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Single Carrier Transmission in Power Line Channels Using Time and Frequency Domain Decision Feedback Equalizations

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Abstract

Orthogonal Frequency Division Multiplexing (OFDM) is a suitable candidate for broadband Power Line Communications (PLC). However, OFDM systems suffer from high Peak to Average Power Ratio (PAPR), subcarriers synchronization. It has shown that single carrier transmission with frequency domain equalization is an alternative technique for OFDM in broadband wireless systems. In this paper we describe different categories of single carrier systems and investigate the BER performance of single carrier PLC systems employing time and frequency domain decision feedback equalization techniques, and convolution coding. The distractive factors like impulsive noise and multipath effects are taken into account. The results of our simulations are compared with OFDM systems.

Keywords: impulsive noise, orthogonal frequency division multiplexing, power line communication, single carrier transmission, time and frequency domain decision feedback equalization

2000 Mathematics Subject Classification: 94A14, 94A99, 94B10, 90B18, 94A05.

Computing Classification System: B.4.4 Simulation

1 INTRODUCTION

Utilizing the power line for data transmission has been the subject of interest for many years. Ability of power lines in high speed data transmission has made them attractive for many different applications like high speed internet transmission services, computer networks design, and etc. However, there are some challenges for communications over power lines such as electromagnetic compatibility issues, noise, attenuation, and multipath propagation (Biglieri, E., 2003), (Ma, Y. H., So, P. L, et al., 2005). The main reasons causing bit errors in Power Line Communication (PLC) are multipath echoes and impulsive noises (Ma, Y. H., So, P. L, et al., 2005).

The noises in power line channels are classified into five different categories (Hooijen, O. G., 1998), (Zimmermann, M., and Dostert, K., 2002): Colored background noise, narrowband noise, periodic impulsive noise asynchronous to the mains frequency, periodic impulsive noise synchronous to the mains frequency, and asynchronous impulsive noise. The first three noises are stationary and considered as background noises. The last two noises are time-variant and categorized as impulsive noises (Zimmermann, M., and Dostert, K., Feb. 2002). The Power Spectral Density (PSD) of impulsive noise is considerably higher than the background noise at most frequency, causing bit or burst errors (Biglieri, E., 2003), (Zimmermann, M., and Dostert, K., Feb. 2002).

The impedance mismatching in the PLC channels causes multipath signal propagation. Hence, the result is a multipath scenario with frequency selective fading (Biglieri E., 2003), (Zimmermann, M., and Dostert, K., Apr. 2002) and (Zimmermann, M., and Dostert, K., 1999). Different models for PLC channels have been proposed. Among them, the proposed echo model in (Zimmermann, M., and Dostert, K., Apr. 2002) has been used most by different researches (Biglieri, E., 2003), (Ma, Y. H., So, P. L, et al., 2005).

The properties of Orthogonal Frequency Division Multiplexing (OFDM) like its, resistance against multipath effects and impulsive noise, bandwidth efficiency, elimination of Inter Symbol Interference (ISI) and Inter Carrier Interference (ICI), make it attractive for PLC systems (Biglieri, E., 2003). Bit Error Rate (BER) performance of OFDM systems in PLC channels have been considered and simulated in (Ma, Y. H., So, P. L, et al., 2005), (Anatory, J., Theethayi, N., et al., 2006) and (Amirshahi, P., Navidpour, S. M., et al., 2006). The impacts of multipath echoes and impulsive noise on performance of PLC were considered in (Ma, Y. H., So, P. L., et al., 2005). OFDM systems suffer from high Peak to Average Power Ratio (PAPR), subcarriers synchronization (Biglieri, E., 2003).

Single-carrier transmission is the conventional approach to digital communications. With time-domain equalization (TDE), this technique has been used for decades on time dispersive channels. Despite this, there was a widely shared perception within the digital broadcasting community in the early 1980' that single-carrier transmission would not work for mobile reception, and OFDM was viewed as the only realistic transmission technique for this application (Sainte-Agathe, F., and Sari, H., 2005). Then, in (Sari, H., Karam, G., et al., 1993), (Sari, H., Karam, G., et al., 1995) it was proposed that Single-Carrier Transmission with Frequency Domain Equalization (SCT-FDE) is as an alternative to OFDM and showed that this technique can achieve the performance of OFDM while avoiding its main drawbacks which are its high PAPR and carrier synchronization. In order to improve the performance of SCT-FDE system, in (Benvenuto, N., and Tomasin, S., June 2002), (Falconer, D., Ariyavisitakul, S. L., et al., 2002) was proposed to use a Decision Feedback Equalizer (DFE) with time-domain feedback filter. More recently, in (Benvenuto, N., and Tomasin, S., Sep. 2002), it was proposed SCT-FDE scheme where both the feedforward and the feedback parts of the DFE are implemented in the frequency domain.

Different categories of SCT systems are shown in Fig. 1. Depending on time or frequency domain equalization, SCT is divided into two categories: Single-Carrier Transmission with Time Domain Equalization (SCT-TDE), and Single-Carrier Transmission with Frequency Domain Equalization (SCT -FDE). Each category based on equalization techniques, is classified into two groups: linear and nonlinear. The BER Performance of SCT-FDE system is close to OFDM and better than SCT-TDE system, so it more attractive than SC-TDE (Khanzada, T. J. S., Ali, A. R., et al., Jan. 2008)-(Benvenuto, N., and Tomasin, S., 2002). Nonlinear (decision feedback) equalization exhibits a better BER performance than linear equalization, so in this work, only the Single Carrier Transmission with Time Domain Decision Feedback Equalization (SCT-TDDFE) and Single Carrier Transmission with Frequency Domain Decision Feedback Equalization (SCT-FDDFE) systems are investigated. There are two types of SCT-FDDFE systems: One type of them was presented in (Benvenuto, N., and Tomasin, S., June 2002), (Falconer, D., Ariyavisitakul, S. L., et al., 2002) in which the feedforward and backward filters are implemented in the frequency and time domain, respectively. The number of feedback coefficients in this type is small, and this limits the performance improvement with respect to linear equalizer (Sainte-Agathe, F., and Sari, H., 2005). According to results in (Benvenuto, N., and Tomasin, S., June 2002), the BER performance of this system is worse than OFDM system without using channel coding, and it performs close to OFDM in presence of channel coding. Another type of SCT-FDDFE was suggested in (Benvenuto, N., and Tomasin, S., Sep. 2002) that both feedforward and backward parts are implemented in frequency domain. The BER performance of this system is better than that of OFDM for both coded and uncoded cases (Khanzada, T. J. S., Ali, A. R., et al., Jan. 2008), (Khanzada, T. J. S., Ali, A. R., et al., May 2008).

Comparison of OFDM and SCT-FDDFE systems in (Khanzada, T. J. S., Ali, A. R., et al., Jan. 2008)-(Benvenuto, N., and Tomasin, S., June 2002) has been made in wireless systems. SCT-FDDFE systems did not investigate in power line channels until now, and there is no paper that compares the BER performance of these systems with OFDM in PLC. As the characteristics of channel and noise in PLC are different from wireless systems, this paper compares the BER performance of SCT-TDE and SCT-FDE systems under the effects of impulsive noise and multipath PLC channel, then the simulation results are compared with OFDM systems.

This paper is organized as follows; in section II the general structures of OFDM, SCT-FDE and SCT-TDE are presented. Then OFDM and SCT-FDDFE systems are described and coefficients of filters are calculated. In sections III and IV the channel and noise models in PLC systems are described. In section V the simulation results are presented. Finally, section VI contains the conclusions.

2 SYSTEM MODEL

Fig. 2, shows the simple transceiver block diagrams of OFDM and SCT-FDE systems. Both OFDM and SCT-FDE systems use Cyclic Prefix (CP) in transmitter for reducing ISI, and utilize one Fast Fourier Transform (FFT), and one Inverse FFT (IFFT) block in there structures. OFDM systems utilize IFFT and FFT blocks in transmitter and receiver side, respectively, and decision was made in frequency domain signal. In SCT-FDE systems both FFT and IFFT operations are used in receiver side. IFFT operation is located between equalization and decision, and spreads the noise over all the samples in time domain. Decision signal in this system is in time domain.

In SCT-TDE systems, the input data is coded and modulated in transmitter, and then enters the channel. At the receiver, the received signal is fed to an equalizer block and decision was made based on equalizer output. CP, FFT, and IFFT blocks do not use in these systems.

2.1 OFDM System Model

The basic idea of OFDM is to transform frequency-selective fading into flat fading by dividing the available bandwidth, W, into N frequency bands with separate orthogonal subcarriers. The subcarrier spacing is small enough to suppose that channel frequency response is flat in each subchannel. The general structure of an OFDM system is shown in Fig. 3. In the transmitter, the high-speed data after coding, interleaving, and mapping, is converted to parallel and transmitted in subchannels. The data in each subchannel are modulated by either Quadrature Amplitude Modulation (QAM) or Phase shift keying (PSK), and then are fed to IFFT block to generate an OFDM signal. Finally, the CP is added to signal for elimination ISI. At the receiver the CP is removed, and the parallel data are fed to FFT block. The FFT output during the k^{th} OFDM symbol can be written as (2.1):

$$R_n(k) = H_n(k)a_n(k) + w_n(k) \qquad n = 1,2,\ldots,N \tag{2.1}$$

Where $a_n(k)$, $H_n(k)$ and $w_n(k)$ are the transmitted data, channel frequency response, and noise in n^{th} subchannel. The data equalization in OFDM system can be done by multiplication of complex coefficient bank at the FFT output. The equalization is performed by either Zero Forcing (ZF) or Minimum Mean Square Error (MMSE) criterion. The coefficient set in ZF and MMSE criterions are calculated by (2.2) and (2.3), respectively (Proakis, J. G., 2001):

$$C_n = \frac{1}{H_n} \qquad n = 1,2,\ldots,N \tag{2.2}$$

$$C_n = \frac{H_n^*}{|H_n|^2 + \sigma_n^2/\sigma_a^2} \qquad n = 1,2,\ldots,N \tag{2.3}$$

Where σ_n^2 is the noise power, and σ_a^2 is the power of the transmitted data symbol. ZF criterion eliminates the channel distortion, regardless of noise effects, while the MMSE criterion aims to cancel both channel and noise distortions.

2.2 SCT-FDDFE System Model

Fig. 3, shows the receiver structure of SCT-FDDFE system that both feedforward and backward filters are implemented in frequency domain. In this structure the received signal block enters FFT operation, then the FFT output signal is multiplied by feedforward coefficients of the equalizer. The resulting signal block feeds to IFFT operation, and the first decision for transmitted signal are made based on the IFFT output signal by threshold detector. When the receiver makes a first decision, the decision block is fed to a feedback filter and an iterative DFE is implemented. Optimization of this iterative DFE was presented under the MMSE criterion in (Benvenuto, N., and Tomasin, S., Sep. 2002). At the l^{th} iteration, the output of DFE $Y_n(l)$ was given by (2.4):

$$Y_n(l) = F_n(l)R_n + B_n(l)D_n(l-1) \qquad \text{for} \quad n = 1,2,\ldots,N \tag{2.4}$$

Where $R_n(l)$, $F_n(l)$, and $B_n(l)$ are the output signal of FFT, coefficient of the feedforward and feedback filters at the l^{th} iteration, respectively. $D_n(l-1)$ is the frequency domain decision at the previous iteration. Coefficient sets of the feedforward and feedback filters for initial equalizer decisions are as follows:

$$F_n(0) = \frac{H_n^*}{|H_n|^2 + \sigma_n^2/\sigma_a^2} \qquad n = 1,2,\ldots,N \tag{2.5}$$

$$B_n(0) = 0 \quad n = 1,2,\ldots,N \tag{2.6}$$

The feedforward and feedback coefficients for the rest of the iterations are calculated by (2.7) and (2.8), respectively:

$$F_n(l) = \frac{H_n^*}{\sigma_n^2/\sigma_a^2 + (1-\alpha_{l-1}^2)|H_n|^2} \qquad n = 1,2,\ldots,N \tag{2.7}$$

$$B_n(l) = \alpha_{l-1}[H_n F_n(l) - \frac{1}{N}\sum_{n=1}^{N} H_n F_n(l)] \qquad \text{for} \quad n = 1,2,\ldots,N \tag{2.8}$$

Where parameter α_l is calculated by (2.9):

$$\alpha_l = 1 - \frac{\sqrt{l}}{\sqrt{L}} \tag{2.9}$$

And L is the total number of iterations.

3 POWER LINE CHANNEL MODEL

Several different models were presented for power line channel in literatures (Zimmermann, M., and Dostert, K., 2002). The channel model in this paper is based on proposed echo model in (Zimmermann, M., and Dostert, K., Apr. 2002). The impulse response function of channel can be described as follows (Ma, Y. H., So, P. L., et al., 2005):

$$h(t) = \sum_{m=1}^{M} \beta_m \delta(t - \tau_m) \tag{3.1}$$

Where M is the total number of path components in the channel impulse response. β_m and τ_m are the amplitude and arrival time of the m^{th} multipath components, respectively. In PLC systems it was assumed that channel response is time-invariant and remains constant during the transmission of data, so the quantities of parameters β_m and τ_m are constant in the simulation process and are shown in Table 1.

4 NOISE MODEL

Noises in power line are categorized into two general groups; background noise and impulsive noise (Zimmermann, M., and Dostert, K., 2002). To analyze the PLC system, background noise is modeled as an Additive White Gaussian Noise (AWGN) w_k with mean zero and variance σ_w^2, and the impulsive noise is modeled as the product of two random processes and is given by (4.1):

$$i_k = b_k g_k \tag{4.1}$$

Where g_k is the white Gaussian process with mean zero and variance σ_i^2, and b_k has the Poisson process and is the arrival of the impulsive noise, which means the arrival of the impulsive noise follows the Poisson process with a rate of λ units per second (Ma, Y. H., So, P. L., et al., 2005). So in this model each transmitted data symbol is hit independently by an impulsive noise with a probability distribution b_k and random amplitude g_k (Ghosh, M., 1996). The behavior of impulsive noise is researched and modeled in (Zimmermann, M., and Dostert, K., Feb. 2002). According to this measurement impulsive noise is classified into three different scenarios, the first scenario was captured during the evening hours in a transformer substation in an industrial area and is named "heavily disturbed" scenario, the second is "medium disturbed" scenario that was recorded in a transformer substation in a residential area with detached and terraced houses, and the third scenario was recorded during nighttime in an apartment located in a large building, is "weakly disturbed" scenario (Zimmermann, M., and Dostert, K., Feb. 2002). The parameters of three impulsive noise scenarios are presented in Table 2. Where IAT is the inter-arrival time of the impulsive noise, which is the reciprocal of the arrival rate λ, and T_{noise} is the average impulsive noise duration time. The inter-arrival time is the distance between two impulsive events.

5 SIMULATION RESULTS

Our simulation results of the BER performance of OFDM, SCT-TDDFE and SCT-FDDFE systems in PLC for coded and uncoded cases, under the effects of AWGN noise, weakly, medium and heavily disturbed impulsive noise scenarios, are presented. In this paper similar to (Ma, Y. H., So, P. L., et al., 2005), the impulsive noise to AWGN power ratio Γ is assumed to be constant and equal to 20dB. The BER performance curve versus the average bit energy to the average AWGN noise power E_b / N_0 has been calculated. BPSK Modulation in OFDM subcarriers and single carrier systems with 1/2 rate convolution coding and hard decision viterbi decoding have been employed. In Fig. 5 the BER performances of OFDM, SCT-TDDFE and SCT-FDDFE systems are compared in presence of AWGN noise only. In Figs. 6, 7 and 8 besides AWGN noise, the impulsive noise with weak, medium and heavy disturbance are also considered. In these Figs. no channel coding has been employed. From Fig. 5 it is seen that when only AWGN noise exists, the BER performance of SCT-FDDFE is better than OFDM at all E_b / N_0. However, for AWGN plus impulsive noise in Figs. 6, 7 and 8, the results show that when the disturbance of impulsive noise is weak, SCT-FDDFE is superior to OFDM at all E_b / N_0. Also, when the disturbance of impulsive noise is medium or heavy, SCT-FDDFE performs better than OFDM at E_b / N_0 lower than 22dB. For all uncode cases in Figs. 5, 6, 7 and 8 results show that the BER performance of OFDM is better than SCT-TDDFE at low E_b / N_0, but by increasing E_b / N_0 OFDM performs similar to SCT-TDDFE. Figs. 9, 10, 11 and 12 are compared the BER performance of these systems for different noise scenarios in presence of convolution coding. These results show improvement in performances of all systems with respect to uncoded cases, and OFDM performs better than SCT-TDDFE at all E_b / N_0. Similar to uncode case, SCT-FDDFE is superior to OFDM at all E_b / N_0 in presence of AWGN and weakly disturbed impulsive noise scenarios. But when the disturbance of impulsive is medium or heavy, SCT-FDDFE performs better than OFDM at E_b / N_0 lower than 22dB.

6 CONCLUSION

In this paper, single carrier transmission with time and frequency domain equalization techniques in PLC channels has been investigated. The BER performances of these systems have been simulated and compared with the OFDM system. We showed that in presence of AWGN and weakly disturbed impulsive, single carrier transmission with frequency domain equalization is superior to OFDM at all E_b / N_0. Also, when the disturbance of the impulsive noise is medium or heavy, SCT-FDDFE performs better than OFDM at E_b / N_0 lower than 22dB. Also, we showed that OFDM performs better than SCT-TDDFE, and it is more obvious in coded situations. Our results show that convolution coding improves the systems performance in all cases, too.

Acknowledgment

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Table 1 PARAMETERS OF THE IMPULSE RESPONSE OF PLC CHANNEL (Ma, Y. H., So, P. L., et al., 2005)

L	β_m	τ_m (μs)
1	0.2	0
2	0.1	0.4
3	0.02	0.6
4	0.01	0.7

Table 2 PARAMETERS OF THE IMPULSIVE NOISE SCENARIOS (Ma, Y. H., So, P. L., et al., 2005)

impulsive noise scenario	IAT (s)	T_{noise} (ms)
heavily disturbed	0.0196	0.0641
medium disturbed	0.9600	0.0607
weakly disturbed	8.1967	0.1107

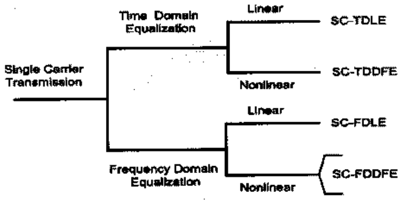

Fig. 1 Different categories of single carrier transmission system

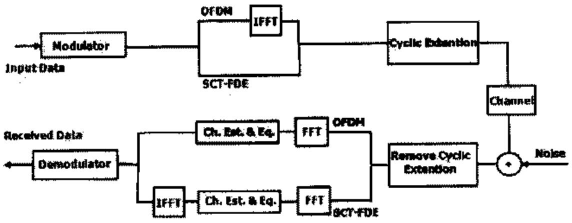

Fig. 2 Transceiver block diagram of OFDM and SC-FDE systems

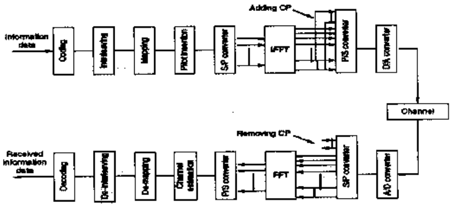

Fig. 3 OFDM system block diagram (Hrasnica, H., Haidine, A., et al., 2004)

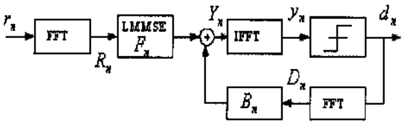

Fig. 4 Block diagram of SC- FDDFE system (Khanzada, T. J. S., Ali, A. R., et al., 2008)

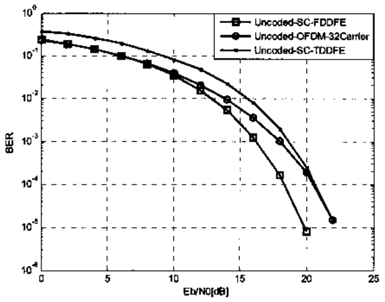

Fig. 5 BER performances comparison of SC-FDDFE, OFDM, and SC-TDDFE systems in the absence of coding, for AWGN noise scenario

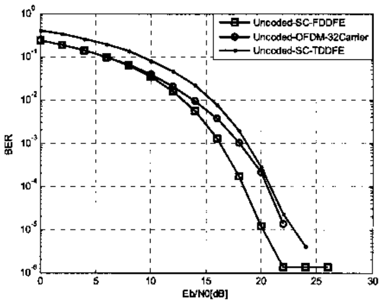

Fig. 6 BER performance comparison of SC-FDDFE, OFDM, and SC-TDDFE systems in the absence of coding, for weakly disturbed impulsive noise scenario

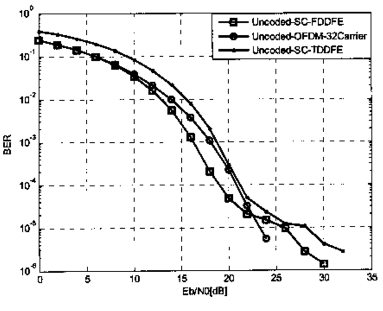

Fig. 7 BER performances comparison of SC-FDDFE, OFDM, and SC-TDDFE systems in the absence of coding, for medium disturbed impulsive noise scenario

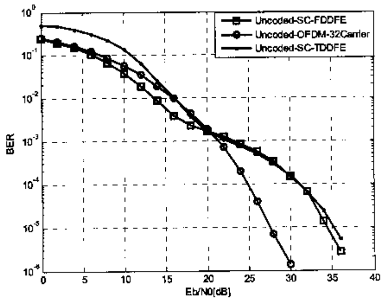

Fig. 8 BER performances comparison of SC-FDDFE, OFDM, and SC-TDDFE systems in the absence of coding, for heavily disturbed impulsive noise scenario

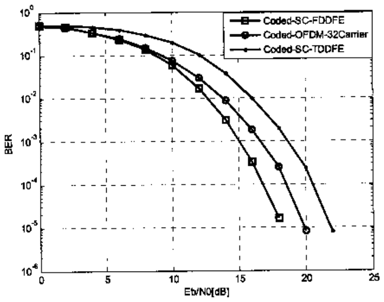

Fig. 9 BER performances comparison of SC-FDDFE, OFDM, and SC-TDDFE systems in the presence of coding, for AWGN noise scenario

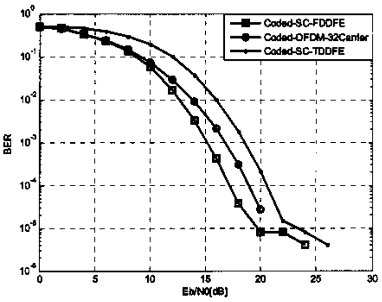

Fig. 10 BER performances comparison of SC-FDDFE, OFDM, and SC-TDDFE systems in the presence of coding, for weakly disturbed impulsive noise scenario

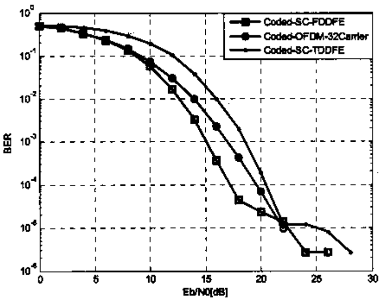

Fig. 11 BER performances comparison of SC-FDDFE, OFDM and SC-TDDFE systems in the presence of coding, for medium disturbed impulsive noise scenario

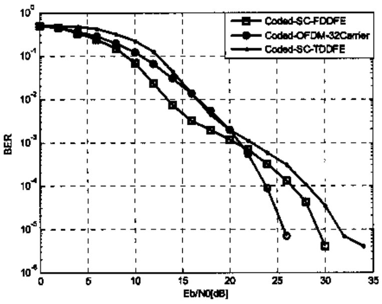

Fig. 12 BER performances comparison of SC-FDDFE, OFDM, and SC-TDDFE systems in the presence of coding, for heavily disturbed impulsive noise scenario

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