Reduction of Out-of-Band Power in SC-OFDM Systems

Fumihiro Hasegawa[1], Masatsugu Higashinaka[2], Akihiro Okazaki[3] and Fumio Ishizu[4]
Mitsubishi Electric Corporation, Kamakura, Kanagawa, 247-8501, Japan

and

Damien Castelain[5], Loïc Brunel[6] and David Mottier[7]
Mitsubishi Electric R&D Centre Europe, Rennes, France

A new out-of-band power suppression method for SC-OFDM is proposed in this paper. In the proposed method, phase continuity between SC-OFDM blocks is preserved by inserting one static "anchor symbol". As a result, out-of-band power emissions are reduced without BER performance degradation. Both simulation and experimental results indicate that reduction of out-of-band emissions up to 13dB can be achieved by using the proposed method.

Nomenclature

CP = cyclic prefix
FD = Frequency Domain
FDE = Frequency Domain Equalizer
MSB = Most Significant Bit
OFDM = Orthogonal Frequency Division Multiplexing
SC-OFDM = Single Carrier - OFDM
TD = Time Domain

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1 Researcher, Wireless Transmission System Group, Wireless Communication Technology Dept., Hasegawa.Fumihiro@bk.MitsubishiElectric.co.jp, Not a Member.
2 Head Researcher, Wireless Transmission System Group, Wireless Communication Technology Dept., Higashinaka.Masatsugu@bk.MitsubishiElectric.co.jp, Not a Member.
3 Group Leader, Wireless Transmission System Group, Wireless Communication Technology Dept., Akhiro.Okazaki,@bk.MitsubishiElectric.co.jp, Not a Member.
4 Senior Manager, Wireless Communication Technology Dept., Ishizu.Fumio@bk.MitsubishiElectric.co.jp, Not a Member.
5 Chief Scientist, Communications Technology Division, D.Castelain@fr.merce.mee.com, Not a Member.
6 Research Manager, Wireless Communications Systems, Communications Technology Division, L.Brunel@fr.merce.mee.com, Not a Member.
7 Head of Research, Communications Technology Division, D.Mottier@fr.merce.mee.com, Not a Member.

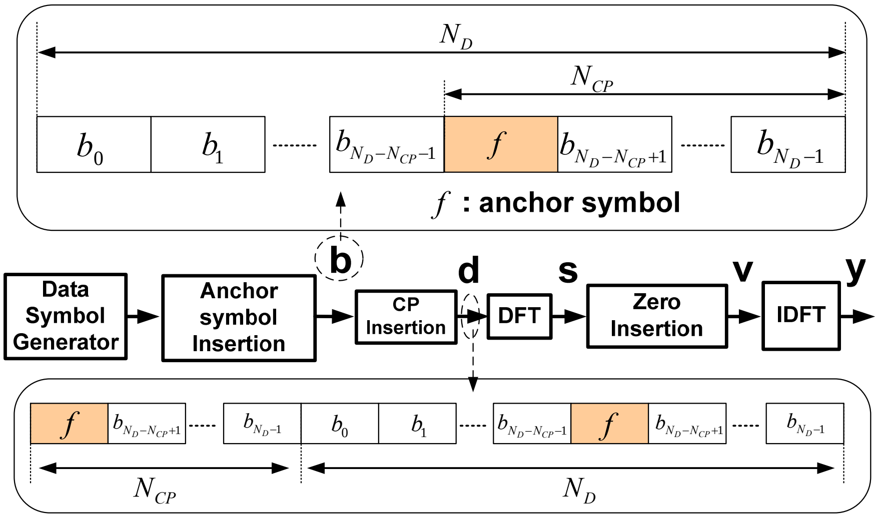

Fig. 1 Proposed SC-OFDM transmission scheme

I. Introduction

SC-OFDM is an attractive block transmission method due to its low peak power and robust performance against multipath fading channels. Peak to average power ratio can be lowered by the use of DFT (Discrete Fourier Transform) as a precoder at the transmitter. Frequency selectivity in the channel can be mitigated with a frequency domain equalizer (FDE). Due to these advantages, SC-OFDM transmission has been adopted as a satellite transmission technique in Digital Video Broadcasting (DVB)-Next Generation Handheld (NGH) [1].

Phase discontinuity between SC-OFDM blocks increases the out-of-band emissions. Techniques to lower out-of-band emissions for OFDM transmission have been proposed in [2,3]. However, these techniques are applicable only to OFDM. Moreover, they are adaptive techniques and optimum parameters must be calculated for each block. Windowing techniques can be implemented to create phase continuity between blocks, but they reduce the effective length of CP (Cyclic Prefix) [4].

Here we propose to use an “anchor symbol”, which “anchors” phases of the first and last sample of each SC-OFDM block. The anchor symbol is inserted at a predetermined position to maintain phase continuity between blocks and to reduce out-of-band emissions. The proposed approach is static and does not depend on data symbols in an SC-OFDM block. Both simulation and experimental results indicate that out-of-band emission can be reduced up to 13dB using the proposed approach.

This paper is organized as follows. The proposed technology is described in Section II. Simulation and experimental results are shown in Section III. Section IV concludes this paper.

II. Proposed SC-OFDM Transmission Schemes

A. Data-only SC-OFDM

The proposed frame structure and SC-OFDM transmitter are shown in Fig. 1. As shown in Fig. 1, the cyclic prefix (CP) is added to N_D information symbols for the k^{th}

block, denoted by $\mathbf{b}^{(k)} = \left[b_0^{(k)}, b_1^{(k)}, \cdots, b_{N_D-1}^{(k)}\right]^T$. The length of CP is defined as N_{CP} and information symbols that correspond to CP can be written as $\mathbf{b}_{CP}^{(k)} = \left[b_{N_D-N_{CP}}^{(k)}, b_{N_D-N_{CP}+1}^{(k)}, \cdots, b_{N_D-1}^{(k)}\right]^T$. Data symbols with the CP for the k^{th} block are precoded by the $N_A \times N_A$ discrete Fourier transform (DFT) matrix where $N_A = N_D + N_{CP}$.

If the $(k,l)^{\text{th}}$ element of an $N \times N$ DFT matrix $\mathbf{W}_N$ is defined as $\left[\mathbf{W}_N\right]_{k.l} = \frac{e^{-j2\pi kl/N}}{\sqrt{N}}$, the precoded symbols can be expressed as $\mathbf{s}^{(k)} = \left[s_0^{(k)}, s_1^{(k)}, \cdots, s_{N_A-1}^{(k)}\right]^T = \mathbf{W}_{N_A}\mathbf{d}^{(k)}$, where $\mathbf{d}^{(k)} = \left[d_0^{(k)}, d_1^{(k)}, \cdots, d_{N_A-1}^{(k)}\right]^T = \left[\mathbf{b}_{CP}^{(k)T}, \mathbf{b}^{(k)T}\right]^T$. Assuming N, N_D and N_{CP} are even numbers, the DFT precoded symbols are mapped onto N subcarriers as follows, $\mathbf{v}^{(k)} = \left[v_0^{(k)}, \cdots, v_{N-1}^{(k)}\right]^T = \left[\mathbf{0}_{1,(N-N_A)/2}, \mathbf{s}^{(k)T}, \mathbf{0}_{1,(N-N_A)/2}\right]^T$, where $\mathbf{0}_{1,M}$ is an all-zero $1 \times M$ vector. The output of the inverse discrete Fourier transform (IDFT) for the k^{th} block, which contains N_A symbols oversampled L times by zero-padding in the frequency domain (FD) can be written as

$$y_{Ln}^{(k)} = e^{j\pi m\left(L - \frac{N_A}{N}\right)} \sum_{m=0}^{N_A-1} d_m^{(k)} \sum_{l=0}^{N_A-1} e^{j2\pi l\left(\frac{n}{N} - \frac{m}{N_A}\right)}, \tag{1}$$

for $0 \le n \le N-1$. For simplicity, a normalization constant is omitted from (1). Note that when $N_{CP} = 0$, phase continuity between SC-OFDM blocks can be preserved by setting the first information symbol in the k^{th} block as an anchor symbol, $d_0^{(k)} = b_0^{(k)} = f$ so that $\mathbf{b}^{(k)} = \mathbf{d}^{(k)} = \left[f, b_1^{(k)}, \cdots, b_{N_D-1}^{(k)}\right]^T$.

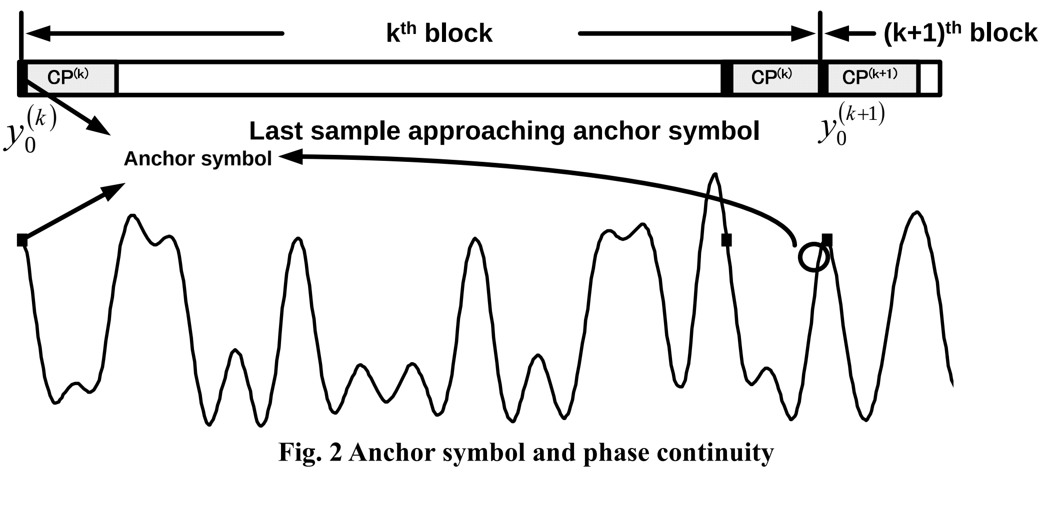

Fig. 2 Anchor symbol and phase continuity

Phase continuity between SC-OFDM blocks can be preserved as follows. As shown in Fig. 2, the anchor symbol f is placed as $b_{N_D-N_{CP}}^{(k)} = f$. In the proposed scheme, an anchor symbol can be any symbol. It is well known that the last sample $y_{LN-1}^{(k)}$ is pulled toward $d_0^{(k)}$ due to the periodic extension of the zero-padded signal at the output of IDFT [5]. Since the first symbol of $\mathbf{d}^{(k)}$ is the anchor symbol, $d_0^{(k)} = b_{N_D-N_{CP}}^{(k)} = f$, phase of $y_{LN-1}^{(k)}$ approaches that of the anchor symbol as shown in Fig. 2.

Note that in the proposed scheme, the loss of spectral efficiency is $\eta = \dfrac{1}{N_D}$. The spectral efficiency can be improved by choosing the anchor symbol from the same quadrant. For example, as shown in Fig. 3, the anchor symbol can be chosen from the symbols in the upper right hand quadrant in 64 Quadrature Amplitude Modulation (QAM) with two most significant bits (MSB) “00”. As the result, phase of the last sample $y_{LN-1}^{(k)}$ returns to the upper right hand quadrant and phase continuity is roughly preserved. If the number of bits per information symbol and number of the fixed MSB are denoted by N_b and N_{bf}, respectively, the loss of spectral efficiency under the proposed scheme is reduced to $\eta = \dfrac{N_{bf}}{N_b N_D}$. However, improvement in the spectral efficiency is obtained by sacrificing the out-of-band emissions performance, as shown in the simulation results in section III.

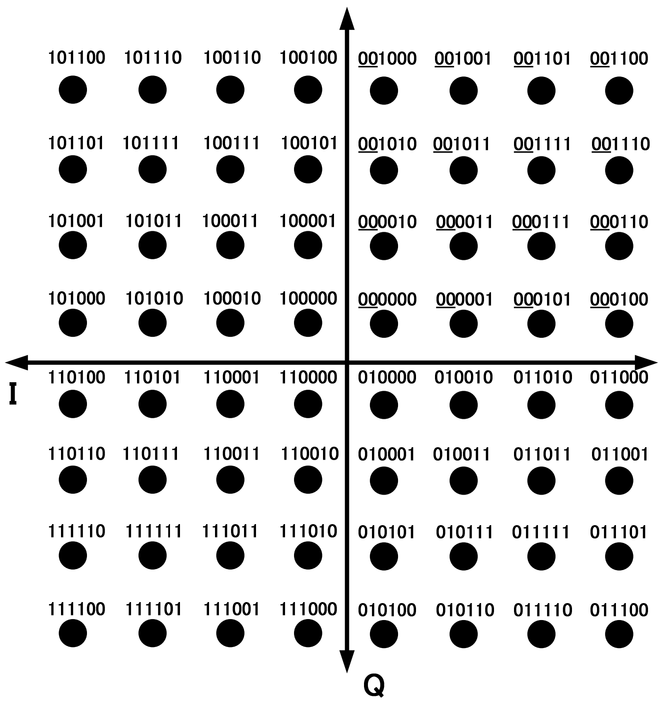

Fig. 3 An example of mapping for the anchor symbol using 64QAM by fixing two MSB in the upper right hand quadrant: fixed bits are underlined in the figure

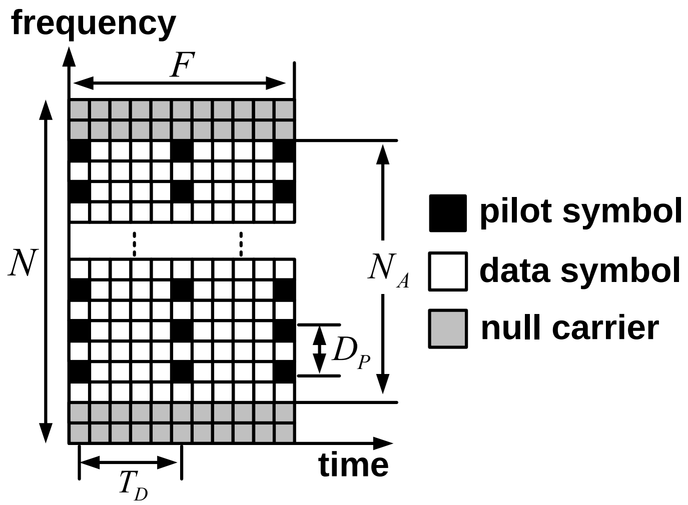

Fig. 4 Proposed frame format using SC-OFDM data blocks and hybrid SC-OFDM blocks

B. Out of Band Emission for Hybrid SC-OFDM Blocks with $N_{CP} = 0$

In this subsection, the proposed scheme is modified for the pilot and data multiplexed "hybrid" SC-OFDM blocks [1]. A case that corresponds to $N_{CP} = 0$ is considered in this section. An arrangement of hybrid and data-only SC-OFDM blocks in a data frame is shown in Fig. 4. Data and pilot multiplexed hybrid SC-OFDM signaling was proposed to improve channel estimation performance in time-varying fading channels [6].

As shown in Fig. 4, N_T pilot symbols are placed in the frequency domain at indices $I_T = \{D_P - 1, 2D_P - 1, \cdots, N_A - 1\}$ with $D_P = N_A / N_T$ where $N_A = N_D + N_T$, and the hybrid symbols are separated by T_D data blocks in the time domain. A data frame contains F data and hybrid SC-OFDM blocks and N_T is assumed to be an even number. The data indices in the frequency domain are given by $k \in I_D$ where I_D contains integer values between 0 and $N_A - 1$ and not belonging to I_T.

Let us define an $N_A \times N_D$ placement matrix for DFT precoded data symbols as

$$[\mathbf{P}_D]_{k,l} = \begin{cases} 1 & k \in I_D, l = k - \lfloor k / D_P \rfloor \\ 0 & \text{otherwise} \end{cases}, \tag{2}$$

and $N_A \times N_T$ pilot symbol placement matrix

$$[\mathbf{P}_T]_{k,l} = \begin{cases} 1 & k \in I_T, l = \lfloor k / D_P \rfloor \\ 0 & \text{otherwise} \end{cases}. \tag{3}$$

Using the placement matrices (2) and (3), the non-oversampled output of the IDFT $\mathbf{x}^{(k)} = \left[x_0^{(k)}, x_1^{(k)}, x_2^{(k)}, \cdots, x_{N-1}^{(k)}\right]^T$ can be expressed as

$$\mathbf{x}^{(k)} = \underbrace{\mathbf{W}_N^H \begin{bmatrix} 0_{N_Z,N_D} \\ \mathbf{P}_D \mathbf{W}_{N_D} \\ 0_{N_Z,N_D} \end{bmatrix}}_{\mathbf{A}_{N,N_D}} \mathbf{d}^{(k)} + \underbrace{\mathbf{W}_N^H \begin{bmatrix} 0_{N_Z,1} \\ \mathbf{P}_T \mathbf{p} \\ 0_{N_Z,1} \end{bmatrix}}_{\mathbf{q}} . \tag{4}$$

As explained in [6], the Zadoff-Chu sequence with phase rotation,

$$p_k = e^{-\frac{j\pi}{N_T}\left(k^2+k\right)} . \tag{5}$$

for $0 \le k \le N_T - 1$, can be used as a pilot sequence to minimize the peak to average power ratio (PAPR) of the hybrid SC-OFDM block.

In this paper, we assume $N_D = N_T$ for the sake of simplicity. If we define a diagonal phase rotation matrix $\mathbf{\Phi} = \mathrm{diag}\left\{1,\cdots,e^{j2\pi n/N},e^{j2\pi(N/2-1)/N}\right\}$ and

$$\mathbf{q}_1 = \left[q_{1,0}, q_{1,1}, \cdots, q_{1,N/2-1}\right]^T = \mathbf{\Phi}\mathbf{W}_{N/2}\left[\mathbf{0}_{1,N_Z/2}, \mathbf{p}^T, \mathbf{0}_{1,N_Z/2}\right]^T , \tag{6}$$

the pilot symbols in the time domain can be expressed as

$$\mathbf{q} = \frac{1}{\sqrt{2}}\left[\mathbf{q}_1^T, -\mathbf{q}_1^T\right]^T . \tag{7}$$

Defining DFT precoded information symbols with guard intervals, $\mathbf{d}_1^{(k)} = \left[d_{1,0}^{(k)}, \cdots, d_{1,N/2-1}^{(k)}\right]^T = \mathbf{W}_{N/2}^H\left[\mathbf{0}_{1,N_Z/2}, \left(\mathbf{W}_{N_D}\mathbf{d}^{(k)}\right)^T, \mathbf{0}_{1,N_Z/2}\right]^T$, it can be shown that

$$\mathbf{A}_{N,N_D}\mathbf{d}^{(k)} = \frac{1}{\sqrt{2}}\left[\mathbf{d}_1^{(k)T}, \mathbf{d}_1^{(k)T}\right]^T . \tag{8}$$

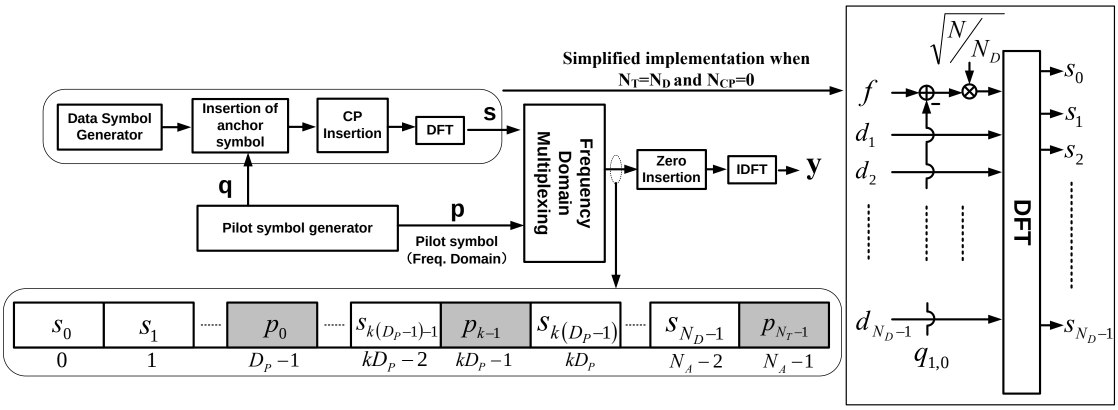

Fig. 5 Proposed hybrid SC-OFDM transmission scheme when $N_{CP} = 0$

It can also be shown that using the pilot sequence defined in Eq. (5), the first element of the pilot symbols in the time domain in Eq. (6) is $q_{1,0} = 0$. To preserve phase continuity between SC-OFDM blocks, the first symbol at the output of IDFT must be the anchor symbol such that $x_0^{(k)} = \left(d_{1,0}^{(k)} + q_{1,0}\right)/\sqrt{2} = f$. Since $q_{1,0} = 0$, $d_{1,0}^{(k)} = \sqrt{\frac{2N_D}{N}} d_0^{(k)}$ and $x_0^{(k)} = f$ can be achieved by setting $d_0^{(k)} = f\sqrt{\frac{N}{N_D}}$. The proposed hybrid SC-OFDM transmission scheme is shown in Fig. 5.

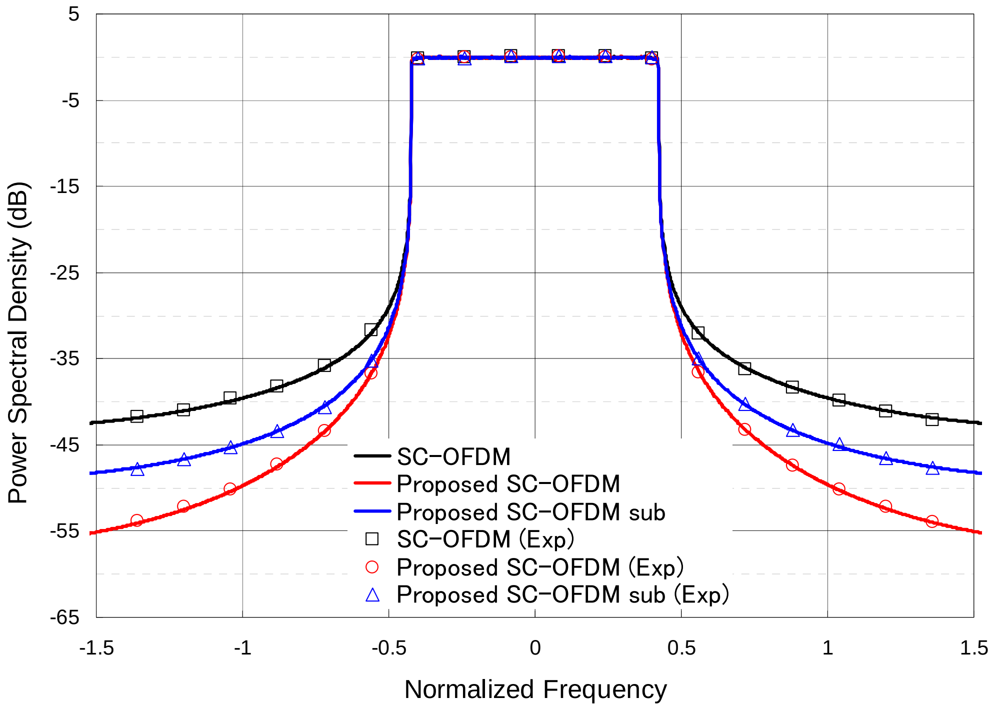

Fig. 6 Power spectrum performance of the proposed schemes for 64QAM

III. Simulation and Experimental Results

The power spectra of the proposed schemes are shown in Fig. 6. Both simulated and experimental results are shown in the figure. In the experiment, signal bandwidth of 5MHz is assumed. Anritsu MG3700A vector signal generator and Anritsu MS2781B signal analyzer are used to generate waveforms and collect data, respectively. In the simulation, a data frame containing 64QAM symbols with the following parameters $N = 512$, $N_A = 432$, $N_{CP} = 0$, $T_D = 5$ and $F = 41$ is assumed. The number of data symbols is set as $N_D = N_A$ and $N_D = N_T = N_A/2$ for a data-only SC-OFDM block and hybrid SC-OFDM block, respectively. In the simulation, the spectra are estimated with the Welch's averaged periodogram method with a NL sample-Hann window [5] and $NL/8$ overlap. As shown in the figure, the proposed scheme labeled "Proposed SC-OFDM" reduces the out-of-band emissions by almost 13dB. The spectrum of the proposed approach with an anchor symbol taken from the upper right hand quadrant of 64QAM constellation shown in Fig. 3 is labeled as “Proposed SC-OFDM sub” in the figure. Note that the loss of data rate due to insertion of the anchor symbol and anchor symbol taken from the upper right hand quadrant is 2.31×10^{-3} and 7.71×10^{-4}, respectively. It is clear from the figure that by improving data efficiency, the out-of-band suppression performance is sacrificed. It is also clear from the figure that simulation and experimental data labeled as “Exp” in the figure agree.

The complementary cumulative distribution function (CCDF) of instantaneous normalized power (INP) of the SC-OFDM, hybrid-SC-OFDM [6] and proposed SC-OFDM transmission schemes are examined. The CCDF of INP is defined as $CCDF(INP(\delta))=P\left(\frac{\left|y_n^{(k)}\right|^2}{E\left[\left|y_n^{(k)}\right|^2\right]}>\delta\right)$. The CCDF of INP for both conventional and proposed hybrid SC-OFDM transmission schemes are shown in Fig. 7. As shown in the figure, the INP performance of the proposed scheme is not affected by insertion of the anchor symbol and remains unchanged from that of the hybrid SC-OFDM transmission scheme [6].

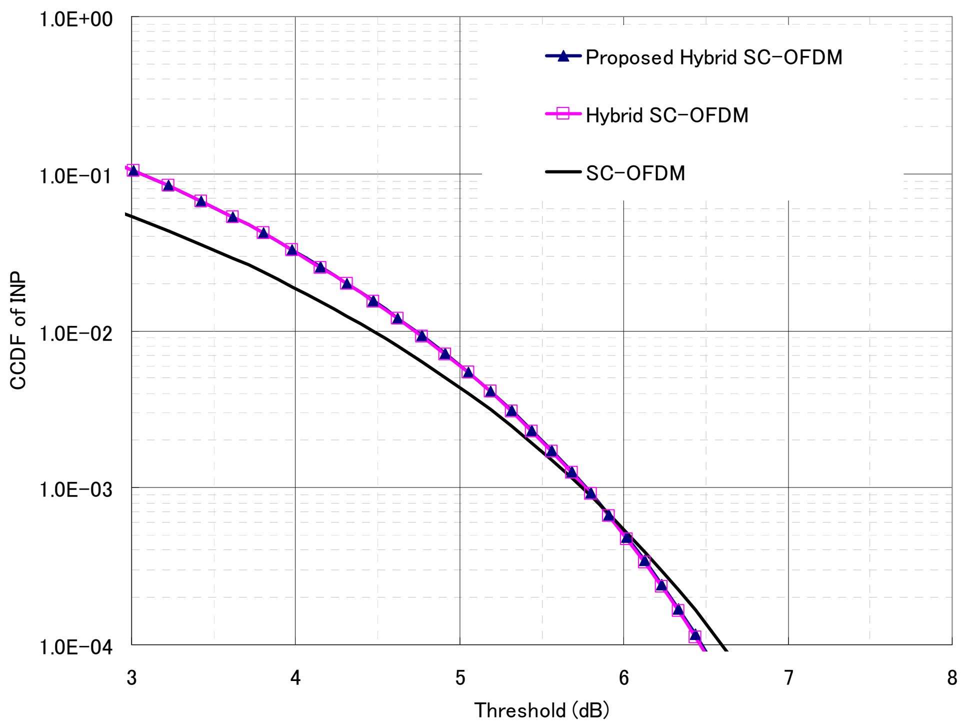

Fig. 7 INP Performance of the proposed schemes

Finally, average bit error performance (BER) of the proposed schemes are shown in Fig. 8. In the simulation, additive noise Gaussian channel (AWGN) and one-path Rayleigh fading channels are considered. In the Rayleigh fading channel, the normalized Doppler frequency is set as $f_D T_S = 5.1\times10^{-3}$. The data frame consists of QPSK symbols and the following parameters $N = 512$, $N_A = 432$, $N_{CP} = 0$, $T_D = 5$ and $F = 41$ are assumed. The received signal model in the frequency domain can be represented by $r_m^{(k)} = g_m^{(k)} \cdot v_m^{(k)} + w_m^{(k)}$ where $E\left[\left|v_m^{(k)}\right|^2\right] = E_S$ and $w_m^{(k)}$ is AWGN with $E\left[\left|w_m^{(k)}\right|^2\right] = \sigma_W^2$. The signal to noise ratio (SNR) per symbol is defined as E_S / σ_w^2. The minimum mean square error equalizer is used where equalization weights can be expressed as $\lambda_m^{(k)} = \hat{g}_m^{(k)*} / \left(\left|\hat{g}_m^{(k)}\right|^2 + \sigma_W^2\right)$ for $0 \le m \le N-1$ and an estimate of channel coefficient is given by $\hat{g}_m^{(k)}$. If we denote M as the number of paths in frequency selective channels, an estimate of the channel coefficients can be obtained with $\hat{\mathbf{g}}^{(k)} = \mathbf{W}_{N,M}\left(\mathbf{W}_T^H \mathbf{W}_T\right)^{-1} \mathbf{W}_T^H \mathbf{S}_T^H \mathbf{r}_T^{(k)}$ where $\mathbf{W}_T$ is obtained by extracting rows that correspond to locations of pilot symbols from $\mathbf{W}_{N,M}$ and $\mathbf{S}_T = \mathrm{diag}\{\mathbf{p}\}$. An $N \times M$ DFT matrix $\mathbf{W}_{N,M}$ is defined as $\left[\mathbf{W}_{N,M}\right]_{k,l} = \frac{e^{-j2\pi kl/N}}{\sqrt{N}}$ for $0 \le k \le N-1$ and $0 \le l \le M-1$. Similarly, $\mathbf{r}_T^{(k)}$ contains observations that correspond to the locations of pilots symbols, extracted from the received signal, $\mathbf{r}^{(k)} = \left[r_0^{(k)}, r_1^{(k)}, \cdots, r_{N-1}^{(k)}\right]^T$. The channel coefficients between hybrid SC-OFDM blocks are estimated by linear interpolation. As shown in Fig. 8, the proposed schemes yield similar BER performance compared to the conventional method.

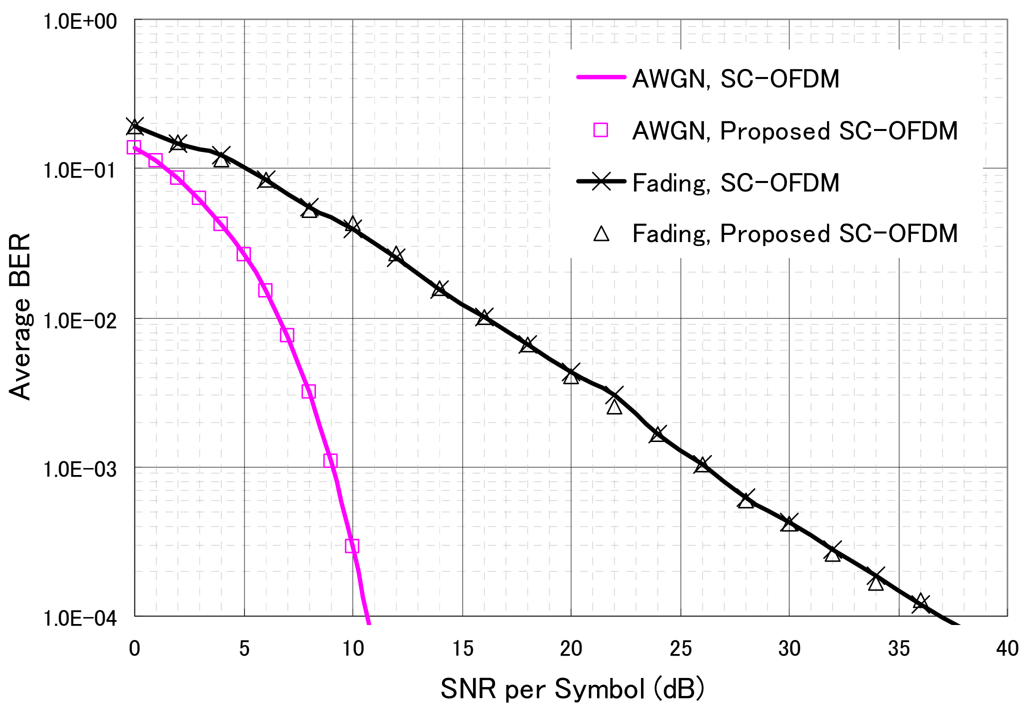

Fig. 8 Bit error performance of the proposed schemes

IV. Conclusion

In this document, a new out-of-band emission reduction method for SC-OFDM was introduced. In the proposed scheme, one fixed symbol was inserted in an SC-OFDM block to reduce the out-of-band power emissions. Both simulation and experimental results show that the proposed scheme reduces the out-of-band emission by nearly 13dB. The proposed scheme has no impact on both BER and INP performance of the SC-OFDM.

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