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周波数選択性フェージングに優れた耐性を有する一般化 OFDM

ガチャニンハリス[†] 高岡辰輔[‡] 安達文幸[‡]

東北大学大学部工学研究科　電気・通信工学 〒980-8579 宮城県仙台市青葉区荒巻字青葉 05
E-mail: [†]haris@mobile.ecei.tohoku.ac.jp, [‡](takaoka, adachi)@ mobile.ecei.tohoku.ac.jp

あらまし OFDM は高速データ信号を多数の直交サブキャリアを用いて並列伝送する．遅延パスの影響を取り除くため，ガードインターバル（GI）を付加する．しかし，GI を超える長遅延パスが存在すると，サブキャリア間干渉（ICI）とシンボル間干渉（ISI）が発生し，OFDM 伝送特性が著しく劣化してしまう．そこで，本論文では，GI 付加前の OFDM シンボルを K 個まとめて，K 倍の長さの GI を付加する一般化 OFDM（GOFDM）を用いることを提案している．GOFDM 受信では，従来の K 倍の長さの FFT 窓を用いて GOFDM 信号を周波数変換して周波数領域等化した上で，OFDM 復調する．このような GOFDM では，従来の K 倍のパス遅延まで許容することができる．本論文では，計算機シミュレーションにより，超遅延パスの存在下での GOFDM 伝送のビット誤り率特性を求め，従来の OFDM 伝送より優れた BER 特性が得られることを明らかにしている．

キーワード OFDM，周波数領域等化，周波数選択性フェージング．

Introduction of the GOFDM for improving robustness against the severe frequency-selective fading channel

Haris GACANIN[†] Shinsuke TAKAOKA[‡] and Fumiyuki ADACHI[‡]

Electrical and Communication Engineering, Graduate School of Engineering, Tohoku University

05 Aza-Aoba, Aramaki, Aoba-ku, Sendai, 980-8579 Japan

E-mail: [†]haris@ mobile.ecei.tohoku.ac.jp, [‡](takaoka, adachi)@ mobile.ecei.tohoku.ac.jp

Abstract In OFDM signal transmission, high-speed data signal is parallel-transmitted using a number of orthogonal low rate subcarriers. To remove the adverse effect of delayed signal, a cyclic prefix of the OFDM signal is inserted into the guard interval (GI). However, if the delayed signal exceeds the GI, the severe inter-subcarrier interference (ICI) and inter-symbol interference (ISI) are produced, thereby severely degrading the OFDM signal transmission performance. In this paper, we propose a generalized OFDM (called GOFDM), which inserts the K-times longer GI after framing the sequence of K OFDM signals. Since the GI length is K-times longer than the conventional OFDM, the K-times longer delay can be allowed. In this paper, we evaluate, by the computer simulation, the transmission performance of GOFDM in the presence of long time delays and compare with the conventional OFDM signal transmission. It is found that GOFDM can improve the transmission performance in comparison to conventional OFDM by taking the advantage of frequency diversity effect while allowing much longer time delays.

Keyword: OFDM, frequency-domain equalization, frequency-selective fading channel

1. INTRODUCTION

For high-speed data transmission, the presence of multipath with different time delays cause frequency-selective fading, which produces severe inter-symbol interference (ISI) and degrades the transmission performance [1]. Recently, orthogonal frequency division multiplexing (OFDM) has been attracting much attention for high data rate transmission because of its robustness against frequency-selective fading [2]-[4]. In OFDM, the high-speed data sequence is transformed into a number of lower rate data sequences, where each data sequence modulates each orthogonal subcarrier to generate the OFDM signal. Before transmission, a cyclic prefix of OFDM signal is inserted into the guard interval (GI). However, OFDM has high peak-to-average power ratio (PAPR) [5], [6]. To avoid the PAPR problem without requiring a sophisticated processing, we recently proposed a generalized OFDM (GOFDM) [7], [8]. In GOFDM, multiple OFDM signals with reduced number of subcarriers are time-multiplexed in the GOFDM frame that is equal to the time window of the fast Fourier transform (FFT) of conventional OFDM. At the GOFDM receiver, the frequency-domain equalization is applied before recovering the GOFDM signal and then, OFDM demodulation is carried out. The bit error rate (BER) performance of GOFDM has been found to be significantly improved by taking advantage of frequency diversity effect due to frequency-domain equalization, compared to the conventional OFDM signal transmission while reducing the PAPR [7], [8].

It is well known that the BER performance of OFDM severely degrades if the delayed signal exceeds the GI [9]. Recently, several equalization techniques [10], [11], have been proposed to reduce the degradation due to the long time delay, which exceeds the GI. In this paper, we take a different approach and propose to apply GOFDM [7], [8]. For improving the robustness agaist the long time delays, we frame a sequence of OFDM signals into one GOFDM frame and then, add the longer GI than the conventional OFDM. Lets assume that a sequence of K OFDM signals is framed and K-times longer GI is added as a cyclic prefix so that the transmission efficieny is kept the same. With longer GI, the GOFDM signal transmission becomes more robust against the long time delays in comparison with the conventional OFDM signal transmission. At the GOFDM receiver, the frequency-domain equalization (FDE) is first carried out to recover the original sequence of OFDM signals while taking advantage of frequency-diversity effect. We use the FDE based on minimum mean square error (MMSE) criterion as used in single-carrier transmission [12], in multicarrier CDMA (MC-CDMA) [13]-[15], and recently in DS-CDMA [16], [17].

Remainder of this paper is organized as follows. In Sect. 2, the GOFDM is presented to expand the GI length. In Sect. 3, we evaluate, by computer simulation, the BER performance of GOFDM in the presence of long time delays and then, compare it with the conventional OFDM. Sect. 4 provides some conclusions and future work.

2. GOFDM TRANSMISSION SYSTEM TO EXTEND THE GI LENGTH

2.1. TRANSMIT SIGNAL

Fig. 1 shows the transmitter/receiver block diagram of the GOFDM system used to extend the GI length. Let's assume that the conventional OFDM has N_c subcarriers to parallel transmit N_c data-modulated symbols. Throughout the paper, the FFT sample-spaced discrete time signal representation is used.

In GOFDM signal transmission, a sequence of KN_c data-modulated symbols $\{d(i);\ i=0\sim KN_c-1\}$ with $|d(i)|=1$ is transmitted during one GOFDM frame which is K time longer than the conventional OFDM signaling interval. The k-th block symbol sequence is denoted as $\{d^k(i);\ i=0\sim N_c-1\}$, where $d^k(i)=d(kN_c+i)$. The N_c-point inverse FFT (IFFT) is applied to each data block to generate a sequence of K OFDM signals with N_c subcarriers. The GOFDM signal can be expressed using the equivalent lowpass representation as

$$s(t)=\sum_{k=0}^{K-1} s^k(t-kN_c)u(t-kN_c)\,,\ (1)$$

where $s^k(t)$ is the k-th OFDM signal with N_c subcarriers, given by

$$s^k(t)=\sqrt{\frac{2E_s}{T_c}\frac{1}{N_c}}\sum_{i=kN_c}^{(k+1)N_c-1} d^k(i)\exp\left[j2\pi t\frac{i}{N_c}\right]\quad(2)$$

with E_s and T_c representing the signal energy per data symbol and sample period, respectively, $u(t)=1(0)$ for $t=0\sim N_c-1$(elsewhere).

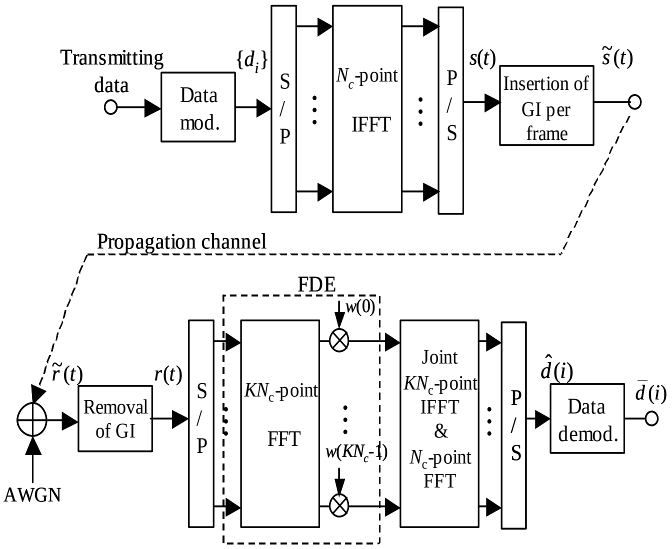


Figure 1. GOFDM signal transmission model.

A sequence of K OFDM signals $\{s^k(t)\}$ makes one GOFDM frame with KN_c samples. Before transmission, the last KN_g samples of the frame are copied as a cyclic prefix and inserted at the beginning of the frame as the GI, as illustrated in Fig.2.

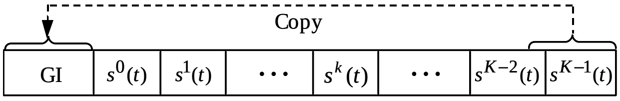


Figure 2. GOFDM frame structure.

2.2 RECEIVED SIGNAL AND FREQUENCY-DOMAIN EQUALIZATION

The GI-inserted sample sequence $\{\tilde{s}(t);\ t=-N_g\sim KN_c-1\}$ is transmitted over the frequency-selective fading channel. We assume that the fading channel is composed of FFT-sample-spaced L discrete propagation paths. We assume block fading, where the path gains remain constant over the duration of N_c+N_g samples (however, path gains are time-varying from one OFDM signal to the next over the duration of GOFDM frame). The discrete-time impulse response $h(t)$ of the channel can be expressed as

$$h(t)=\sum_{l=0}^{L-1} h_l\delta(t-\Delta\tau_l)\quad(3)$$

with $E\left[\sum_{l=0}^{L-1}|h_l|^2\right]=1$, where $\delta(t)$ is the delta function and E[.] denotes the ensemble average operation. The l-th path gain and its time delay are denoted by h_l and $\Delta\tau_l$, respectively. The received GOFDM signal can be represented as

$$r(t)=\sum_{l=0}^{L-1}\tilde{s}(t-\Delta\tau_l)h_l+\eta(t)\quad(4)$$

for t=-N_g~KN_c-1, where $\eta(t)$ is the zero-mean noise sample with a variance of $2N_0/T_c$ due to additive white Gaussian noise (AWGN) with single-sided power spectrum density N_0.

After removing the GI, the received signal is decomposed into KN_c subcarriers by applying KN_c-point FFT:

$$\begin{aligned} R(n) &= \sum_{t=0}^{KN_c-1} r(t)\exp\left[-j2\pi n\frac{t}{KN_c}\right] \\ &= S(n)H(n)+\Omega(n) \end{aligned}, (5)$$

where $S(n)$, $H(n)$ and $\Omega(n)$ are respectively given by

$$\begin{cases} S(n) = \sum_{t=0}^{KN_c-1} s(t)\exp\left[-j2\pi n\frac{t}{KN_c}\right] \\ H(n) = \sum_{l=0}^{L-1} h_l \exp\left[-j2\pi n\frac{\tau_l}{KN_c}\right] \\ \Omega(n) = \sum_{t=0}^{KN_c-1} \eta(t)\exp\left[-j2\pi n\frac{t}{KN_c}\right] \end{cases} . (6)$$

Subcarrier-by-subcarrier one-tap FDE is carried out as follows:

$$\hat{R}(n) = w(n)R(n) , (7)$$

where $w(n)$ is the equalization weight for the nth subcarrier, given by

$$w(n) = \frac{H^*(n)}{|H(n)|^2 + \left(\frac{E_s}{N_0}\right)^{-1}} . (8)$$

for n=0~KN_c-1.

2.3 OFDM SIGNAL DEMODULATION

The equalized nth subcarrier component $\hat{R}(n)$ is transformed back into the time-domain signal $\hat{r}(t)$ by applying KN_c-point IFFT to obtain:

$$\hat{r}(t) = \frac{1}{KN_c}\sum_{n=0}^{KN_c-1}\hat{R}(n)\exp\left[j2\pi t\frac{n}{KN_c}\right] \quad (9)$$

for t=0~KN_c-1, where $\hat{r}^k(t)$ is the k-th OFDM signal with N_c subcarriers. Then, N_c-point FFT is applied to $\hat{r}^k(t)$ to carry out the OFDM signal demodulation as

$$\hat{d}^k(i) = \frac{1}{N_c}\sum_{t=kN_c}^{(k+1)N_c-1}\hat{r}^k(t)\exp\left[-j2\pi i\frac{t-kN_c}{N_c}\right] \quad (10)$$

for i=0~N_c-1 and k=0~K-1, which is the decision variable for data demodulation.

The above KN_c-point IFFT and N_c-point FFT can be jointly performed, which is described below (see Fig.3). From Eqs. (9) and (10), we have

$$\hat{d}^k(i) = \frac{1}{KN_c^2}\sum_{n=0}^{KN_c-1}\hat{R}(n)\sum_{t=kN_c}^{(k+1)N_c-1}\exp\left[j2\pi t\frac{n-Ki}{KN_c}\right] . (11)$$

After some manipulations, we obtain

$$\hat{d}^k(i) = \frac{1}{KN_c}\sum_{n=0}^{KN_c-1}\hat{R}(n)\Psi(n;i,k) , (12)$$

where

$$\begin{aligned} \Psi(n;i,k) &= \frac{1}{N_c}\sum_{t=kN_c}^{(k+1)N_c-1}\exp\left[j2\pi t\frac{n-Ki}{KN_c}\right] \\ &= \frac{1}{N_c}\frac{\sin\left(\pi N_c\frac{n-Ki}{KN_c}\right)}{\sin\left(\pi\frac{n-Ki}{KN_c}\right)} \\ &\quad \cdot\exp\left\{j\pi[(2k+1)N_c-1]\frac{n-Ki}{KN_c}\right\} \end{aligned} . (13)$$

Joint KN_c-point IFFT and N_c-point FFT operation can be seen as a filtering with a transfer function given by Eq.(13) in a frequency-domain (FD).

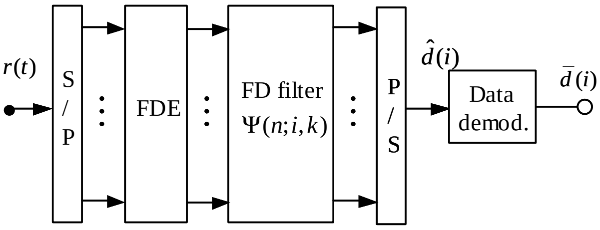


Figure 3. Joint KN_c-point IFFT and N_c-point FFT

3. COMPUTER SIMULATIONS AND DISCUSSION

The average BER performance of GOFDM signal in the presence of long time delays is evaluated by computer simulation and compared with conventional OFDM.

3.1. SIMULATION CONDITION

Table 1 summarizes the simulation conditions. We assume quadrature phase shift keying (QPSK) data modulation. The number of subcarriers of the conventional OFDM signal is N_c=64 while it is 64K for GOFDM. The GI length is N_g=8 samples while for GOFDM it is N_g=8K. The fading channel is assumed to be L=8-path frequency-selective Rayleigh fading channel having uniform power delay profile, i.e., $E\left[|h_l|^2\right]=1/L$ for l=1~L-1, as shown in Fig. 4. Separation between paths $\Delta\tau$ is assumed to be a parameter. For frequency-domain equalization (FDE), we use MMSE-FDE with ideal channel estimation.

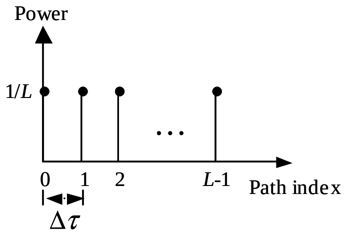


Figure 4. Channel power delay profile.

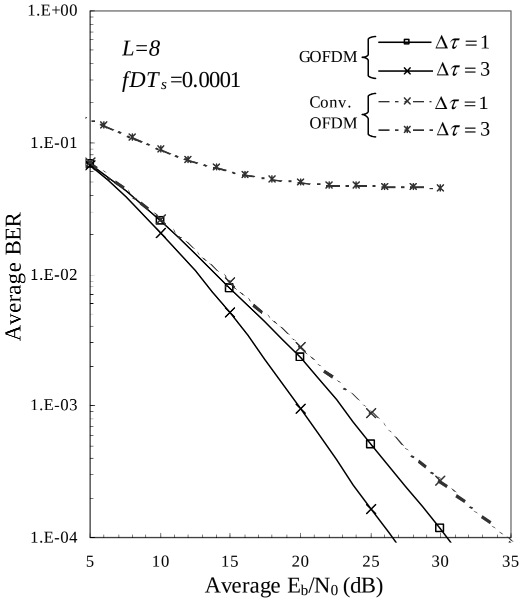
Table 1. Simulation conditions

Transmitter	Transmission System	GOFDM	Conventional OFDM
	Modulation	QPSK	
	FFT points	64	
	Number of block per frame	K=4,8,16	K=1
	GI	N_g=8K	N_g=8
Propagation channel	Frequency-selective Rayleigh fading with L=8-path uniform power delay profile		
Receiver	Number of FFT points	64K	64
	FDE	MMSE	
	Channel estimation	Ideal	

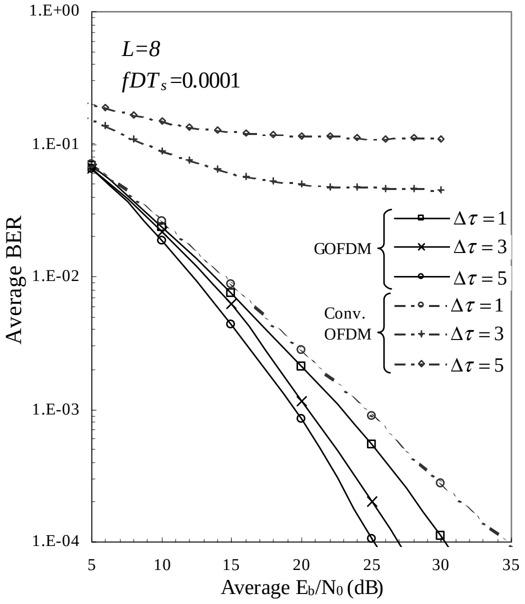
3.2. BER PERFORMANCE

Figs.5(a)-(c) show simulated average BER performance as a function of the average E_b/N_0 with $\Delta\tau$ as a parameter for the GOFDM (K=4~16) and conventional OFDM, where $E_b/N_0=0.5(E_s/N_0)/(1+N_g/N_c)$. It can be seen from Fig.5(a) that when $\Delta\tau$=3, the BER performance of the OFDM degrades because the maximum time delay exceeds the GI and the ICI and ISI are produced. However, for GOFDM, as $\Delta\tau$ increases, the BER performance of the GOFDM with K=4 improves by frequency diversity effect and provides the better BER performance than the conventional OFDM. As can be seen from Figs.5(a)-(c) that as K increases, the GOFDM becomes more robust against longer time delays and furthermore, its BER performance improves.

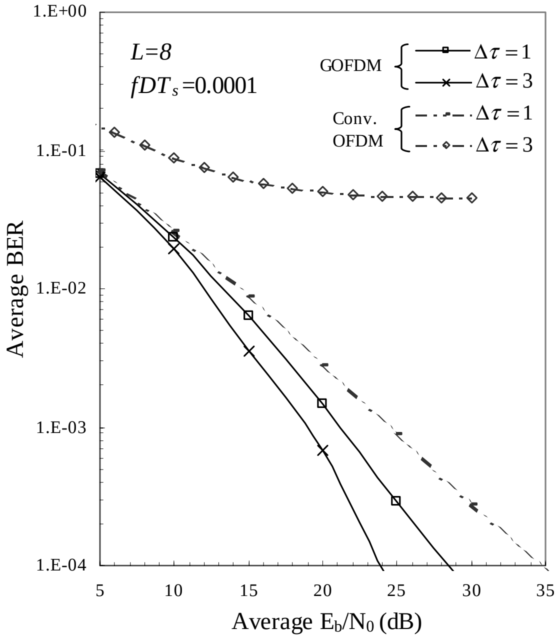
Since the GOFDM expands K times the FFT window size for FDE, compared to the conventional OFDM, the BER performance may be affected by the channel time-selectivity. So, we evaluated how the BER performance of GOFDM is impacted by the channel time-selectivity. Figure 6 plots the simulated BER as a function of the normalized maximum Doppler frequency f_DT_s when E_b/N_0=20dB, where $1/T_s$ is the transmission symbol rate. For comparison, the BERs of the conventional OFDM are also plotted. Since $\Delta\tau$=1 is assumed, all the paths are within the GI even for the conventional OFDM. Assuming 5GHz carrier frequency and a terminal moving speed of 50km/h, the maximum Doppler frequency f_D becomes f_D=231Hz. Then, for a data transmission of 10M~100M symbol/sec (sps), $f_DT_s=2.31\text{x}10^{-6}$ ~ $2.31\text{x}10^{-5}$. It can be seen from Fig.5 that when f_DT_s increases, the BER increases for GOFDM. However, GOFDM gives lower BERs if the value of f_DT_s is below $1.56\text{x}10^{-5}$, $7.81\text{x}10^{-6}$, and $3.85\text{x}10^{-6}$ for K=4, 8, and 16, respectively. These f_DT_s values correspond to the terminal moving speeds of 210km/h, 108 km/h, and 56km/h, respectively, for 5GHz carrier frequency and 100Msps data transmission. This clearly indicates that the proposed GOFDM is very robust against the long time delays while keeping the BER performance better than the conventional OFDM even in the very high-speed mobility conditions.



(a) K=4



(b) K=8



(c) K=16

Figure 5. Simulated average BER performance with $\Delta\tau$ as a parameter.

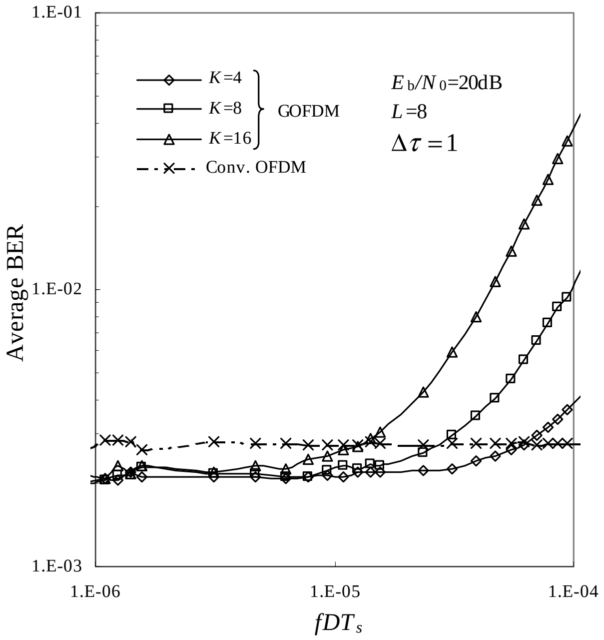


Figure 6. Effect of the Doppler frequency.

CONCLUSIONS

In this paper, we have proposed the GOFDM to expand the GI length for improving robustness against the long time delays, which severely degrades the conventional OFDM signal transmissions. By computer simulation, it has been shown that the proposed GOFDM is more robust against long time delays in comparison to conventional OFDM. Furthermore, the GOFDM provides a better BER performance than the conventional OFDM even in a high-speed mobility environment.

In this paper, the ideal channel estimation was assumed. The achievable BER performance of GOFDM may degrade when practical channel estimation is utilized. The BER performance can be improved by the use of antenna diversity reception, transmit diversity, coding, etc. These are interesting future works.

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