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An Efficient Estimation of Carrier Frequency Error in Multicarrier Spread Spectrum System for Power Line Communications

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Abstract—**Multicarrier spread spectrum (MC-SS) systems exhibit good robustness against all kinds of narrowband interference, coloured noise or selective attenuation for power line communications. However, the systems' vulnerability to frequency synchronization errors, which introduce loss of orthogonality between the subcarriers, is still a challenging problem for robust communications. This paper presents a novel multicarrier spread spectrum system with carrier frequency error estimation and low complexity by frequency division multiple access (FDMA) approach to cope with highly unpredictable harsh power line channel. Experimental results demonstrate that the frequency error estimation and compensation based on a successive phase difference measurement can achieve performance near to that without frequency errors, leading to robust communications for smart grid applications.**

Keywords—**multicarrier spread spetrum system, frequency error estimation and compensation, power line communications**

I. Introduction

Power line communications (PLC) has now become a critical energy control networking technology for smart grid applications, because the power line networks are almost universal in coverage and are easily accessed by wall plugs [1]. However, the distribution network made up of power lines are an extremely harsh environment, where the time-variant characteristics of the noise and the attenuation limit the communication performance that can be achieved [2]. PLC channel can be considered as a frequency-selective multipath fading channel with time-varying behaviour, and is impaired by various sources of noise with the superposition of narrowband interference [3]. This is why sophisticated communication schemes such as spread spectrum (SS) techniques and multicarrier modulation (MCM) such as orthogonal frequency division multiplexing (OFDM) solutions have often been proposed to achieve higher performance [2]. Spread spectrum techniques can exploit spectral diversity to effectively combat the multipath fading [4]. Multicarrier modulation on the other hand can achieve the highest performance in channels with frequency-selective fading [5]. The combination of MCM and SS techniques i.e. multicarrier spread spectrum (MC-SS) system therefore can form a more effective multiple access scheme with data spread over all the subcarriers through a unique spreading code [6]. These systems generally exhibit good robustness against all kinds of narrowband interference, coloured noise or selective attenuation. However, current MC-SS systems using many speading sequences (as in MC-CDMA) or using a large number of closely-spaced orthogonal subcarriers (as in OFDM) to achieve the highest capacity not only increase the system complexity, but also are sensitive to carrier frequency error, which is still a challenging problem for robust communications. For example, OFDM techniques can achieve capacity very near the theoretical limit, but at the cost of an increase in system complexity [7] and with the drawback of requiring the cyclic prefix whose duration depends on the channel memory, which is quite long in PLC channels. In addition, the OFDM systems are sensitive to the frequency synchronization errors in form of carrier frequency error, because it can cause the inter-carrier interference (ICI) which can lead to the frequency mismatched in transmitter and receiver oscillator. For this reason, many methods have been proposed to estimate carrier frequency error in OFDM system [8], but usually with high complexity making implementation difficult. This paper presents a novel multicarrier spread spectrum system with carrier frequency error estimation and low complexity for robust power line communications.

II. System Model

To reduce the system complexity, we develop an MC-SS system using only one spreading sequence and the number of parallel subcarriers is dependent on the available bandwidth and the frequency spacing that meets orthogonally separated condition. The system developed is illustrated in Fig. 1 with receiver equipped with wavelet filtering and coherent accumulation for noise suppression [9].

Consider a baseband digital MC-DSSS (multicarrier direct sequence spread spectrum) communications system, the received signal $y(t)$ can be modeled as

$$y(t) = s(t) + n(t) \tag{1}$$

where $s(t) = \sum_{i=1}^{N} A_i d_i(t) c(t) \cos(2\pi f_{c_i} t + \theta)$ and $n(t)$ is power line noise, $s(t)$ is binary phase shift keying (BPSK) direct sequence spread spectrum signal, $c(t)$ is the spreading (pseudonoise i.e. PN) sequence (PN code) taking on values ± 1, $d_i(t)$ is a binary sequence of data symbols on channel i ,

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f_{c_i} is the ith subcarrier frequency of the transmitted signal, A_i is the amplitude of the signal and θ is the initial phase, N is the number of subcarriers (channels). Data symbols are independently multiplied with an orthogonal variable spreading factor (OVSF) code and transformed into a number of chips. Let C denote the chip rate of the PN code, and 2^n-1 is the length of the PN code (n is a positive integer), then we have the line frequency spacing for one PN code signal

$$\Delta f_l = \frac{C}{2^n-1} = \frac{chip\ rate}{code\ length} \tag{2}$$

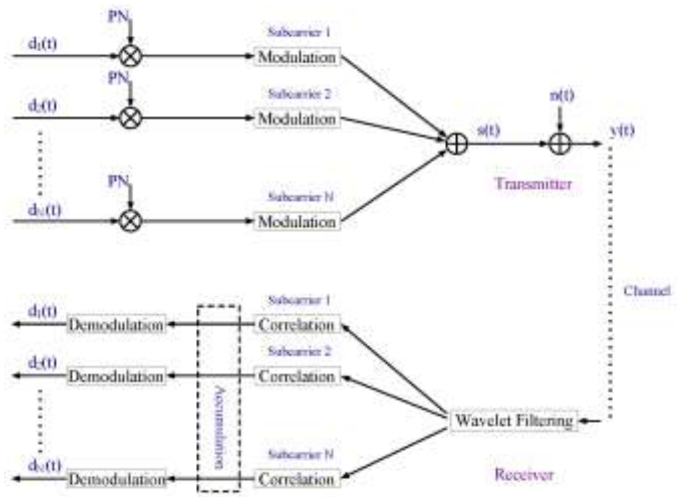

Figure 1. The developed MC-SS system

In fact, the spreading signal is often sampled at the receiver on a block basis. If in a data block we have totally N number PN code spreading signal, then the frequency offset can be:

$$\Delta f = \frac{mC}{(2^n-1)N} = \frac{m}{N}\Delta f_l \tag{3}$$

where m is a positive integer used to adjust the channel spacing. This offset for each subcarrier can satisfy the channel orthogonality condition:

$$\frac{1}{T_\Delta}\int_{iT_\Delta}^{(i+1)T_\Delta} \exp(j2\pi f_k t)dt = \begin{cases} 0 & k \neq i \\ 1 & k = i \end{cases} \tag{4}$$

where $T_\Delta = \dfrac{1}{\Delta f}$, k and i are integers, $f_k = f_c + k\Delta f$.

When $m=1$, it reaches minimum frequency separation as similar to OFDM system. The choice of m is very important as it allows obtaining the maximum frequency spacing of subcarriers within the bandwidth available. Strictly speaking, it is the product Δt and Δf that defines the effective improvement in bandwidth usage. This is because the limitation of time-frequency localization at any frequency in space time is governed by the uncertainty principle, which is expressed by $\Delta t \cdot \Delta f \geq \dfrac{2}{\pi}$, where Δt and Δf represent temporal and frequency deviations from a base-line. So we have

$$\frac{2^n-1}{C}\cdot\frac{mC}{(2^n-1)N} \geq \frac{2}{\pi} \quad \text{thus} \quad m \geq \frac{2}{\pi}N$$

The entire bandwidth is divided into N parallel subcarriers with the center subcarrier frequency of f_c as:

$$\{f_c-(\frac{N}{2}-1)\Delta f\},\cdots,\{f_c-\Delta f\},\{f_c\},\ \{f_c+\Delta f\},\cdots,\{f_c+\frac{N}{2}\Delta f\}$$

The channels are equally spaced around central channel N/2 (subcarrier frequency f_c) and the channel spacing is variable. Consequently, multiple access between the N subcarriers is managed following a frequency division multiple access (FDMA) approach, instead of a code division multiple access (CDMA) approach. The correlation is an FFT (Fast Fourier Transform) based despreading process at the receiver, and the subcarrier frequency error ε can be represented in each subchannel:

$$\{f_c-(\frac{N}{2}-1)\Delta f+\varepsilon_1\},\cdots,\{f_c-\Delta f+\varepsilon_{N/2-1}\},\{f_c+\varepsilon_{N/2}\},$$

$$\{f_c+\Delta f+\varepsilon_{N/2+1}\},\cdots,\{f_c+\frac{N}{2}\Delta f+\varepsilon_N\}$$

Indeed, a residual frequency error between the transmitter and receiver local oscillators leads to a loss of orthogonality between the different subcarriers, thus giving rise to degradation in the overall system performance.

III. Carrier Frequency Error Estimation

The developed MC-SS system is a multicarrier technique with orthogonal subcarriers. Its vulnerability to synchronization errors, which result from misalignment in carrier frequencies, can introduce loss of orthogonality between the subcarriers. The presence of carrier frequency error introduces inter-carrier interference (ICI) and inter-symbol interference (ISI), thus needs to be estimated and corrected.

For frequency error estimation, consider BPSK symbol transmitted on ith subcarrier from (1):

$$s_i(t) = A_i d_i(t)c(t)\cos(2\pi f_{c_i}t+\theta) \tag{5}$$

So the phase change with time t is

$$\phi_{i,l} = 2\pi(f_{c_i}+\varepsilon_i)t_l+\theta \tag{6}$$

where ε_i is carrier frequency error and $l=1,2,\cdots,N$ denotes the location of PN code signal in the time domain. From (4), we have

$$f_{c_i} = f_c + k\Delta f \tag{7}$$

where $k=-(\frac{N}{2}-1),\cdots,-1,0,1,\cdots,\frac{N}{2}$

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Define the phase difference:

$$\Delta\phi = \phi_{i,l+1} - \phi_{i,l} = 2\pi(f_{c_i} + \varepsilon_i)(t_{l+1} - t_l) \tag{8}$$

As $t_{l+1} - t_l$ is the time space between PN codes, it becomes the same as symbol duration T ($T = \frac{2^n - 1}{C}$). Therefore we have

$$\Delta\phi = 2\pi(f_c \frac{2^n-1}{C} + k\frac{mC}{(2^n-1)N}\cdot\frac{2^n-1}{C} + \varepsilon_i\frac{2^n-1}{C})$$
$$= 2\pi(f_c\frac{2^n-1}{C} + k\frac{m}{N} + \varepsilon_i\frac{2^n-1}{C}) \tag{9}$$

By properly selecting center subcarrier frequency f_c and integer m, the phase $2\pi(f_c\frac{2^n-1}{C} + k\frac{m}{N})$ can be a number of complete 2π cycles thus can be cancelled, so that the frequency error can be estimated as

$$\varepsilon_i = \frac{\Delta\phi C}{2\pi(2^n-1)}) \tag{10}$$

The phase difference $\Delta\phi$ can be measured by calculating the phase difference at the correlation peak locations between the N PN code signals and averaging the $N-1$ results. At the receiver, the final result of frequency error estimation could be used for correlation process, where the carrier frequency error of the received signal is compensated before correlation operation as

$$r_i(t)\cdot\cos[2\pi(-\varepsilon_i)t] = A_i d_i(t)c(t)\cos[2\pi(f_{c_i} + \varepsilon_i)t + \theta]\cdot\cos[2\pi(-\varepsilon_i)t] \tag{11}$$

where $r_i(t)$ is the received signal at subcarrier i with carrier frequency error ε_i to compensate.

In practice, when the developed MC-SS system is implemented, we have the received multipath signal

$$r(t) = h(t)*y(t) = \int_{-\infty}^{\infty} h(\tau,t)y(t-\tau)d\tau$$
$$= \sum_{i=1}^{N_p} a_i \exp[j\phi_i(t)]y(t-\tau) \tag{12}$$

where $h(t)$ is the impulse response of the channel, $*$ denotes convolution, τ is time delay, a_i is the path weight and $\phi_i(t)$ is the phase at path i. The received multipath signal is the sum of N_p attenuated, phase shifted and delayed replicas of the transmitted signal $y(t)$. In the frequency domain, we have

$$\hat{R}(f) = \hat{H}(f)\hat{Y}(f) = \hat{H}(f)[\hat{S}(f) + \hat{N}(f)]$$
$$= \sum_{i=1}^{N}[\hat{R}_i(f)\uparrow^N] = \sum_{i=1}^{N}[\hat{R}(f)\downarrow_N] \tag{13}$$

where $\hat{R}(f)$ is the Fourier transform of received signal $r(t)$, $\hat{H}(f)$ is the frequency response of the channel, $\hat{Y}(f)$ is the Fourier transform of transmitted signal $y(t)$, $\hat{S}(f)$ is the Fourier transform of spreading signal $s(t)$, $\hat{N}(f)$ is the Fourier transform of noise $n(t)$, $\hat{R}_i(f)$ is the Fourier transform of received signal $r_i(t)$ at subcarrier i, $\uparrow^N$ denotes the operation of upsampling by a factor of N, $\downarrow_N$ denotes the operation of downsampling by a factor of N. The system thus can be implemented by FFT based correlation with low computational complexity.

IV. Experimental Results and Discussions

To evaluate the proposed system, an example of low complexity MC-SS system was set up for power line communications. The transmitter uses the spreading code to modulate the data transmissions. The system spreading code is a maximal sequence 511 ($n = 9$, $2^n - 1 = 511$) chips PN code clocked at a 1 MHz chip rate. Thus 511 chips were applied to each transmitted symbol. The length of sample data block was chosen to be a complete 8 PN code periods so that the number of subcarriers is: N=8, and the channel spacing is ($m = 72 > \frac{2}{\pi}N$):

$$\Delta f = \frac{mC}{(2^n-1)N} = \frac{72\times 1000\ kHz}{511\times 8} = 17.6\ kHz$$

After low-pass filtering, this data spreading signal is mixed with a carrier frequency (centred on 5 MHz) by BPSK to generate the transmitted spread spectrum signal. Spreading signal is transmitted by frequency-selective multipath fading channel with additive white Gaussian noise (AWGN). BPSK interfering signal from the output of the channel then enters the receiver. At the receiver, modulated signal is downconverted to intermediate frequency (IF) at 1 MHz. The received signal is sampled with data block length of 8 PN code spreading signal. The final detection output is obtained through FFT based correlation. Tests were performed with multicarrier spread spectrum signal passing through the channel and results were measured by conducting bit error rates (BER) performance comparisons versus signal to noise ratio (SNR) at noise levels set. To measure the phase difference for carrier frequency error estimation as in (10), we have

$$2\pi(f_c\frac{2^n-1}{C} + k\frac{m}{N}) = 2\pi(5\times 511 + 9k)$$

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Table I. Measurement of phase difference $\Delta\phi$ between the 8 PN code signals

No	1	2	3	4
$\Delta\phi$	0.1650	0.1463	0.1562	0.1737

No	5	6	7	Average
$\Delta\phi$	0.1287	0.1408	0.2062	0.1596

It is a number of complete 2π cycles. The phase difference was measured by calculating the phase difference between the 8 PN code signals (an example of phase difference $\Delta\phi$ measurements is shown in Table I) and the averaging result is 0.1596 (carrier frequency error estimated is 49.7 Hz), which corresponds to the carrier frequency error 50 Hz. Fig. 2 shows one example of the test results by conducting multicarrier (8 subcarriers) transmission with averaged BER, and setting subcarrier 2 with carrier frequency error 50Hz, subcarrier 4 with carrier frequency error -50Hz, subcarrier 6 with carrier frequency error 100Hz and subcarrier 1 without carrier frequency error for comparison. Using the carrier frequency error estimation method, they were estimated as 49.7Hz, -50.2Hz, 100.8Hz, respectively. The estimations were accurate and the results were used to compensate the received signal. As can be seen in Fig. 2, the frequency error compensation can achieve performance near to that without frequency errors. It is evident that the estimation based on a successive phase difference measurement and compensation at the receiver significantly improves the system performance and can be implemented at the process of FFT based correlation with low computational complexity.

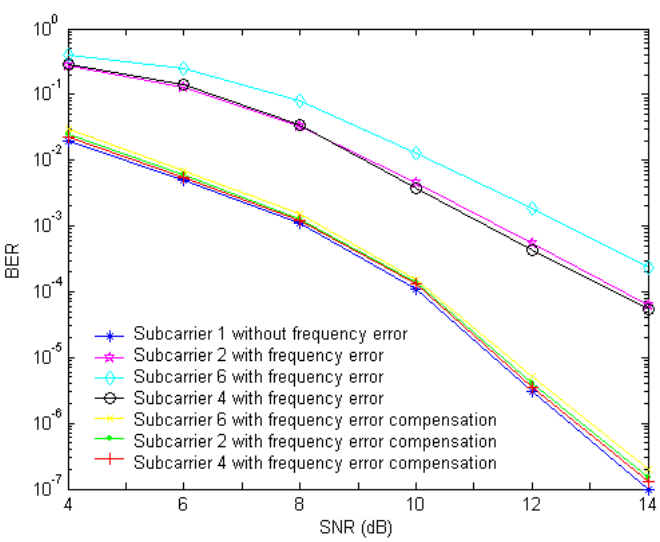

Figure 2. BER performance comparisons

V. Conclusions

In this paper, we proposed a novel multicarrier (MC) spread spectrum (SS) system with carrier frequency error estimation and low complexity for data communications over power lines. We investigated MC-SS system with carrier frequency errors introducing loss of orthogonality between the subcarriers by frequency division multiple access (FDMA) approach. Experimental results demonstrate that the developed MC-SS system with carrier frequency error estimation and compensation at the receiver can effectively improve system performance, while the implementation at the process of FFT based correlation is efficient with low computational complexity.

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Gaoyong Luo is a Professor and has been heading the Department of Electronics Information at Guangzhou University. He has a Ph.D. in Electrical Engineering from Brunel University, UK. Since 1998, he has been with Buckinghamshire Chilterns University College and Buckinghamshire New University. He has taught thousands of students and supervised the work of Ph.D. students. His main research interests are in the field of wavelets, spread spectrum communications, wireless positioning, remote sensing, audio coding, and power line communications, with expertise in coding and modulation theory and applications to communication systems.

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