Inter-symbol Interference Suppression Scheme using Periodic Signal Waveform for Fixed-rate COFDM Systems

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Abstract— **This paper proposes an inter-symbol interference (ISI) suppression scheme using the periodic signal waveform for fixed-rate coded OFDM systems. In this scheme, the periodic signal waveform composed of the even-numbered sub-carrier group is used for extending the guard interval, and the odd-numbered sub-carrier group is also enable to be available by means of frequency conversion in order to realize the sub-carrier group selection. This paper mainly focuses on the combining effect of the sub-carrier group selection and the channel coding scheme in the inter-symbol interference (ISI) condition. Computer simulation results show that the proposed scheme has the great potential to create the combined frequency diversity effect without the error floor even in the severe ISI condition.**

I. INTRODUCTION

As one of the most promising techniques for broadband wireless communications systems, OFDM is well known to counter the effect of severe frequency selective fading with reasonable complexity [1]-[3]. The reason is that the cyclic prefix is intentionally inserted to prevent inter-symbol interference (ISI) between successive OFDM symbols. However, its transmission performance is deteriorated significantly when the multipath propagation delays exceed the duration of the guard interval.

To overcome the ISI, the ISI suppression techniques with the variable guard interval length have been proposed [4], [5], where the guard interval length is changed according to the multipath delays. However, these approaches reduce the achievable data rate and require the alteration of the symbol synchronization mechanism. To solve this problem, the periodic signal transmission technique with the fixed duration of the guard interval was proposed [6]-[8]. This technique makes use of the principle that the time domain waveform of one OFDM symbol using only the even-numbered sub-carriers has the periodicity, which can virtually extend the guard interval length. Especially, in [8], we have proposed the sub-carrier group selection diversity for the periodic signal transmission. In this scheme, frequency conversion is performed at the receiver, which enables the odd-numbered sub-carrier group to be available. Moreover, the proper sub-carrier group is chosen between both sub-carrier groups, which improves the performance based on the frequency diversity effect. However, this work does not take into account the effect of channel coding which provides the huge frequency diversity benefit. Therefore, it is surely interesting to see how much the combined diversity effect of the sub-carrier group selection and channel coding is obtained in a variety of the channel conditions.

Considering the background described above, this paper proposes the ISI suppression scheme using the periodic signal waveform for coded OFDM (COFDM) systems. In this scheme, both the sub-carrier group selection and channel coding create the frequency diversity benefit, while the periodic signal transmission suppresses the ISI caused by the large delay spread. As for channel coding and decoding, convolutional coding with Viterbi decoding is adopted and bit-interleaving is performed within one OFDM symbol [3]. Computer simulation results show the bit error rate (BER) for both the proposed scheme and the traditional OFDM transmission with and without channel coding, and then the effectiveness of the proposed scheme is finally demonstrated.

The following section describes the principle of the proposed ISI suppression scheme for COFDM transmission. Section 3 presents the simulation parameters and demonstrates the effectiveness of the proposed approach in terms of the bit error rate (BER). Finally, Section 4 summarizes this paper.

II. PROPOSED ISI SUPPRESSION SCHEME

A. Half Symbol Transmission using Periodic Signal Waveform

To eliminate the ISI, the cyclic prefix is intentionally inserted between successive OFDM symbols. However, the ISI occurs when the multipath delay is beyond the guard interval length T_G. To cope with this problem, the half symbol using the periodic signal waveform is applied to the proposed scheme.

In OFDM transmission using a discrete Fourier transform (DFT) size of N, N modulated sub-carriers with different frequencies are summed up by the inverse DFT (IDFT). Defining T_S as the symbol duration of the IDFT, the sample duration ΔT is T_S/N and all the sub-carriers are exactly spaced by $1/T_S$ in the frequency band.

The OFDM symbol composed of only the even-numbered sub-carriers at $n\Delta T$ is given by

$$s(n\Delta T) = \sum_{i=0}^{N/2-1} d(2i)e^{j2\pi(\frac{2i}{N})n}, \qquad (1)$$

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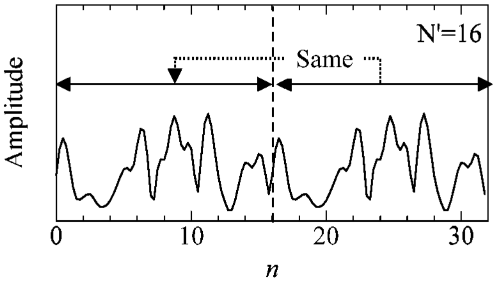
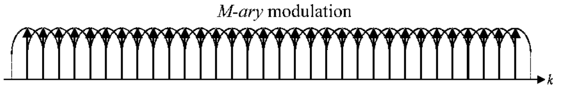
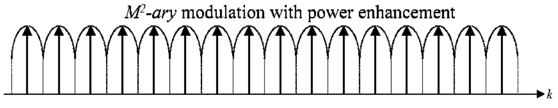


Fig. 1. Periodic signal waveform using only even-numbered sub-carriers for N=32.



(a) Full symbol mode ($\tau_{max} < T_G$)



(b) Half symbol mode ($\tau_{max} > T_G$)

Fig. 2. Spectrum of OFDM signal in each mode for N=32.

where $d(k)$ is the modulated signal.

When N' is defined as $N/2$, Eq. (1) can be rewritten in the following form:

$$s(n\Delta T) = \sum_{i=0}^{N'-1} d(2i)e^{j2\pi(\frac{i}{N'})n}. \qquad (2)$$

From Eq. (2), it can be seen that an OFDM symbol composed of only the even-numbered sub-carriers is defined as the periodic signal with the period of N'(=N/2).

Figure 1 illustrates one example of the periodic signal waveform for N=32. From Fig. 1, it can be confirmed that an OFDM symbol composed of the even-numbered sub-carriers has the period of N'=16. This fact implies that the first half of the OFDM symbol can be considered as the cyclic prefix, while the second half of the OFDM symbol can be used for demodulation at the receiver. In other words, the guard interval length can be virtually extended to $T_G+T_S/2$ by transmitting only the even-numbered sub-carriers.

In the ISI condition such as $\tau_{max} > T_G$, the OFDM symbol is composed of only the even-numbered sub-carriers (half-symbol mode), while the traditional OFDM transmission using N sub-carriers (full-symbol mode) is conducted in the ISI-free condition such as $\tau_{max} < T_G$ [7].

Figure 2 shows one example of the spectrum of OFDM signal at each mode for N=32. As shown in this figure, each sub-carrier power can be enhanced to twice as much as that of the full symbol mode from the point of view of the constant power transmission. Moreover, since the half symbol mode has only N' frequencies, the number of bits per sub-carrier has to be doubled to achieve the constant data rate. Therefore, when M-ary modulation is adopted as the modulation scheme in the full symbol mode, the half symbol mode applies M^2-ary modulation.

B. Sub-Carrier Group Selection in Half Symbol Mode

The sub-carrier group selection is quite effective in improving the performance further [8]. Figure 3 shows the concept of the sub-carrier group selection for N=32. Since the half symbol mode transmits data by using only the even-numbered sub-carrier group, It can be said that the odd-numbered sub-carriers become null. Assuming that the odd-numbered sub-carrier group can be used instead of the even-numbered sub-carrier group, frequency diversity effect is exploited by choosing the sub-carrier groups with the lower average BER. This is because the channel characteristic on the odd-numbered sub-carrier group is different from that on the even-numbered one over the frequency selective fading channels. However, to avoid the ISI in the odd-numbered sub-carrier group, the periodicity has to be generated in the time domain waveform. Thus, when receiving the odd-numbered sub-carrier group, frequency conversion is conducted before the FFT processing, which creates the periodic waveform at the half symbol demodulation. In the odd-numbered sub-carrier group, the received time domain signal after the frequency conversion is expressed as

$$r_{even}(n) = r_{odd}(n)exp(-j2\pi\frac{n}{N}), \qquad (3)$$

where $r_{odd}(n)$ is the received time domain signal for the odd-numbered sub-carrier group.

The feature of the sub-carrier group selection is to choose an appropriate sub-carrier group according to the channel frequency response. In general, the BER of the k-th sub-carrier for the high-level modulation under AWGN conditions is given by

$$P_e(k) = a\ \ erfc(\sqrt{b\gamma_k}), \qquad (4)$$

where γ_k is the instantaneous CNR of the k-th sub-carrier, and both a and b are the coefficients given by a certain modulation scheme. In practice, the variance of noise is required at the receiver to derive the instantaneous CNR γ_k, which is described in the following section.

Thus the average BER for each sub-carrier group is given by

$$P_{even} = \frac{1}{N'}\sum_{i=0}^{N'-1} P_e(2i)$$
$$P_{odd} = \frac{1}{N'}\sum_{i=0}^{N'-1} P_e(2i+1). \qquad (5)$$

After measuring the average BER of each sub-carrier group, the group with lower average BER is chosen as an appropriate

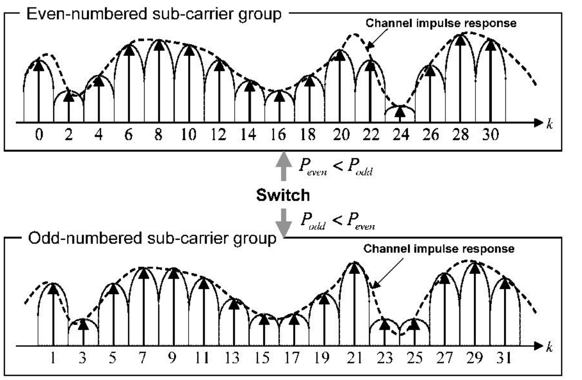


Fig. 3. Concept of proposed sub-carrier group selection for N=32.

TABLE I
TRANSMISSION MODE BASED ON 2-BIT FBI.

ISI condition (b_0)	Sub-carrier group selection (b_1)	Operation
0	0 or 1	Full symbol
1	0	Half symbol using even-numbered sub-carrier group
1	1	Half symbol using odd-numbered sub-carrier group

sub-carrier group. The transmission mode which indicates both the proper sub-carrier group and the ISI condition is sent to the transmitter by using the 2-bit FBI. Table 1 shows the 2-bit FBI b_k, where b_0 and b_1 indicate the ISI condition and the proper sub-carrier group, respectively.

In addition to the sub-carrier group selection, channel coding also provides the frequency diversity effect in the OFDM transmission. The transmission performance depends on the combined effect of these two approaches and the frequency diversity effect is generally enhanced with the increase in the delay spread. Therefore, it is interesting to see how much the combined effect is obtained in various channel conditions, which is the main scope of this work.

C. System Configuration

Figure 4 shows one frame format. The frame has the two pilot symbols only in the head [9], as an example. It is noted that the guard interval length for the pilot symbols is twice as large as that for the following data symbols (=$N\Delta T$/4), which represents the ISI-free condition during the pilot symbols. The channel estimates are used for not only decoding the data symbols but also selecting the proper transmission mode.

Figure 5 shows the configuration of the proposed scheme. At the transmitter, incoming information bits $a(n)$ are are channel coded with bit-interleaving and are modulated according to the transmission mode sent from the receiver. The modulated signal $d(k)$ is fed into the N-point IFFT circuit and the guard interval is added to the IFFT output $s(n)$.

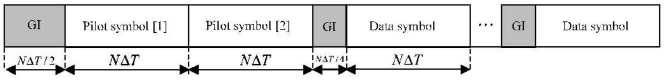


Fig. 4. Frame format.

At the receiver, the guard interval is removed from the received time domain signal. The pilot signals are fed into the N-point FFT circuits and are converted into the N-sub-channel signals $R_p(k)$. The channel frequency response of the k-th sub-carrier $H(k)$ is obtained by multiplying the received signal $R_p(k)$ and the complex conjugate of the pilot signal $P^*(k)$ together. It should be noted that, in the half symbol mode, the channel estimates with N-point has to be modified into that with half N-point because the half symbol mode makes use of only the second half of the received time domain waveform for decoding the data symbols. Regardless of the transmission mode, the received time domain signal is converted into the sub-channel signals by the FFT processing. Finally, the sub-channel signals are de-interleaved and input into a soft decision Viterbi Algorithm (VA).

In order to select the proper transmission mode for the next frame, both the maximum multipath delay τ_{max} and the sub-channel instantaneous CNR γ_k are required. These parameters can be determined by using the channel impulse response $h(n)$ which corresponds to the N-point IFFT processing of the channel frequency response $H(k)$. The maximum multipath delay τ_{max} is measured by extracting only the multipath components beyond a certain threshold level t_h [7]. The criterion for the ISI condition is whether τ_{max} exceeds the duration of the guard interval or not. Moreover, the instantaneous CNR of the k-th sub-channel is given by

$$\gamma_k = \frac{|H(k)|^2}{2\sigma^2}. \tag{6}$$

where σ^2 is the noise variance. It is noted that the noise variance is obtained by averaging the components except for the multipath components. By substituting γ_k into Eq. (4), the BER of each sub-channel is obtained and the appropriate sub-carrier group can be chosen by using Eq. (5).

III. PERFORMANCE EVALUATION

A. Simulation Parameters

Since 2-bit transmission ($M = 4$) is assumed, QPSK and 16QAM are applied to the full symbol mode and half symbol mode, respectively. Hence, the coefficients a and b in Eq. (4) are set to 3/8 and 1/10 [10], respectively. Convolutional coding with Viterbi decoding is adopted as the channel coding and decoding scheme, where a coding rate and a constraint length are 1/2 and 3, respectively. The duration of the guard interval T_G at data symbols is set to $8\Delta T$ for N=32. As the number of data symbols is assumed to be 10 and the channel condition is assumed not to be changed within one frame. The threshold level normalized by the average noise power t_h is set to 15 dB, which is optimized in [7]. Table 2 shows the delay profile of each rms delay spread τ_{rms}, where

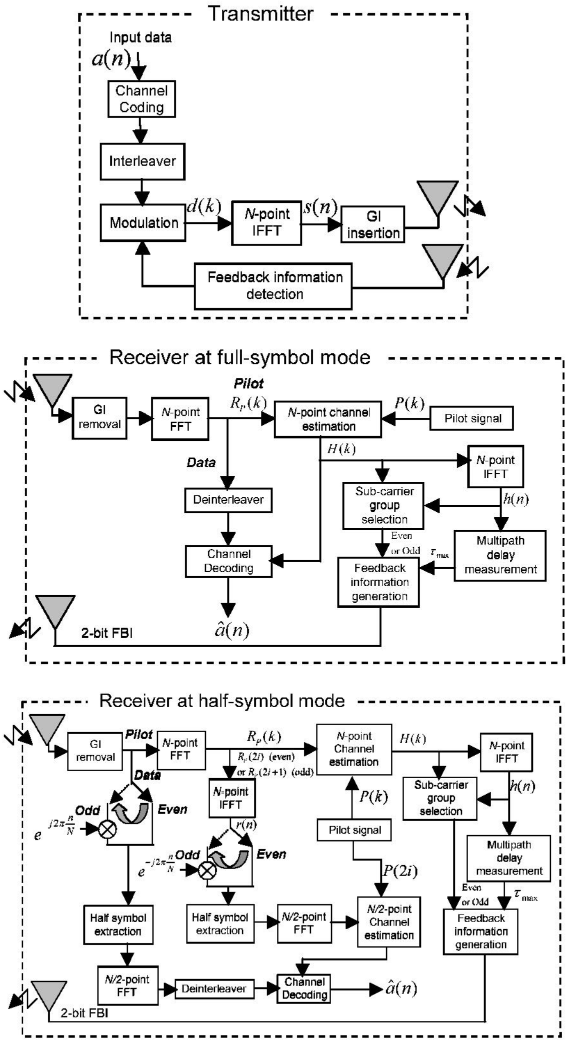


Fig. 5. Overall configuration of proposed scheme.

TABLE II
DELAY PROFILE OF EACH RMS DELAY SPREAD.

Tap number [ΔT]		0.0	3.0	6.0	9.0	12.0	15.0
Average power [dB]	τ_{rms}= ΔT	0.0	-10.0	-20.0	-30.1	-40.1	-50.1
	τ_{rms}= $2\Delta T$	0.0	-5.9	-11.8	-17.8	-23.7	-29.6
	τ_{rms}= $3\Delta T$	0.0	-4.0	-7.9	-11.8	-15.8	-19.7
	τ_{rms}= $4\Delta T$	0.0	-2.5	-4.9	-7.4	-9.8	-12.3
	τ_{rms}= $5\Delta T$	0.0	-0.8	-1.6	-2.4	-3.2	-4.0

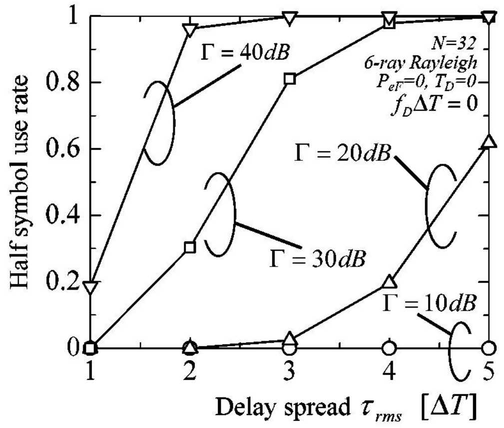


Fig. 6. Half-symbol use rate versus τ_{rms} with a parameter of average CNR Γ.

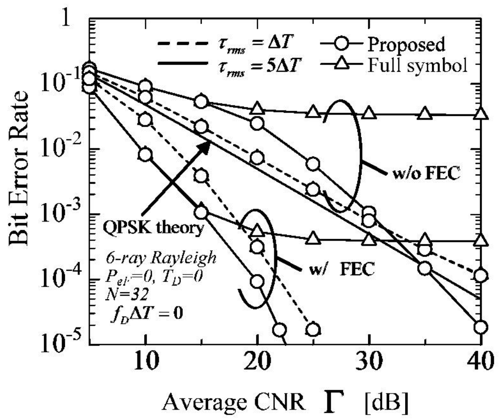


Fig. 7. BER performance versus the average CNR Γ with and without channel coding

a 6-ray exponentially-decaying Rayleigh fading is applied. The frequency and symbol synchronization are assumed to be perfect.

B. Effect of Delay Spread τ_{rms} on Transmission Mode

Figure 6 shows the half symbol use rate versus τ_{rms} with a parameter of Γ, where f_D=0, T_D=0, and P_{eF}=0. From Fig. 9, it is found that the half symbol use rate becomes higher as τ_{rms} increases. This is because the ISI condition due to the large delay spread gives more chances to use the half symbol mode. Moreover, the half symbol use rate depends on Γ and becomes higher as Γ increases. The reason is that the low-level delayed path can be easily observed in the channel impulse response at high average CNRs.

C. BER Performance versus Average CNR Γ

Figure 7 shows the comparison, in terms of the BER performance versus the average CNR Γ, between the proposed scheme and the full symbol scheme, where the maximum

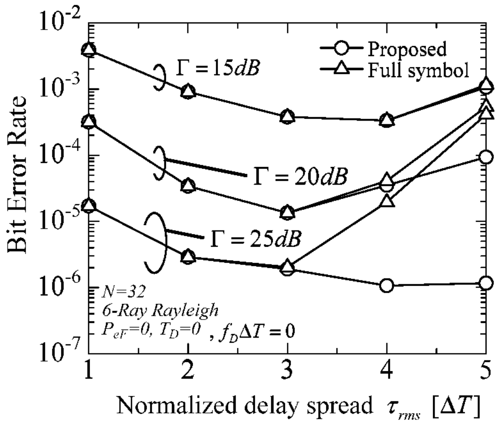


Fig. 8. BER performance versus delay spread τ_{rms} with channel coding.

Doppler frequency $f_D = 0$, the feedback delay T_D=0, and the FBI error rate P_{eF}=0. The theoretical BER for QPSK is also shown for reference. In the case of no channel coding, we can see the effect of the proposed half symbol transmission using the sub-carrier group selection on the BER. In the ISI-free condition τ_{rms}=ΔT, both schemes provide the same performance close to the theoretical BER because the proposed scheme always acts as the full symbol mode. In the severe ISI condition such as τ_{rms}=5ΔT, the full symbol scheme show the significant degradation due to the ISI. On the other hand, the proposed scheme eliminates the error floor perfectly by means of the half symbol transmission and draws the frequency diversity benefit from the sub-carrier group selection for $\Gamma >$ 30dB. Here, it should be noted that, in the proposed scheme, the use of the high-level modulation causes the degradation from the BER of ISI-free condition for $\Gamma <$ 30dB.

When applying channel coding, it is interesting to see that the BER in the ISI condition is superior to that in ISI-free condition irrespective of the scheme. This is because the huge frequency diversity effect due to channel coding is enhanced as the delay spread increases. Moreover, the proposed scheme shows no error floor, while the ISI still troubles the full symbol mode with the error floor. From these results, it can be concluded that the proposed scheme has the great potential to create the combined frequency diversity effect without the error floor even in the severe ISI condition.

D. BER Performance versus Delay Spread τ_{rms}

Figure 8 shows the comparison, in terms of the BER performance versus the delay spread τ_{rms}, between the proposed scheme and the full symbol scheme, where $f_D = 0$, T_D=0, and P_{eF}=0. In the full symbol mode, the BER is improved for $\tau_{rms} < 3\Delta T$ because the frequency diversity benefit is enhanced in the relatively ISI-free condition. However, the BER is degraded significantly for $\tau_{rms} > 3\Delta T$ because of the ISI. On the other hand, the proposed scheme is quite effective in the ISI condition. Especially at Γ=25dB, the BER is gradually improved as τ_{rms} increases. This is because the increase in τ_{rms} enhances the combined diversity effect, and its effect outperforms the degradation due to the use of the high-level modulation.

IV. CONCLUSION

This paper proposed an inter-symbol interference (ISI) suppression scheme using the periodic signal waveform for fixed-rate coded OFDM systems. The proposed scheme utilizes the periodic signal waveform to prevent the ISI and applies the sub-carrier group selection and channel coding to exploit the combined frequency diversity effect. Computer simulation results showed that the proposed scheme not only suppresses the ISI perfectly by using the periodicity of the waveform but also retains the huge combined effect even in the ISI condition. The proposed scheme shows the significant improvement in the BER compared with the traditional OFDM transmission as the ISI condition becomes severe.

REFERENCES

[1] V. Nee and R. Prasad, "OFDM for Wireless Multimedia Communications," Artech House, 2000.
[2] T. S. Rappaport, A. Annamalai, R. M. Buehrer, and W. H. Tranter, "Wireless Communications : Past Events and a Future Perspective," IEEE Communications Magazine, Vol. 40, No. 5, pp.148-161, May 2002.
[3] S. Hara and R. Prasad, "Multicarrier techniques for 4G mobile communications," Artech House Publishers, 2003.
[4] ETSI, "Digital Broadcasting System for Television, Sound and Data Services; Channel Coding and Modulation for Digital Terrestrial Television," ETS 300744.
[5] Y. Asai, Y. Suzuki, and M. Umehira, "Adaptive Coded OFDM System Employing Guard Interval Length Control," Proc. of WPMC 2001, pp. 1071-1076, Sept. 2001.
[6] W. Matsumoto and H. Imai, "Study on Half-symbol Scheme of OFDM Modulation and MC-CDMA Modulation," IEICE Trans. Commun., vol. J85-B, no.6, pp. 910-921, June. 2002.
[7] F. Maehara, F. Sasamori, and F. Takahata, "Inter-symbol interference suppression scheme using even-numbered sub-carriers for fixed-rate OFDM systems," IEICE Trans. Commun., Vol.E87-B, No.4, pp. 866-872, April 2004.
[8] F. Maehara, H.-P. Kuchenbecker, "Inter-symbol interference suppression scheme employing sub-carrier group selection for fixed-rate OFDM systems," Proc. 9th International OFDM-Workshop, Sept. 2004.
[9] IEEE P802.11a, "High speed physical layer (PHY) in 5GHz band," 1999.
[10] S. Sampei, "Applications of digital wireless technologies to global wireless communications," Prentice Hall PTR, 1997.