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Further Results on Performance of LDPC coded IM-OFDM-QOS System

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Abstract

This paper describes a low-density parity-check (LDPC) coded index modulated orthogonal frequency division multiplexing with quasi-orthogonal sequence (IM-OFDM-QOS) and provides performance evaluations of the proposed system. By using QOS as the spreading code, IM-OFDM-QOS scheme can improve the reception performance than IM-OFDM-SS scheme for a given data rate. On the other hand, LDPC code is widely used to the latest wireless communication systems as forward error correction (FEC) scheme and has Shannon-limit approaching performance. Therefore, by applying LDPC code to IM-OFDM-QOS system as FEC scheme, the reception performance can be further improved. Simulation results show that significant signal-to-noise ratio (SNR) gains can be obtained for LDPC coded IM-OFDM-QOS system compared to the LDPC coded IM-OFDM-SS system and the SNR gain increases with the higher code rate.

Keywords : Index modulated orthogonal frequency division multiplexing, log-likelihood ratio, low density parity check code, quasi-orthogonal sequence, spreading code

Ⅰ. Introduction

As a technology to improve a channel capacity and a robustness in wireless communication systems, multiple-input multiple-output (MIMO) and orthogonal frequency division multiplexing (OFDM) are widely used. MIMO can obtain various benefits over single antenna systems by using multiple antennas. Also, OFDM can improve a spectral efficiency by dividing an entire bandwidth into several subchannels. These schemes are applied to the latest mobile and broadcasting communication systems such as Fifth-Generation New Radio (5G NR) and Advanced Television Systems Committee (ATSC) 3.0 [1][2].

On the other hand, spatial modulation (SM), one of the multiple antenna techniques, transmits the information by activating a specific transmit antenna as well as by using constellation symbol mapping [3]. Since only one antenna is activated, the receiver of SM system is not affected by any interference and synchronization problems induced by other antennas. Subcarrier index modulation (SIM) and enhanced SIM (eSIM) were proposed by using the concept

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of SM scheme [4][5]. These schemes transmit information bits by activating or inactivating one or more subcarriers according to the assigned information bit. Also, each active subcarrier can carry a constellation symbol as the additional information. In order to improve SIM and eSIM, OFDM with index modulation (OFDM-IM) which consists of two steps was proposed [6]. First, all available subcarriers are divided into several groups and the subcarriers in each group are indexed. Then, by selecting the index according to the assigned information bits, the subcarrier of corresponding to the selected index is activated. Each active subcarrier can carry the constellation symbol as the additional information in each group.

For OFDM-IM scheme, since only a few of subcarriers are activated, the reception performance gets worse under a deep fading environment. In order to improve the performance under deep fading channel, index modulated OFDM with spread spectrum (IM-OFDM-SS) which combines the ideas of SS and IM was proposed [7]. The concept of IM-OFDM-SS scheme spreads the constellation symbol into all subcarriers in each group by using the spreading code corresponding to information bits. The spreading code is selected by the value of the input index bit in each group instead of the active subcarrier for OFDM-IM scheme. In IM-OFDM-SS scheme, an orthogonal sequence, such as Walsh sequence, is used as the spreading code. Using orthogonal sequence, the required number of the subcarriers in each group and the size of the orthogonal sequence set are equal to the sequence length. Hence, the data rate for the index bits in OFDM-IM and IM-OFDM-SS schemes are same each other.

Recently, for higher data rate, IM-OFDM with quasi-orthogonal sequence (IM-OFDM-QOS) was proposed [8]. IM-OFDM-QOS scheme transmits the index bits by selecting the QOS instead of the orthogonal sequence compared to IM-OFDM-SS scheme. In the sacrifice of the orthogonal property of the sequences, the size of the QOS set is increased to K^2 for a given sequence length of K [9][10]. Therefore, while the number of the subcarriers in each group for IM-OFDM-SS and IM-OFDM-QOS schemes is same, IM-OFDM-QOS scheme can transmit twice index bits compared to IM-OFDM-SS scheme.

On the other hand, low-density parity-check (LDPC) code is applied to the latest communication systems, such as 5G NR, digital video broadcasting (DVB), and ATSC 3.0, as forward error correction (FEC) scheme [11]-[14]. By applying LDPC code to the communication systems, the improved robustness and reception performance can be obtained [15]. Also, LDPC code can offer higher coding gain and lower error floor than the convolutional codes, such as turbo code. In this paper, LDPC code is applied to IM-OFDM-QOS scheme and the performance evaluations are provided. The simulation results show that the significant signal-to-noise ratio (SNR) gain can be obtained by applying LDPC codes to IM-OFDM-QOS system compared to the LDPC coded IM-OFDM-SS system and the SNR gain increases with the higher code rate.

The rest of the paper is organized as follows: Section II introduces the system model of LDPC coded IM-OFDM-QOS. In Section III, the performance evaluations are provided and discussed. Finally, this paper is concluded in Section VI.

Ⅱ. System Model of LDPC Coded IM-OFDM-QOS

1. System Structure of LDPC Coded IM-OFDM-QOS

In LDPC coded IM-OFDM-QOS system, dividing the total available L subcarriers within the bandwidth into G groups, $n(=L/G)$ subcarriers are allocated to each group. And then, the information is transmitted by selecting a QOS of length n according to the input index bits in each group. Since the set size of total possible QOSs is n^2, the number of the index bits that can be transmitted is $(2\log_2 n)$. The detail of QOS is provided in subsection II.2. In addition, when M denotes a modulation order to map the constellation symbols, $(\log_2 M)$ bits can be additionally transmitted by being assigned to the constellation symbol in each group.

Fig. 1 shows the block diagram of the transmitter for LDPC coded IM-OFDM-QOS system. First, the information bits is input into the FEC encoder block and encoded by Bose-Chaudhuri-Hocquenghem (BCH) and LDPC codes. Here, the parity-check matrix of LDPC code for DVB-Satellite-2nd Generation (DVB-S2) is used. Bit splitter divides the encoded bits into G groups and assigns the index and constellation bits according to the required number of bits for each group. In each group, there are three blocks, i.e., a QOS selector, a mapper, and a spreader, and the IM and constellation mapping is independently performed. In QOS selector, the QOS is selected for spreading according to input index bits. Mapper, which is equal to that of the conventional OFDM system, generates the constellation symbol. In spreader, using the selected QOS, the constellation symbol is spread to all subcarriers in the group. The spread symbol vector, s_g, for g-th group can be written as follows:

$$\begin{aligned}\mathrm{s}_g &= [s_{g,0},...,s_{g,n-1}]^T \\ &= [x_g c_{l_g,0},...,x_g c_{l_g,n-1}]^T, \quad l_g \in 0,...,n^2-1\end{aligned} \tag{1}$$

where x_g and $\mathrm{c}_{l_g} = [c_{l_g,0}, c_{l_g,1} ..., x_g c_{l_g,n-1}]^T$ denote the constellation symbol from the mapper in g-th group and the selected QOS according to the input index bits for g-th group, respectively. The spread symbol vectors of all groups are re-arranged to an OFDM block in OFDM block

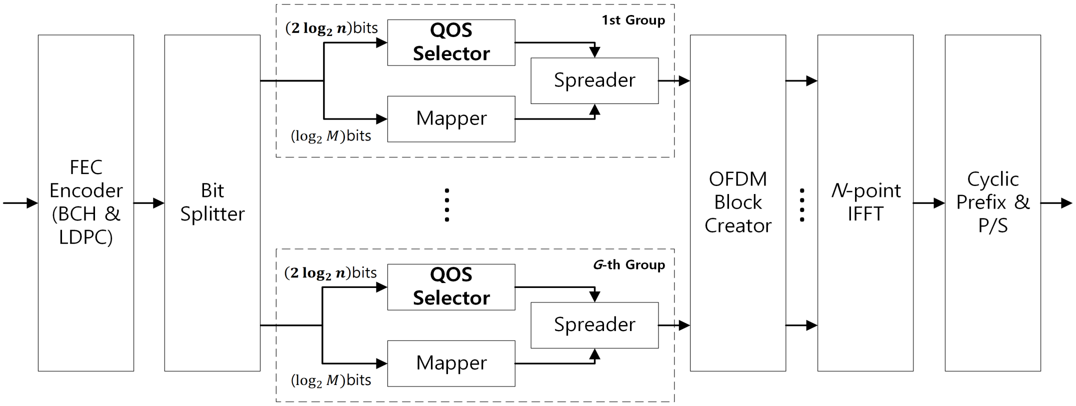

Fig. 1. Block diagram of the transmitter for LDPC coded IM-OFDM-QOS system

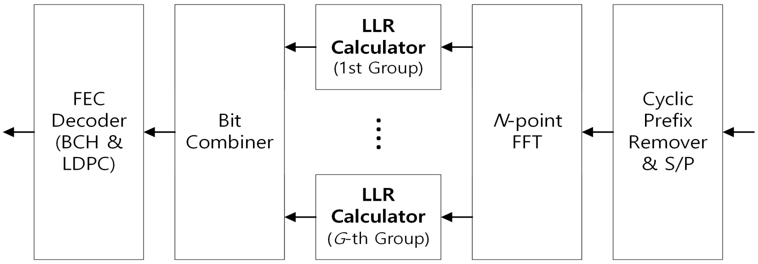

Fig. 2. Block diagram of the receiver for LDPC coded IM-OFDM-QOS system

creator. And then, the OFDM block is passed through N -point inverse fast Fourier transform (IFFT), cyclic prefix (CP) insertion, and parallel-to-serial (P/S) converter in order where N denotes the FFT size. Finally, the generated OFDM signals in the time domain are transmitted.

Fig. 2 shows the block diagram of the receiver for LDPC coded IM-OFDM-QOS system. The received signals are transformed into the signals of the frequency domain by being passed through serial-to-parallel (S/P) converter, CP remover, and N-point FFT. The received signal vector in the frequency domain, r_g, for g-th group can be written as follows:

$$\mathrm{r}_g = \mathrm{h}_g \mathrm{s}_g + \mathrm{w}_g \tag{2}$$

where h_g and w_g denote the channel gain between the transmitter and the receiver for g-th group and additive white Gaussian noise (AWGN) for g-th group, respectively. The FFT output signals are divided into G groups and log-likelihood ratio (LLR) calculation for the index and constellation bits is performed in each group. In (3), the LLR of γ-th bit for g-th group can be calculated where σ^2, l, and x denote the noise variance, all possible indices vector of QOSs, and all possible constellation symbol vector, respectively. And $\chi_{\mathrm{l,x}}^{\gamma_{\mathrm{i}},0}$ and $\chi_{\mathrm{l,x}}^{\gamma_{\mathrm{i}},1}$ denote the sets that γ_{i}-th bit, that is about the index bits, is 0 and 1 for the combinations of all possible indices of QOSs and constellation symbols, respectively. In addition, The LLR of γ_{c}-th bit for g-th group can be calculated in (4) where $\chi_{\mathrm{l,x}}^{\gamma_{\mathrm{c}},0}$ and $\chi_{\mathrm{l,x}}^{\gamma_{\mathrm{c}},1}$ denote the sets that γ_{c}-th bit, that is about the constellation bit, is 0 and 1 for the combinations of all possible indices of QOSs and constellation symbols, respectively. The result bits from LLR calculation in each group are combined in a bit combiner and then BCH and LDPC decoding are performed in FEC decoder. After performing the FEC decoding, the information bits can be obtained.

2. Quasi-Orthogonal Sequences

Let $W_m = \{\omega_i | i = 0, 1, ..., K-1\}$ be the set of binary Walsh sequences of length $K = 2^m$ for a given positive integer m. Then, the set of quaternary sequences $2W_m = \{2w_i | i = 0, 1, ..., K-1\}$ is derived from W_m by multiplying each sequence in W_m by 2 over $\mathbb{Z}_4 = \{0, 1, 2, 3\}$. Based on the Family $\mathscr{A}$ sequences [16], the set of the quaternary QOSs was derived in [10]. For the set of QOSs of length K, the family size is K^2. Let $Q = \{\mathrm{q}_i | i = 0, 1, ..., K^2-1\}$ be the set of quaternary QOSs of length K. The set of QOSs can be partitioned into K nonoverlapping equal size groups $Q_p = \{\mathrm{q}_{pK+i} | \mathrm{q}_{pK+i} = \mathrm{c}_p \quad \oplus_4 2w_i,\ 2w_i \in 2W_m,\ i = 0,1,...,K-1\}$, $p = 0,1,...,K-1$. Here, c_p is the masking sequence for the group Q_p and $\oplus_4$ denotes element-wise in $\mathbb{Z}_4$. Note that any two distinct QOSs belonged to the same group are orthogonal to each other but the correlation between any two distinct QOSs belonged to different groups can be taken on one of four values, i.e., $\pm\sqrt{K/2} \pm j\sqrt{K/2}$ for p of odd number , $\pm\sqrt{K}$ or $\pm j\sqrt{K}$ for p of even number where $j = \sqrt{-1}$ [10].

$$\mathrm{LLR}\left(b_g^{\gamma_{\mathrm{i}}}\right) = \ln\left\{\frac{\sum_{\hat{l}_g \in \chi_{\mathrm{l,x}}^{\gamma_{\mathrm{i}},0}} \left\{\exp\left(-\|\mathrm{r}_g - \mathrm{h}_g \mathrm{c}_{\hat{l}_g} \mathrm{x}\|^2/\sigma^2\right)\right\}}{\sum_{\hat{l}_g \in \chi_{\mathrm{l,x}}^{\gamma_{\mathrm{i}},1}} \left\{\exp\left(-\|\mathrm{r}_g - \mathrm{h}_g \mathrm{c}_{\hat{l}_g} \mathrm{x}\|^2/\sigma^2\right)\right\}}\right\}, \quad \gamma_{\mathrm{c}} = 0, ..., (2\log_2 n) - 1 \tag{3}$$

$$\mathrm{LLR}\left(b_g^{\gamma_{\mathrm{c}}}\right) = \ln\left\{\frac{\sum_{\hat{x}_g \in \chi_{\mathrm{l,x}}^{\gamma_{\mathrm{c}},0}} \left\{\exp\left(-\|\mathrm{r}_g - \mathrm{h}_g \mathrm{c}_{\mathrm{l}} \hat{x}_g\|^2/\sigma^2\right)\right\}}{\sum_{\hat{x}_g \in \chi_{\mathrm{l,x}}^{\gamma_{\mathrm{c}},1}} \left\{\exp\left(-\|\mathrm{r}_g - \mathrm{h}_g \mathrm{c}_{\mathrm{l}} \hat{x}_g\|^2/\sigma^2\right)\right\}}\right\}, \quad \gamma_{\mathrm{c}} = (2\log_2 n), ..., (2\log_2 n) + (\log_2 M) - 1 \tag{4}$$

Ⅲ. Performance Evaluations and Discussions

In Section III, bit error rate (BER) performance of BCH and LDPC coded IM-OFDM-QOS system. In this paper, it assumes that a synchronization between the transmitter and the receiver is perfect and the receiver perfectly knows the channel state information. Computer simulations are performed using MATLAB-based simulator and the parameter set for computer simulations is shown in Table 1.

Table 1. Parameter set for computer simulation

Parameter	Value
FFT size	1024
# of groups	256
Modulation order	IM-OFDM-SS: 16QAM IM-OFDM-QOS: QPSK
LDPC type	DVB-S2 LDPC
LDPC code rate (CR)	3/4, 8/9

Figs. 3 and 4 show the BER performances of IM-OFDM-SS and IM-OFDM-QOS systems for with or w/o BCH and LDPC code under AWGN channel when the data rate is 1536 bits/symbol. Here, the code rate (CR) of 3/4 and 8/9 are used in Figs. 3 and 4, respectively. For the conventional IM-OFDM-QOS system, the SNR gain of 3.3 dB can be obtained at BER=10^{-4} compared to the conventional IM-OFDM-SS system. In Fig. 3, for BCH and LDPC coded IM-OFDM-QOS system, the SNR gains of 8.5 dB and 5.3 dB can be obtained at BER=10^{-4} compared to the conventional IM-OFDM-SS and IM-OFDM-QOS systems, respectively. Also, the SNR gain of 0.5 dB can be obtained at BER=10^{-4} for BCH and LDPC coded IM-OFDM-QOS system compared to BCH and LDPC coded IM-OFDM-SS system. In case of CR of 8/9 as shown in Fig. 4, for BCH and LDPC coded IM-OFDM-QOS system, the SNR gains of 7.2 dB and 4.0 dB can be obtained at BER=10^{-4} compared to the conventional IM-OFDM-SS and IM-OFDM-QOS systems, respectively. Also, the SNR gain of 1.6 dB can be obtained at BER=10^{-4} for BCH and LDPC coded IM-OFDM-QOS system compared to BCH and LDPC coded IM-OFDM-SS system.

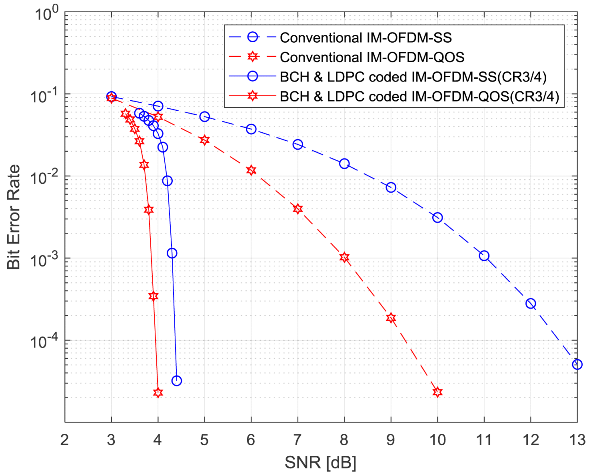

Fig. 3. BER performance of IM-OFDM-SS and IM-OFDM-QOS systems for with or w/o BCH and LDPC code (code rate: 3/4) under AWGN channel, data rate=1536 bits/symbol

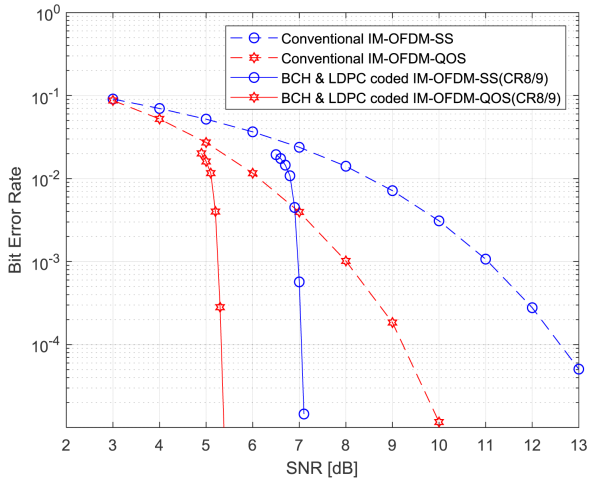

Fig. 4. BER performance of IM-OFDM-SS and IM-OFDM-QOS systems for with or w/o BCH and LDPC code (code rate: 8/9) under AWGN channel, data rate=1536 bits/symbol

Since IM-OFDM-QOS system can transmit twice index bits compared to IM-OFDM-SS system, IM-OFDM-QOS system can use lower modulation order than IM-OFDM-SS system for the same data rate. In the sacrifice of the orthogonal property of the spreading code for IM-OFDM-QOS system, the reception performance outperforms the IM-OFDM-SS system by using a lower modulation order. In addition, BCH and LDPC coded systems can significantly obtain additional robustness by LDPC code.

As a result, BCH and LDPC coded IM-OFDM-QOS system can significantly improve the reception performance compared to the conventional systems. In this paper, we focus on the SNR gain of the proposed scheme with different code parameters for the coded systems. Especially, as shown in Figs. 3 and 4, the SNR gain decreases with the lower code rate. The SNR gains of 1.6 dB and 0.5 dB can be obtained at BER=10^{-4} for code rates of 8/9 and 3/4, respectively. Therefore, the proposed scheme is more suitable for higher code rates.

Ⅳ. Conclusions

In this paper, LDPC coded IM-OFDM-QOS system was described and the performance evaluations were provided. IM-OFDM-QOS system can improve the reception performance compared to OFDM-IM. Also, for IM-OFDM-QOS, since more index bits can be transmitted by using QOS than IM-OFDM-SS, a lower modulation order can be used for a given data rate. Therefore, the improved reception performance can be obtained in the sacrifice of the orthogonal property of the spreading code for IM-OFDM-QOS system. In order to further improve the robustness, LDPC code can be applied to IM-OFDM-QOS system as the FEC scheme. The simulation results show that LDPC coded IM-OFDM-QOS system significantly outperforms the LDPC coded IM-OFDM-SS system and the SNR gain increases with the higher code rate.

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