

High-speed Power Line Communication System based on Wavelet OFDM

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Abstract

Recently, the demand of high-speed network in home is increasing. PLC (Power Line Communication) is expected as one method of realizing it. OFDM is one of the methods, which realizes high-speed PLC. But the minimum stopband attenuation of OFDM modulation is only -13dB. It indicates that OFDM subchannels are not spectrally isolated, therefore OFDM is sensitive to the locations of narrow band interferences. In order to hardly give interference to other systems, OFDM scheme needs skipping many subchannels or using a notch filter in the frequency bands used by the other systems. The former method degrades the efficiency of frequency use and the latter method increases circuit scale.

The system we propose is not Fast Fourier Transform (FFT) based OFDM but wavelet based OFDM. Wavelet OFDM (WOFDM) provides subchannel isolation that is superior to FFT based OFDM. In WOFDM, the stopband attenuation and the transition width from stopband to passband can be selected. Thus WOFDM can be designed for a given level of interference rejection by skipping a few subchannels in the frequency bands. And narrowband interference affects only a few subchannels which correspond to these interferences due to a limited spectral overlap between its subchannels. In this paper, we show the WOFDM system suitable for PLC and its Bit Error Rate (BER) characteristic in Additive White Gaussian Noise (AWGN) and its Carrier to Noise Ratio (CNR) property with an imitated transmission channel.

1. Introduction

Multicarrier modulation (MCM) is now a widely used technique for high-speed transmission over channels such as digital subscriber line and power line. Its basic idea is to divide the channel spectrum into parallel, narrowband subchannels. Multicarrier signaling offers the advantages of simpler equalization, immunity to impulse noise and flexibility in allocating subchannels. OFDM results in a simple and computationally efficient implementation of the system, using FFT. But Fourier based OFDM is sensitive to

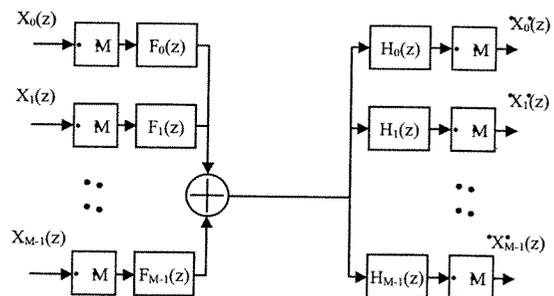


Fig. 1. Maximally decimated M-channel TMUX.

the location of narrowband interference. Because the minimum stopband attenuation of conventional Fourier OFDM modems is only -13 dB. This limitation is a major weakness of FFT. OFDM scheme needs additional narrow band interference canceller (e.g. notch filter) before forward FFT transform for performance improvements. As alternative technique, discrete wavelet transform (DWT) in the form of perfect reconstruction (PR) filter bank [1]-[3] used in place of FFT was proposed in [4]-[8]. DWT consists of an M-band transmultiplexer (TMUX) as shown in Fig. 1. Connection between an M-band filter bank and an M-band TMUX was first observed by Vetterli in [9]. The TMUX uses filters of greater length than the rectangular filters of OFDM and typically results in much lower sidelobe levels. Better stopband attenuation results in both lower levels of interchannel interference (ICI) and greater robustness to narrowband interference. In particular, critically decimated perfect reconstruction cosine-modulated filter bank (PR-CMFB) with TMUX is used because they can be implemented in a computationally efficient manner using polyphase representation of the filterbank and fast DCT algorithm, and the design is simpler than for general filterbanks because all the filters are derived from a single prototype filter. PR-CMFB is of length gM , where M is the number

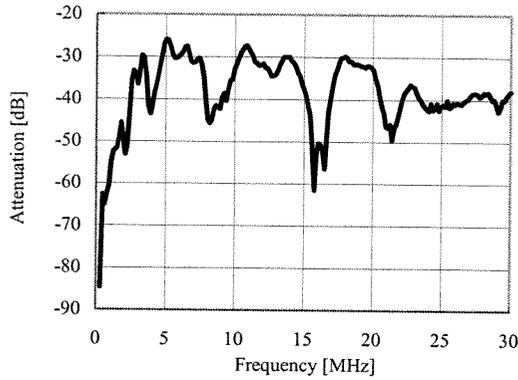


Fig. 2. An attenuation characteristic of the power line at an apartment.

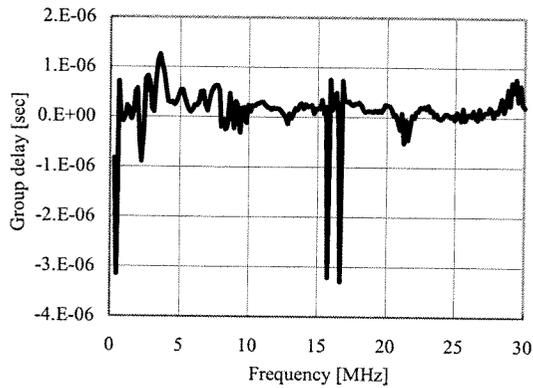


Fig. 3. A group delay characteristic of the power line at an apartment.

of subchannels and g is the overlapping factor. The comparative performance of OFDM and PR-CMFB was already studied in [4]-[8] and it was demonstrated that PR-CMFB systems are worthy candidates for MCM. The main interest here is on PR filterbank. However, near perfect reconstruction (NPR) filter bank can also be an interesting choice. Sometimes it is judicious to relax the PR conditions by allowing small amplitude and aliasing errors. This results in improved stopband attenuations.

In this paper, we use a form of DWT, called PR-CMFB and analyze the performance of WOFDM in AWGN and imitated transmission channel of power line.

2. Transmission Channel Characteristic of Power Line

The transmission channel characteristic of power line differs one outlet from another. Figs. 2 and 3 show an attenuation characteristic and a group delay characteristic of the power line at an apartment. In power line channel, transmitted signals are particularly decreased in local bands.

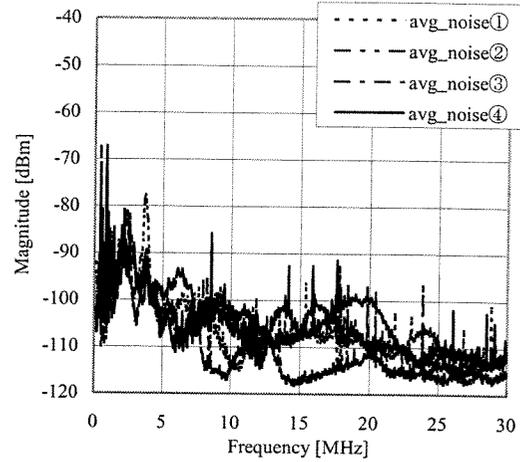


Fig. 4. Noise properties of the power line at an apartment (Average, RBW=10KHz).

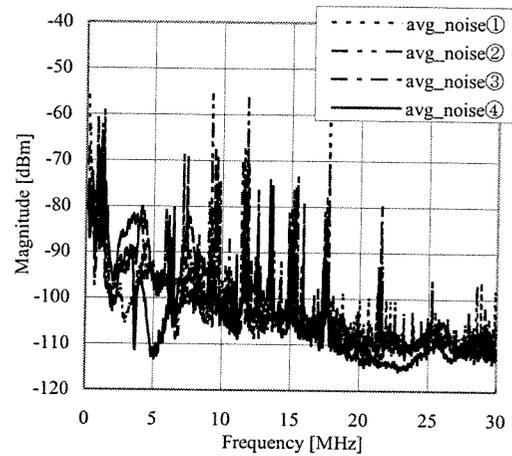


Fig. 5. Noise properties of the power line at a house (Average, RBW=10KHz).

And large group delays of several microseconds exist there. Figs. 4 and 5 show noise properties of an apartment and a house, respectively. Particularly, there are a lot of narrowband interferences in Fig. 5.

3. WOFDM System

3.1. Block diagram of WOFDM

The block diagram of the WOFDM system, using an M-band TMUX is shown in Fig. 6. The modulator and the demodulator can be implemented efficiently using prototype filters and fast transforms. The coding is a simple Pulse Amplitude Modulation (PAM). The data bits are

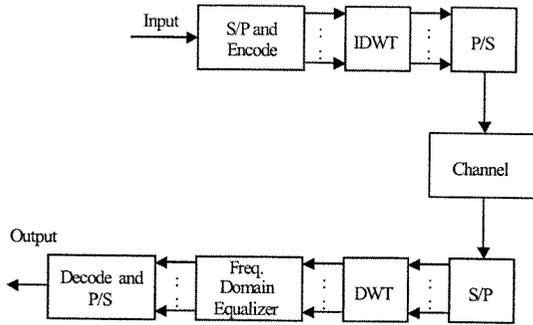


Fig. 6. Block diagram of WOFDM.

encoded into multi-level PAM symbols and the PAM symbols are then mapped to individual subchannels. The IDWT produces a time domain sequence. At the receiver, the digital time domain signal is transformed back into the PAM symbols via the DWT. The frequency domain equalizer (FEQ) is a complex single tap equalizer that compensates each subchannel output with the inverse of the channel frequency response at the subchannel frequency. A similar idea for modulated complex lapped transform, which can be used in audio processing applications, is considered in [10]. And a complex lapped transform was introduced in [11], with the purpose of using its phase information for motion estimation in video coding. In addition, various FEQ schemes are proposed in [4], [12], [13].

3.2. Spectrum characteristic of an OFDM and a WOFDM

Figs. 7 and 8 show the spectrum characteristic of an OFDM and a WOFDM (the overlapping factor $g = 4$) implementation, respectively. A WOFDM spectrum has the additional 22dB of stopband, allowing much superior adjacent band rejection as compared to an OFDM. OFDM scheme needs additional narrow band interference canceller (e.g. notch filter) before forward FFT transform for performance improvements and skipping many subchannels or using a notch filter in the frequency bands used by other systems in order to reduce interference to them.

3.3. WOFDM property

The property of WOFDM is such that the subchannels overlap spectrally and the pulses transmitted in a subchannel overlap in time, while orthogonality among the pulses for different symbols is maintained. The frequency overlap of adjacent subchannels results in spectrally efficient transmission and the time-overlapped pulses provide spectral shaping of the individual subchannel

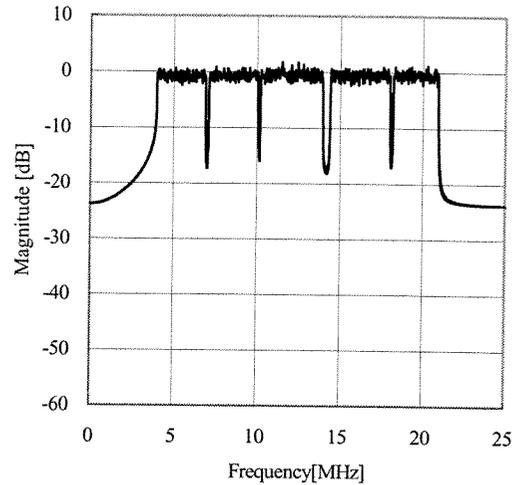


Fig. 7. OFDM Spectrum.

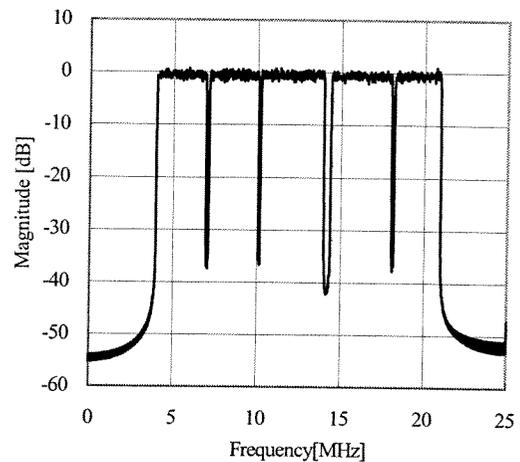


Fig. 8. WOFDM Spectrum.

filters. A WOFDM symbol spans g symbols and the latency of a WOFDM depends on the overlapping factor g . Therefore there is a system level trade-off between immunity to noise (impulse and ingress) and system latency. As g grows, the immunity to impulse noise grows and the sidelobe levels in the WOFDM subchannels decrease thereby providing better spectral containment and better immunity to ingress noise.

WOFDM does not require the use of a guard period or cyclic prefix (guard interval) between symbols because of its superior subchannelization by design. Hence, the overhead for WOFDM is less than that of OFDM.

WOFDM is a multicarrier modulation with a one-dimensional constellation. The energy per bit to noise power density ratio (E_b/N_0) requirements for a given BER

are the same as for OFDM.

4. Simulation Results

We propose a WOFDM system in PLC application. It is a better multicarrier modulation scheme compared to OFDM due to its better-localized subchannels in frequency. In order to decrease the spectral overlapping of subchannels, WOFDM uses better stopband properties for its subchannels.

In our simulation, we use 1024-channel DWT with $g=4$. The bandwidth to be used is $4 \cdot 21$ MHz (including about 654 subchannels) as shown in Fig. 8. The symbol period is 20.48 (μ sec). These subchannels have less than -35 dB stopband sidelobe properties. The synchronization of this simulation is ideal except subsection 4.3. The training sequences for the FEQ are four symbols of 1.

4.1. Narrowband interference

At the receiver, we calculate the Carrier to Interference and Noise Ratio (CINR) for each subchannel. Here we use variances $\sigma_{x_k}^2$ of the k -th transmitted signal and $\sigma_{e_k}^2$ of the difference of the k -th transmitted signal and received signal in calculating the CINR

$$CINR_k = 10 \log_{10} \frac{\sigma_{x_k}^2}{\sigma_{e_k}^2}, \quad k = 0, 1, \dots, M-1 \quad (1)$$

In this simulation, the singletone interference with $f_0 = 12.55$ (MHz) is injected at the receiver, with Carrier to Interference Ratio (CIR) = 0 (dB) and $E_b/N_0 = 27$ (dB). After initial training, the CINR is calculated and shown in

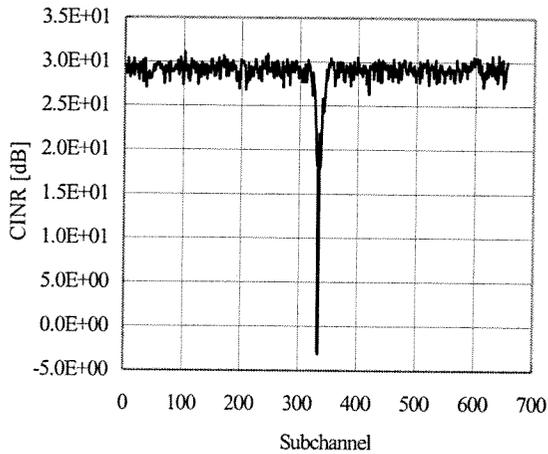


Fig. 9. WOFDM CINR characteristic.

Fig. 9. The FEQ works fine except around the subchannel 334 where the singletone interference locates.

4.2. Timing Errors

For actual systems with channel component induced distortions and timing errors, orthogonality between the subchannels is no longer preserved. The FEQ at the output of the WOFDM demodulator are used to compensate for these practical imperfections that result in Interchannel Interference (ICI), Intersymbol Interference (ISI) and

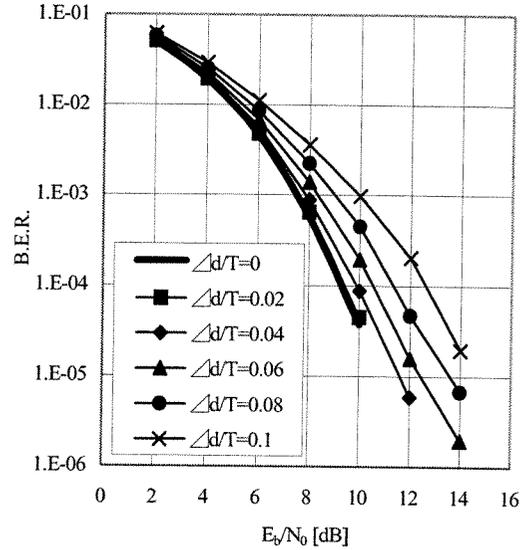


Fig. 10. BER performance of 2-PAM.

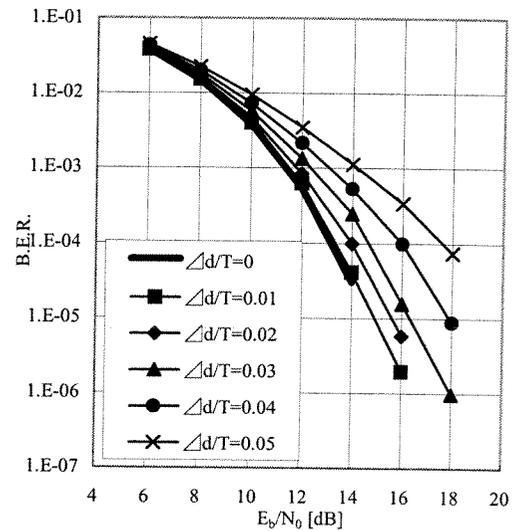


Fig. 11. BER performance of 4-PAM.

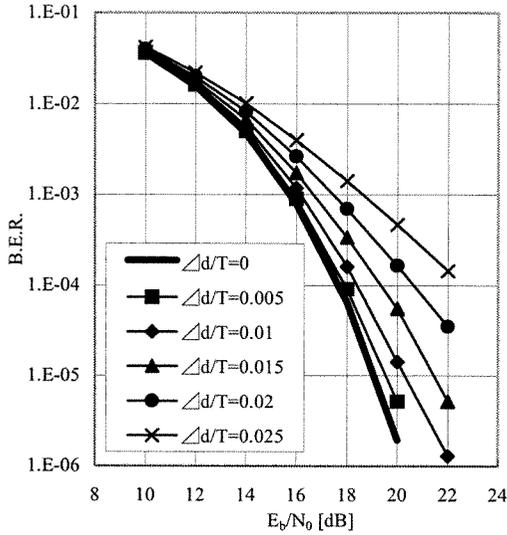


Fig. 12. BER performance of 8-PAM.

Intersymbol-Interchannel Interference (ISCI).

We are concerned here only with timing errors. The BER performance of 2-PAM, 4-PAM and 8-PAM with several timing errors ($\Delta d/T$: T is a symbol period) is shown in Figs. 10, 11 and 12, respectively. The only phase errors are almost corrected by the FEQ. The BER performance of WOFDM in AWGN is nominally the same as OFDM. But the WOFDM BER performance without timing error is bad theoretical BER performance in Figs. 10, 11 and 12. Because the training sequences for the FEQ are only four symbols. The BER characteristic of WOFDM degrades because of ICI, ISI and ISCI when the timing error is large. Fig. 10 shows that the influence of timing error is not important for the WOFDM using 2-PAM when the mean timing delay is less than several percent of the symbol period.

4.3. CNR characteristic with an imitated channel

The WOFDM CNR characteristic with the channel property in Figs. 2 and 3 is shown in Fig. 13. In this simulation, we assumed that the noise is AWGN with $E_b/N_0 = 57$ (dB). And CNR is calculated with the formula (1). The synchronization with this simulation is using a synchronization of frequency domain. The bands where group delays are large tend to be very attenuated as shown in Figs. 2 and 3. The CNR of these bands are not enough to communicate any longer. As a result, the effects of timing error due to large group delays are negligible in Fig. 13.

5. Conclusions

We have introduced a WOFDM for PLC. It is a better

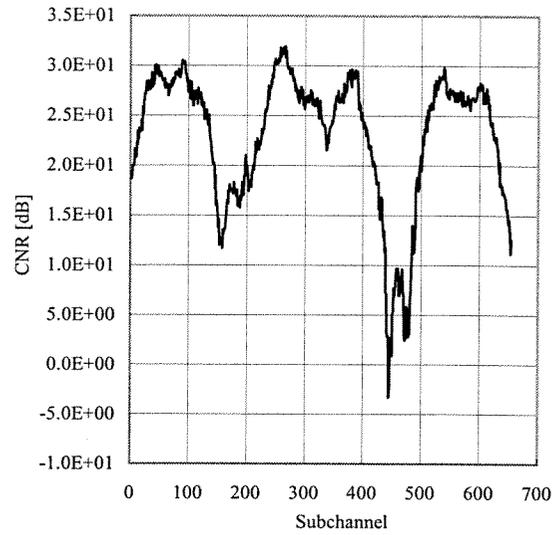


Fig. 13. WOFDM CNR characteristic with the channel property in Figs. 2 and 3.

multicarrier modulation scheme compared to OFDM due to its better-localized orthogonal subchannels in frequency. In our simulation, we used 1024-channel DWT with $g=4$. These subchannels have less than -35 (dB) stopband sidelobe properties. In BER performance, the influence of timing error is not important for the WOFDM of 2-PAM when the mean timing delay is less than several percent of the symbol period. And the effects of timing error due to large group delays are negligible because the bands where group delays are large tend to be very attenuated.

In future work, we will do the WOFDM simulation in many imitated channels.

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