. Channel estimation and Symbol Detection

3.1 Channel estimation

In this subsection, the minimum mean square error (MMSE) channel estimator is presented for the OFDM-based PLC systems that use a superimposed hidden pilot. To mitigate inherent interference between the data and pilot symbols at the receiver, the channels can be estimated by postprocessing the received signal using the correlation properties of the designed precoder and the hidden pilot. By multiplying B^{H} by Eq. (3), the received symbol block can be expressed as

$$\begin{aligned} z &= B^{H}y = B^{H}Hb + \underbrace{B^{H}HAs}_{v} + B^{H}\overline{n} \\ &= B^{H}Bh + v + B^{H}\overline{n}. \end{aligned} \tag{5}$$

From Eq. (5), it is clear that $v = B^{H}HAs$ becomes a data interference when the channel estimation is carried out. It is noted that $Hb = B\tilde{h}$, where B is the $N \times M$ column-wise circulant matrix with first column b, due to the commutativity of circular convolution. Here, A_i is set to an $N \times M$ column-wise circulant matrix with the i-th column of A as the first column, which is denoted by a_i. Based on the property of commutativity of circular convolution, $HA = [Ha_1, Ha_2, \ldots, Ha_N]$ can be converted to $HA = [A_1h, A_2h, \ldots, A_Nh]$. As $B^{H}A_ih$ becomes small, due to the periodic cross-correlation of the polyphase sequences, the data interference v on the channel estimation can be reduced; hence, the channel can be successfully identified.

Then, the MMSE channel estimate can be derived as

$$\begin{aligned} \hat{h} &= R_{hz}R_{z}^{-1}z \\ &= R_{h}B^{H}B(B^{H}BR_{h}B^{H}B + R_{v} + (\sigma_{n}^{2}/N)B^{H}B)^{-1}z. \end{aligned} \tag{6}$$

Based on the channel estimation error $\tilde{h} = h - \hat{h}$, the MSE of the MMSE channel estimator can be expressed as $tr[E[\tilde{h}\tilde{h}^{H}]]$. With some mathematical manipulation, MSE of the MMSE channel estimator is given by

$$\begin{aligned} \sigma_{\tilde{h}}^{2} &= tr \ \ E\left[\tilde{h}\tilde{h}^{H}\right]\Big] = tr \ \ R_{h} - R_{hz}R_{z}^{-1}R_{hz}^{H} \Big] \\ &= tr \ \ \left(R_{h}^{-1} + B^{H}B(R_{v} + (\sigma_{n}^{2}/N)B^{H}B)^{-1}B^{H}B\right)^{-1}\Big] \end{aligned} \tag{7}$$

where is the channel covariance matrix.

3.2 Symbol Detection

As discussed earlier in this paper, the interference between the precoded data and the hidden pilot affects the performance of symbol detection because the scheme exploits a hidden pilot, which is superimposed on the precoded data. To mitigate the degradation of decoding performance caused by interference, the interference of the hidden pilot is subtracted from the received signal using the estimated channel which is presented as $h-\tilde{h}$. Taking the reduction in the interference caused by the hidden pilot into account, Eq. (4) can be rewritten as

$$\begin{aligned} r &= r - D(h_f)t \\ &= \hat{D}(h_f)Ps + \eta, \end{aligned} \tag{8}$$

where

$$\eta = D(h_f)t + \tilde{D}(h_f)Ps + n. \tag{9}$$

$\tilde{D}(h_f)$ denote the diagonal matrix with main diagonals of $\tilde{h}$.

We consider a linear MMSE receiver to decode information data vector from the received symbols. Then, symbol detection is presented as

$$\begin{aligned} \hat{s} &= R_{s r} R_{\bar{r}}^{-1} \bar{r} \\ &= \frac{P_s}{-2} \hat{D}(h_f) \quad \frac{P_s}{N-2} \hat{D}(h_f) \hat{D}(h_f)^H + R_\eta \Big)^{-1} r, \end{aligned} \tag{10}$$

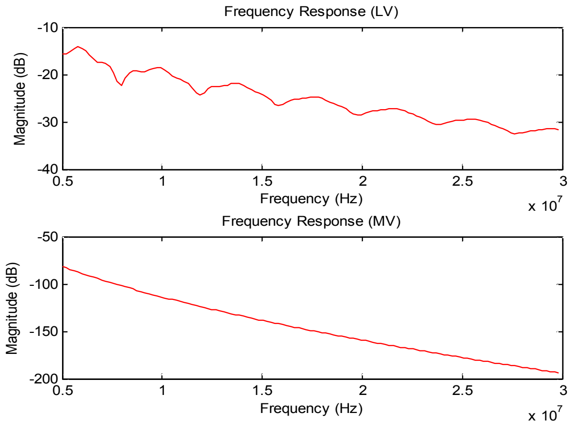
where $R_{s\bar{r}} = E[s\bar{r}^H]$, $R_{\bar{r}} = E[\bar{r}\bar{r}^H]$, $R_\eta = E[\eta\eta^H]$, and P_s is the total data symbol power in one symbol block.

4. Simulation Results

To simulate the proposed HP scheme in the powerline channel, we used the parameters derived from the frequency response measurement done in [17], which is: $K = 0.5$, $a_0 = 0$ $a_1 = 8 \times 10^{-6}$, for four paths $(L = 4)$, $g_1 = 0.4, g_2 = -0.4, g_3 = -0.8, g_4 = -1.5$, and $v_p = 150 \times 10^6 m/s$. We have considered line length for the four paths for LV and MV cases, shown in <Table 1>.

<Table 1> PLC Channel Length

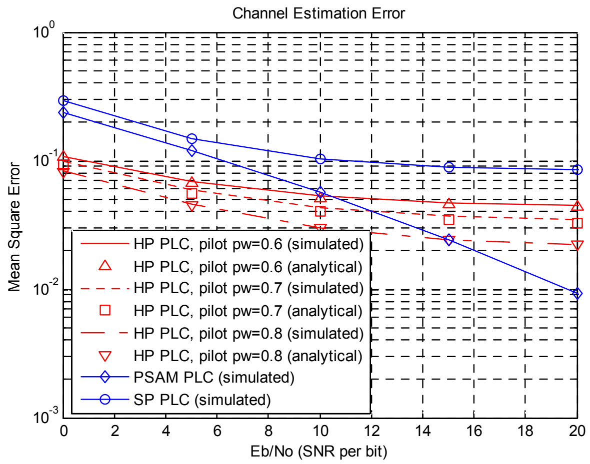
Line type	Line distance
Low voltage	$= 150m, d_2 = 188m,$ $d_3 = 264m, d_4 = 397m$
Medium voltage	$d_1 = 1km, d_2 = 2km,$ $d_3 = 3km, d_4 = 4km$



<Fig. 2> Frequency Response of PLC Channel

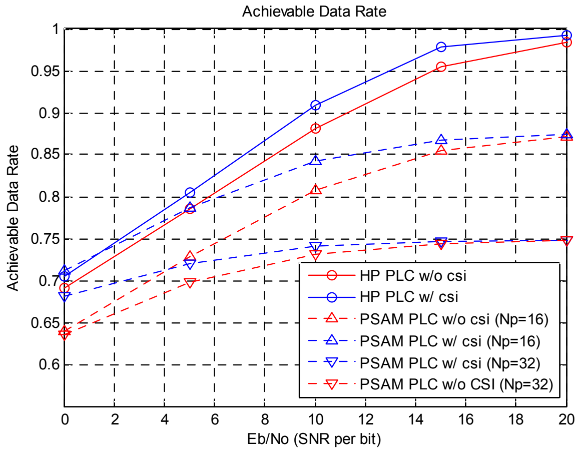
For simulations on OFDM-based PLC, the total subcarrier number is set to 128 and the channel length $M = 16$. The total transmitted power is normalized to 1. For the PSAM scheme, the number of the disjoint pilot symbols is 16. The ST method uses a superimposed chirp sequence with a normalized power of 0.5.

<Fig. 2> shows channel frequency response of LV and MV power lines. The attenuation of the MV case is found to be about 120 dB over a frequency range of 30 MHz. The multi path frequency response in the LV case exhibits several notches at between 1 MHz and 30 MHz. This frequency selective fading characteristic will influence data communication.



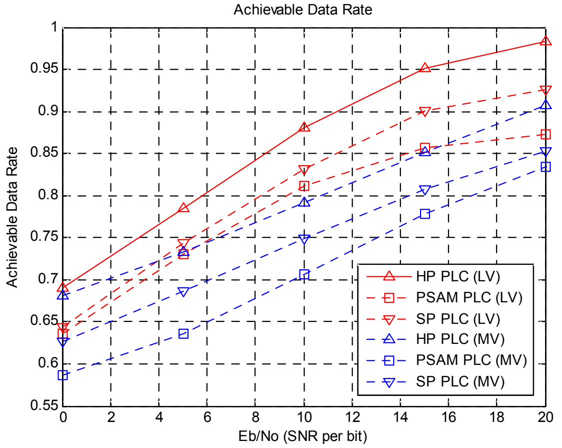
<Fig. 3> Channel Estimation Error in PLC

The result of channel estimation with various values of power allocated to a hidden pilot is depicted in <Fig. 3>. It is shown that the derived MSE of channel estimate is similar to that of the simulated one. In addition, the channel estimation performance of the proposed HP scheme is better than the PSAM and SP schemes in the low SNR because the proposed scheme uses superimposed hidden pilots over the available entire subcarriers, different from PSAM. However, in the high SNR, the channel MSE of the proposed scheme is worse than the PSAM because the data interference is not perfectly removed, resulting in degradation of channel estimation. Such a residual interference can be further reduced by iteratively updating the detected symbols and the estimated channel.



<Fig. 4> Comparison of Achievable Data Rate

<Fig. 4> displays the performance of achievable data rate with regard to both the estimated channel and the previously known channel. The pilot power ratio loaded to the hidden pilot is set to 0.6. For a PSAM scheme, the number of subcarriers allocated for disjoint pilot symbols is set to 16 and 32. Note that the proposed HP scheme outperforms the PSAM scheme whether CSI is known or not. For channel estimation, the proposed scheme does not waste valuable bandwidth, while the PSAM scheme uses pilot tones that degrade spectral efficiency.



<Fig. 5> Achievable Data Rate for
LV and MV Cases

The performance of achievable data rate with regard to LV and MV cases are presented in <Fig. 5>. It is shown that the performance is in MV compared to LV due to the large attenuation of PLC channel frequency response. For both LV and MV powerline channels, the proposed HP scheme can provide better performance than the other schemes. This result shows a key insight into the merits of using the HP scheme in PLC systems for high data rate services.

5. Conclusion

Power line communication (PLC) is considered as an attractive alternative to traditional networks as it provides various access services. Due to the increasing demand on high data rate, spectral efficiency is an important factor to consider in data transmission in PLC. This paper shows the novelty of the hidden pilot-aided precoding (HP) scheme for the PLC channel with frequency selective fading. This scheme can effectively utilize bandwidth with the aid of designing a precoder and superimposed pilot. Simulation results show that the proposed scheme provides significant performance of achievable data rate compared to the conventional schemes in the presence of multipath fading of PLC in both low and medium voltage powerlines.

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