Performance of synchronous CDMA for the PLC-based remote multi-machine control

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Abstract: This paper considers a multi-machine control system using power line communication (PLC). The signal-to-noise ratio (SNR) of PLC channels has cyclostationary features synchronous to the mains voltage. As a promising candidate of the multiple access scheme for the system, this latter proposes a synchronous code division multiple access (SCDMA) scheme that uses mains voltage as its system clock. By using orthogonal codes, the communication performance of each code-channel is equalized, and the worst-case performance is improved.

Keywords: PLC, Synchronous code division multiple access (SCDMA), Multiple machine control, Cyclostationary channel

Classification: Wireless communication technologies

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1 Introduction

The demand for the remote control for factory automation and smart grids is on the increase [1]. As means of communication for indoor remote control, power line communication (PLC), using the existing power lines as communication media, has attracted considerable attention [2]. This paper considers narrow band-PLC (NB-PLC) that is suitable for long-distance communication between the controller and multiple machines in large factories and buildings.

In feedback control, communication is repeated periodically. The period of communication is often about 10 \( [\text{ms}] \) in smart grid equipment [3]. This cycle is close to that of the absolute value of the mains voltage flowing in the power lines. Therefore, the authors considered the application of time division multiple access (TDMA) which uses the strong mains voltage as a clock for system synchronization [4].

Since the impedance and the noise of the electrical equipment connected to the lines vary synchronously with (the absolute value of) the mains voltage, the signal-to-noise power ratio (SNR) also fluctuates according to the cyclic mains voltage [5]. As a result, the communication quality of TDMA time slot assigned to each machine varies, and when multiple machines work together such as in factories, the poor quality machines dominate the total quality of the entire system. If we use frequency division multiple access (FDMA) instead of TDMA, this variation of SNR per channel still may not be mitigated as PLC noise is non-white [5].

This study thus proposes synchronous code division multiple access (SCDMA) with orthogonal codes using the stable mains voltage with high SNR as a clock. By performing communication of each machine at the same time and frequency using code channel, the communication quality of all channels is made to be uniform.

2 System Overview

2.1 1:M Feedback Control System Using NB-PLC

Fig. 1(a) shows the NB-PLC based 1:M multiple machines control system discussed in this paper. The feedback controller controls \( M \) machines via power lines at every control cycle of \( T_C \) seconds. In Fig. 1(a), \( x_m[i] \) is the state information of the \( m \)-th \( (m = 0, 1, 2, \cdots, M-1) \) machine in the \( i \)-th \( (i = 0, 1, 2, \cdots) \) control period transmitted in an \( N_P \)-bits packet. The receiver output corresponding to \( x_m[i] \) is \( \hat{x}_m[i] \). Based on \( \hat{x}_m[i] \), the controller calculates the control command \( u_m[i] \), and send it back to the machine by an \( N_P \)-bits packet. The receiver output at the \( m \)-th machine corresponding to \( u_m[i] \) is \( \hat{u}_m[i] \).

2.2 NB-PLC Channel model

In PLC systems, the receivers connected to the same power lines often observe the same time variation of SNR [6]. Therefore, in this paper, we assume that
Fig. 1: System model.

the noise voltage waveform \( n(t) \) in the signal band is common to all receivers\(^1\). Furthermore, it is assumed that \( n(t) \) is cyclostationary colored Gaussian noise with a cycle duration \( T_N = T_{AC}/2 \) (\( T_{AC} \) is the main voltage cycle duration). The power spectral density, mean, and variance of \( n(t) \) are respectively given by the following equations [5]

\[
S_n(f) = \frac{a}{2} \exp(-a|f|), \quad (1)
\]

\[
E[n(t)] = 0, \quad (2)
\]

\[
E[n^2(t)] = \sigma^2(t) = \sum_{\ell=0}^{L-1} A_\ell |\sin(2\pi t/T_{AC} + \theta_\ell)|^{n_\ell}. \quad (3)
\]

2.3 TDMA for NB-PLC

For comparison, we first describe the system using TDMA [4]. As shown in Fig. 1(b), the control period is divided into 2M slots.

The binary phase shift keying (BPSK) modulated signal in the \( \mu \)-th slot \((0 \leq \mu < 2M)\) of the \( i \)-th control cycle is expressed as

\[
s_{i,\mu}[T](t) = \sqrt{2P} \sum_{p=0}^{N_p-1} \Re[b_{i,\mu}[p] h_c(t - pT_S - T_{i,\mu}^{[T]}) \exp(j\omega_c t)], \quad (4)
\]

\[
T_{i,\mu} = \mu T_P^{[T]} - iT_C, \quad (5)
\]

where \( P \) is the received carrier power, \( h_c(t) \) is a pulse of the symbol duration \( T_S \), and \( b_{i,\mu}[p] \in \{\pm 1\} \) is the \( p \)-th bit of the packet transmitting the status information \( x_{\mu/2}[i] \) for an even \( \mu \) or the control command \( u_{(\mu+1)/2}[i] \) if \( \mu \) is odd.

The receiver demodulates the signal arrived with noise \( n(t) \) by integrating for the bit duration \( T_b \) to obtain the sample corresponding \( b_{i,\mu}[p] \) to each bit

\(^1\)Precisely, \( n(t) \) is the noise voltage normalized by the received signal voltage.
expressed as
\[ r_{i,\mu}[p] = \frac{1}{T_b} \int_{(p+1)T_b + T_{i,\mu}^{[T]}}^{pT_b + T_{i,\mu}^{[T]}} (s_{i,\mu}^{[T]}(t) + n(t)) dt = \sqrt{2P} b_{i,\mu}[p] + n_{i,\mu}^{[T]}[p]. \] (6)

The mean and variance of this Gaussian random sample are given by
\[ E[r_{i,\mu}^{[T]}[p]] = \sqrt{2P} b_{i,\mu}[p], \] (7)
\[ E[(r_{i,\mu}^{[T]}[p])^2] = \frac{1}{T_b} \int_{(p+1)T_b + T_{i,\mu}^{[T]}}^{pT_b + T_{i,\mu}^{[T]}} \hat{\sigma}^2(t) dt = \hat{\sigma}_{i,\mu}^{2[T]}[p]. \] (8)

Based on this sample \( r_{i,\mu}^{[T]}[p] \), the receiver makes the decision.

### 2.4 Synchronous CDMA for NB-PLC

Using SCDMA multiple signals are transmitted simultaneously. Therefore, the control period is divided into two equal length slots, as shown in Fig. 1(c).

In the SCDMA system, the data bit stream is first spread by an orthogonal spreading code
\[ w_m = (w_m[0], w_m[1], \ldots, w_m[M - 1]). \] (9)

Then, each chip is interleaved to mitigate the influence of bursty noise. The signals from and to the \( m \)-th machine in the \( i \)-th control cycle are thus expressed as \( s_{i,2m}[t] \) and \( s_{i,2m+1}[t] \), respectively, with \( s_{i,\mu}[t] \) defined as
\[ s_{i,\mu}^{[C]}(t) = \sqrt{2P} \sum_{q=0}^{MN_p-1} \text{Re}[c_{i,\mu}[q]h_c(t - qT_S - T_{i,\mu}^{[C]}) \exp(j\omega_c t)], \] (10)
\[ T_{i,\mu}^{[C]} = (\mu - 2\lfloor \mu/2 \rfloor)T_p^{[C]} + iT_C, \] (11)

where \( c_{i,\mu}[q] \in \{\pm 1\} \) is an interleaved chip data given by
\[ c_{i,\mu}[q] = b_{i,\mu}[q - N_P\lfloor q/N_P \rfloor]w_{\lfloor \mu/2 \rfloor}[[q/N_P]], \] (12)

where \( \lfloor \cdot \rfloor \) is the floor function.

The receiver demodulates the signals \( s_{i,\mu}^{[C]}(t) \) arrived with noise \( n(t) \) and the integration with the chip length \( T_S \), and obtains the received samples corresponding to each chip expressed as
\[ r_{i,\mu}^{[C]}[q] = \frac{1}{T_S} \int_{qT_S + T_{i,\mu}^{[C]}}^{(q+1)T_S + T_{i,\mu}^{[C]}} \left( \sum_{m=0}^{M-1} s_{i,2m+\lfloor \mu/2 \rfloor}[t] + n(t) \right) dt \]
\[ = \sqrt{2P} \sum_{m=0}^{M-1} c_{i,2m+\lfloor \mu/2 \rfloor}[q] + n_{i,\mu}^{[C]}[q]. \] (13)

Thus, its mean and variance are respectively given by
\[ E[r_{i,\mu}^{[C]}[q]] = \sqrt{2P} \sum_{m=0}^{M-1} c_{i,2m+\lfloor \mu/2 \rfloor}[q], \] (14)
\[ E[(r_{i,\mu}^{[C]}[q])^2] = \frac{1}{T_S} \int_{qT_S + T_{i,\mu}^{[C]}}^{(q+1)T_S + T_{i,\mu}^{[C]}} \hat{\sigma}^2(t) dt = \hat{\sigma}_{i,\mu}^{2[C]}[q]. \] (15)

Then, the receiver de-spreads the sequence of the samples with the spreading code \( w_m \) corresponding to the \( m \)-th machines, and the interference component disappears by the orthogonal code. Thus, \( q_{i,\mu} \) correspondence of \( b_{i,\mu} \) is obtained. Based on this value \( q_{i,\mu}[p] \), the receiver makes the decision.
Table I: Parameters

(a) For communication

| Modulation scheme | BPSK       |
|-------------------|------------|
| Average SNR       | 3~7[dB]   |
| \( M \)           | 4          |
| \( N_P \)         | 40[bit]   |
| \( 1/T_{AC} \)    | 60[Hz]    |
| Spreading code    | Walsh      |
| Length of codes   | 4          |

(b) For the PLC noise \((L = 3)\).

| \( \ell \) | 0 | 1 | 2       |
|-------------|---|---|---------|
| \( A_\ell \) | 0.230 | 1.38 | 7.17 |
| \( \theta_\ell \) [deg] | - | -6 | -35 |
| \( n_\ell \) | 0 | 1.91 | \( 1.57 \times 10^5 \) |
| \( a \) | \( 1.2 \times 10^{-5} \) |

3 BER and PER

The error rate of the \( p \)-th bit of the \( \mu \)-th slot in the \( i \)-th period of TDMA is given by

\[
BER_{i,\mu}^{[T]}[p] = \frac{1}{\sqrt{2\pi \sigma_{i,\mu}^{[T]}[p]}} \int_{-\infty}^{\infty} \exp\left(-\frac{x^2}{2\sigma_{i,\mu}^{[T]}[p]^2}\right) dx = \frac{1}{2} \text{erfc}\left(\frac{P}{\sqrt{\sigma_{i,\mu}^{[T]}[p]^2}}\right),
\]

where \( \text{erfc}(\cdot) \) is the complementary error function. Similarly, the error rate of the \( p \)-th bit of the signal of \( \mu \)-th slot in SCDMA is given by

\[
BER_{i,\mu}^{[C]}[p] = \frac{1}{2} \text{erfc}\left(\frac{P M^2}{\sum_{l=0}^{M-1} \sigma_{i,\mu}^{[C]}[p + lN_P]^2}\right).
\]

The packet error rate \( \text{PER}_{i,\mu} \) becomes

\[
\text{PER}_{i,\mu} = 1 - \prod_{p=0}^{N_P-1} (1 - BER_{i,\mu}[p]).
\]

4 Numerical Examples

In this section, we present numerical examples of BER and PER with system and noise parameters shown in Tables I(a) and I(b). Since SNR is time-varying, we use the average SNR \((\text{SNR})\) defined below as the parameter of communication channel quality

\[
\text{SNR} = \frac{1}{MT_C} \int_{T_C} \frac{\sum_{m=0}^{M-1} s_m^2(t)}{E[\nu^2(t)]}. \tag{19}
\]

In the transmission of states information, SCDMA has \( M \) times transmission time compared with TDMA. Therefore, under the condition that \( \text{SNR} \) is the same, the transmission power of each device of SCDMA is \( 1/M \) of TDMA.

Fig. 2(a) and Fig. 2(b) show the BER of each bit within one control period with TDMA and proposed SCDMA, respectively. The BER of each bit with TDMA varies greatly, whereas that with SCDMA is almost equal by chip-level interleaving. Also, since the bit duration of SCDMA is four times longer than that of TDMA, the influence of the cyclic impulse noise at the 224-th bit of TDMA, which often dominates the overall system performance, is mitigated as the 61-th bit of SCDMA.
As shown in Fig. 2(c), the PER in each slot of TDMA varies because of fluctuation of noise power. Therefore each machine has a different communication quality. On the other hand, as shown in Fig. 2(d), the PER of all four code channels of SCDMA are equal. Comparing Figs. 2(c) and 2(d), we find that the slots 3-7 of TDMA have worse PER than that of SCDMA. This suggests that the machines using these TDMA slots may have better control performance if SCDMA is used.

5 Conclusion

In this paper, we proposed the introduction of SCDMA with orthogonal codes in multiple machine control system using PLC, and compare the communication quality of TDMA. It is confirmed that the proposed system provides a perfectly equal-quality channel to every machine, while each TDMA channel has quality difference. In conclusion, SCDMA is suitable for multiple machine communication because of its perfect equal-channel quality for each machine, ease of synchronization using the strong mains voltage as a clock, and good PER performance.

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