A channel estimation method for wireless communication in HPLC&RF dual mode system

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Abstract. With application of high-speed power line carrier communication (HPLC), some problems are emerging such as network outliers, low success rate of power outage reporting and short single hop communication distance. Wireless communication (RF) can effectively solve these problems and thus become an effective complement to HPLC. For OFDM based wireless communication in HPLC&RF dual mode system, a channel estimation method is proposed. Compared with LTF-based and pilot-based channel estimation methods applicable to cases with few and multiple physical layer load symbols respectively, the proposed method can be applied in all cases. When the number of symbols is small, it outperforms pilot-based method by 2~3 dB and is still better than LTF-based method. When the number of symbols is large, it outperforms LTF-based method by 2~5 dB and still better than pilot-based method.

1. Introduction

High-speed power line carrier communication (HPLC) is a broadband power line carrier technology for data transmission on low-voltage power line. It has the characteristics of high speed, high reliability, real-time, anti-interference, and can realize chip interconnection. Therefore, it can meet the requirements of power consumption information collection, and is being widely used now. However, with the development of power system, power electronic devices and frequency conversion equipment have been widely used, and the electromagnetic environment of power system has become more and more complex which brings problems to HPLC, such as network outliers, low success rate of power outage reporting and short single hop communication distance [1]. Wireless communication (RF) can solve these problems and thus become an effective supplement to HPLC. The combination with RF will greatly expand the application and development space of HPLC. On the premise of meeting the requirements of power grid meter reading, it can also be used in various expansion applications of smart grid, and provide high-speed and reliable solutions for smart home.

The physical layer of RF in HPLC&RF dual mode system [2] is based on OFDM. The transmit signal of physical layer includes synchronization head and physical layer load. The long training field (LTF) in synchronization head can be used for channel estimation. In addition, for channel estimation, multiple sets of pilot pattern are defined and used in OFDM symbols of physical layer load including physical layer header (PHR) and physical layer service data unit (PSDU). PHR carries the necessary control information for PSDU to demodulate.

It is well known that channel estimation is very important for OFDM system. There are many papers on it [3-11]. But in the existing literatures, for a system with LTF, channel estimation is mostly based on LTF only. However, in HPLC&RF dual mode system, LTF is located in front of physical layer load, LTF-based method is applicable only to time invariant channels or cases with few physical
layer load symbols. For time-varying channels and multiple physical layer load symbols, its performance will deteriorate. For pilot-based channel estimation, when the number of physical layer load is small, the number of pilots is small which will result in poor channel estimation performance. Up to now, few literatures utilize both LTF and pilots for channel estimation\cite{[11]}. Therefore, this paper proposes a channel estimation method for RF using STF, LTF and pilot. Simulation results show that the proposed method is suitable for all cases with different number of physical layer load symbols in both time-invariant channels and time-varying channels. When the number of symbols is small, it outperforms pilot-based method by 2 ~ 3 dB, and is still better than LTF-based method. When the number of symbols is large, it outperforms LTF-based method by 2 ~ 5 dB and is still better than pilot-based method about 1 dB in time-varying channels.

2. RF system model

| STF | LTF | PHR | PSDU |
|-----|-----|-----|------|

Figure 1. Frame structure.

The physical layer frame structure of RF is shown in figure 1. The transmit signal in each frame includes synchronization head (STF, LTF) and physical layer load (PHR, PSDU). Both STF and LTF are known periodic sequences. PHR carries the control information for PSDU. In addition, Multiple sets of pilot pattern are defined and used in physical layer load symbols.

RF supports 4 physical layer modes: Option 1, Option 2, Option 3 and Option 4. The corresponding system parameters are shown in table 1.

| Option 1 | Option 2 | Option 3 | Option 4 |
|----------|----------|----------|----------|
| Nominal bandwidth(kHz) | 1094 | 552 | 281 | 156 |
| Channel Spacing(kHz) | 1200 | 800 | 400 | 200 |
| FFT number | 128 | 64 | 32 | 16 |
| Effective carrier number | 104 | 52 | 26 | 14 |
| Data carrier number | 96 | 48 | 24 | 12 |
| Pilot carrier number | 8 | 4 | 2 | 2 |

The transmitting and receiving flow of RF is shown in figure 2.

At the transmitter, PHR is processed by turbo coding, puncturing, interleaving and diversity copying; PSDU is processed by scrambling, turbo coding, puncturing, interleaving and diversity copying. Finally, the processed PHR and PSDU are mapped to constellation points, and the pilot is added in. After that, IFFT is used to convert the signal from frequency domain to time domain. Then, STF and LTF are added. The resulted signal is processed by windowing, DAC, up conversion, power amplifying, and finally transmitted through antenna.

At the receiver, baseband data is obtained after LNA, down conversion and filtering. FFT is used to convert the signal from time domain to frequency domain. Then, the frequency domain data is used to estimate the frequency offset and channel, and then demodulate. After diversity merging, de-interleaving, de-puncturing and turbo decoding, the received data need to be descrambled to get the corresponding information carried in PSDU.
3. RF known signals
In RF, STF, LTF and pilot are all known signals in frequency domain. In the following, a brief introduction on STF, LTF and pilot in Option 1 will be given.

For STF in Option 1, the frequency sequence is defined in formula (1) [2]. After 128-point IFFT, cyclic prefix (CP) with length of 1/4 OFDM symbol (32 points) is added, and then repeat 4 times to obtain a 640-point time domain sequence. The time domain sequence is then scrambled and windowed before transmitting.

$$X(k) = \begin{cases} \frac{-\sqrt{104/12}}{12} & k = -48, -40, -32, 16, 40 \\ \frac{\sqrt{104/12}}{12} & k = -24, -16, -8, 8, 24, 32, 48 \\ 0 & \text{Otherwise} \end{cases}$$  \hspace{1cm} (1)$$

For LTF in Option 1, the length of the frequency sequence is 104 and each element in the frequency sequence takes value either +1 or -1[2]. After 128-point IFFT and repeating once, CP with length of 1/2 OFDM symbol (64 points) is added in front to obtain a 320-point time domain sequence. The time domain sequence is then windowed before transmitting.

For pilot in Option 1, 13 sets of frequency domain pattern are defined and each set is corresponding to one physical layer load OFDM symbol. The pilot carrier indexes of each set are shown in table 2[2].

| Pilot Tone | #1 | #2 | #3 | #4 | #5 | #6 | #7 | #8 |
|------------|----|----|----|----|----|----|----|----|
| Pilot Set 1 | -38 | -26 | -14 | -2 | 10 | 22 | 34 | 46 |
| Pilot Set 2 | -46 | -34 | -22 | -10 | 2 | 14 | 26 | 38 |
| Pilot Set 3 | -42 | -30 | -18 | -6 | 6 | 18 | 30 | 42 |
| Pilot Set 4 | -50 | -38 | -26 | -14 | -2 | 10 | 22 | 50 |
| Pilot Set 5 | -46 | -34 | -22 | -10 | 2 | 14 | 34 | 46 |
| Pilot Set 6 | -42 | -30 | -18 | -6 | 6 | 18 | 26 | 38 |
| Pilot Set 7 | -50 | -38 | -26 | -14 | -2 | 30 | 42 | 50 |
| Pilot Set 8 | -46 | -34 | -22 | -10 | 10 | 22 | 34 | 46 |
| Pilot Set 9 | -42 | -30 | -18 | -6 | 2 | 14 | 26 | 38 |
| Pilot Set 10 | -50 | -38 | -26 | 6 | 18 | 30 | 42 | 50 |
| Pilot Set 11 | -46 | -34 | -14 | -2 | 10 | 22 | 34 | 46 |
| Pilot Set 12 | -42 | -30 | -22 | -10 | 2 | 14 | 26 | 38 |
| Pilot Set 13 | -50 | -18 | -6 | 6 | 18 | 30 | 42 | 50 |

The overall pattern of frequency domain known signals is shown in figure 3. In time domain, the first four symbols are STF, the fifth and sixth symbols are LTF, and the remaining symbols are physical layer load, i.e. PHR and PSDU. The number of physical layer load symbols are variable...
depending on physical layer load size and MCS. In frequency domain, STF symbols are evenly distributed with spacing of 8 carriers. LTF symbols are distributed over all effective carriers. Pilot symbols are unevenly distributed with average spacing of 4 carriers. Totally, in one frame, there are 48 STF symbols, 208 LTF symbols and 8 pilot symbols in each physical layer load symbol.

![Known signals in frequency domain](image)

**Figure 3.** Known signals in frequency domain.

### 4. Proposed channel estimation method

RF only supports antenna configuration of 1x1. The received signal in frequency domain can be modelled as:

\[ y = h x + n \] (2)

Wherein \( y \) is the receive signal, \( x \) is the transmit signal, \( h \) is frequency domain channel response, \( n \) is noise with zero mean and variance of \( \sigma^2 \).

Firstly, LS channel estimation is performed at positions of known signals (STF, LTF and pilot) by

\[ \hat{h}_{LS} = y / x \] (3)

Wherein \( \hat{h}_{LS} \) is the result of LS channel estimation, \( y \) is the receive signal, \( x \) is the transmit signal known in receiver.

Many methods can be used to estimate the frequency channel response based on LS of known signals, such as MMSE and DFT. 2D MMSE is best theoretically in the sense of minimum mean square error, but its computation complexity is too high. In order to facilitate implementation, 2D MMSE is generally divided into two 1D MMSE: time domain MMSE and frequency domain MMSE. MMSE needs to know or estimate Doppler frequency shift, time delay spread, etc. Therefore, sometimes 1D MMSE can be further simplified to linear interpolation. DFT transforms the frequency domain channel transfer function into the time domain impulse response. In the time domain, noise is reduced, and then the impulse response is transformed back into the frequency domain to obtain the channel response for all the carriers. DFT does not need to estimate channel characteristics and has low complexity, so easy to implement.

RF has 9 typical channels defined which are AWGN, rural 1, rural 2, typical city 1, typical city 2, bad city 1, bad city 2, mountain area 1, mountain area 2[12]. Figure 4 shows their temporal correlation. It can be seen that all channels change slowly with time. Even when the interval is 50 OFDM symbols, the correlation is still more than 0.95. Figure 5 shows their frequency domain correlation. High frequency selectivity can be seen for some channels, such as bad city 1 and mountain 2. For bad city 1, when the spacing is 10 carriers, the frequency domain correlation is already less than 0.5.
Considering the time-frequency characteristics of 9 typical channels and also trying to avoid to estimate channel characteristics, such as Doppler frequency shift and time delay spread, the following method is proposed.

For the first \(N(52)\) physical layer load OFDM symbols, an improved DFT-based method is used\[6,7\].

1) For each effective carrier, if the known signal is only LTF, LS channel estimation values of two LTF symbols are averaged; if the known signals are STF and LTF, LS channel estimate values of STF and LTF are averaged; if the known signals are LTF and pilots, LS channel estimate values of LTF and all pilots in the first \(N\) physical layer load symbols are averaged. Finally, a channel estimation value is got for each effective carrier with indexes \([-52, -1]\) and \([1,52]\);

2) The channel estimation values for carriers with indexes \([-64, -53]\) and \([53, 63]\) can be obtained by linear interpolation using the channel estimation values at carriers \(-52\) and \(52\) in step 1).

3) The channel estimation values obtained in step 1) and step 2) are transformed into time domain by IDFT. It is assumed that the time domain impulse response for each path is

\[
\hat{h}_l = h_l + n_l
\]  

(4)

Wherein \(l \in [1,128]\) is the path index, \(h_l\) is ideal channel impulse response, \(n_l\) is noise.

4) Wiener filtering is performed for each path with coefficients

\[
W = \frac{\left|\hat{h}_l\right|^2}{\left|\hat{h}_l\right|^2 - \sigma_n^2}
\]

(5)
Wherein $\sigma_n^2$ is noise power obtained by averaging power of paths from 41 to 108.

5) After Wiener filtering, the impulse response is transformed back into frequency domain to get the channel estimation for all carriers.

6) For each physical layer load symbol with index $n > N$, linear interpolation and filter are used in time and frequency domain respectively.

7) For each effective carrier $k$ in symbol $n$, if there is no pilot, time domain linear interpolation is performed with LS values of pilots within interval of $N$ OFDM symbols.

$$\hat{h}_{k,n} = \sum_i w_i \hat{h}_{LS,k,t} / \sum_i w_i$$  \hspace{1cm} (6)

Wherein $\hat{h}_{k,n}$ is the result of linear interpolation and the interpolation coefficients are

$$w_i = 1 - \left\lfloor d_i / 14 \right\rfloor \cdot 0.01, \quad d_i = |t-n| \leq N$$  \hspace{1cm} (7)

The time domain density of pilots is 4 pilot symbols in every 13 OFDM symbols, so the number of pilot symbols participating in each interpolation is about 32 within the interval of 52 OFDM symbols.

8) After linear interpolation, frequency domain filtering is used for each carrier $k$.

$$\hat{h}_{k,n} = \sum_f c_f \hat{h}_{f,n} / \sum_f c_f, \quad |f-k| \leq M$$  \hspace{1cm} (8)

Wherein $c_f$ is the filter coefficient which can be got by correlation of frequency channel responses in step 5), thus avoiding estimation of multipath delay spread which is necessary for MMSE. The value of $M$ depends on the channel type but is fixed to 12 in the proposed method in order not to estimate the channel type. The average spacing in frequency domain is 4 carriers, so there are about 6 channel estimate values participating in filtering.

5. Simulation results

In order to evaluate the performance of proposed method, link-level simulation is performed. 9 typical channels are all used in simulation.

Three different channel estimation methods are compared:
- M1: the proposed channel estimation method using STF, LTF and pilot
- M2: LTF-based channel estimation method
- M3: pilot-based channel estimation method

Two cases are simulated:
- C1: Option 1, PSDU TBS 16 bytes, MCS0(BPSK)
  C1 has 28 physical layer load symbols. It’s corresponding to the case with few physical layer load symbols.
- C2: Option 1, PSDU TBS 520 bytes, MCS0(BPSK)
  C2 has 364 physical layer load symbols. It’s corresponding to the case with large number of physical layer load symbols.

The simulation results of C1 are shown in table 3. The data in the table are SNR corresponding to block error rate BLER = 1%. It can be seen that when the number of physical layer load symbols is small, the proposed method (M1) is slightly better than LTF-based method (M2). The performance gain comes from the fact that STF and pilots participate in the noise reduction of LS channel estimation in frequency domain before IDFT. Both the proposed method (M1) and LTF-based method (M2) are about 2 ~ 3 dB better than pilot-based method (M3). This is mainly because both the proposed method and LTF-based method use LTF which are distributed over all effective carriers and the number of LTF symbols is large. However, pilot-based method only uses pilot and the number of pilots is small.
### Table 3. SNR corresponding to BLER=1%(C1).

| Channel    | M1  | M2  | M3  |
|------------|-----|-----|-----|
| AWGN       | -5.8| -5.5| -3.1|
| Rural 1    | -10.3| -10.2| -8.0|
| Rural 2    | -6.1| -6.0| -3.6|
| Typical city 1 | -7.0| -6.5| -4.4|
| Typical city 2 | -6.1| -6.1| -3.8|
| Bad city 1 | -6.2| -6.2| -4.0|
| Bad city 2 | -4.1| -3.9| -3.6|
| Mountain 1 | -7.1| -7.0| -4.5|
| Mountain 2 | -4.1| -4.0| -1.3|

The simulation results of C2 are shown in table 4. The data in the table are SNR corresponding to block error rate BLER = 1%. It can be seen that the proposed method (M1) is about 1.7 ~ 4.7db better than LTF-based method (M2). The reason is that for time-varying channels, such as bad city 1, mountain 2 and rural 2, when the interval between LTF and physical layer load symbols exceeds 200 OFDM symbols, the channel correlation is less than 0.5. At this time, LTF-based method is not applicable. The maximum performance loss can reach 4.7 dB (Bad city 1). The proposed method (M1) is still about 1dB better than pilot-based method (M3). This is mainly due to the participation of STF and LTF in the channel estimation of the first 52 symbols.

### Table 4. SNR corresponding to BLER=1%(C2).

| Channel    | M1  | M2  | M3  |
|------------|-----|-----|-----|
| AWGN       | -6.3| -6.1| -6.3|
| Rural 1    | -11.1| -11.0| -11.0|
| Rural 2    | -6.8| -5.1| -6.8|
| Typical city 1 | -8.1| -7.1| -7.2|
| Typical city 2 | -7.0| -7.0| -7.0|
| Bad city 1 | -10.0| -5.3| -9.3|
| Bad city 2 | -7.0| -4.1| -6.5|
| Mountain 1 | -8.0| -7.7| -8.0|
| Mountain 2 | -5.0| -1.3| -4.0|

### 6. Conclusion

HPLC can improve the data rate of power line carrier communication greatly. Therefore, it is widely used in automatic meter reading, intelligent home, intelligent community and other fields. However, there are some problems with HPLC, such as network outliers, low success rate of power outage reporting and short single hop communication distance. RF can effectively solve these problems and thus become an effective supplement to HPLC. For RF in HPLC&RF dual mode system, LTF-based channel estimation method is not applicable for time-varying channels especially when the number of physical layer load symbols is large. Pilot-based channel estimation method is not suitable for the case with few physical layer load symbols due to few pilot symbols and uneven frequency domain distribution, so this paper proposes a joint of STF, LTF and pilot based channel estimation scheme which can meet the requirements of different scenarios and has low complexity and easy for implementation.

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